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Results from tests of a Preshower Prototype during 1996

P. Aspell, D. Barney, P. Bloch, S. Reynaud, A. Van Hove

CERN, Geneva, Switzerland

J. Bourotte

LPNHE, Ecole Polytechnique, Palaiseau, France

ECAL Group

Abstract

During 1996 a first version of the front-end electronics for the CMS preshower was tested in the laboratory. The 40MHz electronics contained a 32 channel, 128 time-slot analogue memory. Satisfactory results obtained from laboratory tests led to its use in tests using high energy beams incident on a silicon detector placed downstream of a thickness of lead absorber, representative of the CMS preshower. Adequate noise performance was achieved (leading to the measurement of single mip signals) after individual pedestals for each time-slot were subtracted; this will not be necessary in the future. The spatial precision obtained from the prototype is in good agreement with simulation. The contribution to the ECAL energy resolution is found to be negligible for incident electron energies greater than about 100 GeV (corresponding to about 40 GeV Et at eta=1.7) after a 'correction function' has been applied to the energy measured in the lead tungstate (PbWO4) crystals. This correction function uses the signals measured in the silicon plane, and is virtually independent of the incident particle energy. The angular resolution of the ECAL system is also presented.

1 Introduction

1.1 Preshower Analogue Front End

The preshower electronics is a challenging item: in contrast to the CMS tracker, a large dynamic range (in the region of 250 to 400 mips [1]) is needed whilst still retaining the possibility of measuring single mips with a good signal to noise ratio (~5) - particularly for calibration purposes. The principle functions of the preshower are to reject π^0s and to improve upon the e/π separation capabilities of the ECAL whilst not degrading the energy resolution too much. The charge deposited in the silicon is used to estimate the amount of energy deposited in the lead absorber, and thus make a correction to the energy seen in the crystals; the charge must therefore be measured to a good precision - 5 to 10% error.

A scheme has been chosen in which the collected charge is integrated over 25ns time samples. The intrinsically fast response of the silicon detectors and a fast, DC-coupled preamplifier (FCICON 18ns rise time), ensure that the total charge is collected within 2 time samples. The preamplifier is followed by an analogue memory which allows retrieval of the charges for trigger latency up to 3.2 microseconds (128 ‘timeslots’). The preamplifers and memory form the front end analogue chip, designated DYN_{LDR}. Each DYN_{LDR} chip measures the charges for the 32 strips on a single preshower silicon detector; the silicon detector was produced at ELMA (Zelenograd, near Moscow). For each measurement, four 25ns samples (3 for the full charge collection and 1 for baseline subtraction[a)]) are transmitted via a 2.5MHz multiplexer to an ADC (Pentek with 12 bit dynamic range). A schematic view of the DYN_{LDR} chip is shown in figure 1 below.

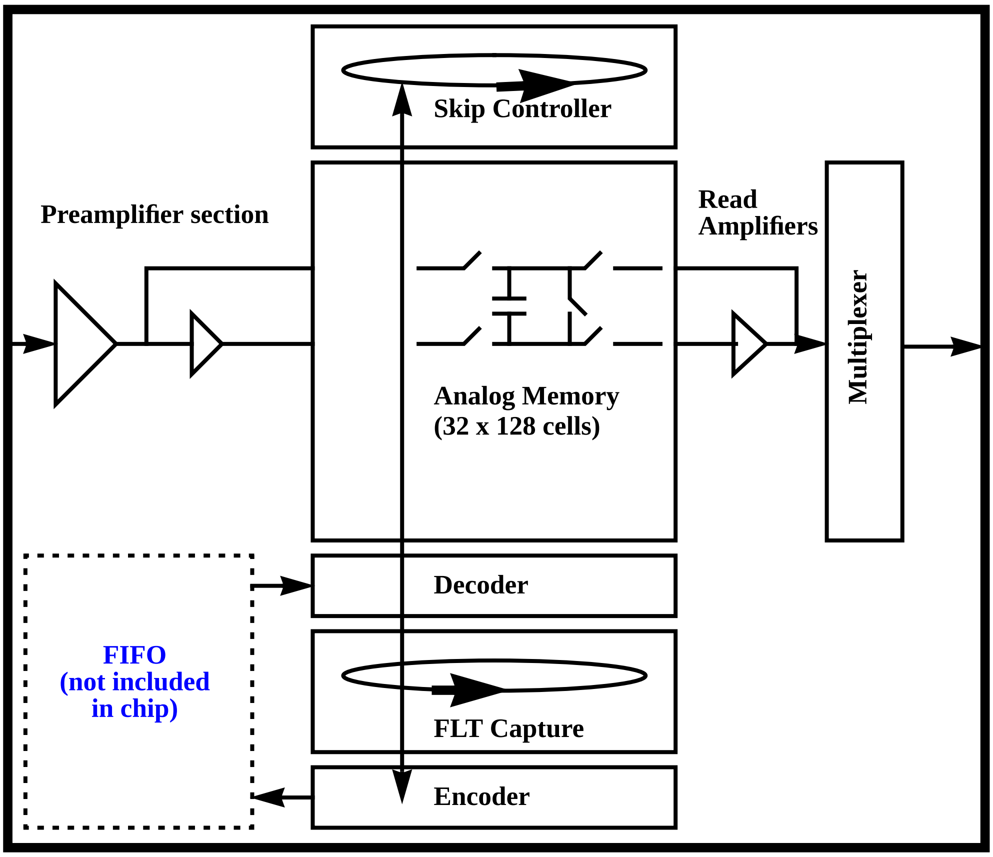


Figure 1: Schematic diagram of the DYN_{LDR} chip as used in the 1996 CMS preshower tests

An Altera programmable logic array was used to provide all timing/control signals for the DYN_{LDR} chip. The complete system was under VME control.

a. in the final design, 3 timeslots will be read out - 2 for the signal and one for baseline subtraction. The asynchronous beam in H4 necessitated the use of 3 timeslots for the signal.

1.2 1996 Tests

In 1996 a first version of the front end analogue memory was tested in the laboratory. This non radiation-hard (Mietec 1.5μm CMOS) version had been designed in 1994 by the MIC/ECP electronics group at CERN. It contains the full 32 channels and 128 timeslots. All the control signals, calibration signals and bias controls were on a mother board, with the DYN_LDR chip on a daughter board. Results concerning the electronics, including the visibility of single-mip signals, are presented in section 2.

A single silicon detector plane, 6cm x 6cm with 32 strips, was placed downstream of a thickness of lead (between 2 and 3 radiation lengths), with its output connected to a mother board containing the prototype front end analogue chip. This system was extensively tested in the X3 beam in CERNs West Hall with incident electrons. No crystals were present; the principle aims of the X3 tests were to ensure the correct operation of the electronics. The system was then moved to the H4 beam line (in CERNs North Hall) and attached to the box containing the ECAL crystal array for two short (~8 hour) periods of data taking. Spatial precision, energy and angular resolution results from the H4 beam tests are presented in section 3.

