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Test Beam Results for an Endcap Electromagnetic Calorimeter for the SSC

April 18, 1996

Abstract: We have tested a calorimeter test beam module intended to simulate the endcap electromagnetic calorimeter of the Solenoidal Detector Collaboration (SDC) experiment at the SSC. The test module is manufactured from scintillating tiles and is read out via 1 mm diameter wave-length shifting fibers with shower sampling at ~ 1 radiation length intervals. We describe the mechanical structure of the calorimeter, the shower maximum detector and a pre-shower detector. The results of test beam calibration show that the calorimeter is linear to within 1% and has a resolution of $19.5 \pm 0.1\% / \sqrt{E} \oplus 0.47\% \pm 0.05\%$ for energies up to 200 GeV. Extensive simulated and test beam data show that non-uniform, longitudinal radiation damage to the calorimeter can be corrected allowing the original linearity the calorimeter to be maintained with only a small degradation of resolution with up to $\sim 50\%$ light loss at shower maximum. A "pre-shower detector" improves the charged π rejection by a factor of 2-3 at an electron detection efficiency greater than $97.5\% \pm 0.3\%$.

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1. Introduction

This paper summarizes the design of the endcap electromagnetic calorimeter for the Solenoidal Detector Collaboration (SDC) and the research and prototyping effort that accompanied the design. Because the Superconducting Super Collider was cancelled, the detector will not be built. We hope that the research which led to the design will be useful for other experiments.

The motivation for and requirements on the calorimeter are described, followed by the design of the device. A large prototype was constructed and tested in a beam. We discuss its design and construction and present the results of laboratory measurements, which are compared to performance of the prototype in the test beam.

A significant amount of the effort expended in the design of SSC experiments involved understanding and mitigating the deterioration of the detector components from radiation induced damage. We include a chapter in which Monte Carlo results are compared with test beam data, and where signals (*i.e.* light yield from individual scintillators) in the prototype were degraded to simulate the depth dependence of radiation damage to the active calorimeter components as anticipated at the SSC.

2. SDC Endcap Calorimeter

2.1. CALORIMETER REQUIREMENTS

The basic function of the electromagnetic calorimeter in a 4π magnetic detector is to measure the direction and energy of photons and electrons, and to help distinguish these particles from pion-induced background. In future accelerators, this task must be

accomplished in an environment where the average particle density *per event* is of order 7 charged particles and 15 neutral particles per unit of pseudo-rapidity $(\eta)^\dagger$, and where there may be several events in a single beam-beam crossing. The time between bunch crossings in the detector may be as short as ~ 20 nsec, and the radiation damage induced by these events is sufficient to damage most detector elements over the intended lifetime of the experiment.

We have designed an electromagnetic calorimeter to operate in this environment. It was intended to cover the endcap region of the SDC detector, hence is called the endcap electromagnetic calorimeter (ECEM)^[1], (see fig.1). Table 1 lists the physics requirements for ECEM.

The energy resolution $\sigma(E)$ of the calorimeter is expressed by

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \quad (1)$$

where: a is a constant describing “stochastic” processes (sampling statistics due to shower fluctuations and photon statistics); b is the “constant term” including systematic effects such as calibration, transverse and longitudinal non-uniformities and the effects of radiation damage and c is a noise term, expected to be negligible for this calorimeter. The symbol $\oplus$ indicates addition in quadrature. The SDC calorimeter design report requires that the *transverse* energy resolution be $\sigma(E_t)/E_t = 15\%/\sqrt{E_t} \oplus 1\%$ or better, where $E_t = E \sin\theta$. When combined with the angular coverage of the endcap calorimeter, this translates to a somewhat cruder *total energy* resolution in the endcap region. For our particular design choices, the energy resolution is dominated by the thickness of the absorber plates: 6 mm Pb, just over 1 radiation length ($1 X_0$) thick.

† In our notation the polar angle θ is measured with respect to the beam direction, ϕ is the azimuthal coordinate around the beamline, r is the radius from the beam line in cylindrical coordinates and z is the distance along the beam line. Pseudo rapidity (η) is given by $\eta = -\ln(\tan(\theta/2))$.

Fig. 1 Three dimensional drawing of the SDC detector, showing the ECEM's on the "inside" faces of the endplugs.

The calorimeter is segmented into "towers" whose boundaries project back to the interaction region. The transverse size of a tower is typical of the lateral spread of an electromagnetic shower: $10 \text{ cm} \times 10 \text{ cm}$, or $\delta\eta \times \delta\phi \approx 0.05 \times 0.05$ near $\eta = 1.4$. For an electron that strikes near the center of a tower, about 90% of the total energy is captured within a single tower.

Below we discuss the specific choices for the depth of the pre-shower detector, shower

Table 1. ECEM Calorimeter Performance Requirements.

Calorimeter Property	Requirement
Coverage	$1.4 < \eta < 3.0$
E_t Resolution (<i>rms</i>)	$\delta E_t/E_t < 0.15/\sqrt{E_t} \oplus 0.01$
Pb Absorber Thickness	6 mm
Depth	$25 X_o$ ($1.14 X_o$ per layer)
Longitudinal Segmentation	EM1 ($9X_o$) + EM2 ($16X_o$)
Non-Linearity	$< 1\%$ after correction
Dynamic Range	$20 \text{ MeV} < E_t < 5 \text{ TeV}$
Lifetime	100 yr at $\mathcal{L} = 10^{33} \text{ sec}^{-1} \text{ cm}^{-2}$ (includes safety factor of 10)
“Pre-shower” detector depth	$2.2X_o$
“Shower Max” detector depth	$5.5X_o$
Transverse Segmentation	
$1.4 < \eta < 2.0$	$\delta\eta \times \delta\phi = 0.05 \times 0.05$
$2.0 < \eta < 2.6$	$\delta\eta \times \delta\phi = 0.1 \times 0.1$
$2.6 < \eta < 3.0$	$\delta\eta \times \delta\phi = 0.2 \times 0.2$
Dimensions	
Shape	Right Cylinder
Diameter	5.44 m
Length	0.54 m
Inner Radial Boundary	$\eta = 3.0$
Outer Can Thickness	0.6 cm Al
Front/Back Support Plate thickness	3.0 cm Al

maximum detector, and the method used to compensate for radiation damage to the detector.

2.2. SHOWER MAXIMUM DETECTOR

In addition to measuring the energy of an electron or photon, the calorimeter must measure the position and shape of the electromagnetic showers to aid in particle identification: tagging charged pions that undergo a charge exchange reaction early in their shower develop-

ment and identifying pairs of closely spaced photons from π^0 decay. Because these showers are caused by processes other than pure, single electromagnetic showers their transverse shape is broader. Hence, the calorimeter incorporates a Shower Maximum Detector (SMD) that measures the transverse shape of the shower near the maximum electromagnetic longitudinal energy deposition. The location of the average energy deposition computed from the SMD can also be compared with information from the tracking detectors to associate the EM energy deposition with a charged track. The typical spacial resolution for an EM shower in the SMD is ~ 2 mm perpendicular to the particle direction.

The transverse size (or granularity) of the strips in the shower maximum detector has a lower bound that is determined by cost, and an upper bound determined by the need to measure the transverse shower profile in two orthogonal directions approximating the Moliere radius of the electron shower ($\sim 1 X_0$). The width criterion are satisfied by strips $1/8$ the width of a tower, about 1.3 cm. This allows for convenient electronics packaging as well. The length of the strips is ultimately designed to match the segmentation of the trigger towers (4 physical EM towers or $\delta\eta \times \delta\phi = 0.1 \times 0.1$.)

The optimum depth of the shower maximum detector has been determined from Monte Carlo studies to obtain the best separation between single γ 's and photons from π^0 decay^[2]. This result is shown in fig. 2, where the π^0 rejection factor is plotted as a function of energy for $\eta = 1.3$, assuming 80% photon acceptance. Note that on this plot, 20% pion rejection corresponds to no distinction between π^0 's and γ 's. A SMD at a depth of $6X_0$ has better π rejection than the same detector located deeper in the calorimeter. Consequently, we have located the SMD detector after the 5th Pb plate in the calorimeter, or at $5.5X_0$.

2.3. PRESHOWER DETECTOR DESIGN

Fig. 2. Monte Carlo study of π^0 rejection versus particle energy for the Shower Maximum Detector at $6X_0$ and $8X_0$ deep in the calorimeter.

To help isolate electromagnetic showers from hadronic interactions, there is a “pre-shower” detector which measures the energy deposition early in the shower development. This device separates electron or photon induced showers from hadronic showers based on the faster longitudinal development of electromagnetic showers. Electrons (and photons) interact with the absorber material on the scale of a radiation length ($1 X_0$ or $\sim 13\text{mm}$), while the longitudinal development of a hadronic shower is measured in units of the hadronic interaction length of $\sim 300\text{ mm}$ (in the EM part of the calorimeter). Hadronic showers, therefore, are characterized by lower energy depositions in the pre-shower detector. These elements of the EM calorimeter are designated in fig. 3.

Fig. 3 Cross section of the endcap EM calorimeter near the outer radius. The tower boundaries are indicated by dotted lines. The locations of the shower maximum detector and pre-shower detector are identified. The large gap at the back of the calorimeter is expansion space for servicing of individual scintillator multi-tiles.

The function of the pre-shower detector is three-fold: 1) where the acceptance of the ECEM is obscured by other structures (*e.g.* the coil), the pre-shower detector can be used to correct for energy lost in these structures; 2) the pre-shower detector can statistically discriminate between single photons and pairs of photons from π^0 decay; 3) the pre-shower detector can be used to improve the separation of electrons and charged pions, as indicated above.

Good energy correction requires that the pre-shower detector appear directly after any

inactive material in front of the calorimeter and that there be no inactive material between the pre-shower detector and the active parts of the calorimeter^[3]. If there are equal numbers of photons and neutral pions, the optimal depth of the pre-shower detector for the best $\gamma - \pi^0$ discrimination can be shown to be $0.9 X_0$. However, this location is not optimal for other π^0/γ ratios. The best statistical separation depends on the *fraction* of real photons to pions in the data sample. The optimal depth is between $1.3 X_0$ and $2.2 X_0$ as the fraction of real single photons in the sample ranges from 50% to 10%^[4]. It varies slowly, however, and any depth between 1.2 and $2.2 X_0$ yields a statistical separation within 10% of the optimal value.

