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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Quality control and calibration of the ZEUS forward and rear calorimeters with ^{60}Co sources

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We present the motivation for and the design of a mobile ^{60}Co source system used as part of the quality control and calibration monitoring scheme for the ZEUS calorimeters. A 2 mCi ^{60}Co source is pushed by a computer controlled drive mechanism through guide tubes which extend into the calorimeter. Measurements of induced photocurrents as a function of the source position allow checks on the calorimeter response. We present results obtained during the initial scan of all 916 towers of the forward and rear calorimeter modules.

1. Introduction

The ZEUS detector [1] constructed to study e–p collisions at HERA, relies on a high precision uranium/scintillator calorimeter for much of its physics results. The calorimeter is compensating and has excellent energy resolution for hadrons/jets ($35\%/\sqrt{E}$), and electrons ($18\%/\sqrt{E}$) over a wide energy range. For a description of construction details and test beam results see refs. [2,3]. To fully realize the potential of the ZEUS calorimeter requires unprecedented attention to details of calibration monitoring; the design goal is to reduce systematic errors to a level of less than 1%. It is with this in mind that the calorimeter group has undertaken the development of several monitoring systems.

To understand the monitoring systems it is useful to consider the operation of the calorimeter. A simplified overview is shown in fig. 1. Incident particles give rise to showers in the stack of depleted uranium (DU) plates and scintillator tiles. Blue light from the scintillator tiles proceeds by internal reflection to the edge of the module where it is absorbed in wavelength shifter (WLS) plastic light guides. The absorbed light causes fluorescence at green wavelengths in the WLS and this light propagates by internal reflection to the photomultiplier tube coupled to the particular light guide. The resultant photoelectrons are amplified in the phototube dynode structure and the output pulse is processed by the readout electronics.

The recorded signal depends on the performance of scintillator, wavelength shifter, photomultiplier and

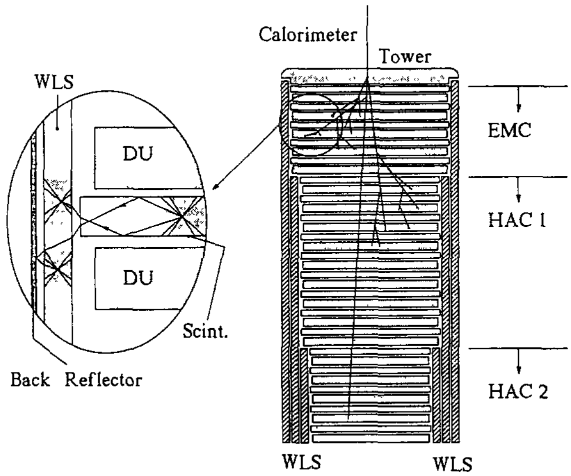

Fig. 1. Schematic representation of a uranium/scintillator stack read out by wavelength shifter light guides (not to scale).

read-out electronics. Not all of these components can be expected to remain stable at the one percent level throughout the life of the experiment. Thus several monitoring systems, which will access different parts of the chain, have been foreseen. These can be shortly summarized as follows:

Electronics calibration. Test pulses injected into the front-end cards of the readout are used to calibrate preamplifiers and determine parameters of the electronics pipeline.

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Laser calibration. A system of optical fibres, supplied with light by a laser, injects light immediately in front of the photocathodes to test the gain and linearity of the phototubes. In addition, these light pulses are used to calibrate the low gain electronics channels. They can also be used for precise timing calibration and the determination of the number of photoelectrons per GeV.

Uranium "noise" (UNO) calibration. The constant, low level, radioactivity of the depleted uranium gives rise to a steady glow in the scintillator tiles. This results in a small photocurrent in the phototubes which is used to monitor the stability of the calorimeter as a whole. This also provides a standard to allow for tower-to-tower equalization at the level of 1% and to carry the absolute calibration from the test beam to the final position in the ZEUS detector.

With the preceding systems, one can isolate the cause of a change in calorimeter behaviour by process of elimination. For example if the phototube gain on a given calorimeter tower changes it will show up in the UNO signal and the laser data but not in the test pulse results. However if the UNO signal alone changes it may be difficult to conclude what inside the calorimeter has changed. Such changes could be:

- mechanical damage to or shifting of the WLS/light guides and scintillator tiles during shipment of the calorimeter module,
- ageing or radiation damage to the scintillator or WLS/light guides resulting in changes to absolute light output or attenuation length.

The ^{60}Co source system was designed to monitor such effects. By introducing in addition to the DU a controlled source of activity in a specific position of the calorimeter, one is able to provide more information. For example, by scanning with the source along the DU/scintillator stack in a direction parallel to the WLS, one can measure its attenuation length. By com-

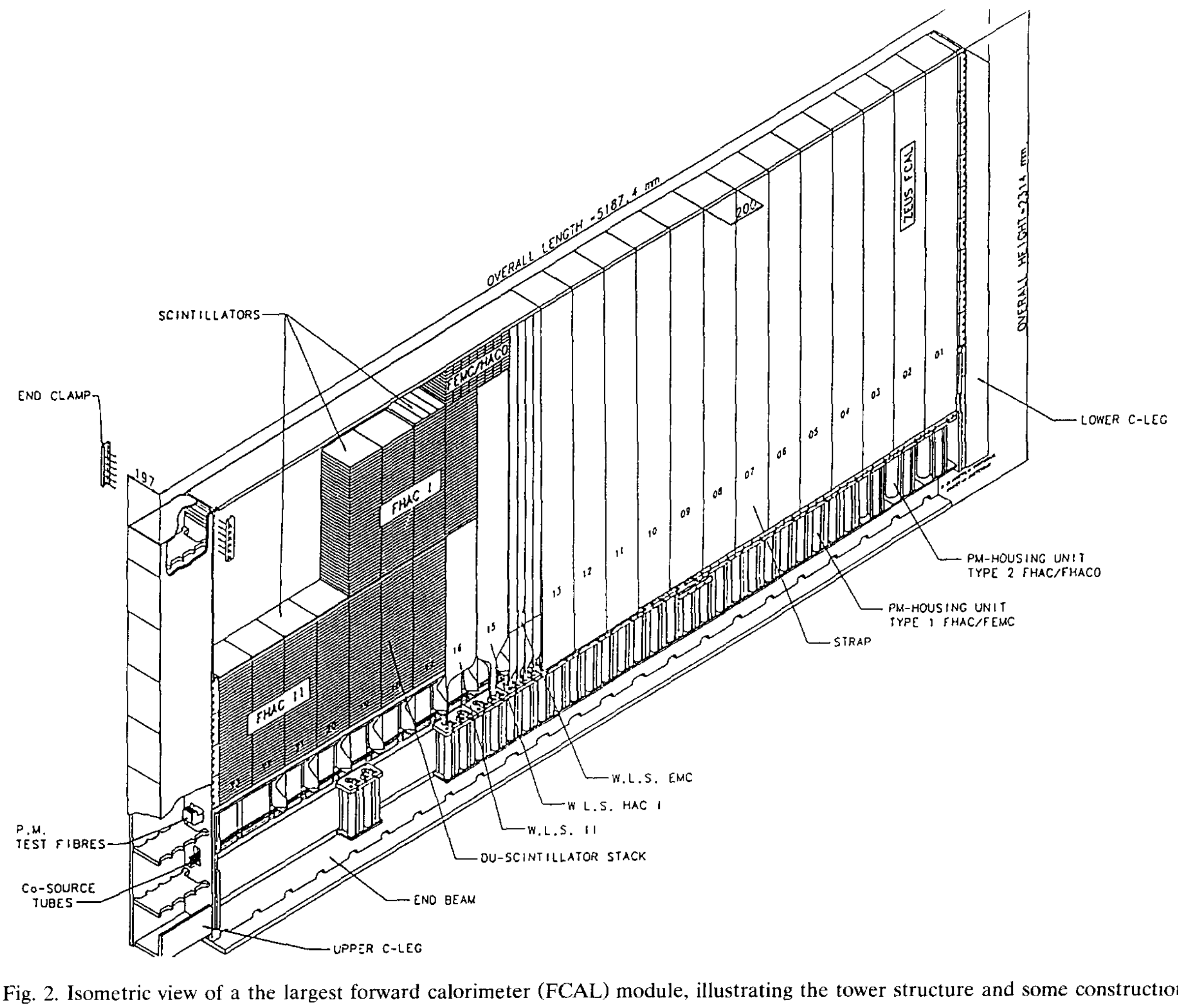

Fig. 2. Isometric view of a the largest forward calorimeter (FCAL) module, illustrating the tower structure and some construction features.