2 Results from Tests of Front-end Preshower Analogue Electronics

2.1 Main Results

The principle results from the tests of the prototype DYN_{LDR} chip are the following:

- the chip functions well at the required 40 MHz frequency
- the linearity of the pre-amplifier stage is good ($\pm 3\%$) up to 300 mips - see figure 1
- the rms noise for an individual cell of the memory is equivalent to about 4600 e^- after common noise and transmission noise subtraction. This is not far from the 3600 e^- measured for the preamplifier alone

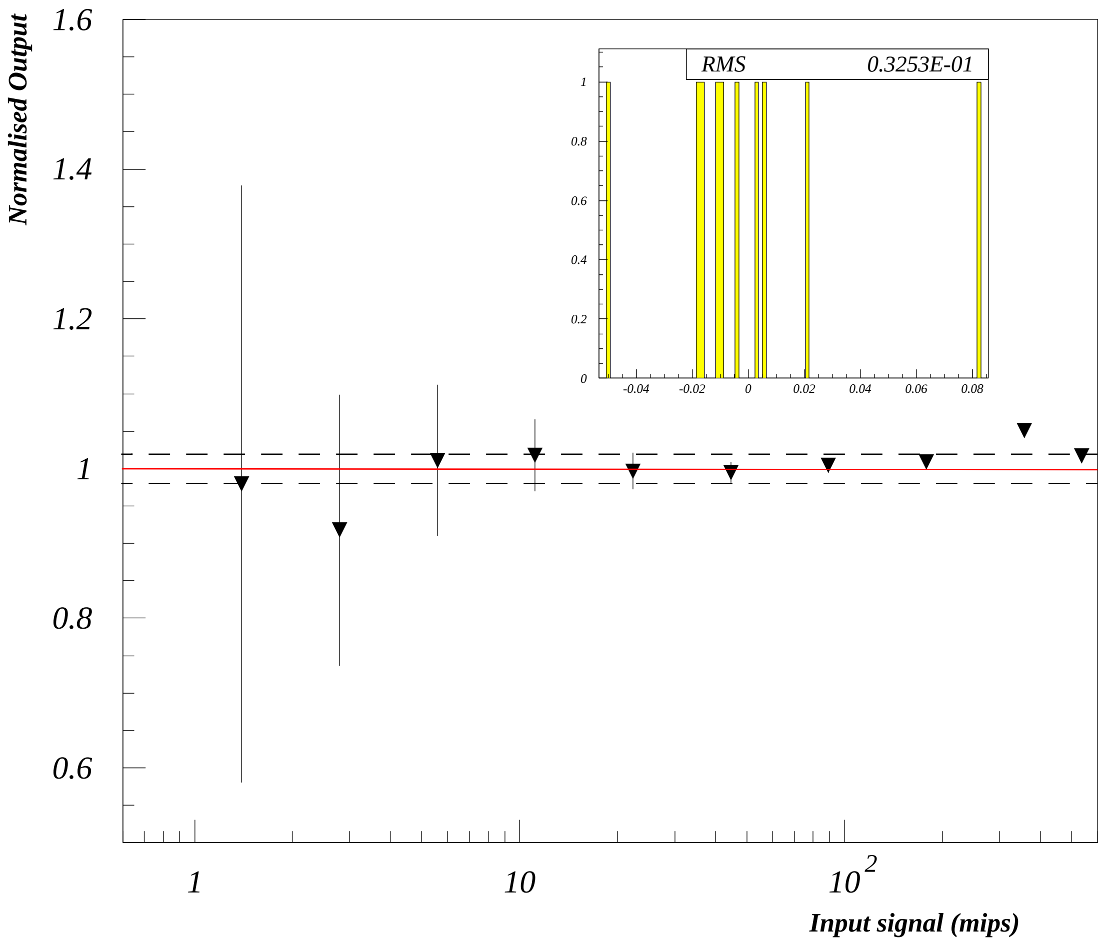


Figure 2: Linearity of Preshower electronics. The dashed lines represent the $\pm 2\%$ region (around the normalised mean). The inset shows the distribution of the individual points around the mean; only two points (at about 2.8 and 360 mips) are more than 2% from the mean.

2.2 Memory Non-uniformity

Figure 3 shows, for a single channel, the pedestals for each of the 128 timeslots. It is apparent that there is a considerable non-uniformity which, in the worst case, has an rms spread of around 6mV (equivalent to around 18000 e^-) which is clearly unacceptable for mip observation. The observed pedestal variations are reproducible between DYN_{LDR} chips. With no lead present incident electrons (50 GeV e^-) were used to determine whether 'mip' signals were visible[a)]; the mip can be clearly distinguished from noise, as shown in figure 4, if individual pedestals are applied to each memory cell for each channel: the mip signal-to-noise (S/N) ratio is around 2.9in this case. Obviously it is undesirable to have to perform this operation, and we hope to avoid it in the future.

a. The energy deposited by a high energy electron is about 10% higher than a true 'mip' signal; the measured S/N of 3.2 was thus scaled-down to about 2.9.

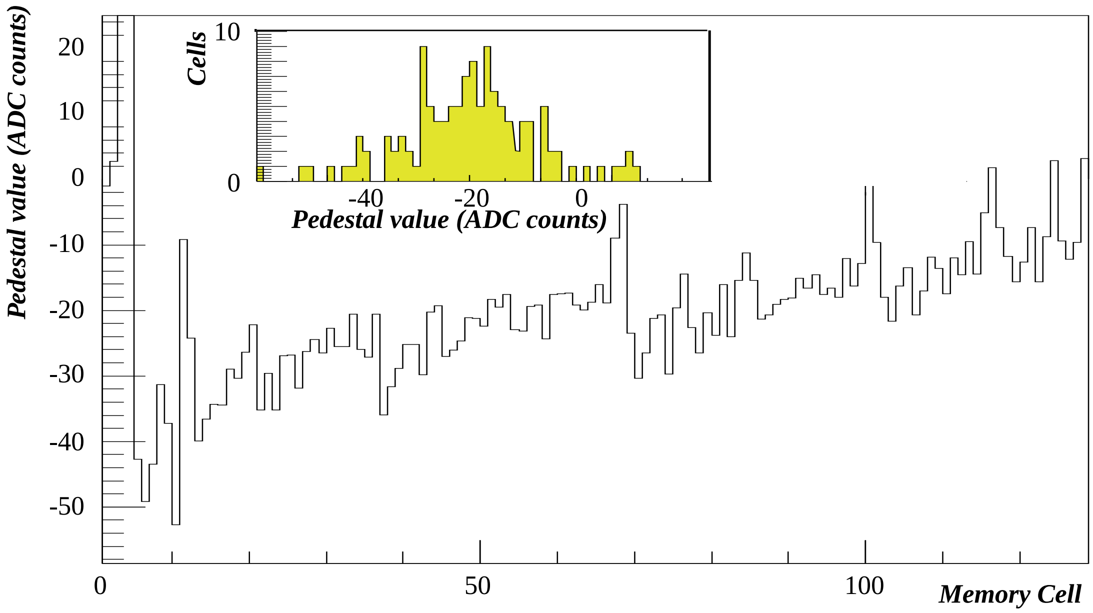


Figure 3: Pedestal variation for 128 memory cells of a single channel. The inset shows the distribution of the pedestals.