Electron-pion discrimination using a pre-shower detector has been previously studied in a test beam at 15 and 35 GeV^[3]. While these energies may seem low with respect to the energy scale of the SSC, electron identification is most difficult at energies near (or below) trigger threshold (a typical trigger threshold is $E_t \sim 20$ GeV). At high E_t electrons are usually more isolated and backgrounds are lower. The pion rejection as a function of the electron acceptance was measured for pre-shower depths of 1 and $2 X_0$. At 35 GeV the pion acceptance for 97% electron acceptance is 1.6% for a pre-shower depth of $1 X_0$ and 0.9% at $2 X_0$. To satisfy these combined goals, we have located the pre-shower detector after the second absorber plate in the calorimeter, *i.e.* at $2.2 X_0$.

2.4. LONGITUDINAL SEGMENTATION - RADIATION DAMAGE

The endcap must satisfy its performance objectives despite a radiation dose that ranges (after 100 years operation at design luminosity of $10^{33} \text{cm}^{-2} \text{sec}^{-1}$ or 10 years at ten times design luminosity) from 50 Mrad at the inner radius to 500 krad at the outer radius. This radiation damage is induced predominately by low energy photons from π^0 decays in minimum bias events. While significant efforts have been made to extend the lifetime of plastic

scintillator^[5] in high radiation areas, no scintillator/fiber combination known to us can sustain the radiation dose listed above without significant loss of light. The radiation damage, and consequently the light loss, is not uniform in depth, and cannot be corrected with a simple overall change in gain.

Hence, the calorimeter must incorporate a scheme to maintain its performance characteristics while compensating for the non-uniform loss of light. The endcap calorimeter is divided into two longitudinal compartments (EM1 and EM2) to aid in correcting the effects of radiation damage. The correction is made by unequal weighting of the measured energy in the two sections when summing to find the total energy in the calorimeter. Monte Carlo studies using GEANT(Version 3.15)^[6] indicate that the effects of radiation damage can best be compensated if the transition between the EM1 and EM2 sections occurs at $9X_0$. Figure 4 shows the change in constant term (“ b ” in eq. 1) in the resolution as a function of the boundary between the EM1 and EM2 sections. There is a clear minimum at about $9X_0$, independent of the total amount of radiation damage. Since 2 GeV photons (typical of the energy of photons from π^0 decay in this region of the detector) have their maximum shower development at $4-5X_0$, the boundary is selected so that most of the radiation damaged scintillator is incorporated into the EM1 section. Therefore, we have put the boundary between the EM1 and EM2 sections at $\sim 9X_0$.

Fig. 4. Change in constant term b_1 versus the depth in radiation lengths of the division between the EM1 and EM2 sections of the calorimeter for 20%, 30% and 50% damage at shower maximum.

3. Mechanical Design of the ECEM

In its simplest terms the internal structure of the ECEM calorimeter consists of 6.0 mm thick Pb absorber plates alternating with pieces of 4.0 mm thick polystyrene with 3HF scintillator, a scintillator which emits predominately in the yellow. The light inside the scintillating tiles is collected by O2 (“orange”) wavelength shifting fibers, spliced just outside the tiles to clear readout fibers which transport the light to the photodetectors.

Additional materials must be used to support the weight of the lead, and mechanical restraints must be added to route the optical fibers and calibration services to the individual scintillating tiles. Choices of material for the mechanical structure of the ECEM must be determined by factors in addition to those required by physics and engineering criteria: a)

the potential for activation of radionuclides and the eventual disposal of low-level radioactive components; b) the control of forces generated via eddy currents during the quench of a superconducting magnet.

Below we briefly describe our plan for the mechanical structure of the ECEM and then explain the details of the calorimeter test station module.

3.1. OPTICAL DESIGN

In this section we discuss our best understanding of the fibers and scintillator system planned for final design of the ECEM. Measurements on the calorimeter test station module, assembly and quality control assessments are discussed in Chapter 4. The critical issue for the calorimeter is light yield versus radiation dose. To date, the scintillator and fiber combination with a long term record of use and with superior radiation hardness is polystyrene plastic tiles doped with 1000 parts per million (PPM) 3HF and 200 PPM O2 wavelength shifting fibers (WLS)^[5,7]. This choice of fibers and tiles exploits the fact that radiation damage is less severe at longer wavelengths, *i.e.* towards the red.

The scintillator layers of the calorimeter are each divided into 32 wedge shaped, each containing the tiles for 62 towers (fig. 5). The wavelength shifting fibers are inserted into the scintillator via an groove cut in the surface of the scintillator. We do not use glue or any optical grease between the fiber and the scintillator to avoid possible time dependent effects caused by these materials. To maximize light output, the free end of the O2 WLS fiber is mirrored with an aluminum coating. The opposite end is thermally bonded to the clear readout fiber.

The technique used to manufacture the scintillator tiles is analogous to that used to build our calorimeter test station module (see Chapter 4) and is only outlined here. The

Fig. 5. The division of the endcap into scintillator towers. The 32 fold symmetry matches the segmentation of the barrel calorimeter. A single multi-tile is divided into 62 towers, with three different tile sizes (when measured in units of $\Delta\eta \times \Delta\phi$).

individual tiles are glued edge to edge using epoxy into a wedge-shaped array of tiles, or “multi-tile”. The epoxy glue is loaded with TiO_2 powder to reflect light at the edges of the tile preventing cross talk. Tyvek^[8] covers are applied to both large faces of the multi-tile and the remaining 4 edges are painted white.

Grooves cut in a second, translucent cover sheet of white polystyrene are used to route the fibers to an optical disconnect at the outer radius of the multi-tile. These cover sheets mechanically protect the fibers, the splice between O2 fibers, and the clear fibers connecting them to the readout device (photomultiplier tube). This cover sheet is also used to route a stainless steel source tube past the center of each tile. To calibrate the response of each tile a radioactive source on the end of a fine wire is passed through this tube.

The optical path from WLS fiber to the photosensor contains two optical disconnects: one is at the outer radius of the wedge. This allows each wedge to be manufactured and tested as a separate opto-mechanical package; a second optical connection is required between the readout fiber and the photosensor to re-organize the fibers from their wedge-based orientation into collections of fibers coming from a common tower. This reorganization, from [62 fibers $\times$ 24 wedges] into [62 towers $\times$ 2 EM compartments] is accomplished in a “matrix box” mounted outside the calorimeter. The transmission efficiency of a joint between two fibers is about 90%-95%.

At the output of the matrix box the fibers are held in a “cookie” that keeps the individual fibers of a tower centered on the photocathode of the photomultiplier. This cookie has a provision for insertion of a filter to equalize, at the $\sim 1\%$ level, the light yields from the individual fibers, due to either manufacturing differences or radiation damage.

3.2. MECHANICAL DESIGN

Overall, the outline of the ECEM is a right cylinder 5.44 meters in diameter and 0.541 meters long, with a conical inner boundary at $\eta = 3.0$. As shown in fig. 3, the outer cylindrical shell is ~ 0.6 cm thick, and the front and back plates are each 3.0 cm thick aluminum. The 6.0 mm thick Pb absorber plates are clad on both sides with 1.5 mm thick aluminum sheets of

nearly the same diameter as the calorimeter. These aluminum sheets are made from several sheets joined edge to edge by continuous wave laser welding. The Pb plates are then glued between two sheets of aluminum. Careful attention must be paid to the lead-aluminum glue joint at the outer boundary. Analytic calculations show that differential thermal expansion between the Pb and the aluminum can cause very large stresses resulting in delamination at the glue joint, if the outer edge of the lead is cut perpendicular to the plane of the sheet. This thermal instability can be prevented by tapering the lead thickness within 1 cm of the outer radius. The most extreme temperature variations ($\pm 20^\circ$ C) were expected to occur during shipping.

The Pb absorber plates are supported at the outer radius by 16 hollow, aluminum perimeter posts. Only the upper 9 posts support the actual weight of the detector; the other 7 are present to maintain cylindrical symmetry. The absorber assemblies slide over the posts on custom, solid urethane bushings in aluminum housings. Urethane was chosen because it is relatively radiation hard and its elastic modulus allows adequate deflection to equalize the load between all 9 supports without yielding. The scintillator wedges, pre-shower, and SMD are in turn hung from the absorber assemblies. Removable panels in the outer can allow the scintillator to be installed/dismounted in a radial direction.

In normal operation the Pb plates and the scintillator wedges are compressed towards the front of the calorimeter by a gas bladder inflated with N_2 at $\sim 1/10$ atmosphere gauge pressure. This keeps the stack as dense as possible to reduce the transverse spread of EM showers; and, in the event of a quench of the superconducting magnet, minimizes the displacement of the calorimeter components.

The eddy currents induced in the absorber plates during a quench act to push the calorimeter towards the interaction point at the center of the SDC detector. The total axial

force due to quench currents in the aluminum supports (outer can and absorber plates) is about 25 Tons^[10], or about equal to the gravitational load. About half of this load comes from the 3.0 cm thick front plate of the calorimeter. This axial load is carried to the endcap hadron calorimeter via the outer cylinder and a set of tie rods around the inner diameter. Quench currents in the Pb absorber can be minimized by segmenting the Pb into electrically insulated, wedge shaped pieces which, in turn, are electrically insulated from their aluminum face sheets. This can be accomplished by embedding a fine, insulating mesh in the glue joints between the Pb and the aluminum. The thickness of the front and back plates of the calorimeter (30 mm Al) is determined by the requirement that they not buckle under the combined gravitational plus electromagnetic forces during a quench^[11].

Instead of aluminum, another choice for the ECEM mechanical structure is stainless steel. Stainless steel has significantly lower conductivity than aluminum, and its thermal coefficient of expansion is more closely matched to Pb. However, all stainless steels contain nickel, which, when activated, decays to Co⁶⁰, a long lived radioactive isotope. Hence, stainless steel must be avoided in high radiation areas that require personnel access. Aluminum, when activated, forms isotopes with relatively short lifetimes comparable to the length of time necessary to gain access to the ECEM. Titanium is another candidate material, but its coefficient of thermal expansion is much smaller than that of Pb, aggravating thermal stress problems.