paring scans done on one side of the stack with those done on the other, the attenuation of light in the scintillator tiles can be measured.

Such information may be crucial for the understanding of anomalous behaviour in the calorimeter module. It is clearly desirable that all calorimeter towers can be scanned at least once (thereby establishing a large statistics data base and defining what is the "normal" behaviour) and it should be capable of being obtained in situ so that one is not forced to uncable and partially disassemble the calorimeter in order to understand anomalies. These considerations have driven the design of a system for the scanning of the forward and rear calorimeter with ^{60}Co sources to provide a final quality control.

2. System design

2.1. Source guide tubes

The ZEUS front and rear calorimeters (FCAL and RCAL) are built from modules like the one shown in fig. 2. Full length DU plates are fixed in a steel C structure comprising an end beam and an upper and lower box beam. Scintillator tiles are sandwiched between the DU layers and WLS/light guides are fixed to the sides. Each layer of DU plus scintillator is one radiation length thick (3.3 mm DU, 2.6 mm scintillator). The width of each module is 20 cm and the height of the active area is a multiple of 20 cm.

The active depth is divided into a tower structure which can be seen in fig. 1. The first 25 layers of DU and 26 layers of scintillator absorb incident electrons and photons. This part is referred to as EMC. It is vertically subdivided into 5 cm strips in the FCAL and 10 cm strips in the RCAL. For the towers near the top and bottom of the modules which are shadowed by the barrel calorimeter, the granularity is reduced and the first 25 layers are vertically subdivided into 20 cm strips in both FCAL and RCAL. These subdivisions are called HAC0 towers. In FCAL the remaining 160 layers absorb that part of hadronic showers not contained in the EMC part. They are divided into two equal parts called HAC1 and HAC2. In RCAL there are only 80 layers backing up the EMC section and so there is only HAC1.

Thus the geometry of the calorimeters is based on 20 cm by 20 cm towers with further subdivision into 5 cm by 20 cm strips in some parts of FCAL and 10 cm by 20 cm strips in parts of RCAL. Each of these subdivisions has its own pair of WLS/light guides [9]; one per side.

Let us consider one of the FCAL EMC towers as an illustrative example. If one is to explore all the active regions of such a tower with a gamma-ray source, it

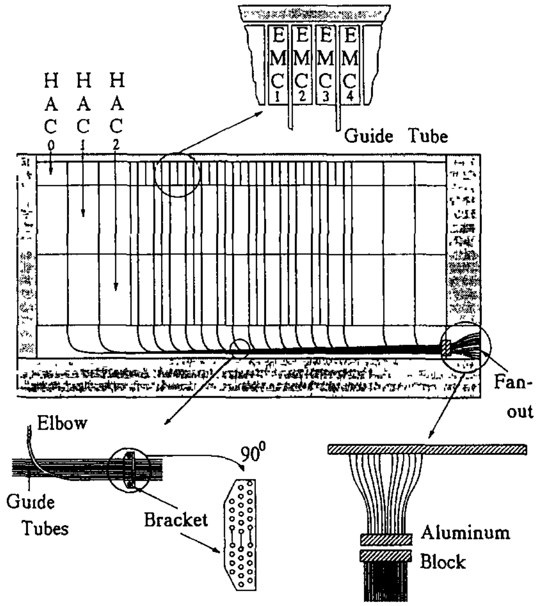

Fig. 3. The tube system for guiding the cobalt source inside the calorimeter modules.

will be necessary to bring the source close to each of the 5 cm strips. This is because the absorption of low energy (1 MeV) gammas in the uranium, coupled with the thin layer structure (8 mm), limits the effective range of the source to the order of a few millimetres. A scheme for doing this, which is consistent with the geometry of the WLS/light guides is shown in fig. 3. Two guide tubes, located between WLS/light guides 1 and 2 and between 3 and 4, allow irradiation of the corresponding EMC towers. The tubes continue to the back behind the WLS/light guides which read the HAC1 and HAC2 towers. Moving the source through these tubes allows irradiation of HAC1 and HAC2 from two different places on the same side.

For RCAL towers a single tube between the two (10 cm) EMC WLS/light guides is sufficient and for HAC0 towers a tube at one edge is provided. Guide tubes on both sides of the 20 cm wide towers are desirable for consistency checks and for measuring attenuation in the scintillator.

This scheme leads to the requirement of at least two and very often four guide tubes for every 20 cm by 20 cm tower in the calorimeter module. Modules can have as many as 23 towers; the maximum number of guide tubes in a module is 84, which requires an automated system that can drive a source into each of these guide tubes under computer control.

As previously mentioned, this source system will be most useful if it can also be deployed after the calorimeter modules have been installed in the ZEUS

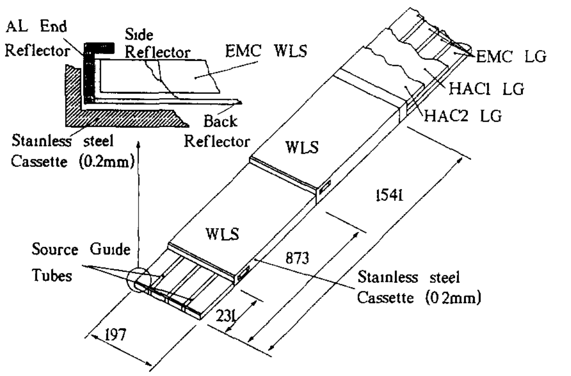

Fig. 4. Detail of how the guide tubes are incorporated into the light guide assemblies.

experiment. This has led to a design where all guide tubes in a given module are brought to a common location on the upper box beam where a compact, portable source driver can be quickly installed and operated. This is realized in the following way.