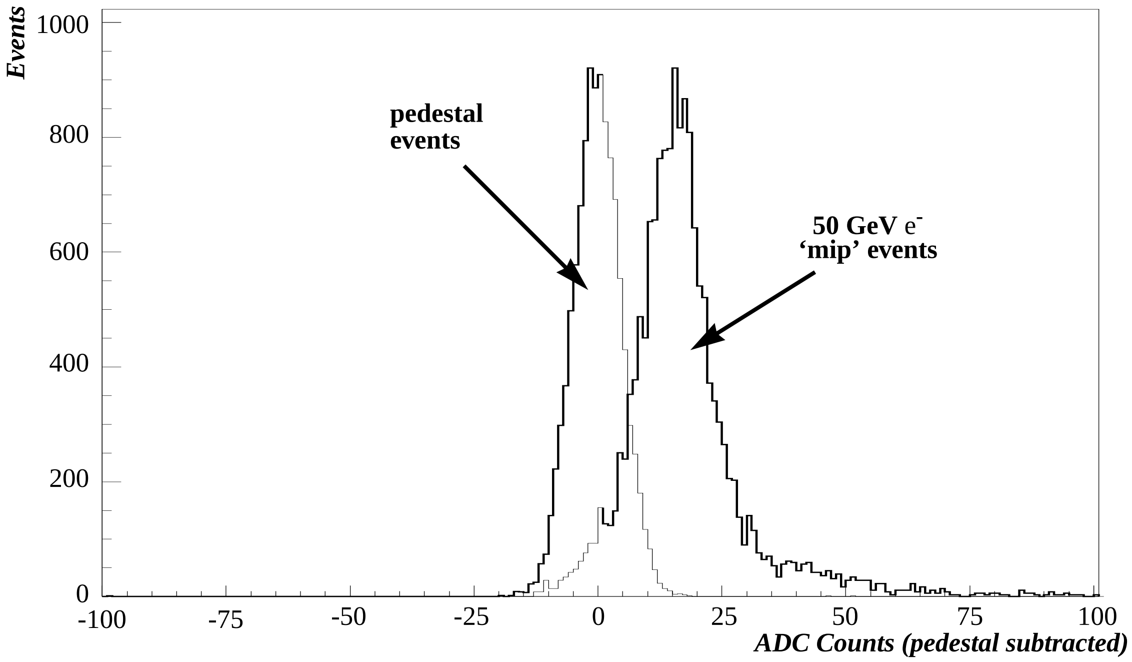


Figure 4: Visibility of 'mip' signal. The S/N ratio is around 2.9

There is clearly a need for improvement. Our goal is to achieve a S/N ratio of 5 at the mip level, preferably without individual memory cell pedestal calibration - one pedestal per channel should eventually be sufficient. We are optimistic that these goals will be achieved; a similar type of memory designed for the ATLAS SCT in 1996 (using the radiation-hard DMILL process) has given much better results (rms pedestal uniformity around 1mV). We will therefore take advantage of this work. It should also be possible to increase the gain of the preamplifier slightly, which will improve the S/N ratio. Recent studies [1] have shown that the resulting reduction in dynamic range should not be a problem.

3 Beam Tests

3.1 Preshower Prototype Setup in H4 - with Crystals

The mother board containing the preshower prototype (electronics and silicon strip detector) was mounted on a large-area piece of PCB, which was drilled in such a way as to facilitate its connection to the crystal containment system[a]: the preshower prototype could be mounted on to the ECAL box in less than ten minutes, minimizing disruption to ‘normal’ ECAL data taking. The PCB can accommodate two orthogonal mother boards. A schematic diagram showing the basic setup is shown in figure 5 below.

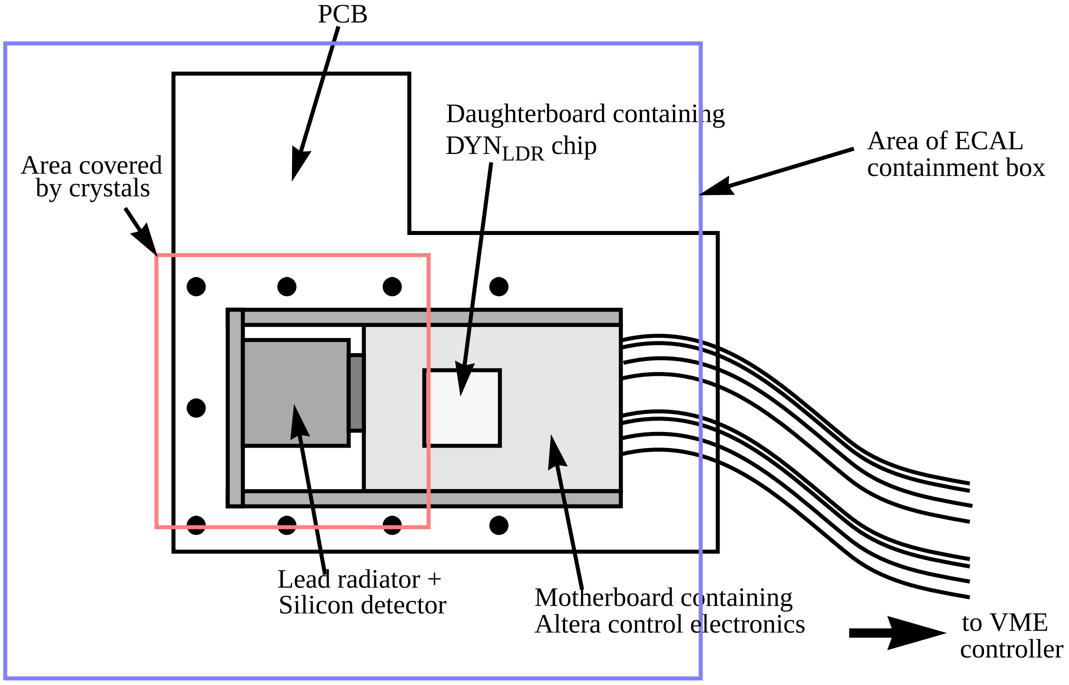


Figure 5: Schematic diagram showing basic preshower prototype setup on front (‘upstream’) of ECAL containment box