3.3. ASSEMBLY AND MAINTENANCE

The calorimeter is originally assembled on with its back plate laid in a horizontal position. Tile/fiber layers are laid down, and then the absorber plates are lowered over them using a vacuum chuck. The proper response of each tile/fiber combination is verified before it is

covered with the next Pb layer. This process is repeated for each of the 23 layers in the calorimeter. Once the tile/fiber layers have been covered, they cannot be accessed again until the entire stack is complete, and tipped into a vertical (*i.e.* operating) orientation. Any remedial repair work can be carried out at this time, prior to shipment.

For *in-situ* maintenance, the entire ECEM is slid out of its pocket in the endcap hadron calorimeter on two rails attached to the bottom of the calorimeter. Temporary rails mounted to the face of the endcap hadron calorimeter support the ECEM when it is pulled from its recess. The deflated N₂ bladder is compressed to the back plate, allowing the Pb/scintillator stack to be expanded by up to 6 cm. This permits removal of a damaged scintillator or installation of repaired instrumentation by sliding them in a radial direction. Given the large diameter of the absorber plates, it is unlikely that they will hang perfectly vertically when the calorimeter is expanded. We have calculated that the force necessary to displace the inner diameter of one of these plates 2.5 cm is of order 2.5 kg perpendicular to the plane of the absorber plates. This force is low enough that the absorber plates do not damage the scintillator wedges as they are slid into, or out of, the expanded stack. In an emergency, one slot in the expanded stack can be expanded by up to 6 cm.

3.4. DESIGN AND CONSTRUCTION OF THE CALORIMETER TEST STATION MODULE

To verify our ideas about the calorimeter structure we have used a calorimeter test station module^[12] in beam tests at the H6 Beam of the CERN SPS and at the T9 Beam of the CERN PS. Table 2 describes most of the mechanical features of the module. There are 16 towers in the module, arranged in a 4×4 array. The calorimeter incorporates a pre-shower detector and Shower Maximum Detector (SMD), as well as a source calibration system and a light flasher system for the photosensors. A schematic drawing of the calorimeter is shown in fig. 6. The

tower boundaries are tilted 12.3° in one view to simulate the projective boundaries of the ECEM towers near $|\eta| = 2.2$. In this view, the boundaries of the towers are “stair-stepped” from one layer to the next. In the orthogonal view the boundaries of the towers are aligned.

Fig. 6. Cross section of the calorimeter module. The towers are inclined at 12.3° with respect to the front face to simulate the tower boundaries near $\eta = 2.2$. The lead absorber plates and aluminium cladding plates extend beyond the scintillator plates for convenience. The lower gap in the figure is for the pre-shower detector, and the upper gap is for the Shower Maximum Detector

All of the scintillators are identical (fig. 7): 4 mm thick square tiles, 11 cm on a side. The first step in the machining process is to cut 16 fiber grooves in a 44 cm square piece of scintillator, corresponding to the fiber grooves for all 16 tiles in a single layer. Then the individual tiles in a scintillator layer are cut from the sheet with a 0.635 mm thick slitting saw. We maintain the orientation and relative separation of the tiles by temporarily applying a thick sheet of protective tape^[13] prior to dicing the scintillator plate into the 16 tiles. This

Table 2: Parameters of the Calorimeter Test Station Module

Parameter	Value
Depth	$24.2X_0$
Number of Towers	16
Depth of Front EM1 Section	$8.8X_0$
Depth of Back EM2 section	$15.4X_0$
Calorimeter Unit Cell	
Aluminum Cladding	0.635 mm
Pb Absorber	6.35 mm
Aluminum Cladding	0.635 mm
Polystyrene Cover Plate	2.0 mm (white)
Tyvek 1025D reflective wrapping	0.125 mm
3HF polystyrene Scintillator	4 mm
(Pre-shower: SCSN 81 polystyrene Scintillator)	(6 mm)
Tyvek 1025D reflective wrapping	0.125 mm
Polystyrene Back Plate	1.0 mm (white)
Depth of Pre-shower detector	$2.2 X_0$ (after 2 unit cells)
Depth of SMD	$5.5 X_0$ (after 5 unit cells)
Absorber	97.9% Pb - 1.5% Ca - 0.6% Sn, 6.35 mm thick
Tile Size	11 x 11 cm ²
Fiber diameter	1.0 mm nominal (all fibers)
Calorimeter WLS Fiber	Kuraray 100 PPM O2, double clad
Pre-shower WLS fiber	Bicron BCF 91A
WLS Fiber Length	45 cm
Light Yield Gain from mirror on WLS fiber	+29% (end of clear readout fiber)
Clear Fiber	Kuraray , double clad
Clear Fiber Length	3.0 m nominal
Tile edge paint	Bicron BCF 620, 3 applications
Epoxy between Tiles	Stycast 1266 + 30% TiO ₂
Depth of WLS groove	1.65 mm
Diameter of groove at bottom	1.30 mm
Distance from edge of tile to groove	9.52 mm
Minimum WLS fiber bend radius	25.4 mm
Photomultiplier Tube	Philips 2270
Light Mixer	25 x 25 x 75 mm ³ UVA Lucite
Cookie	40 mm dia x 10 mm thick Grey PVC
Extension of fibers beyond cookie	0.25 mm
Air gap between fiber ends and light mixer	1.0 mm

tape (or a replacement piece) stays with the scintillators throughout the machining and gluing process, allowing us to keep fairly tight tolerances on the gap between tiles. Details can be found in ref [14]. Each tile is joined to its neighbors by 0.6 mm of Stycast 1266 Epoxy^[15] mixed with 30% by weight TiO_2 . The glue joining the tiles was injected into the gaps made by the slitting saw using hypodermic needles.

As this epoxy cures, it shrinks slightly, leaving a slight depression or meniscus between tiles. We used hypodermic needles to lay a small bead of epoxy in this groove, and then applied a Tyvek covering directly over the glue and the surface of the multi-tiles. The epoxy spreads for a few millimeters over the edges of the tiles and wicks into the Tyvek, but this did not affect the transverse uniformity of the light yield. The process was repeated for the opposite surface. After the glue had cured, the free edges of the "multi-tiles" were painted by hand with 3 coats of Bicron 620 white paint^[16].

Although WLS fibers with 200 PPM O2 dye were planned for the calorimeter, fibers with 100 PPM O2 dye were used for this test. One end of each O2 wavelength shifting fiber was aluminized and the opposite end was spliced to a clear readout fiber 3.0 meters long. This fiber length simulates the actual length to be used in the ECEM. The fibers were inserted into the groove in the scintillators via small access holes cut in the Tyvek. The fibers and Tyvek covering are protected on the front by a 2 mm thick white polystyrene cover sheet with grooves cut for passage of the fibers. Grooves cut in the cover also allow source tubes to pass by the center of each tile in the stack. A second piece of polystyrene 1 mm thick protects the Tyvek on the reverse side. After installation of the fibers, each multi-tile was tested for light yield.

When fabrication of all the multi-tiles was complete, we stacked them in the test station module with the alternating layers of aluminum clad Pb. For this test, the aluminum

Fig. 7. Mechanical drawing of a scintillator tile. Dimensions are in $\frac{\text{mm}}{\text{inches}}$. The fiber is inserted by pushing it through the entrance hole at one end of the groove. The slot for the wavelength shifting fiber is as close to the edge of the tile as possible. The fiber is bent through a 30mm radius at each corner of the tile.

was not bonded to the Pb. The pre-shower layer and shower maximum layers were added to the stack at the appropriate depths.

The free ends of the the clear plastic readout fibers, already polished, were glued into 1.0 mm diameter holes drilled in a circular pattern in a PVC "cookie", as shown in fig. 8. The fibers protrude ~ 0.25 mm from the surface of the cookie as tests demonstrated that having the end of a fiber even slightly below the surface caused a significant light loss (see fig 9). The mechanical structure of the cookie provides for a filter to be inserted between the ends of the fibers and the photomultiplier tubes. Filters could be used to equalize the light yield between tiles in a single tower (so called "longitudinal filters"), but they were not needed for this purpose as the tile-to-tile uniformity was within specifications. During the beam tests, we used these absorbing filters to *simulate* radiation damage in the calorimeter (see chapter 7).

Fig. 8. Mechanical drawing of a cookie. In the right most cross-section the fibers from the calorimeter enter the cookie from the left hand side, and are glued into the cookie using epoxy in the 1.0 mm diameter hole. The fibers are individually polished prior to insertion in the cookie, and the polished end protrudes from the surface of the cookie by 0.250 mm.

Fig. 9. Fractional light loss versus depth of the fiber end with respect to the surface of the "cookie." A positive number corresponds to the fiber protruding from the surface, and a negative number means the fiber terminates inside the PVC cookie

External light was excluded from the entire assembly by putting the calorimeter, readout fibers and photomultipliers in a common light tight box. The box, shown in fig. 10, was designed to allow access to both ends of the photomultiplier tubes, a feature needed for dressing of fiber bundles and installation of the phototubes. Each fiber of the 16 fibers of the pre-shower detector is read out by one channel of a multi-channel photomultiplier tube. These multichannel phototube for the pre-shower (and SMD) was mounted in an auxiliary enclosure at the top of the calorimeter.

A N_2 laser, a scintillator block, and a set of clear fibers were used to monitor the gain of all the photosensors. A fast pulse from the laser illuminated a piece of scintillator, which in turn illuminated about 40 fibers. Each photosensor was connected to one fiber from the

Fig. 10. Three views of the calorimeter test beam module as mounted in the test beam at CERN. In the upper figure (plan view) the boundaries of the towers are tipped 12.3 degrees with respect to the outer light tight box (i.e. the boundaries are parallel with the beam). In the elevation view, transverse to the beam line, the tower boundaries are parallel to the beam.

laser assembly. The fiber bundle from the laser assembly included a special, spring-loaded connector. This connector grouped the individual fibers to each of the photosensors together

into a single mass connector, while allowing for the convenient rearrangement of individual fibers as needed.

Thermocouples monitored the temperature at the scintillators, at several photosensors and at the digitizing electronics. The light yield from most scintillators has a small temperature dependence.

4. Calibration, Monitoring and Quality Control of the Test Station

The calibration system for the calorimeter consisted of a movable radioactive source, a light flasher, charge injection for the ADCs, temperature monitoring, and use of beam particles. In addition, a number of calorimeter components were measured before their installation in the calorimeter. The goal was to overconstrain the response of the detector in order to understand the performance of both the detector and the calibration system. Each system is discussed independently, and then the performance of the system as a whole is presented.