All guide tubes are made of brass (2.5 mm outside diameter, 0.2 mm wall thickness). Straight tubes are incorporated into the "cassettes" which contain the WLS/light guides (fig. 4) or, in the case of HAC0 towers, are secured between cassettes after they have been installed on a module. Long guide tubes, pre-cut to finish at correct intervals, are mounted along the end-beam of the module using specially made brackets (fig. 3). These two types of guide tubes are joined by an

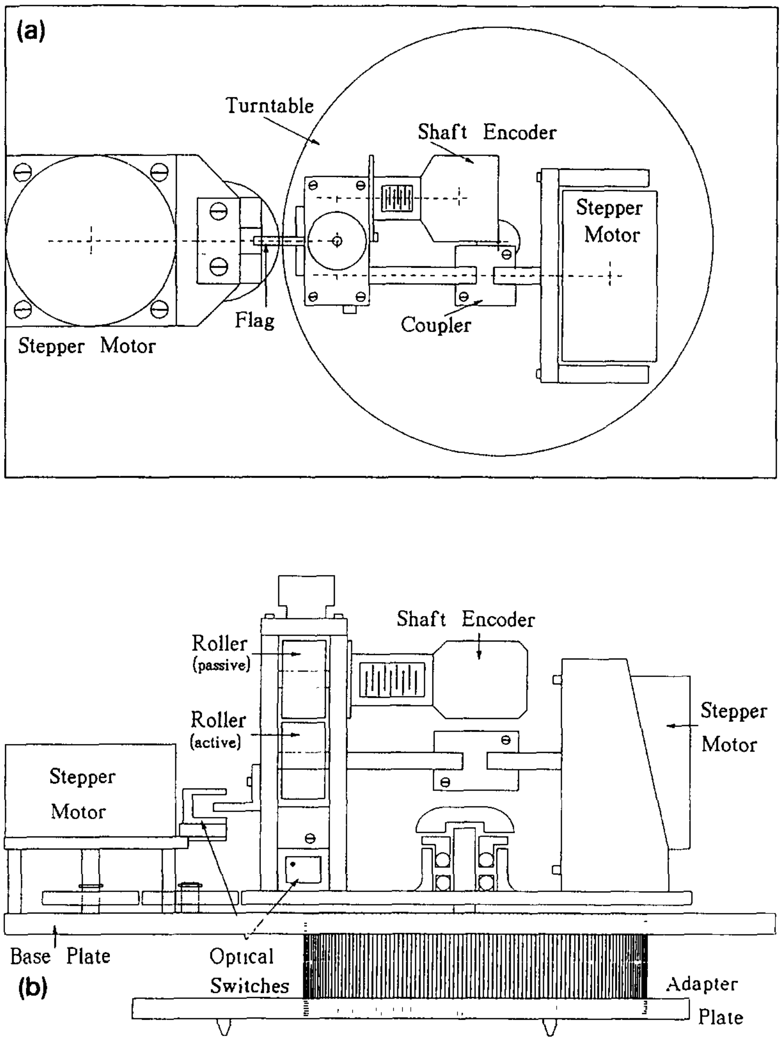

Fig. 5. The source driver, (a) top view, (b) side view.

"elbow" which is shaped to pass through the bent strips of the adiabatic light guide structure. The elbow changes the direction of the source travel by 90° and moves the plane of its motion from the end beam (essentially the mid-plane of the calorimeter module) to the outside edge. The elbows are installed after the light guides have been fixed to the calorimeters and are joined using 3 cm splice tubes (3.0 mm outside diameter, 0.2 mm wall thickness) secured with cyano-acrylic glue.

Just below the upper box beam, the end beam guide tubes terminate in an aluminum block (fig. 3) that is part of a matched pair having an array of aligned holes into which the tubes are glued. The mate to this block forms the lower end of a "fan-out" (fig. 3). This is a construction in which the end-beam guide tubes, which are bundled in the form of two rectangular arrays, are fanned out into a circle of radius 55 mm. The upper end of the fan-out is an aluminum plate installed just below the removeable top plate of the upper box beam. Tapped holes, precisely located in this plate, allow the source driver to be bolted on whenever a source scan is to be carried out.

2.2. Source driver

The source driver is shown in fig. 5. It consists of two parts; a device which can drive the source up and down a guide tube and a device for selecting a particular tube.

The selection of which tube to drive a source down is done by mounting the drive mechanism on a turn-able, which is a spur gear of 140 mm diameter. This gear is rotated by a 36 mm idler gear which is in turn driven by a 36 mm spur gear mounted on the shaft of a stepper motor, (fig. 5a). To address a particular guide tube, it suffices to rotate the turntable until the hole through which the source emerges is directly above the tube. The angular orientation of the turntable is calculated relative to a zero position by counting steps of the motor. The zero position is defined by a TRW OPB804 optical switch interrupted by a small flag on the turntable.

The drive mechanism is shown in fig. 5b. It makes use of a second stepper motor which directly drives a 20 mm diameter polyurethane roller. This roller together with an identical idler roller, push or pull on the wire attached to the source using friction. Polyurethane has been chosen because it combines high friction with durability at an optimum level.

A pair of identical rollers, located just above the drive pairs, are passive and are used to measure the amount of wire which has been paid out. This is done using a shaft encoder (REX 32-400) which is mounted coaxially with one of the readout rollers. The shaft encoder produces 400 pulses per revolution and these are decoded by a Hewlett-Packard HCTL-2000 quadrature decoder. Counting these pulses allows one to calculate how many revolutions of the roller have taken place and hence what length of wire has passed through. The shaft encoder information is used in off-line analysis of source scans but is also valuable for on-line calculation of the source location at any given moment. This is used in conjunction with a data base of the guide tube lengths to slow down the drive speed when passing elbows and when arriving at the end of the guide tube. Another important function of the shaft encoder is to indicate immediately if the source has jammed inside a guide tube.

Just below the drive wheels there is an optical switch (TRWOPB804) which is used as a further check on the shaft encoder, indicating whether or not the source is retracted or is down one of the guide tubes. Only if the switch signals that the source has been fully retracted (and is therefore not blocking the LED beam) the turntable is allowed to be rotated to a new hole.

All of the driver components are mounted on an adapter plate which has a hole pattern like that of the fanout. This allows the quick connection of the assembly to a given calorimeter module with a minimum of screws.

2.3. Source

The source design is shown in fig. 6. A 1 mm length, 0.75 mm diameter radioactive cobalt wire is enclosed within a hard-drawn stainless steel tube (1.08 mm outside diameter, 0.15 mm wall thickness), the end of which is closed with a smooth tip. The tube itself is 7 m long and the cobalt piece is pushed up against the sealed end of the tube by a 7 m long spring steel piano wire, 0.7 mm in diameter which acts as a "filler" inside the tube. The length is dictated by the requirement that the source structure acts as a seamless "wire", able to penetrate the longest guide tube down to the end.

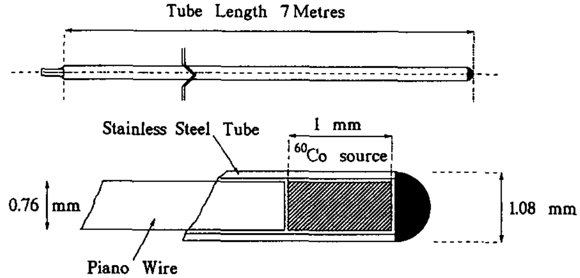

Fig. 6. The source assembly. Active cobalt is encapsulated within a stainless steel tube with a closed end. It is held in with a flexible filler wire.

The tubing itself is used routinely in the manufacture of hypodermic needles but is not readily available in the length we required. Thus a special mill run was commissioned to obtain the desired length after disappointing results were obtained with a hybrid design.

The hybrid was made from a 2 m length of tubing and a 7 m length of piano wire with the piano wire acting as filler and extender. The tubing was chosen to be 2 m long in order that the joint where it was hard soldered to the piano wire did not have to travel through the elbow joints in the guide tubes. Unfortunately, the piano wire had a tendency to spiral inside the guide tube when pushing against the thicker tubing ahead of it and this caused a great deal of resistance due to friction. This source was ultimately abandoned in favour of the continuous one described above. An interim solution wherein the calorimeter modules were scanned with a modified apparatus will be described later in this paper.

The source activity was chosen to be 74 MBq (2 mCi). This produces a photocurrent which is of the same order as that due to the UNO signal.