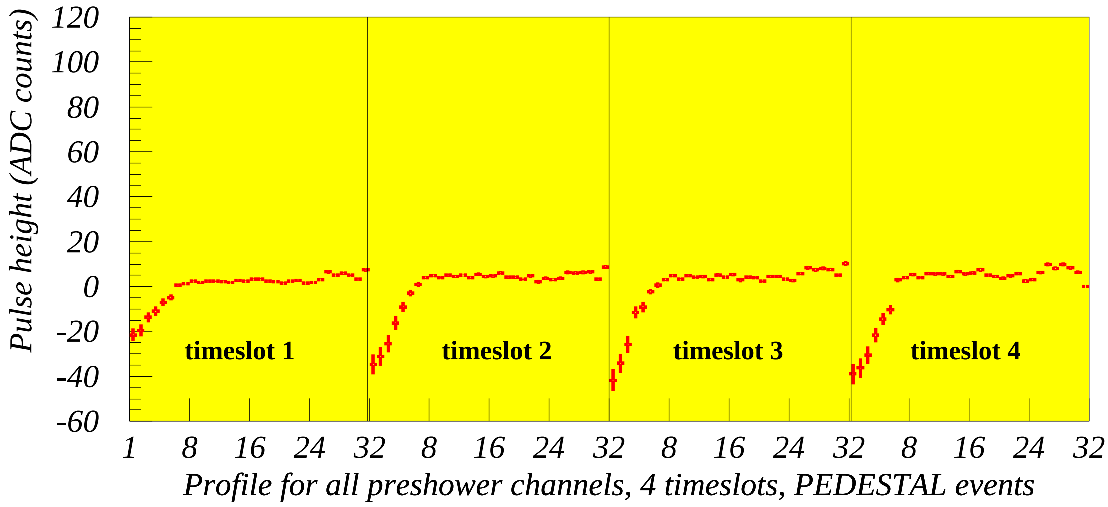
The centre of the silicon detector was aligned with the central crystal (id = 1315, from Bogoridisk) of a 7x7 matrix of $PbWO_4$ crystals. Each crystal was trapezoidal, with a front face of 20.5 x 20.5 mm^2 and a nominal length of 230.0mm. The matrix ‘pointed’ to a position approximately 1455.0mm upstream (along the beam direction), representative of the CMS ECAL at η=0.0. The distance between the lead radiator and the silicon detector was approximately 5mm, whilst the distance between the silicon and the crystals was around 8cm. This was the first opportunity to test a preshower prototype in front of a large crystal matrix; the setup was a significant improvement over that used in the 1995 preshower beam tests [2].

3.2 Energy Resolution

Data were taken in H4 with 2.5 and 3.0 radiation lengths of lead radiator, with incident high energy electrons. The signal in the silicon strips was in general spread over 3 timeslots (3 x 25ns) and several strips. Figure 6 below shows, for both pedestal events and 50 GeV incident electrons the signals seen in each of the 32 strips in four

a. In the 1996 tests a large light-tight and thermally stable plywood box was used to hold the crystals, APDs and front-end electronics. This box was mounted on a moveable table (which allowed rotation in two directions and horizontal translation).

adjacent timeslots.



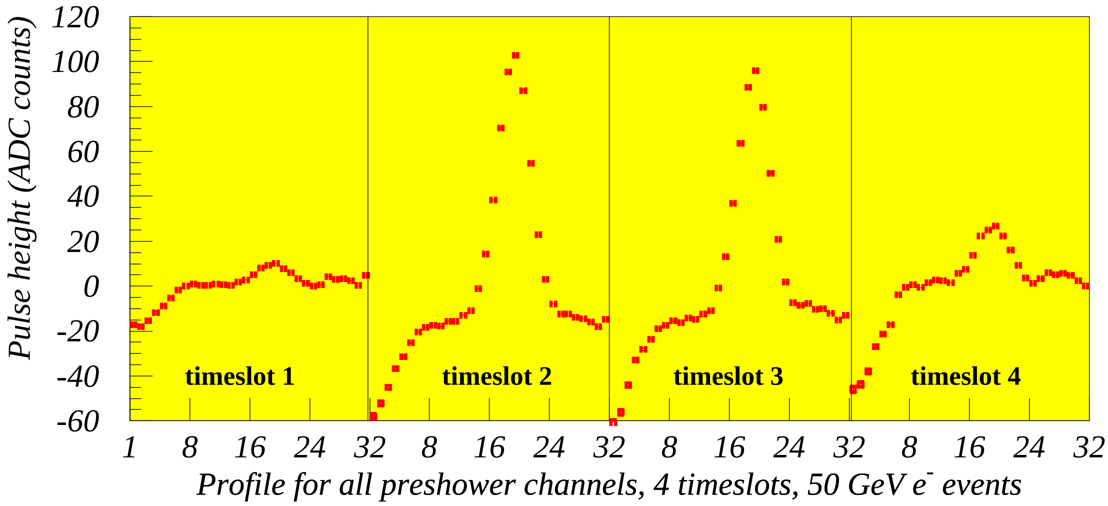


Figure 6: Signals seen in each preshower strip in 4 adjacent timeslots (averaged over one run ~100000 events) for pedestal and 50 GeV electron events. It is clear that the 'signal' is fully contained in 3 adjacent timeslots.

The signals seen in the preshower silicon strips are used to make a correction to the energy deposited in the crystals due to energy loss in the lead radiator. The total energy can thus be written as:

$$E_{tot} = E_{crystals} + \alpha E_{preshower}$$

where:

$E_{crystals}$ = energy deposit in array of crystals (3x3 or 5x5), centred on the crystal with the highest energy deposit,

$\alpha E_{preshower}$ = weighted sum of signals in 5 preshower strips (highest + 4 nearest neighbours) in 3 timeslots

It should be noted that even though a 7x7 array of crystals was available, only the central 3x3 had a low level of electronic noise (around 40 MeV per crystal). The level of noise in the remaining crystals was quite large (around 100 MeV per crystal); in the absence of the preshower the energy resolution obtained from a 5x5 array of crystals was not significantly better than with a 3x3 array. However, when the preshower is introduced, an appreciable amount of energy is deposited outside of the central 3x3 so the use of a 5x5 array is advantageous.

The parameter α is slightly dependent on the incident electron energy and has a value around 0.0168 GeV/mip for the 3x3 matrix and 0.0160 GeV/mip for the 5x5 matrix, for 50 GeV electrons. Figure 7 shows the (noise subtracted) energy resolution plotted as a function of electron energy, using a preshower equipped with $2.5X_0$ of lead. Three cases are shown: no preshower (using a 3x3 crystal array on its own[a)]), $2.5X_0$ preshower with 3x3 crystals and $2.5X_0$ preshower with 5x5 crystals. A similar plot is shown in figure 8 for the preshower equipped with $3.0X_0$ lead. The resolution with $3X_0$ of lead absorber is poorer than with $2.5X_0$ as only one silicon plane is present (with which to make the correction). One should recall that the CMS barrel preshower will have 2.5 X_0 absorber and one silicon plane, whilst the endcap will have 3.0 X_0 absorber and 2 silicon planes; the scenario described above - 3.0 X_0 and one silicon plane is therefore pessimistic. Simulations have shown that after inclusion of a second silicon plane the energy resolution with $3X_0$ is similar to that with $2.5X_0$ and one silicon plane.