4.1. PREASSEMBLY QUALITY CONTROL

Fiber assemblies were manufactured and initially tested at KEK, Tsukuba Science City, Japan. A fiber assembly consisted of a 45 cm long, 1 mm diameter wavelength-shifting fiber (WLS), mirrored on one end and thermally spliced to a 3 m long 1 mm diameter clear polystyrene fiber at the other end. The free end of the clear fiber was polished. The assemblies were tested by exposing the WLS to a radioactive source and monitoring at the end of the clear fiber with a photomultiplier tube. Fibers whose response deviated from the mean by more than 10% were rejected.

Sixteen randomly selected fibers were placed into each multi-tile. The response of each combined tile/fiber assembly was measured using the current induced in a Philips XP2013B photomultiplier tube by a radioactive source located 12 cm directly in front of and co-linear with the center line of the tile. Each tile was measured twice, once with a Sr^{90} source and once with a Ru^{106} source. The two measurements always gave very good agreement. The responses of the 352 tile/fiber combinations are shown in fig. 11. The *rms*/mean for this distribution is 4.7%. In eight cases tile/fiber response was $< 15\%$ below average and the fibers were replaced. Subsequent testing showed the new tile/fiber combination to be acceptable. No scintillator tiles were found to be bad.

The response of each tower can be estimated by averaging the responses of the 22 tiles in the tower. The *rms*/mean of the 16 tower responses was 1%. Uniformity at this level satisfies the requirement on initial calibration ($< 2\%$) of the calorimeter, eliminating the need for masking the fibers or tiles.

A single tile/fiber combination exposed to a Sr^{90} source was used to select the operating HV of 26 of the 32 photomultiplier tubes such that the induced current was at a specified value. Because the HV supply could be set only in 20V increments, the signals deviated as much as 6% from the nominal value. Note that this process does not normalize the gain for each photomultiplier tube, but rather the product of the gain times the quantum efficiency. The remaining six photomultiplier tubes were calibrated relative to each other in a similar way, but were adjusted to a different $[\text{Gain} \times \text{QE}]$ from the first 26 photomultiplier tubes.

Fig. 11. Response of 352 tile fiber assemblies as measured by a Ru-106 source

4.2. CALIBRATION USING RADIOACTIVE SOURCES

A radioactive source could be moved next to every tile in the completely assembled calorimeter. This source calibration system had several functions:

- control quality;
- estimate initial response;
- monitor stability of response during operation;
- measure radiation damage.

Design of System

The calibration system consisted of a “source wire,” a mechanical drive unit^[17] to direct the source past each tile in the calorimeter, and a scanning ADC to record the response of the photomultipliers. A thin brass tube was placed in a groove milled into the coverplate next to each tile. One tube ran next to four tiles in a single layer, requiring a total of 88 source tubes for the calorimeter (*i.e.* four tubes $\times$ 22 layers). Additional tubes were placed in the shower-max and pre-shower layers.

The Cs^{137} source was located at one end of a ~ 6 m long hypodermic tube, which was electro-beam welded shut after installation of the radioactive material. A custom-made, electro-mechanical “source driver,” with appropriate safety controls, moved the source into and out of each of the 88 guide tubes. The guide tubes in turn directed the hypodermic tube containing the source past the center of each scintillating tile in the calorimeter.

The calibration system worked by measuring the currents induced in the 32 photomultiplier tubes. All 32 currents were sampled and recorded at a rate of 10 Hz by the data acquisition system (DAQ) while the source was moved into and out of each guide tube. The DAQ recorded which guide tube was being used, but otherwise was not synchronized to the movement of the source.

The current from each photomultiplier tube was converted into a voltage using custom designed 16-channel NIM modules that were accurate to 1% over the range of interest. The 32 voltages were measured using a CAMAC scanning ADC. The response of each photomultiplier tube for a particular source tube was characterized by the peak current. Two current measurements were made for each source tube in a tower, one as the source moved into the tube and the second as it was withdrawn. The average of the two was used to characterize

the response. The two measurements were always consistent, with an *rms* difference of 0.3%.

The current measured when the source was next to a tile came not only from energy deposited in that tile, but also to energy in tiles in other layers. The relative strength of the source was measured as a function of the distance (in units of the number of layers) between the source and the tile by masking all but one of the fibers in a tower. As can be seen in fig. 12, approximately 72% of the observed signal is due to the tile closest to the source. From this distribution, the response of each tile can be extracted from the current measured with the source in each layer.

Fig. 12. Depth of penetration of the Cs^{137} source, as measured by the scintillator tiles inside the calorimeter. The source was inserted at different layers in the calorimeter stack as the signal from layer 7 was monitored.

Calibration Using the Cs¹³⁷ Source: Two calibrations using the source system were performed after the calorimeter was assembled but before it was shipped to the beam line. All 88 source tubes were used, but only 30 of the 32 photomultiplier tubes were installed at the time. The other two locations were to be equipped with Avalanche Photodiode Photomultipliers (APDPMT), which had not yet arrived^[18]. The first set of measurements located a pair of fibers that had been routed to the wrong photomultiplier tubes and a pair of photomultiplier tubes whose locations were interchanged. The second source calibration was used to derive the response of each tile/fiber combination.

The *rms*/mean of this second, *in situ* calibration run was 5.0%, in quite good agreement with the 4.7% *rms* of the single tile calibration done prior to installation. The numerical values from the two calibrations were, however, not well correlated. We believe the difference can be explained by the fact that the *in situ* source calibration depends much more on the response of the tile near its center, whereas the full tile is illuminated in the single tile calibration.

The full calibration was also used to predict the relative response of each tower to beam particles. A comparison with data is presented below. This calibration system was also used throughout the beam test to monitor the response of the calorimeter. Variations in response could result from temperature or high-voltage variations, for example. For this purpose, only a single measurement was performed for each photomultiplier tube, rather than one per tile.

4.3. LIGHT FLASHER

The light flasher system was also used to calibrate the calorimeter response. This system consisted of a pulsed nitrogen laser that illuminated a piece of scintillator. One fiber assembly (including the same WLS used in the calorimeter) ran from the scintillator to each

photomultiplier tube. The pulse duration was much less than the time constant of the WLS, so that the time structure of the pulse at the photomultiplier tube was the same as for beam particles. A 1 μ sec long optical fiber was placed between the laser and the scintillator to minimize the impact of the large prompt RF noise associated with the laser pulse.

The relative intensity of each laser pulse—pulse-to-pulse variation was approximately 5%—was measured using a PIN diode which was selected for its temperature stability.

The light flasher system was used frequently throughout the beam test, for the purpose of monitoring photomultiplier tube gain variations between calibrations with the source system and calibrations with beam particles. Note that this system would not detect variations in scintillator response due to temperature variations, for example.

4.4. CHARGE INJECTION

A dual-range 32 channel ADC (corresponding to a 15 bit dynamic range) was used to measure the photomultiplier tube pulses in the test beam setup. The gain and linearity of each channel were measured by injecting charge with a pulse generator and a calibrated attenuator box. The *rms*/mean variation of the gain was 1.2%. A similar measurement performed four months later gave results that agreed channel to channel within 0.4%. This stability indicated that charge injection measurements were not needed on a regular basis throughout the beam test.

4.5. TEMPERATURE MEASUREMENTS

Several components of the optical system—such as the scintillator and photomultiplier tubes—were known to vary or suspected of varying with temperature. To understand and possibly correct this effect, 16 Omega thermistor temperature probes (Part Number 44201^[19])

were distributed throughout the calorimeter: on the calorimeter stack, photomultiplier tubes, and electronics. A custom designed CAMAC module supplied current to the thermistors and provided a voltage output proportional to the temperature. The voltages were read by a scanning ADC every 15 seconds during data taking.

4.6. PERFORMANCE OF THE CALIBRATION SYSTEM

The purpose of the calibration and monitoring system is to correct for pulse height non-linearity, channel-to-channel variations, and variations versus time, so that an observed signal in ADC counts can be converted into a deposited energy. In the beam test, the beam energy is known independently and can be used to understand the performance of the system.

Initial Calibration

A prediction for the response of the calorimeter was derived from the complete calibration with the source system and the charge injection calibration of the ADC. The relative responses of the 30 sections (15 towers times 2 depth segments; two of the APDPMT'S missing) measured in the source calibration were characterized by the sum of the response for each tile/fiber combination in the sections, a quantity that reflects the gains of the photomultiplier tubes as well as the optical properties of the tiles and fibers. This sum was multiplied by the measured gain of the ADC channel to arrive at an overall calibration correction.

To test this prediction, 120 GeV electrons were sent into the center of each tower. The tower signal was characterized by the mean sum of its two channels, EM1 and EM2, after pedestal subtraction and calibration corrections. Figure 13a is a histogram of the corrected energy sum for the 15 calibrated towers. The $rms/mean$ is 3.3%, adequate for the initial calibration of a full-scale calorimeter.

Fig. 13. Response of the 15 calorimeter towers to 120 GeV electrons a) after calibration, and b) prior to calibration.

Figure 13b shows the same distribution with no calibration correction for the 13 towers (see section 4.1) with matched photomultiplier tube gains. The *rms/mean* of this distribution (2.9%) includes variations in tile/fiber response, deviations of photomultiplier tube gain due to the $\Delta V = 20V$ limitation of the high voltage supply (*rms* $\approx 1.7\%$), and the

gain variation of the ADC ($rms \approx 1.2\%$). The estimated rms of the optical system is, therefore, $\sqrt{(2.9\%)^2 - (1.7\%)^2 - (1.2\%)^2} = 2.0\%$. This implies that the variance of the response of the optical system is better than the ability of the calibration system to measure it. The measured response to 120 GeV electrons was used as a calibration in subsequent measurements.

Stability of Response

Three calibrations using the radioactive source system were recorded in a 100 hour period. The mean response of the 32 channels showed a gradual (1.3%) drop as the calorimeter and phototube temperatures increased by 0.6°C over this time. The flasher runs did not show any systematic shift, indicating that changes in the scintillator were responsible, rather than the photomultiplier tubes or ADCs.

5. Test Beam Setup

Data were taken at the CERN H6 Test beam using beam particles with momenta from 20 GeV/c to 200 GeV/c. For any particular momentum setting, the momentum (P) bite ($\Delta P/P$) was 0.2%. The layout of the beam line in the immediate neighborhood of the calorimeter is shown in fig. 14.