2.4. Driver control

The source driver is controlled locally by a microprocessor (Motorola 68HC11) running a program written in the Max-Forth (TM) computer language. It is responsible for controlling the stepping motors, reading the output of the shaft encoder, monitoring the optical switches and passing relevant parts of this information to the host computer. To step the motors the micro sends TTL logic pulses to translators (Superior Electric 430-PT) which supply the necessary currents to the motor coils.

The microprocessor and translators are located close to the calorimeter and are connected by a serial link to the host computer which is an MVME-bus computer running the OS-9 operating system.

Currents from the calorimeter phototubes are sent to integrator modules, used especially for the source scans. They have time constants of 24 ms and are read into 12-bit multiplexer ADCs [8].

The digitized photocurrents, along with information as to the position of the source are grouped into files which are sent to the DESY VAX cluster via Ethernet.

3. Data taking procedure

Before scanning a given calorimeter module for the first time, a data base is constructed and stored in the host computer. This data base contains a map of which tower is connected to which guide tube, which photomultipliers (PMTs) are to be read out, the length of each guide tube and a flag which may be used to indicate whether a tube has a bad joint or is not connected.

A run commences when the operator selects a specific tube or range of towers to be scanned. The host instructs the microprocessor to rotate the turntable to the correct tube. Then the microprocessor drives the source into the tube at a speed of 5 mm/s for a distance of 30 mm. If this proceeds without problems, the source has successfully passed the interface between the "fanout" and the end beam tube. At this point the drive speed is increased to 60 mm/s until the source reaches the elbow region and is slowed to a speed of 10 mm/s. After the elbow has been passed, the source is driven at a speed of 30 mm/s until, just before the end of the tube, it is slowed down to 5 mm/s. When the shaft encoder indicates that the source is no longer moving the microprocessor ceases sending pulses to the stepper motor.

Data taking then begins. The source is withdrawn at a constant speed of 5 mm/s ($\pm 3\%$). Position measurements are sent to the host machine every 3 or 4 mm. Between these updates, 10 measurements of the currents are made on each of the 12 PMTs in the selected tower. Response vs source position is displayed on-line as this proceeds.

After the source passed the HAC2 section data taking stops and the source is withdrawn at 60 mm/s to the home switch. The turntable is then rotated to the next tube on the list and the procedure begins again.

The host program has provisions for special source movements, allowing it to be driven to an arbitrary place in the calorimeter along an arbitrary guide tube. Also, the microprocessor program can be halted immediately by the operator in response to an emergency.

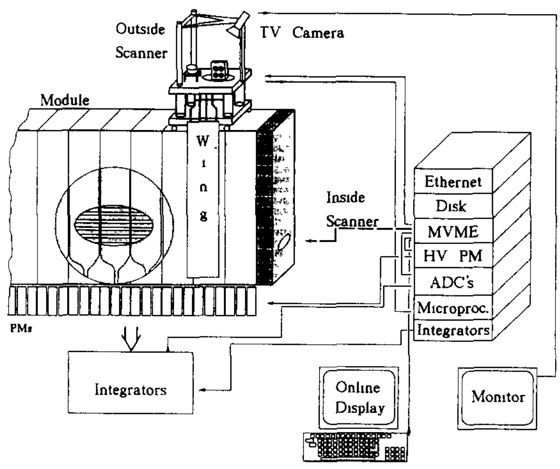

Fig. 7. The "outside" scanner used for most of the data presented in this paper.

4. Outside scanning

The preceding description of scanning equipment and procedures applies to the initial source scanning and to what is planned for in situ operations in the ZEUS detector. However, due to difficulties with the first version of the source, as well as constraints imposed by the limited time between the manufacture of the calorimeter modules and their installation into the detector, we relied on a less ambitious scanner to check out the modules as they arrived at DESY. This scanner, shown in fig. 7, consisted of the driver described previously mounted on an assembly which rolled along the front plate of the calorimeter module. The modules were scanned while in a position such that the towers were vertical and the front plate was on top. Two "wings" each with four guide tubes 5 cm apart from one another, hung down from the scanner, one on each side of the module. For most of the scanning, only two guide tubes per side were used. These were the ones which corresponded in position with the inner guide tubes already described.

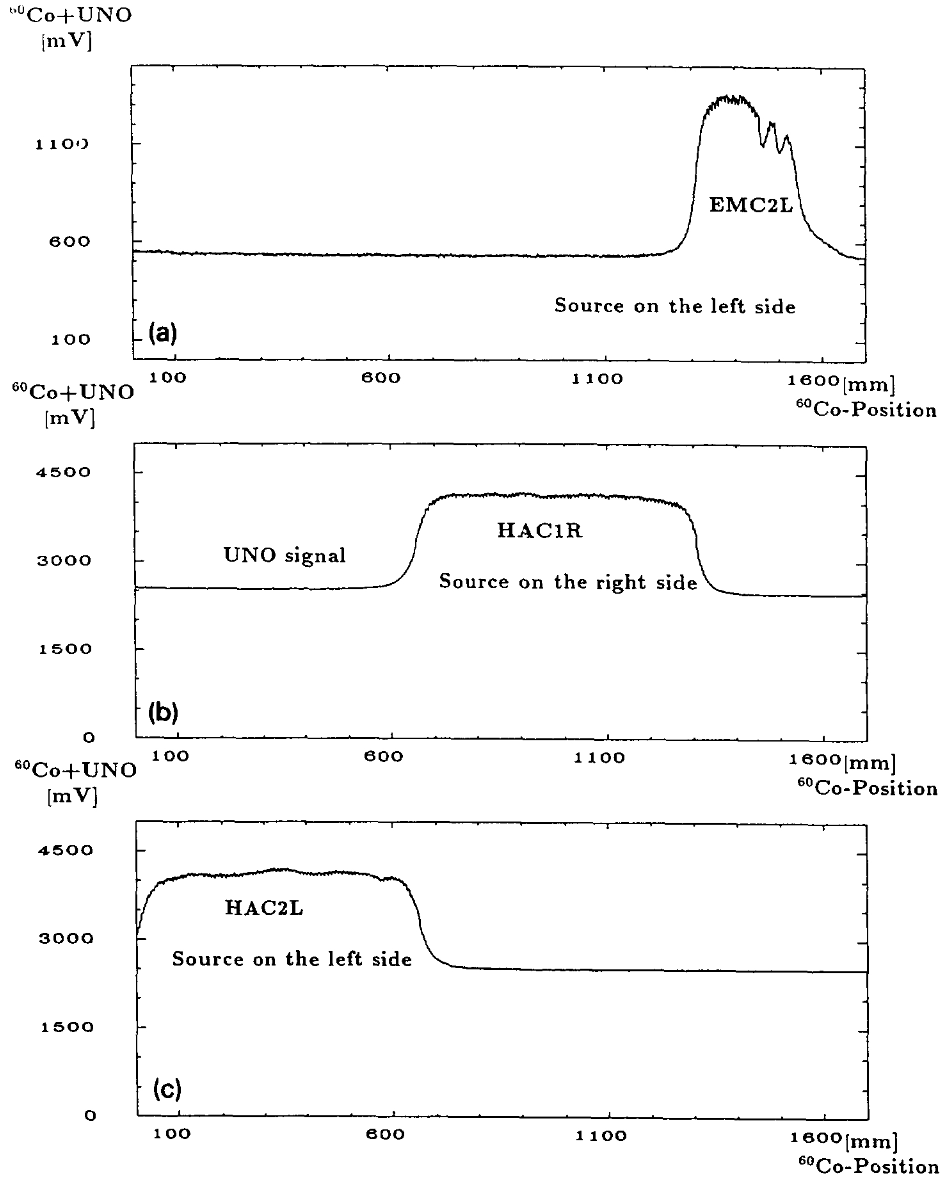

Fig. 8. Typical data from a source scan for (a) EMC, (b) HAC1 and (c) HAC2 sections of a tower. Note the fine structure which results from the layer construction of the calorimeter. The background is due to the uranium activity (UNO). EMC2L for example indicates the read out of the left PMT.