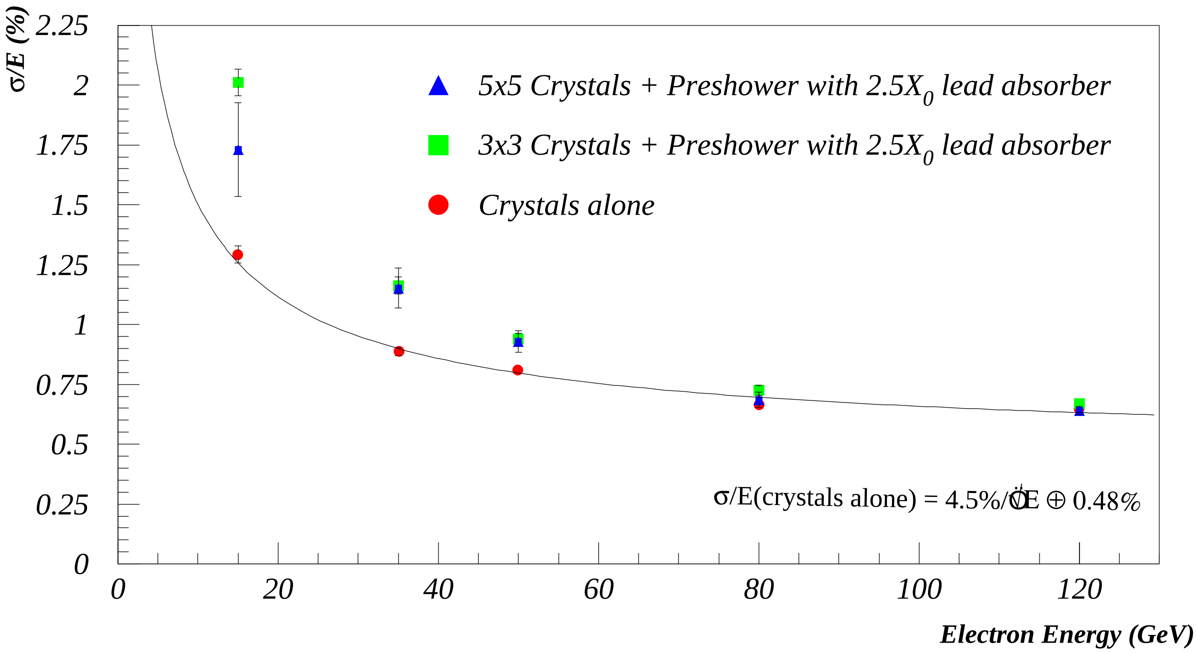


Figure 7: Energy resolution for 3x3 and 5x5 crystal arrays, with and without a $2.5X_0$ preshower.

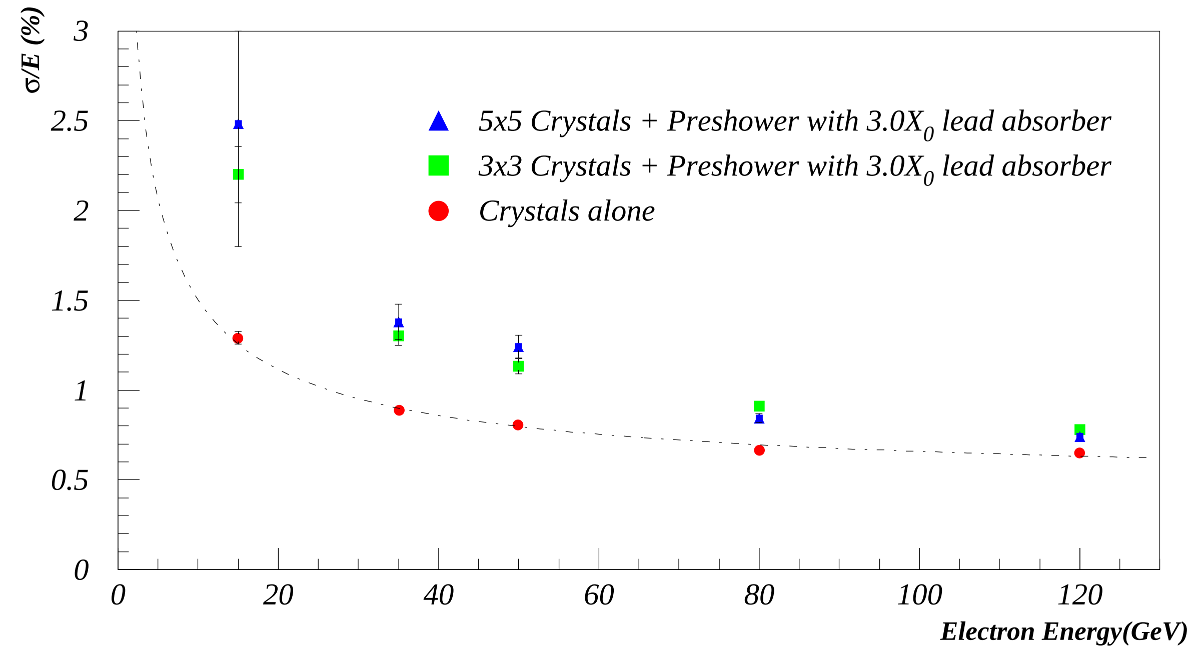


Figure 8: Energy resolution for 3x3 and 5x5 crystal arrays, with and without a $3.0X_0$ preshower.

a. The resolutions obtained for the 5x5 crystal array with no preshower present show only slight improvement over the 3x3 array, so are not plotted here.

The inclusion of the preshower results in an additional term in the energy resolution equation.

$$\text{Preshower additional term: } \frac{\sigma_{preshower}}{E_{beam}} = \sqrt{\left(\frac{\sigma_{both}}{E_{beam}}\right)^2 - \left(\frac{\sigma_{crystals}}{E_{beam}}\right)^2}$$

where:

σ_{both}/E_{beam} = energy resolution for crystals+preshower system

$\sigma_{crystals}/E_{beam}$ = energy resolution with crystals alone

Figures 9 and 10 show this 'preshower term' as a function of incident particle energy when 9 (3x3) and 25 (5x5) crystals are used respectively. It is apparent that for the CMS barrel configuration (2.5X_0, one silicon plane) the dominant term in the energy resolution calculation above about 60 GeV will not be from the preshower[a)], especially if 25 crystals are used.

Corresponding results from simulations are also shown, offset horizontally from the data for clarity; there is an extremely good agreement between data and simulation. The expected preshower term for the case of 3X_0 and two silicon planes (as will be the situation in the CMS endcaps) have been previously predicted [2] to be 0.54% and 0.39% for 50 GeV incident electrons for a 3x3 and a 5x5 crystal array respectively.