5.1. TRIGGER

A set of scintillators placed along the beam line detected the presence of beam particles. The one upstream counter ($S3$) was made large enough to cover the beam spread. $S0$, $S1$ and $S2$ were three small counters (1cm x 1cm). $V1$ and $V2$ were two veto counters with the hole in the middle measuring 2cm x 2cm and 1cm x 1cm respectively.

The primary trigger consisted of $S0 \cdot S1 \cdot S2 \cdot S3 \cdot \overline{V1} \cdot \overline{V2}$ (fig. 14). A random trigger, at about 1Hz, collected pedestal data for the ADC's. Approximately every 15 sec a third read the temperature monitors. No particle identification was used, as the high energy beam had relatively good electron purity.

Fig. 14. Layout of the trigger scintillators along the beamline at the CERN SPS.

5.2. ELECTRONICS AND DAQ

DAQ Hardware

The signals from the ECEM and the SMD were digitized by CAMAC-based current-integrating ADC's (CAEN^[20] 32 channel model C205). The 288 drift chamber signals were read out by the LRS 4290 time digitizing system specifically designed for multiwire drift chambers. The system consisted of a TDC controller (model LRS 4298), nine 32 channel time digitizers (model 4291B), and a databus interface/buffer (model LRS 4299). The general DAQ architecture was based on the VIC-bus (VME Interconnect Crate Bus from CES^[21]), allowing the interconnection of the VME crate and the CAMAC crate and the interface to a SUN workstation (Sparc2-IPX) with high speed communications up to 10 Mbytes/sec. The modules used to interconnect the various backplanes into the VICbus were the VIC8251, a one slot VIC master/slave VME interface, and the VCC2117, a CAMAC to VIC-bus interface and crate controller. The SVIC7213 was used to interface the SUN SBus to the VIC-bus.

DAQ software

The DAQ software used in this test was UNIDAQ, the SDC Portable Data Acquisition System^[22] developed at SSCL in collaboration with KEK, Tokyo, University of Michigan, and LBNL. This system was Unix-based and consisted of a buffer manager (NOVA) and a set of small processes ("Collector" for the readout and acquisition of the event data and an "Analyzer" for the on-line histogramming of the event data, for example), which were developed using a generic template structure. This approach is appropriate to UNIX (and real time) systems where image activation is quick and the operating system is designed to handle many small processes efficiently. The processes interact with each other by passing command messages, event data and process data via buffers handled by the buffer manager.

The event rate, including the CAMAC bottle neck, was acceptable, of the order of 200 Hz.

5.3. DRIFT CHAMBER

The drift chamber measured the horizontal beam coordinate (x) with six planes of 32 sense wires and the vertical beam coordinate (y) with four planes of 24 sense wires. Planes measuring x were located along the beam axis (z) at 0mm, 19mm, 102mm, 121mm, 203mm, and 222mm, while planes measuring y had z coordinates 51mm, 70mm, 152mm, and 171mm. Sense wires (13μ gold-plated tungsten) and field wires (76μ beryllium-copper) formed hexagonal cells with 24 mm spacing in x or y . Planes paired in z were offset by 12 mm in x or y to resolve the left-right drift direction ambiguity. The chamber gas was 90% Ar, 9% CO₂, 1% CH₄. The field wires were held at a voltage -2080 V; the eight "internal" sense planes were run near 0 volts, while the two planes nearest the entrance and exit windows were biased to $+100$ V to improve efficiency. LeCroy Research Systems (LRS) 7791 cards (set for $450 \mu\text{V}$ threshold) amplified and discriminated signals from the sense wires and sent $1 \mu\text{sec}$ long pulses to LRS 4291B TDCs, which recorded drift times up to 512 nsec in 1 nsec bins.

To obtain the drift distance $d(t)$ we selected runs in which the distribution of beam particles' drift distances was expected to be uniform and integrated the resulting TDC time distribution: $d(t) = \frac{12\text{mm}}{N_{\text{hits}}} \int_0^t d\tau \frac{dN}{d\tau}$. In each projection (x - z or y - z) we chose a hit in each of the outer pairs of planes to define a road of half-width 2 mm and fit a track in the road containing the most hits. We required numbers of hits $n_x \geq 4$, $n_y \geq 3$, and events with more than eight hits left unattached to the track were rejected.

A plot of residuals shows a resolution of $300\mu\text{m}$. The run-dependent mean residual, typically $\pm 100\mu\text{m}$, leads us to assign a $200\mu\text{m}$ systematic error due to run-to-run variation of $d(t)$.

6. Calorimeter Module Test Beam Performance

This chapter discusses the linearity and energy resolution of the calorimeter test station module at the CERN SPS test beam. We use test beam data to extract the light yield (number of photoelectrons per minimum ionizing particle) and compare this number with measurements made in the laboratory on single fiber/tile assemblies. We measure the signal speed for electromagnetic showers and show that pulse shaping can reduce the collection time by almost a factor of 3, but at the cost of considerable electronic noise. We also present measurements of the transverse uniformity of individual tiles and compare these results to the transverse uniformity of the calorimeter as a whole.

6.1. LINEARITY AND RESOLUTION

The linearity of the calorimeter was measured using electrons of 10–193 GeV energy incident on the centers of towers 10 and 11, both near the center of the calorimeter array. The calorimeter was calibrated as described above. No temperature corrections were applied to the data, as the temperature variations between runs were small. The energy in the calorimeter was measured using a nine-tower sum centered on the appropriate tower. EGS studies and comparisons of the signal in nine versus sixteen towers indicated that $< 0.5\%$ of the energy at 120 GeV leaked laterally beyond the nine towers.

Figure 15 shows the pulse height spectrum for 120 GeV electrons in tower 6. The mean and *rms* of the response are based on a Gaussian distribution fit to the peak region. As can be seen from this figure, the calorimeter response follows a Gaussian distribution and the beams were clean, with only a small pion and muon contamination. Figure 16 is a plot of the mean ADC counts per incident GeV for the two data sets. The deviations from linearity are $\leq 1\%$.

Fig.15. Single tower pulse height spectrum of 120 GeV electrons on the center of tower 6.

Fig.16. Mean ADC counts per GeV of incident energy. Dotted lines represent 1% deviations from linearity.

Figure 17 is a plot of σ_E/E versus incident energy, together with a fit to the data:

$$\sigma_E/E = (0.195 \pm 0.001)/\sqrt{E} \oplus 0.0047 \pm 0.0005$$

with E in GeV, and $\oplus$ meaning to addition in quadrature. A pickup noise contribution to the resolution of 0.3 GeV (*rms*) has been subtracted in quadrature from the data in fig. 17.

Fig. 17. Resolution of the calorimeter (σ_E/E) for incoming electrons as a function of energy. The smooth curve is a fit to the data as described in the text.

6.2. LIGHT YIELD AND MINIMUM IONIZING PARTICLE RESPONSE

The light yield has been measured for three towers (4,6 and 7), two were instrumented (with two photomultiplier tubes in each tower) with Philips XP2013B phototubes and the third tower instrumented with two Hamamatsu R5802's. The R5802 is a 10-stage, prismatic window version of the R5380. The four XP2013B photomultiplier tubes in the two towers have cathode luminous sensitivities (to white light) in the upper 15% of the 36 photomultiplier tubes purchased for this test. The wavelength of interest for this test is 580 ± 20 nm, corresponding to the peak of the emission spectrum from the wavelength shifting fibers.

Light Yield Measurement with 120 GeV Electrons

120 GeV electrons were measured in each tower, both with and without a 10% transmission neutral density filter at the phototube face. The light yield was deduced from the change in resolution. For this purpose, the signal from a single tower (which contains 111 GeV of the 120 GeV incident) was used to measure resolution.

Figure 18 shows the pulse height spectrum in tower 7 (Philips photomultiplier tube) before and after the neutral density filter was installed. The resolution at a particular energy can be characterized as a contribution from light yield plus a contribution from everything else: $\sigma_E/E = \sigma_{other}/E \oplus 1/\sqrt{N_{pe}}$. The neutral density filter does not change σ_{other} but reduces N_{pe} to $x \times N_{pe}$, where $x \approx 0.1$ is the transmission of the filter. The actual value of x was deduced from the change in peak pulse height.

Table 3 summarizes the resolutions and light yields (photoelectrons per incident GeV) for the three towers. The Hamamatsu R5802 phototube yielded approximately 30% more photoelectrons than the Philips XP2013B. These data indicate that the prismatic photocathode provides a significant improvement in quantum efficiency for orange-red light.

Table 3. Number of photoelectrons (N_{pe}) per minimum ionizing particle (mip) for towers 4, 6, and 7 as measured in the test beam and as measured in the laboratory.

Tower	PMT Type	Cath. Lum. Sensitivity	σ/E for 100% light	σ/E for 10% light	N_{pe}/GeV	N_{pe}/mip
6	Philips	337	0.0206	0.0363	89 ± 3	2.0 ± 0.1
7	Philips	305	0.0193	0.0385	74 ± 2	1.6 ± 0.1
4	Hamamatsu	345	0.0188	0.0341	105 ± 5	2.3 ± 0.1
Laboratory	Philips	245	—	—	—	2.3 ± 0.3

Minimum Ionizing Response

To compare the light yield to laboratory measurements, the data have also been interpreted as photoelectrons per minimum ionizing particle per scintillator tile. Figure 19 shows the pulse height spectrum in tower 6 for 120 GeV pions. This plot when taken together with similar data for 200 GeV pions indicate a pulse height of 0.395 ± 0.018 ADC counts per mip per scintillator tile. The observed peak pulse height of 2000 ADC counts for 111 GeV

Fig. 18. Response of the calorimeter to 120 GeV electrons in tower 7 before (upper figure) and after (lower figure) the installation of neutral density filters with 10% transmission.

deposited in a tower (by 120 GeV electrons) implies an energy deposition in the scintillator of 45 ± 2 mip-tiles per incident GeV. This factor is used to convert N_{pe} per GeV into N_{pe}

Fig. 19. Pulse height distribution for 120 GeV pions in tower 6.

per mip per tile.