Scanning proceeded by manually rolling the driver to a position atop the tower of choice where-upon the wings were bolted to the calorimeter to ensure precise location of the guide tubes just outside the placement of the inside guide tubes. Following this, scanning continued under computer control, as described above. Once the source had been sent down each of the four possible guide tubes, the wings were unbolted and the driver was rolled to the next tower.

The main advantage of outside scanning is that one has short, essentially straight, guide tubes so that friction is not a problem and the restrictions on source design are not so severe. The scanning time is shorter since there is no time spent moving the source from the upper C-arm to the tower of choice, although this saving is balanced by the time required to manually move the driver from tower to tower. Spatial resolution is compromised somewhat due to the fact that the source is approximately 2 mm further away from the uranium scintillator stack than with the inside scanning. This washes out the finer details but is not too serious, as can be seen later in this paper.

5. Scanning results

5.1. Data analysis

Before making detailed studies, the raw data had first to be processed. To understand the following it is

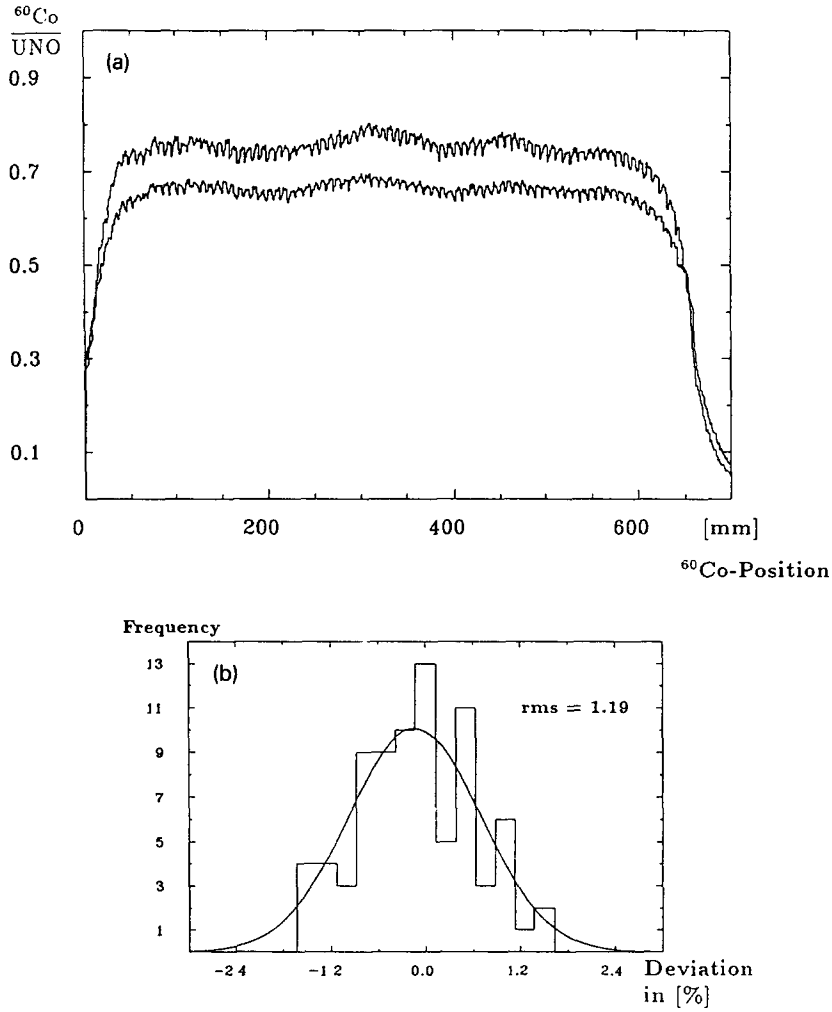

Fig. 9. Comparison of two different scans done to test reproducibility. (a) Data from a typical tower. The upper curve was taken using the inside scanner at CERN and the lower curve was taken using the outside scanner, months later at DESY. (b) The ratio of the curves plotted in (a) is calculated for identical source positions. (b) presents the frequency distribution of the derivation of this ratio ($S_L/S_R - 1$) from the mean value.

suggested to refer to fig. 8. A raw data "point" consisted of a number which was related to the position of the source inside the guide tube, along with the currents from all the phototubes associated with the tower which was being scanned by the source. The position of the source could be easily determined by applying a calibration factor to the first number. The signal due to the source was extracted from the photocurrents by subtracting the contribution due to the uranium activity (UNO) only.

The source signal consists of two components; the light from the scintillator plates and Cherenkov light induced in the WLS by recoil electrons created by the high energy gammas from the source. This latter contribution is only evident in the phototubes which are on the same side of the calorimeter as the source. Its size can be estimated quite reliably by looking at the photocurrents obtained while the source was travelling in a region of the calorimeter where the light guide is not viewing any scintillator. (For example this contribution is evident in the EMC currents when the source is next to the HAC sections – see fig. 12). The Cherenkov component is much smaller than the scintillator component and is not subtracted in most of the studies presented here.

After the UNO contribution has been subtracted from the signal I, the signals are normalized to the UNO currents. This is to take out the effects of unequal PMT gains. Assuming that all towers of a given type are identical, they should have the same UNO signal.

Thus in the following we use the term "signal" to refer to the quantity

$$(I - \text{UNO})/\text{UNO} = {}^{60}\text{Co}/\text{UNO}.$$

5.2. Reproducibility

One of the first measurements performed with the source drive was a check of the reproducibility. As was mentioned previously, one of the aims of source scanning was to monitor the long term stability of the scintillator and wavelength shifter plastic. Clearly, it is important to demonstrate that any observed changes are due to changes in the components and not just artefacts of the scanning process or random fluctuations from run to run. In addition, since we scanned all the modules before installation using the outside scanner and will do future scanning using the inside scanner, it is necessary to show that the two methods give equivalent results.

The first concern can be addressed by scanning the same module twice in quick succession. The second can be addressed by comparing data from modules where both inside and outside scanning were done.