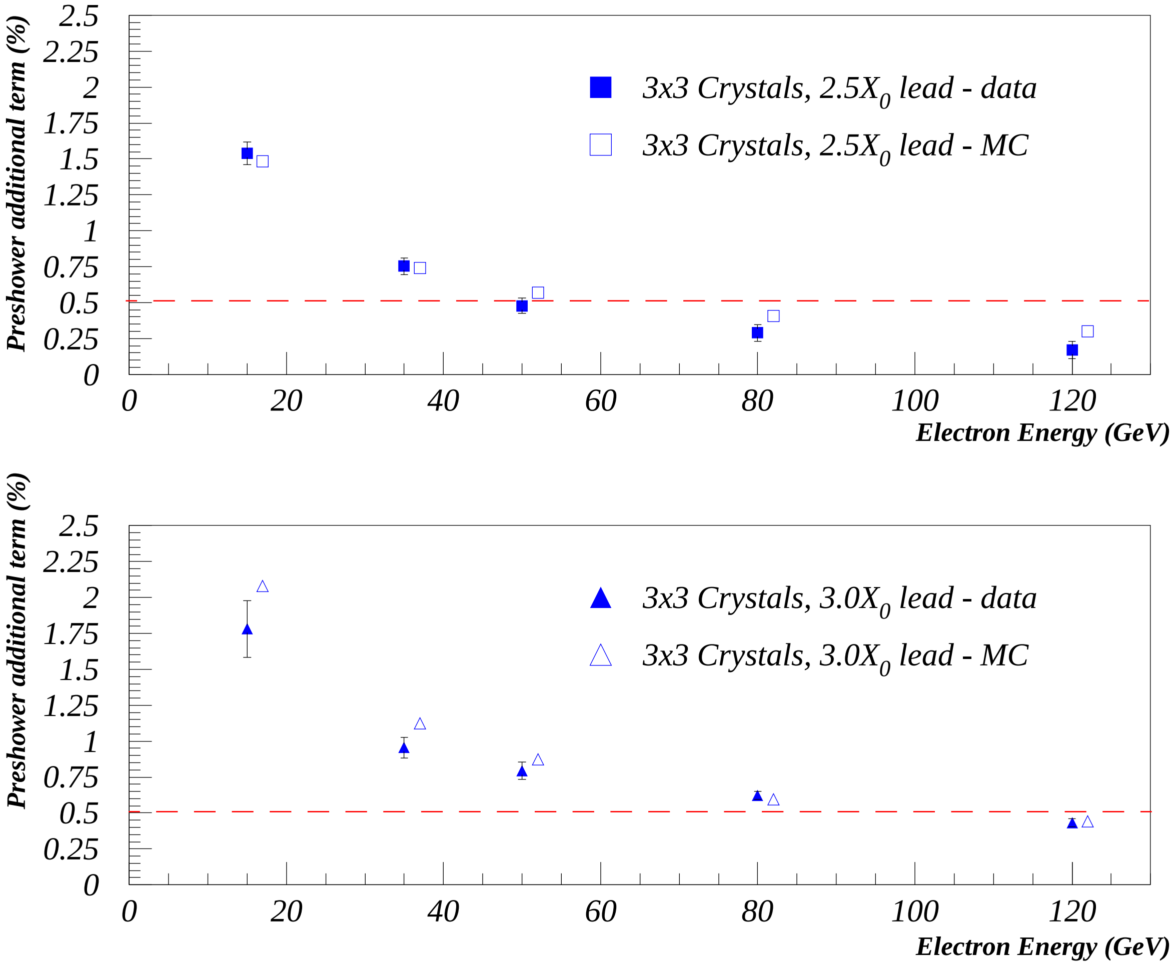


Figure 9: Preshower term as a function of incident electron energy when a 3x3 crystal array is used.

a. Recall that the CMS ECAL constant term is around 0.5%.

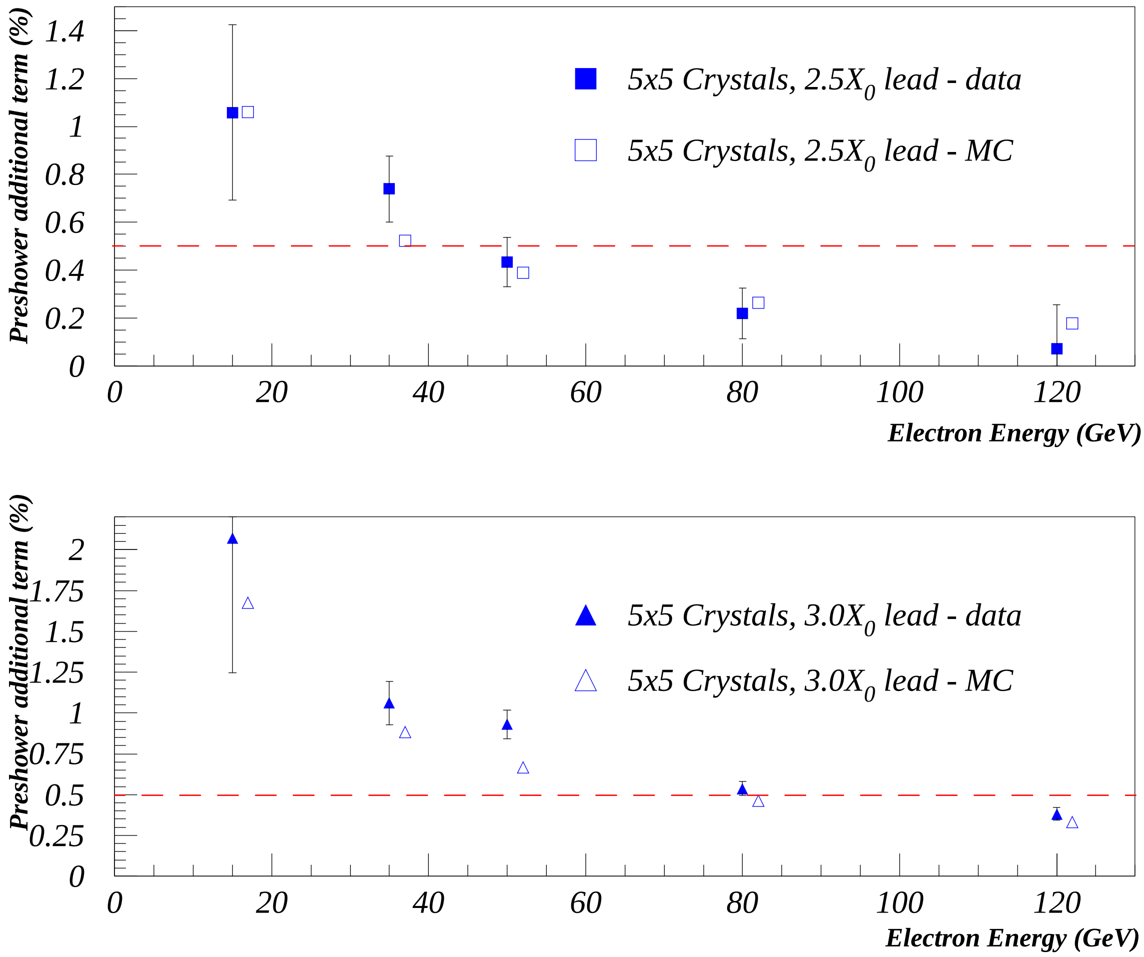


Figure 10: Preshower term as a function of incident electron energy when a 5x5 crystal array is used.

3.3 Spatial Precision

A centre-of-gravity method using 3 strips (highest + 2 nearest neighbours), as described in previous notes, was used to calculate the position of incidence of the electron at the preshower. This measurement is compared to a 'reference' position, as given by beam chambers [3]. A plot of the difference between these two measurements as a function of the preshower position measurement yields a characteristic 'S-curve' (see [2]); this curve is used to apply a correction to the preshower measurement position. Figure 11 shows the spatial precision for 50 GeV electrons incident on the preshower equipped with either 2.5 or 3.0 radiation lengths of absorber. It should be noted that the curves are very Gaussian, with very small tails.