Laboratory Measurements of Light Yield

The light yield of a tile/fiber combination was measured using a momentum analyzed Ru-106 source configured as a miniature “beamline”^[23], producing a collimated (2 mm x 8 mm) beam of ~ 3 MeV kinetic energy electrons directed into the center of the scintillator tile. The charge induced in a Philips XP2013B photomultiplier tube viewing the fiber was measured using a LeCroy 2249A ADC. A coincidence between a pair of trigger counters located on the side of the tile away from the source provided the trigger for the event. The mean number of ADC counts per electron was converted into a number of photoelectrons using the location of the ADC pedestal and the number of ADC counts per single photoelectron. The latter quantity was determined by reducing the light intensity until the average number of PE/pulse was much less than unity.

The measurement with the Ru-106 source implies a light yield of 2.3 ± 0.3 photoelectron per mip per tile for the Philips XP2013B photomultiplier tube. This value is somewhat

inconsistent with the SPS test beam measurements (Table 3). The test beam measurements gave lower light yields, even though they were made with phototubes of greater luminous sensitivity and used particles with a noticeable relativistic rise in dE/dx .

Similar laboratory measurements were performed on the pre-shower tile, which was 6 mm thick SCSN38 read out with 1 mm diameter Y11 WLS fiber thermally spliced to a 3.0 m long clear fiber. Both the WLS and clear fibers were of high numerical aperture (multi-clad) polystyrene fibers. The fiber was viewed using a Hamamatsu R580-17 photomultiplier tube. This optical combination—in which both the fiber and the photomultiplier tube were different from those at the calorimeter test station—gave a light yield of 12.1 ± 0.6 pe per tile per mip. The light yield observed in the beam was significantly lower (as will be discussed below).

Light Yield and EGS Studies

Simulations using the EGS Monte Carlo Program^[24] can also be used to estimate the light yield of the calorimeter. The EGS model included the Pb, aluminum cladding, scintillator cover sheets, and the mechanical structure (box, front and back plates). The predicted resolution, based on incident energies of 20 GeV to 200 GeV, is

$$\frac{\sigma E}{E} = \frac{(0.149 \pm 0.004)}{\sqrt{E}} \oplus (0.0052 \pm 0.0012). \quad (2)$$

Interpreting the difference between the predicted stochastic term of 0.149 and the observed 0.195 as a degradation from limited light yield would indicate 63 ± 5 photoelectrons per incident GeV. This is somewhat smaller than the XP2013B measurements listed in Table 3, probably because the phototubes in towers 10 and 11, used to measure the resolution, have an average luminous sensitivity 15% lower than those in towers 6 and 7, which were used to measure the light yield.

6.3. SIGNAL SPEED

One of the advantages of scintillator calorimeters is the fast response that can be achieved. The 3HF scintillator with O2 fiber readout is slightly slower than shorter wavelength scintillators that were considered for other regions of the SDC calorimeter. Figure 20 a) is an oscilloscope picture showing the response of the calorimeter to a 120 GeV electrons. The measurement was made at the end of 300 ns of air-core coax cable. The duration of the pulse could be reduced by clipping (fig. 20 b). The clip line was a 4.5 ns long 50 ohm RG174 cable terminated at $17\ \Omega$ and connected to the anode of the photomultiplier tube. The clip line canceled the exponential tail of the scintillator pulse so that the signal returned to baseline in approximately 30 ns, compared with 80 ns without the clip line.

The clip line caused a factor of two reduction in peak height and a factor of four reduction in total charge. The resolution (measured with a 100 ns gate) was consistent with the unclipped value, after the subtraction in quadrature of a noise contribution to the resolution. The noise was significantly worse with this arrangement, approximately 0.24 GeV *rms* for a single tower, compared to 0.03 GeV unclipped.

6.4. UNIFORMITY

Uniformity of a Single Tile

The Ru^{106} momentum analyzed source was also used to measure the uniformity of a single tile in the multi-tile structure. On an x-y scanning table the tile was coupled by a standard readout fiber going to a Hamamatsu R580-17 photomultiplier tube. The uniformity was characterized by the current induced in the photomultiplier tube (measured with a Keithley 485 picoammeter) as a function of beam position. Figure 21 is a "Lego" plot of current

Fig. 20. Oscilloscope pictures of the pulse height from the calorimeter for 120 GeV electrons a) (upper) without clipping and b) (lower) with a 4.5 nsec clip line. In both figures the horizontal scale is 10 nsec per large division, and the amplitude scale is 200 mV per large division.

versus position. The falloff at the edge is due to part of the beam entering the neighboring tile. A histogram of the data points fully containing the beam is presented in fig. 22. The *rms* divided by the mean is 1.8%, including a small low-side tail from the response in the

Fig. 21. "Lego" plot of the transverse uniformity of a single tile. The vertical height of each "element" is proportional to the relative current when the Ru-106 beamline is centered over that area of the tile. The amplitudes are normalized to 1 at the center of the tile.

corners. The deviation from the mean along a line through the center is approximately $\pm 2\%$.

This uniformity represents the best achieved after five iterations of selecting a design for the fiber groove, manufacturing several test tiles, and measuring their uniformity. The major improvement over earlier designs is the placement of the fiber as close as possible to the edge of the tile.

Uniformity of the Calorimeter Response

Variation in the response of the calorimeter to electrons as a function of impact point is a contribution to the constant term of the resolution. The lateral uniformity of tower 10 was measured by scanning 120 GeV electrons in both transverse directions over the face of the tower. The step size of the scan was less than the FWHM of the beam.

Fig. 22. Distribution of the response of the tile/fiber assembly for points from fig. 21 fully containing the Ru-106 beam.

A nine tower sum was used to calculate the energy in the calorimeter. Figure 23 shows scans through the center of the tower in x and y for events within 2 cm of the center line. The region within the loop of the fiber is very uniform. The overall response variation in these plots is approximately 4%, with the response highest at the location of the fiber, and lowest at the boundary between towers.

The impact of the non-uniformity can be estimated by comparing the resolution for events in the center of the tower (fig. 24 a) and for events over the full tower (fig. 24 b). The resolution in the first case is $\sigma_E/E = 0.0192 \pm 0.0002$; in the second case it is $\sigma_E/E = 0.0255 \pm 0.0001$. To the extent that the non-uniformity is not a strong function of

Fig. 23. Response of the calorimeter (nine tower sum) as a function of the impact point of 120 GeV electrons. The upper plot is for a vertical scan, and the lower plot is for a horizontal scan through the center of tower 10.

energy, the degradation in resolution represents a 1.7% constant term in the resolution.

The gross features of the non-uniformity are similar from tower to tower. Figure 25 is a scan with 120 GeV electrons similar to that shown in fig. 23, but extending from the center of tower 9 to the center of tower 12. A single location-dependent correction applied to all towers would significantly reduce the constant term.

Fig. 24. Distribution of pulse heights for 120 GeV electrons a) at the center of a tower ($rms/mean = 0.0192 \pm 0.0002$), and b) for all events over the full transverse area of the tower ($rms/mean = 0.0255 \pm 0.0001$).

7. Radiation Damage Correction Tests

As described in chapter 2, the optical system of the ECEM and our calorimeter test beam module provided for a “longitudinal filter” to equalize the light between different tiles in a tower. In our case, the longitudinal filter consisted of a piece of photographic film located between the end of the fibers and the photomultiplier tube. Printed on the film were thin, opaque lines (one line per fiber) that partially block the light coming from the fibers. Each line on the film is centered on a diameter of a fiber. Fig. 26 shows an example of such a mask.

Fig. 25. Mean pulse height as a function of horizontal position taken from the center of tower 9 to tower 12. The dotted lines represent 2% deviations from the average at the center of the tower. Note the similarity of the response near the boundaries of the towers. No position dependent corrections have been applied to the data.

Fig. 26. Drawing of a longitudinal filter for all 7 fibers (A-G) of the EM1 section of the calorimeter. The exploded view shows that the line masks for two of the fibers are collinear with the diameter of the fibers.

To second order, the attenuation of the light is proportional to the width of the line, and because the line is colinear with a diameter, errors due to mis-alignment vanish to first

order in the displacement from ideal position. The attenuation of the light as a function of the line width is shown in fig. 27. The light is attenuated by 1.24×10^{-3} per micron of line width for our combination of film and developing process. All masks for fibers from the EM1 or EM2 sections of a calorimeter tower are printed on the same piece of photographic film; the film is aligned with the individual fibers on the cookie by two precision machined pins, shown in fig. 26. About 10% of the overall light is lost due to the introduction of the clear photographic film without any lines.

Fig. 27. Relative attenuation of light for line masks centered on a 1 mm diameter fiber versus the width of the line. The two sets of data points are for two different sets of masks, and the solid line is a simple calculation of the fractional, unobscured area at the end of a fiber for a given line width. The data points have been normalized to 1.0 for a clear mask (*i.e.* a line width of 0.0 mm on clear mask material)

We have used these filters to simulate radiation damage in the calorimeter. We begin with the longitudinal profile (dE/dt) of 2.5 GeV photons, corresponding to decay products of 5 GeV (total energy) π^0 's:^[26]

$$dE/dt = At^{2.809}e^{-0.4635t} \quad (3)$$

where A is an arbitrary amplitude and t is the depth into the calorimeter measured in radiation lengths.

We assume that the radiation damage to the tile/fiber assemblies as a function of depth is proportional to this profile, and use this to create a set of masks for each fiber in a tower, based on the results of fig. 27. The width of the line for the mask of a particular fiber is proportional to the relative radiation dose for the tile, and we adjust one overall scale parameter to obtain the overall reduction in light yield desired.

At this point we have created a set of masks for each fiber/tile assembly in a tower that corresponds to a level of light loss for a specified radiation dose as a function of depth into the calorimeter. We installed each mask on a cookie, and with our source calibration system we measured the light loss from each tile/fiber combination in a tower. From this data we compute the ratio of [the light yield with a mask] to [the light yield without a mask]. The results are shown in Fig 28 for filters corresponding to roughly 25% and 50% light loss at shower maximum. The continuous solid line is the prediction of equation (3) (*i.e.*, the expected effect). The agreement between the predictions and the measurements are good to 1.4% *rms*. One overall constant was fitted to each set of filters to obtain the overall gain reduction from the plastic substrate on which the masks are printed: 9.9% for our choice of filter material.