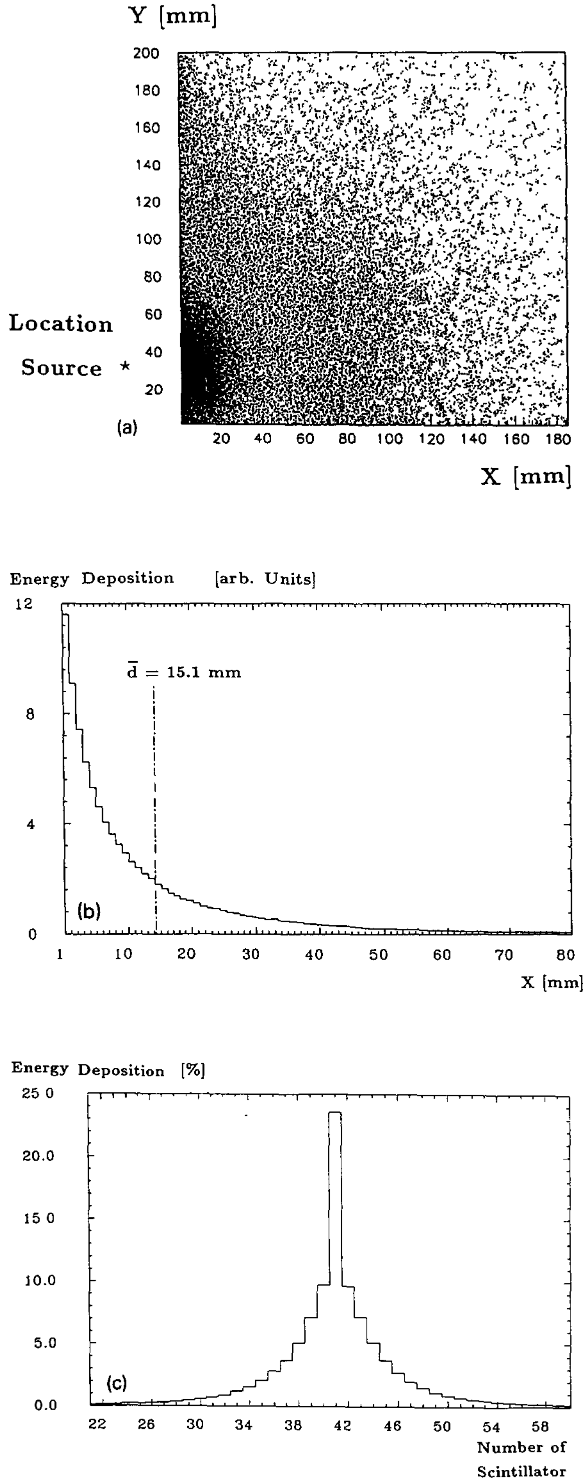

Fig. 10. Energy deposition patterns as determined by the EGS4 Monte Carlo. (a) First interaction points of photons in a scintillator tile. (b) Projection of the plot in (a) indicating that the mean depth of penetration of the cobalt photons is 15 mm. (c) Energy deposition as a function of layer number in the calorimeter stack.

Fig. 9a shows the results of such comparison. The differences in the pulse height comes from in-/outside scanning where the distance from source to scintillator is different and not from time delay. The top curve was obtained with inside scanning at CERN while the bottom curve was obtained with outside scanning several months later at DESY. The gross structure of the curves appears to be the same and this is verified by point to point comparison where ratios were found to be constant at the 1% level (fig. 9b).

These curves also demonstrate the mechanical stability of the calorimeter modules since for scanning at CERN the module was lying on its side (i.e. with the large face parallel to the floor) while the scanning at DESY was done with the module positioned in the stacking position (i.e. with the towers pointing vertically upwards). This is important since the modules are installed in the ZEUS detector in a third orientation, with the towers pointing horizontally.

5.3. *Quality of the optical components*

One of the important tasks of the source scanning system is to control the quality of the optical components of the calorimeter, namely the scintillator tiles and the wavelength shifter light guides. This can be done by comparing signals from phototubes on opposite sides of the calorimeter and by comparing runs taken with the source on different sides.

Studies made using the EGS4 Monte Carlo [4–6] show that most of the light induced by the cobalt source comes from near the edge of the scintillator tile which is closest to the source. This can be seen in fig. 10. Fig.10a shows a satter plot of the positions where

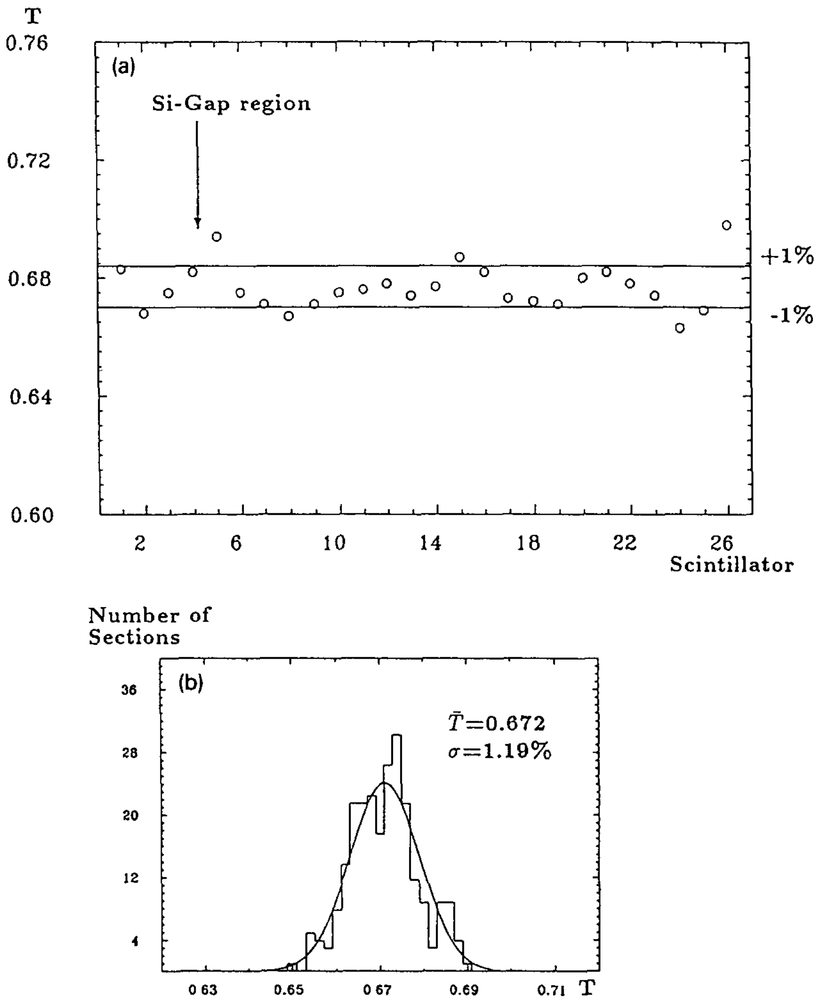

Fig. 11. (a) Transmission T vs scintillator number in a typical EMC tower indicating that the attenuation length in the scintillator tiles is uniform to within 1%. (b) Distribution of average values $\bar{T}$ from all HAC1 sections in 15 FCAL modules.