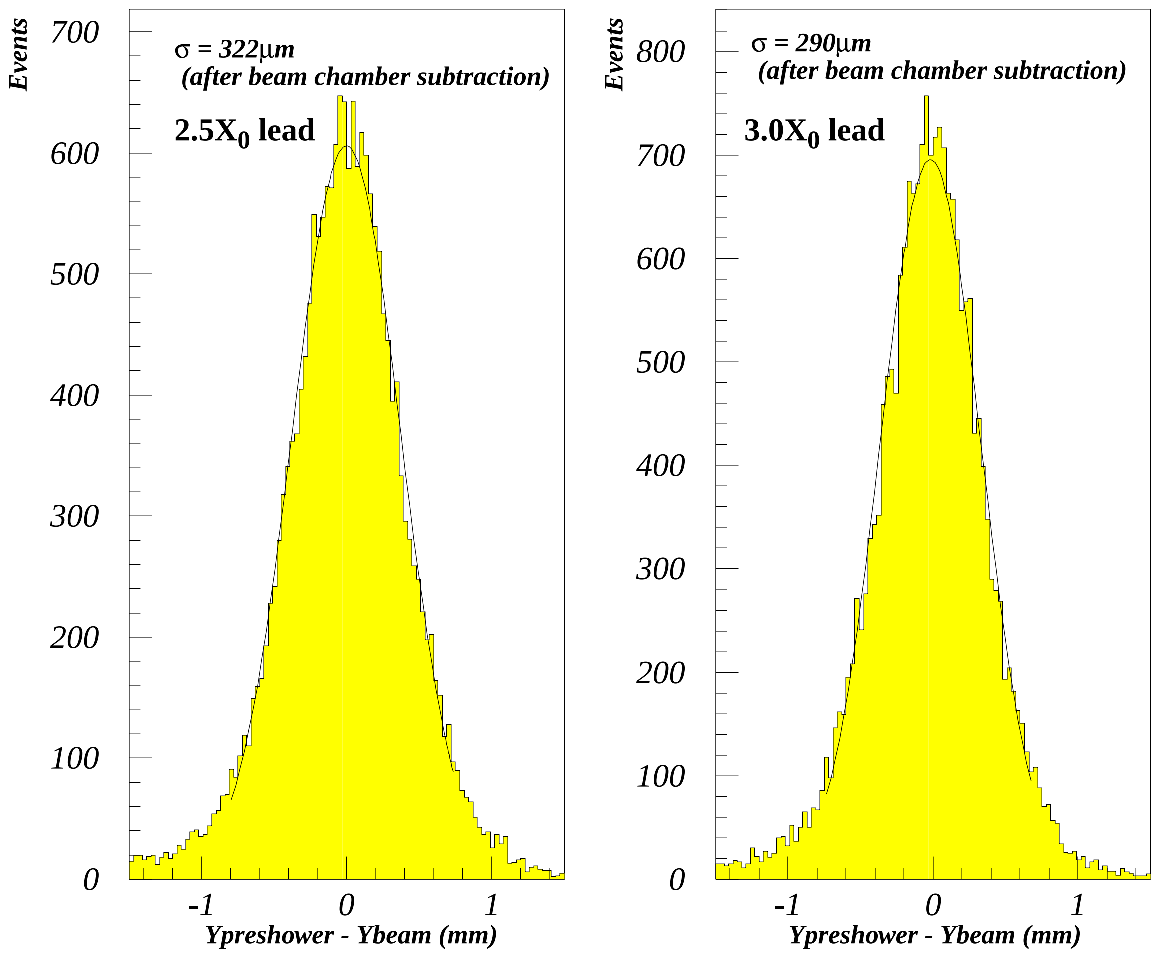


Figure 11: Example distributions of spatial precision of the single-layer preshower for incident 50 GeV electrons.

Figures 12 and 13 show the variation of preshower spatial precision with energy for the two thicknesses of lead. The solid points are results from the test beam, whilst the open points were obtained from simulation. Again there is a good correspondence between data and simulation except for the low energy points with $2.5X_0$, where the testbeam results are worse than expected..

If the square of the preshower spatial precision is plotted as a function of the reciprocal of the beam energy a linear relationship is found; after least-squares fits have been applied to these data, one obtains:

$$\sigma Y_{2.5X_0}(\mu\mathrm{m}) = \frac{1325}{\sqrt{E}} \oplus 260 \qquad \sigma Y_{3.0X_0}(\mu\mathrm{m}) = \frac{1369}{\sqrt{E}} \oplus 222$$

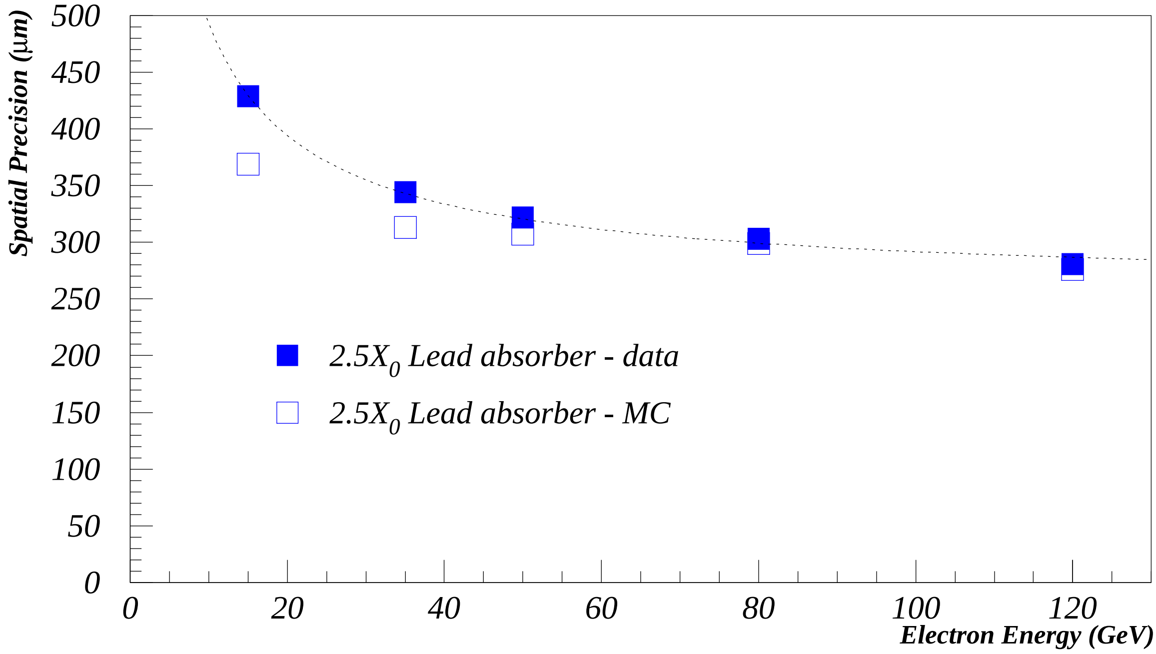


Figure 12: Variation of preshower spatial precision with incident electron energy, for a single silicon plane after $2.5X_0$ of lead absorber)