From Monte Carlo studies using the GEANT simulation package we fit

$$(E_{EM1} + E_{EM2})_{RADDAM} / (E_{EM1} + E_{EM2})_{NO\ RADDAM}$$

versus

$$(E_{EM1})_{RADDAM} / (E_{EM1} + E_{EM2})_{RADDAM}$$

Fig. 28. Relative light yield for the first 8 tiles in the EM1 section of the calorimeter using the calibration system to irradiate single tiles with two different sets of masks installed between the ends of the fibers and the photomultiplier tubes. The two sets of data points are for the two different filter sets corresponding to 25% and 50% light yield reduction at shower maximum. The continuous lines are the predictions of equation 2 normalized to the data, given the line widths used in our masks. The differences between the prediction and the measured value are good to 1.4% *rms*. Radiation from the calibration source penetrates more than one tile in a tower, and the data points have been corrected for this effect.

where the subscript *(NO)RADDAM* refers to the data taken with(out) the filters, E_{EM_i} is the energy in the i^{th} ($i = 1, 2$) section of the calorimeter in depth. In the fit, the quadratic form ($y = a_0 + a_1x + a_2x^2$) is used where y is given by $(E_{EM1} + E_{EM2})_{RADDAM} / (E_{EM1} + E_{EM2})_{NO\ RADDAM}$, and x is equal to $(E_{EM1})_{RADDAM} / (E_{EM1} + E_{EM2})_{RADDAM}$. We took test beam data with 25% filters at 20, 50, 70 and 120 GeV/c and at 20, 50, and 120 GeV/c data with 50% filters. There is only one set of coefficients used to correct both sets of data corresponding to the 25% and 50% light loss filters. This function is then used to correct the energy distribution on an event by event basis. Figures 29(a,b) show the raw and corrected energy distributions for 25% and 50% light loss for 120 GeV electrons.

Fig. 29. Calorimeter energy distributions for 120 GeV electrons with longitudinal filters installed simulating a) 25% and b) 50% radiation damage at shower maximum. The dotted lines are the raw data and the solid lines are the same events after correction on the basis of the EM1 versus EM2 energy depositions on an event-by-event basis. The corrected data is symmetric about the average and has no long tails towards high energy.

Figure 30 shows the ratio, before correction, of the measured energy to the beam energy, before correction for both data (solid circles) and simulation (open circles). The calorimeter was simulated using GEANT (Version 3.15), including all of the inactive material in the calorimeter, photon statistics, and the reduction of the light yield by the filters. The most significant light loss occurs at lower energies; as the beam energy increases, the relative energy lost approaches a constant value. This is consistent with the deeper penetration of showers as the electron energy increases. The filters follow the longitudinal energy deposition of a 2.5 GeV photon shower. As the penetration increases, the fraction of light in the relatively less damaged EM2 section increases. For 50% light loss at shower maximum the calorimeter

measures about two-thirds the ideal energy, and for 25% light loss the calorimeter measures about 80% of the ideal energy. The lines in the figure are fits to the simulated data with the form $R = A + Be^{\alpha E}$, where A , B and α are constants, and R is the ratio of the measured energy to the beam energy E .

Fig. 30. The ratio of the mean energy to its ideal value, before correction for both data (solid circles) and simulation (open circles) for data with 25% and 50% filters. The calorimeter was simulated with GEANT, including all of the inactive material in the calorimeter, photon statistics, and the reduction of the light yield from the filters. The lines in the figure are fits to the simulated data with $R = 0.843 - 0.0215e^{-0.0152E}$ for the 25% filters, and $R = 0.688 - 0.0447e^{-0.0270E}$ for the 50% filters, where R is the ratio of the measured energy to the beam energy, E (in GeV).

A consequence of the light-loss illustrated in fig. 30, is a corresponding loss of resolution in the calorimeter. We parameterize the degradation in the resolution by adding an additional contribution to the systematic term b in eqn (1), i.e. $b = b_0 \oplus b_1$, where b_0 is the resolution of the calorimeter without filters (no radiation damage), and b_1 is the contribution to the resolution due to the filters. Figure 31 shows the dependence of b_1 on beam energy for real

and simulated data. As expected, the degradation in resolution is worse for the data collected with the 50% filters installed. There is good agreement between the simulated data and the data taken in the test beam. We fitted the simulated data to the function $b_1 = C + D \log(E)$, where C and D are constants, and E is the beam energy in GeV.

Fig. 31. Systematic term b_1 as a function of energy for test beam data and simulation with 50% and 25% filters installed, prior to correction. The open circles are the GEANT simulation and the solid circles are the data. The lines are a fit to the simulated points with $b_1 = 3.53 - 0.662 \log_{10}(E)$, for the 25% filters, $b_1 = 6.57 - 1.00 \log_{10}(E)$ for the 50% filters, with E the energy in GeV.

In fig. 32 we show the ratio of the average energy to the beam energy before and after correction. As can be seen, using the correction based on the ratio of energies in the EM1 and EM2 sections, we are able to restore the linearity of the calorimeter up to the highest measured energy, even with 50% light loss at shower maximum.

Finally fig. 33 shows b_1 , the additional systematic term in the resolution, before and after correction. With the two EM compartments we are able to restore the calorimeter

Fig. 32. The ratio of the mean energy to its ideal value, before (solid points) and after (open points) correction for data with 25% (circles) and 50% (squares) filters. The solid points are the same data as plotted in fig. 30. Note the suppressed zero on the vertical scale. As the open circles show, we are able to correct the linearity of the calorimeter based on the EM1/EM2 ratio even for light loss up to 50% at shower maximum.

linearity and the resolution is degraded only by a small addition to the stochastic term. At high energy, the additional systematic term is $\lesssim 1\%$ or smaller, about equal to the expected contribution of tile-to-tile variations and transverse uniformity (each expected to be $\sim 0.5\%$ ^[27]).

Fig. 33. The additional contribution to the calorimeter resolution b_1 as a function of energy before and after correction on the basis of the EM1/EM2 energy ratio. The squares are the data taken with the 50% filters installed in the calorimeter and the circles are the data taken with the 25% filters. The solid points are before correction and the open points are after correction.

8. Pre-Shower Detector Test Beam Response

Each tower of the calorimeter has an 8 mm thick scintillating tile/fiber combination after two unit cells of the calorimeter (*i.e.* $2.2 X_0$ deep) to help identify electrons on the basis of their early shower development in the calorimeter. The 16 tiles in the pre-shower detector are readout using 16 channels of a 64 channel Philips XP1722 multi-channel photomultiplier tube (MCPMT). The pre-shower detector must be able to identify single minimum ionizing particles; hence, the scintillator tiles in the pre-shower detector are twice as thick as the tiles in the rest of the calorimeter. We used SCSN38 scintillator, because its emission spectrum is more closely matched to the photocathode response of the XP1722. The MCPMT signals, without further amplification, were sent directly to an ADC (C.A.E.N. model CIA) via a

300 nsec long RG58 coaxial cable.

For the measurements taken at high energy at the CERN SPS (20 to 120 GeV/c), there was no event by event particle identification, and both the electron and pion beams were generally contaminated with particles of the other type. In the following analysis we consider the response of the pre-shower detector for the 120 GeV data only. Below 120 GeV/c there is significant contamination of the pion beam with electrons.

8.1. ELECTRON RESPONSE

Fig. 34 shows the response of the calorimeter to the 120 GeV/c electron beam on a logarithmic scale, indicating the pion contamination in the beam. To identify electrons we require the measured pulse height to be between 1875 and 2200 ADC counts. The peak near zero is significantly wider than the pedestal (the pedestal has an *rms* width of less than 1 ADC count) and suggests a shoulder from minimum ionizing particles (*i.e.* muon contamination in the beam,).

Fig. 35 a) shows the energy in the calorimeter for 120 GeV/c electron beam versus the pulse height in the pre-shower detector for tower 11. A clear band of points due to the electrons is visible near the top of the figure, well separated from most pions that appear along the left edge of the plot. Fig. 35b) is a projection of this plot, integrated over all calorimeter energies. The peak near zero ADC counts is from minimum ionizing particles, and the broad maximum near 1000 ADC counts is attributed to electrons.

Fig. 34. Response of the calorimeter to 120 GeV/c electrons in tower 11. The vertical scale is logarithmic to show more clearly the pion and muon contamination at lower pulse heights.

8.2. MCPMT GAIN UNIFORMITY

We have measured the relative gain of each tower and pre-shower tile by centering the beam on each of the 16 towers. The broad maximum from electrons (fig. 35-b)) was fitted with a Gaussian distribution, and the mean from the fit was used to represent the product of the light yield and MCPMT response. The results are shown in fig. 36-a), a distribution of the responses of the 16 channels of the MCPMT, each normalized to its mean value. As can be seen in fig. 36-a), the response of the individual pre-shower channels varies by a factor of three and the ratio of the *rms* width of the distribution to the mean is 29%. Measurements of the individual tiles using the same photomultiplier tube indicated a tile-to-tile variation of 4%. The gain variation of a factor of 3 is in agreement with the manufacturer's expectation

Fig. 35.(a) Scatter plot of calorimeter energy versus pre-shower signal for 120 GeV/c electrons in tower 11. Electrons are in the band at the top of the figure, while most pions are near the left edge. (b) Projection of the data in a) onto the pre-shower energy axis. The peak near zero is from minimum ionizing pions in the beam, and the broad maximum near 1000 ADC counts is from electrons.

for the MCPMT. Fig 36-(b) shows the ratio of the average electron response to the average response measured by the radioactive source calibration, again normalized to one. After calibration, the ratio of the *rms* width to mean energy deposition for electrons is 14%, indicating a significant improvement of the uniformity.

8.3. PION RESPONSE

The pulse height response of the calorimeter to 120 GeV pions is shown in fig. 37. Figure 38 is a the scatter plot for pions of energy deposited in the calorimeter versus energy in the pre-shower tile. Most of the pions are near the left edge of the plot, with only a few

Fig. 36. (a) Distribution of responses for 16 channels of the MCPMT as determined from the dedicated runs of 120 GeV/c electrons, normalized to one. The *rms* width of the distribution is 29%. (b) Distributions of the relative gain after source calibration, normalized to 1. The ratio of the *rms* width to the mean value is 14%. Only 14 towers are represented in this plot, because two towers were not calibrated with the radioactive source.

points in the electron region between 1875 and 2200 counts of calorimeter energy. We also note a correlation between the pre-shower tile and the measured calorimeter energy in the lower right hand corner of this plot: a roughly triangular area with fewer points. This can be explained by observing that the particles which deposit significant energy in the pre-shower tile must also deposit a larger energy in the calorimeter.