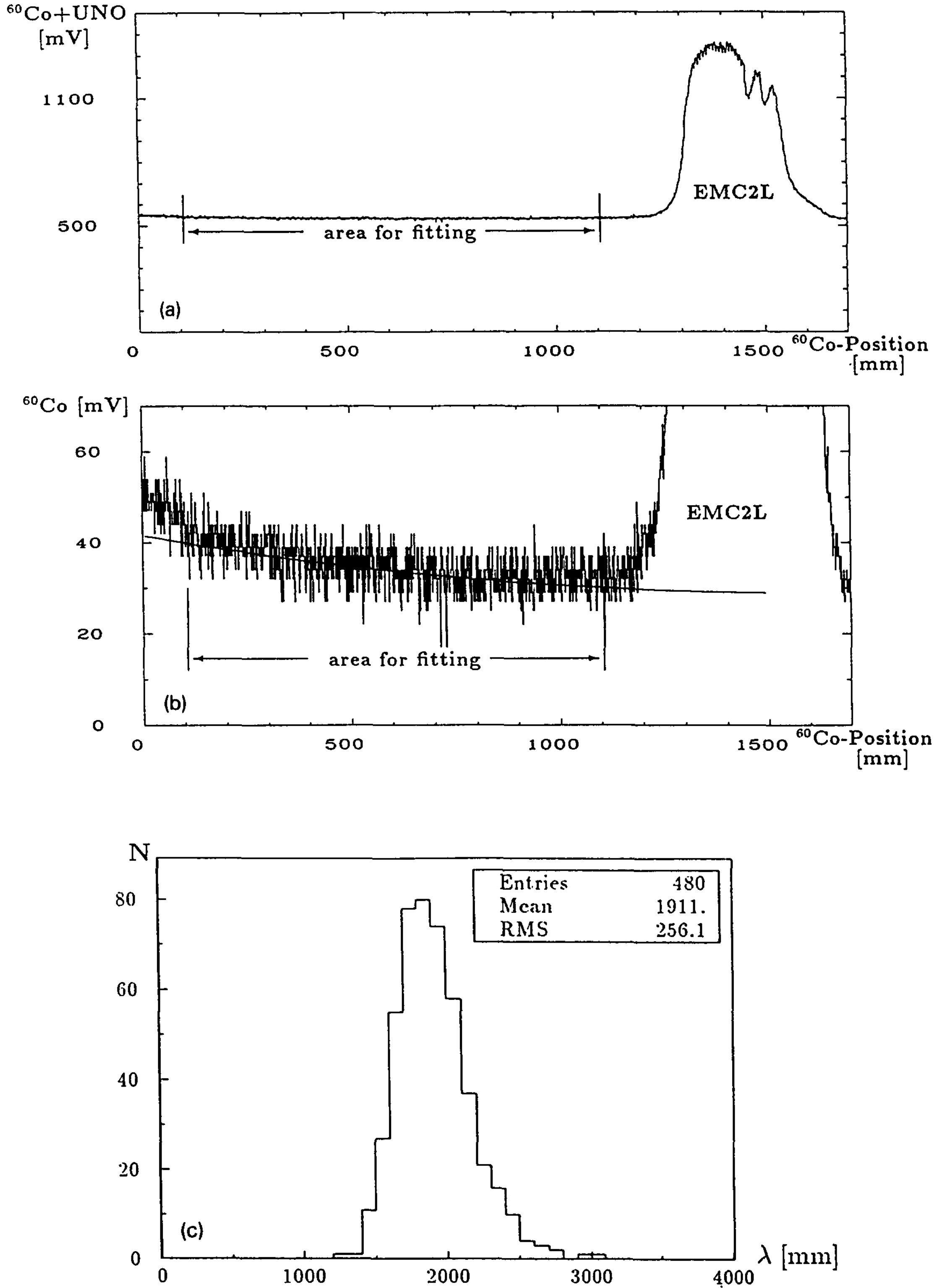

Fig. 12. (a) Current vs source position for a typical EMC light guide. (b) As in part (a) but with UNO signal subtracted and an exponential fit. (c) Distribution of attenuation lengths in all EMC light guides in all inside scanned FCAL modules.

the photons first interact in a HAC section and fig. 10b shows a projection of fig. 10a onto an axis perpendicular to the WLS light guides, indicating that the mean depth of penetration is about 15 mm.

This means that light exciting the WLS which is on the same of the module as the source comes directly from the near edge of the scintillator whereas light in the WLS on the opposite side has had to traverse the entire length of the scintillator tile. The comparison of the signals from both sides can be used to compute the effective attenuation length of the scintillator tile.

Finally, fig. 10c shows how the energy is distributed in the different scintillators as a function of layer number. When the source is next to a given layer, that layer receives more than twice as much energy as any of the others so it is possible to use the source scanning as a way to examine calorimeter properties on an almost layer-by-layer basis. Next we describe how the transmission of the scintillators can be obtained from the measurements [11].

We measure four signals for a given tower section (EMC, HAC1, HAC2):

- I_{RR}; the current in a PMT on the right side of the calorimeter when the source is on the right side,
- I_{RL}; the current in a PMT on the left side of the calorimeter when the source is on the right side,
- I_{LL}; the current in a PMT on the left side of the calorimeter when the source is on the left side,
- I_{LR}; the current in a PMT on the right side of the calorimeter when the source is on the left side.

Let S_R be the light yield emitted on the right side by the scintillator when the source is on the right side of the calorimeter and S_L be the light yield when it is on the left. These values can change from one scintillator tile to another.

Let W_R be the response of the wavelength shifter on the right side of the calorimeter and W_L be the response on the left. These need not be constant over the length of the wavelength shifter.

If T represents the transmission of the scintillator tile then we have (excluding Cherenkov light effects in the wavelength shifters)

$$I_{RR} = S_R W_R,$$
$$I_{RL} = S_R W_L T,$$
$$I_{LR} = S_L W_R T,$$
$$I_{LL} = S_L W_L.$$

One can use these relations to solve for T:

$$[(I_{RL} I_{LR})/(I_{LL} I_{RR})]^{1/2}.$$

5.3.1. Attenuation in the scintillator tiles

The quantity T is plotted vs scintillator layer for a typical EMC tower in fig. 11a. It is evident from this plot that the scintillator tiles are uniform to within about 1%. This shows that the effort expended during the procurement and assembly operations to achieve good uniformity has been successful. The source scanner will thus able to monitor the long term stability of the transmission accurately.

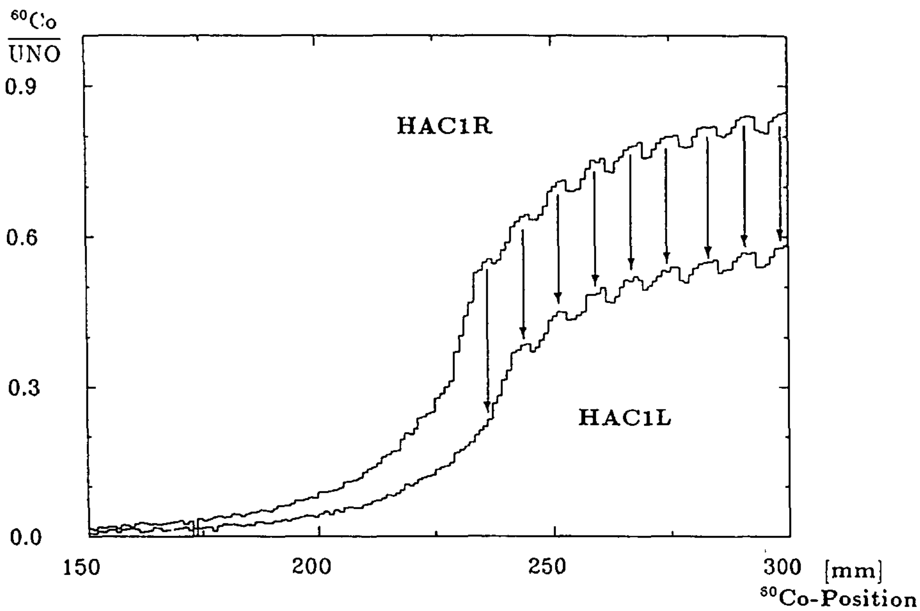

Fig. 13. Scan indicating the misalignment of a WLS cassette of the left side such that the first scintillator of the HAC1 stack is seen by the right WLS, but not by the left one.

Another example of uniform response is shown in fig. 11b where the average value of T for each HAC1 tower in 15 different FCAL modules is histogrammed. Here the values have a spread characterized by a σ of 1.2%.

The quantity T is related to the scintillator's effective attenuation length, λ_s, by the following simplified formula:

$$T = \exp(-(D - 2\delta)/\lambda_s).$$

where D is the length of the scintillator tile (191 mm for EMC towers) and δ is the average distance of light production in the scintillator as measured from the edge near the source (≈ 15 mm). The mean value of the distribution corresponds to a value of $\lambda_s = 413 \pm 16$ mm for an EMC section in a RCAL tower.