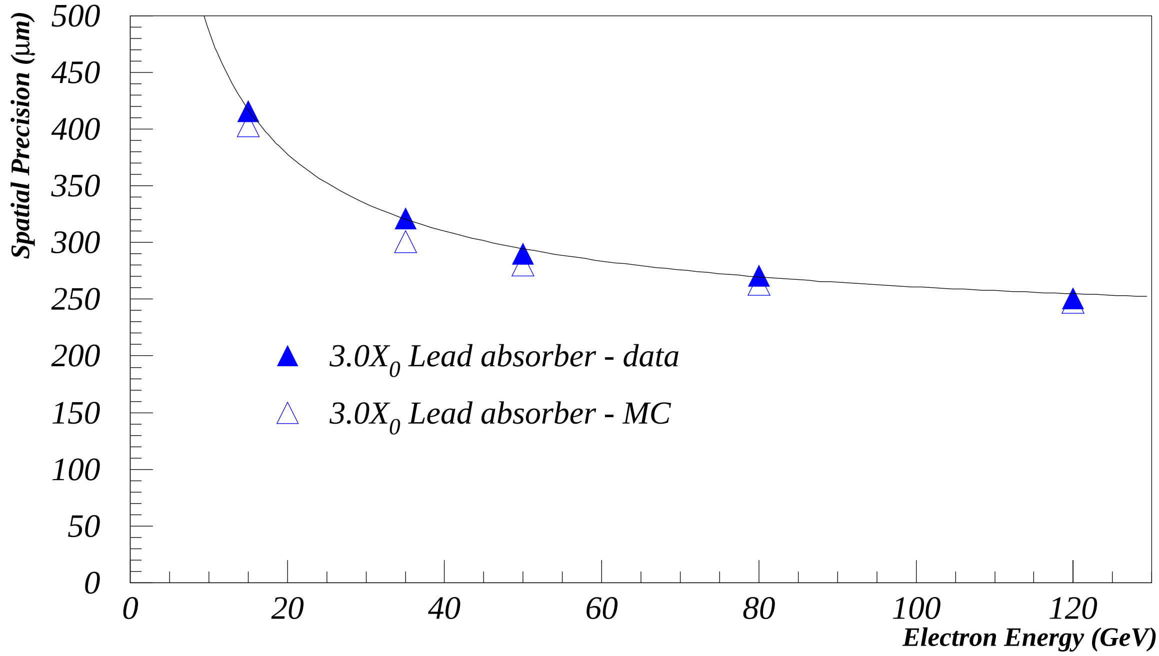


Figure 13: Variation of preshower spatial precision with incident electron energy, for a single silicon plane after $3.0X_0$ of lead absorber)

4 Angular Resolution

In the high luminosity phase of CMS the barrel preshower will be used, in conjunction with the crystals, to perform measurements of the angle of incidence of photons: this will enable the assignation of photons with particular primary interaction vertices. The accuracy of measurement of the angle between the two photons in the intermediate-mass Higgs decay is a contributing factor to the overall Higgs mass resolution [4].

The angular resolution is in principle a simple measurement, and is given by:

$$\text{Angular Resolution} = \frac{\sigma(Y_{Presh} - Y_{Crystals})}{LeverArm}$$

where:

Y_{presh} = position of particle incidence measured by the preshower (after S-curve correction)

$Y_{crystals}$ = position of particle incidence measured by the crystals (after S-curve correction)

LeverArm = the distance (along the beam direction) between the two measurements

The largest uncertainty is in the measurement of *LeverArm*. In a previous note [5] this was extracted from the data using electrons incident at different angles; in 1996 only one incidence angle was used (3 degrees in both η and ϕ) so a Monte-Carlo simulation [6] was used to try to determine *LeverArm*. The shower maximum position in a 3x3 array of crystals was measured both with and without a $2.5X_0$ preshower present, and with three different distances between the preshower and the crystals: a preshower-to-crystal distance of 8cm was used to simulate the testbeam scenario whilst 4cm and 6cm were used to represent possible situations foreseen for the CMS barrel at η=0[a)]. The results are shown in table 1 below. For comparison, the shower maximum position in the central crystal is also given.

Simulation Details	Central Crystal		3x3 Crystal Array	
	Shower Max (cm)	Shower Max (X_0)	Shower Max (cm)	Shower Max (X_0)
No lead	6.9	7.7	7.2	8.1
$2.5X_0$ Lead, 4cm gap	4.2	4.7	4.6	5.2
$2.5X_0$ Lead, 6cm gap	4.2	4.7	4.6	5.2
$2.5X_0$ Lead, 8cm gap	4.6	5.2	4.9	5.5

Tab. 1. Shower maximum position (from front of $PbWO_4$ crystals) for incident 50 GeV electrons

The shower maximum position clearly depends upon whether or not there is a thickness of lead in front of the crystals, as expected. The transverse spread of the shower also has effects:

- low energy shower particles which deposit a large fraction of their energy (or stop) are usually produced with a large fraction of their momentum transverse to the incident electron direction; this means the shower maximum for a 3x3 array is 'deeper' than for a single (central) crystal due to these particles depositing some of their energy outside of the central crystal.
- this effect is increased if the gap between the lead and the crystals is increased appreciably as the shower is allowed to spread more transversely in the gap.

The *LeverArm,* and subsequent angular resolution, is thus different for the different preshower-crystal gaps:

LeverArm (4cm) = 12.9cm *LeverArm* (6cm) = 10.6cm *LeverArm* (CMS) = 8.6cm

The angular resolution for these three scenarios is given in table 2.

a. There is still uncertainty as to the exact distance between the front face of the crystals and the silicon preshower detector. The TP design had a 4cm gap, but it is likely that this will increase to around 6cm, or perhaps slightly more.

Electron Energy (GeV)	**σ(Y_{presh}-$Y_{crystals}$) (mm)**	**TB (8cm gap) σΘ (mrad)**	**CMS (6cm gap) σΘ (mrad)**	**CMS (4cm gap) σΘ (mrad)**
15	1.21	9.4	11.5	14.1
35	0.82	6.3	7.7	9.5
50	0.72	5.6	6.8	8.4
80	0.60	4.6	5.6	7.0
120	0.56	4.3	5.3	6.5
	Fit Results:	$\sigma\Theta(\mathrm{mrad}) = \frac{34.9}{\sqrt{E}} \oplus 2.6$	$\sigma\Theta(\mathrm{mrad}) = \frac{52.1}{\sqrt{E}} \oplus 4.0$	$\sigma\Theta(\mathrm{mrad}) = \frac{42.6}{\sqrt{E}} \oplus 3.1$

Tab. 2. Angular resolution of crystal-preshower system as measured in the testbeam and as predicted for the CMS barrel.

The result for the 4cm-gap configuration is worse than found previously [5] and is a result of the poorer measured spatial resolution in the crystals. This may be due to several factors, including the 3-degree off-pointing and perhaps unfavourable longitudinal light yield profiles (in terms of the spatial precision measurement). However, the angular resolution is close to the design criteria of $50\mathrm{mrad}/\sqrt{E}$. If the preshower-crystal gap is indeed around 6cm (or larger) the angular resolution will easily meet the design criteria.

5 Summary

The first tests in an electron beam of a prototype preshower using ‘LHC-style’ 40 MHz electronics were extremely encouraging: results of energy and spatial resolutions were good, and agree well with simulation. The single mip signal was visible, but with a rather low S/N ratio (~2.9); decreasing the dynamic range and removing the pedestal variation of the memory cells should improve this. The beam triggers were asynchronous with the 40 MHz clock, which also introduced noise - this will obviously not be the case in CMS.

The angular resolution is slightly worse than expected, due mainly to the relatively poor spatial precision of the crystals used in the testbeam.

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[6] David Barney, *H4Sim96*, CMS IN 1996/009

Acknowledgments

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