Fig. 37. Pulse height distribution in tower 11 of the calorimeter for a 120 GeV/c π beam. The reconstructed tracks from beam particles were required to be within the beam envelope. Inset shows, on a linear vertical scale, the distribution from non-interacting pions and muons near zero (pedestal subtracted). The pedestal distribution has an *rms* width less than 1 ADC channel.

8.4. PRESHOWER LIGHT YIELD

To measure the light yield of the pre-shower detector, we have used pions that do not interact in the calorimeter. We require the pions to be within the beam profile and the pulse height in the EM1 section of the calorimeter to be less than 20 counts. Fig. 39 shows the distribution of energy in the pre shower tile for these particles. We have fit this distribution with the sum of three Gaussian distributions. The fit parameters are listed in table 4.

Fig. 38. Scatter plot of the energy measured in the calorimeter versus the energy in the pre-shower detector for 120 GeV/c π beam.

The peak near zero ADC counts has a fitted mean of 1.5 ± 0.3 counts and width 7.84 ± 0.25 counts, consistent with the measured pedestal mean and width of 0.0 ± 1.4 and 8.9 ± 1.4 counts, respectively. The other two Gaussian distributions, which we take to be the one and two photoelectron (P. E.) peaks have means of 21.5 ± 2.0 counts and 43.3 ± 18 counts (although identification of this second peak with the two photoelectron signal is not convincing because of the large errors on the fit parameters). From the ratio of the number of events in the pedestal peak to the total number of events in the plot we compute the average number of photoelectrons/min-ionizing particle as 0.62 ± 0.08 in the pre-shower tile. From this the fraction of events in the one and two photoelectron peaks are predicted to be 0.333 and 0.103, versus 0.325 ± 0.10 and 0.125 ± 0.10 measured from the fit to the data. After

removing the width of the pedestal peak in quadrature, the *rms* widths of the the 1PE and 2PE peaks are 11.0 ± 1.4 and 17.3 ± 4.5 counts, respectively. The ratio of these widths, 1.6 ± 0.5 , is consistent with the ratio expected from photon counting (*i.e.* $\sqrt{2} = 1.4$).

On the basis of laboratory measurements described earlier, we would have expected about 4 PE/mip in the pre-shower tile, when the attenuation in the clear readout fibers is included. We are unable to account for the low photoelectron yield from the pre-shower detector. It is possible that the pre-shower fibers were mis-aligned with the channels of the MCPMT, or that the transmission of light through a fiber connector was significantly lower than anticipated. Although it does not affect our estimate of the $e-\pi$ separation with no radiation damage, any significant radiation damage would compromise the usefulness of a pre-shower detector with similar light yield.

Table 4. Parameters for the sum of three Gaussian distributions $G(x) = Ae^{-(x-x_0)^2/2\sigma^2}$ fit to the data of Fig. 39.

Peak	A	x_0	σ
Pedestal	451 ± 34	1.51 ± 0.32	7.84 ± 0.25
1 P.E. Peak	158 ± 30	21.5 ± 2.0	13.5 ± 3.4
2 P.E. Peak	31.6 ± 26	43.3 ± 19	25.7 ± 3.1

8.5. PION REJECTION

The naive π rejection factor is computed by counting the number of particles in the 120 GeV π beam which a) satisfy the electron energy requirements and b) leave a signal in the pre shower detector larger than minimum ionizing. We show the π rejection factor and electron efficiency as a function of the pre-shower cut in fig. 40. In this figure a pre-shower cut of zero (*i.e.* no pre-shower cut) gives the pion rejection and electron efficiency irrespective

Fig. 39. Distribution of pulse heights in the pre-shower detector for 120 GeV/c π beam for particles that are minimum ionizing in the EM1 section of the calorimeter. The average pedestal has been subtracted and the distribution has been fit with the sum of three Gaussian distributions (solid line, see Table 4). The peak near zero (dashed line) is consistent with the location and width of the pedestal. The dot-dashed line is interpreted to be the one-photoelectron peak, and the dotted line is consistent with the two-photoelectron peak.

of the pre-shower signal. For this case we define the electron efficiency as 100% and measure the π acceptance as $0.62\% \pm 0.09\%$. As an example, if the pre-shower cut is increased to 325 ADC counts, the electron efficiency drops to $97.5\% \pm 0.3\%$ and the π acceptance decreases to $0.23\% \pm 0.05\%$; roughly a factor of 3 smaller than with no pre-shower cut.

We were concerned that the “ π ’s” measured to be within the electron acceptance were actually real electrons. To examine this possibility we have estimated the electron contamination by extrapolating the rate of π ’s outside the electron region into the region of electron

Fig. 40. The electron efficiency (left hand scale) and pion acceptance (right hand scale) as a function of the pulse height in the pre-shower tile. A pre-shower cut of "0" means no cut on the pre shower tile. The horizontal scale is the same as in fig. 35-(b), 38 and 39. Most of the pion rejection comes from removing pions that leave one or zero photoelectrons in the pre-shower detector.

acceptance. To understand this, consider fig. 41, where we have designated π regions 1, 2 and 3, as well as the region for accepted electrons. Our technique will be to compute the number of π 's in region 1 as a function of calorimeter energy and then extrapolate this quantity into the electron region of the plot. This is shown in fig. 41-(b), which is the projection of the data from region 1 onto the calorimeter energy axis (i.e. the vertical axis of fig. 41). The extrapolation predicts 29.1 ± 6.2 events, compared to 26 seen in the data. To test the validity of this extrapolation procedure, we have also tried to predict the π population in region 3 by extrapolating from pion region 2. From this extrapolation we expect 38.1 ± 7.4 events in region 3 compared to the 24 actually measured. We conclude that for the 120 GeV/c pion

Fig. 41. (a) Scatter plot of fig. 38 for 120 GeV/c pion beam in tower 11, showing the four regions used to estimate the number of pions in the electron region. We estimate the number of pions in the “e region” by extrapolating the number of events from “ π region 1” into the electron region. We test the technique by comparing the extrapolation from “ π region 2” into “ π region 3” and comparing the predicted number of pions with the measured number. (b) Projection of the data from π region 1 onto the vertical axis. The line is a fit of an exponential distribution to the data. Extrapolating this distribution onto the electron region we predict 29.1 ± 6.2 events versus 22 observed.

beam, the “ π ’s” satisfying electron cuts are mostly, if not entirely, pions.

8.6. PRE-SHOWER CONCLUSIONS

We have examined the performance of the pre-shower detector for the data taken at the CERN SPS. We find that, at a minimum, the pre-shower detector provides an additional factor of 2-3 rejection against charged pions simulating electrons in the calorimeter. Additionally, we have found there is a factor of 3 in the channel-to-channel gain variation of

the Philips XP1722 multi-channel Photomultiplier tube, consistent with the manufacturer's specification. Using a source calibration, the gain of the individual channels of the MCPMT can be corrected to reduce the ratio of the *rms* width to the mean value from 29% to 14%. Based on laboratory measurements the photon yield of the MCPMT in test beam data was about a factor of 6 less than expected. We have no verifiable explanation for this discrepancy.

9. Conclusions

We have tested a calorimeter module at the CERN H6 Test beam intended to simulate the endcap electromagnetic calorimeter of the Solenoidal Detector Collaboration (SDC) experiment at the SSC. The test module was manufactured from scintillating tiles read out via 1 mm diameter wave-length shifting fibers. The transverse uniformity of the response of an individual tile has an *rms* width $\pm 2\%$ of the mean and the transverse response appears to be the same for all tiles tested. Test beam and calibration results show the calorimeter response is linear to within 1% and has a resolution of $(19.5\% \pm 0.1\%)/\sqrt{E} \oplus 0.47 \pm 0.05\%$ for energies up to 200 GeV. The resolution degrades near the tower boundaries in a way that is similar from tower to tower; thus it may be corrected with a single location-dependent term applied to all towers. Using a simple clip line, we have shown that the signal from the calorimeter can be restored to baseline in as little as 30 ns, compared to 80 ns without the clip line. The price of this faster signal is an eight fold increase in the noise, although even with this degraded performance the calorimeter would meet our resolution specifications.

We have presented *extensive* simulated data and test beam data to show that longitudinally varying radiation damage to the calorimeter can be corrected offline. We find the Monte Carlo simulation and the test beam results to be in very good agreement. The original linearity ($\sim 1\%$) and resolution requirements for the calorimeter performance can be

maintained with up to $\sim 50\%$ light loss at shower maximum. The calorimeter is equipped with a "pre-shower detector," which improves the charged π rejection by a factor of 2-3 for an electron efficiency greater than $97.5\% \pm 0.3\%$, even though the light yield was less than expected.

To conclude, we find the tile/fiber technology described in this report well suited to the environment of high luminosity hadron colliders. The linearity and resolution of the calorimeter is within the required specifications, and we believe these results show that despite severe radiation damage to the active components, the offline calorimeter performance can be maintained. Furthermore, we expect that any deterioration from radiation damage will be "graceful": *i.e.* it would not lead to sudden changes in the performance. Even in the worst of circumstances, our design would allow for the *in situ* replacement of the components during a shutdown of the accelerator, permitting us to substitute new scintillation material, perhaps more radiation hard, if such materials are developed. We hope this design study and presentation of test beam results will be helpful as a new set of experiments are prepared for the Large Hadron Collider at CERN.

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- ^[17] Built by V. Barnes, Purdue University. See V. Barnes *et. al.*, "Calibration of Scintillating Calorimeters," *Proceedings of the International Conference on Calorimetry*, (Oct. 29, 1990).

- ^[18] P. Cushman, R. Rusack, Nucl. Inst. and Meth., A333 (1993) 381.
- ^[19] Product of OMEGA Engineering, One Omega Drive, P.O. Box 4047, Stamford, CT 06807-0047.
- ^[20] A product of C.A.E.N, 55049 Viareggio, Italy.
- ^[21] A product of CES-Creative Electronics System, PO Box 107 CH-1213 Petit Lancy 1, Switzerland.
- ^[22] UNIDAQ- Software for UNIX Based Data Acquisition, SDC note SDC-93-573 and UM-HE-93-29 (University of Michigan).
- ^[23] "Particle Beam Generator Using a Radioactive Source" U.S. Patent Number 5,198,674 , Inventor David G. Underwood, March 30, 1993.
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