5.3.2. Attenuation in the wavelength shifter

The WLS light guides have an effective attenuation length which may change with time and/or radiation damage so it is important to be able to monitor it. In the "active" regions of the light guides (i.e. those parts which are exposed to the light from the scintillator tiles) the WLS response has been modified by the use of patterned back reflection [3] to give uniformity. Thus to measure the attenuation in the plastic ifself it is necessary to use the Cherenkov light generated in the regions which do not see scintillator light and therefore have no back reflectors. This is easily done with the EMC light guides which have a long stretch of inactive material which gets irradiated as the source scans along the HAC1 and HAC2 sections. Fig. 12a shows the current vs source position for a typical EMC light guide and fig. 12b shows the same with the UNO signal subtracted and the vertical scale expanded. The fitted curve represents a superposition of an exponential for direct light and an other for the reflected light at the Al-end reflector of the WLS (see fig. 4). A summary plot of the attenuation lengths for all the EMC light guides in several calorimeter modules is presented in fig. 12c.

5.4. Assembly faults

Another important function of the initial source scans was the identification of assembly faults in the calorimeter modules. In this section we present a few examples.

The most common problem was misalignment of the WLS cassettes on the calorimeter. Occasionally, the number of scintillator layers that was read out by a given WLS was one less than the nominal number (either the first or last layer was not read out). This would show up in the scans as a missing layer and could be found automatically by counting layers or looking at the "width" of the entire distribution. (See fig. 13 for an example.) Once located, these faults were fixed by adjusting the cassettes.

Another fault was due to displaced scintillator tiles. These show up as an isolated dip in the scan distribution on one side and a spike in the corresponding position on the other side (see fig. 14). These were

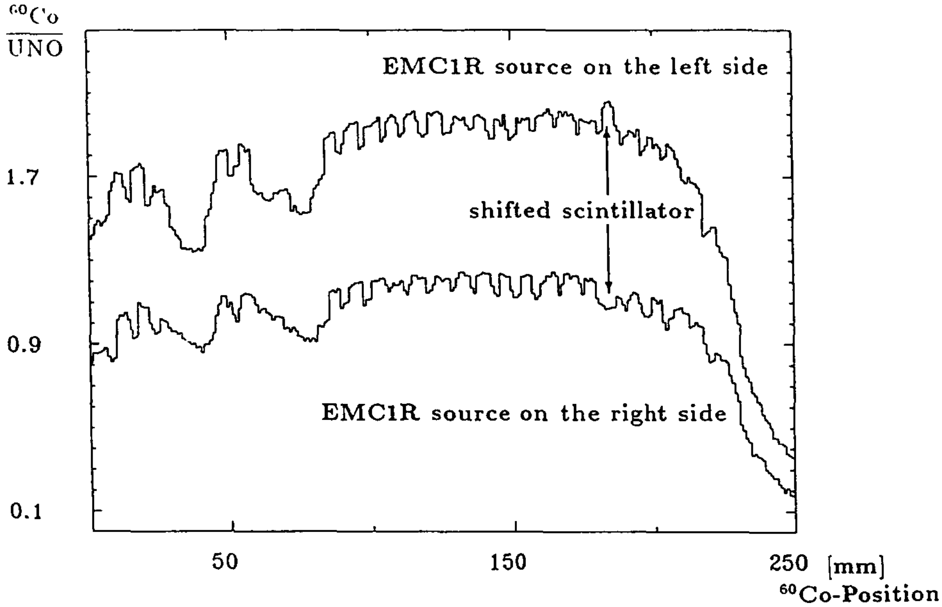

Fig. 14. Scan indicating a shifted scintillator tile. The particular layer shows up as a spike on one side of the tower and a dip on the other.

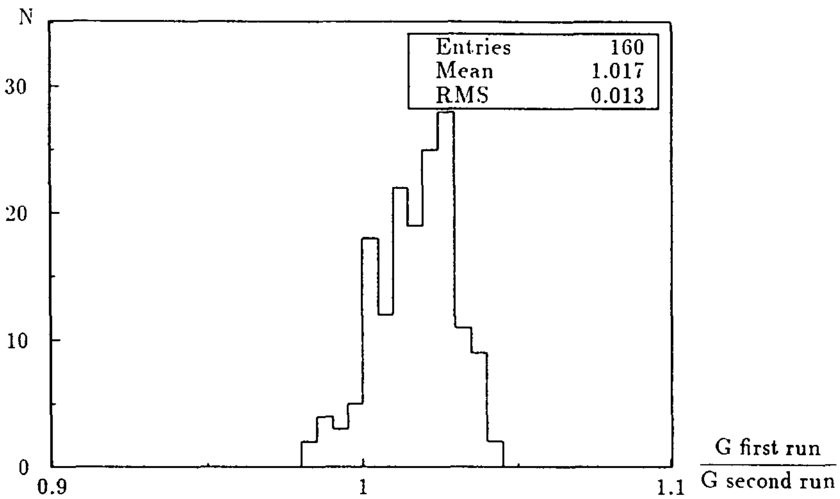

Fig. 15. Test of reproducibility using the cobalt source as an absolute reference standard. Scans were taken 1 1/2 months apart and the profiles for each HAC1 tower were integrated.

quickly fixed by opening the relevant tower and pushing the displaced tile into its proper position.

Various other problems showed up as anomalies in the scans and were usually resolved upon inspection of the calorimeter. It is clear that many of the problems that were found would have gone unnoticed and uncorrected without the source scans. Not all of them have affected the overall performance in a major way, as seen with cosmic ray runs, the other quality control method before installation but they would possibly have contributed to a degradation of the resolution for electrons and hadrons.

5.5. The ^{60}Co source as an absolute reference

One of the advantages of uranium as absorber material in a calorimeter is its constant signal (UNO) for monitoring and calibration. Different towers can be equalized by requiring that their photocurrents be the same or be related according to their specific geometries. This is called UNO calibration.

For calorimeters made from nonradioactive material such as lead or steel, gain monitoring must be done using other methods, such as light flashers or radioactive sources. To see if the source system as constructed is capable of providing a calibration standard as good as the UNO calibration we have performed a reproducibility test. This test uses data from two inside scanning runs on the same module taken 1 1/2 months apart. Fig. 15 shows the frequency distribution of the ratio of HAC1 signals (obtained after integration over every point of a response function like in fig 8) for all towers of a module. Since any gain changes between the two scans have been taken out by normalizing to the UNO signal, one expects the ratio to be constant. The value of this constant is given by the ratio of the source strengths for the two scans and is 1.017. The 1.7% effect is expected from the half-life of ^{60}Co which is 5.2 y.

The spread of values about this mean value is 1.3% which indicates that the source can be used as a gain monitor at the percent level. However ^{60}Co is limited as a primary calibration tool if frequent use is needed or if the calorimeter is very large due to consumption.

6. Conclusions

We have presented the source scanning systems for the ZEUS forward and rear calorimeters. They are based on a computer-controlled driver which can select a guide tube for a cobalt source and push the source down this tube and pull it back while the currents from the corresponding phototubes are recorded. A complex network of guide tubes has been installed inside the calorimeter modules to allow in situ scanning after the experimental has begun operation. A simpler set of guide tubes was used for initial scanning of completed modules before they were installed in the experiment.

The scanner has proven to be simple and reliable to use and has been very valuable for detecting manufacturing faults. It promises to be a useful tool for examining the long term behaviour of the scintillator and wavelength shifter plastic in the calorimeter.

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