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ELSEVIER

Beam test results of a Shashlik calorimeter in a high magnetic field

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Abstract

Shashlik calorimeter prototypes equipped with preshower detector have been tested in 3 T magnetic field with electron beam at CERN-SPS. The signal from electrons increases as much as 11% at 3 T magnetic field. No significant deterioration on the energy resolution as well as the preshower detector performance have been observed.

1. Introduction

In the design of the CMS detector at LHC [1,2], the electromagnetic calorimeter operates inside a strong magnetic field (4 T). An option for the CMS detector is a lead/scintillator sandwich sampling calorimeter read by wave-length-shifting (WLS) fibres, called "Shashlik" [3,4]. We have tested a prototype of projective towers assembled in a 3×5 matrix, including a preshower detector, in the 3 T field generated by the EHS magnet at the SPS-H2 beam line at CERN during April–May 1994.

The experimental setup is described in Section 2. Signal response in a magnetic field is discussed in Section 3. The energy resolution with/without preshower detector will be discussed in Section 4.

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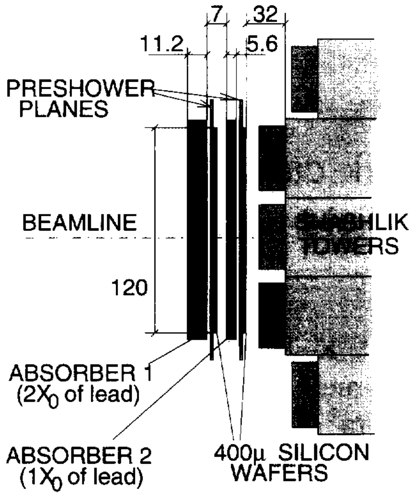

Fig. 1. Schematic view of the Shashlik and preshower detector setup used for the beam test.

2. Experimental setup

The schematic view of the beam test setup is shown in Fig. 1. The Shashlik towers were assembled as a 3×5 matrix. The central tower of this matrix was exposed to 15–150 GeV electron beams to study the energy resolution response.

2.1. Shashlik and preshower detector

The projective prototypes studied here were constructed in 1993. The basic parameters are given in Table 1. These towers have a truncated pyramid shape, and consist of 75 layers of lead (2 mm) and scintillators (4 mm). The scintillation light is readout via 6×6 matrix of WLS fibres which are perpendicular to the plates. The fibres themselves are in parallel each other, thus the distance between the outermost set of fibres and the scintillator edges will increase for deeper position. The WLS fibres are curved as U-shape in front of the calorimeter, and are bundled into a silicon PIN photodiode (Hamamatsu S3590-05) with an area of 1×1 cm^2.

Table 1
Parameters for the Shashlik projective towers

Number of towers	16
Tower lateral size	52×52 mm^2 (front) 64×64 mm^2 (rear)
Number of planes	75
Scintillator/lead	4 ± 0.05 mm/2 ± 0.005 mm
Total radiation length	$27.5 X_0$
Radiation length	16.9 mm
Molière radius	34 mm
Scintillator	polystyrene + 0.5% POPOP + 2% para-terphenyl
WLS fibre	K27 or Y7, ⌀ = 1.2 mm
Number of fibres	36
Interfibre distance	9.5 mm
Front fibre ends	U-shape loop
Readout	photodiode + amplifier

The silicon photodiode and the charge amplifier are insensitive to the magnetic field. The signals have been readout by LeCroy 2282A (12 bits) ADCs. The beam test results, in the absence of magnetic field, are reported in previous papers [5–7]. The light yield of these towers is measured to be 12 photons/MeV.

The preshower detector contains two planes of silicon strip detectors. Each plane is built out of four wafers (6×6 cm^2 each), with $2X_0$ and $1X_0$ absorber (Pb) in front, respectively. The pitch of the strips is 2 mm. The strips have been oriented orthogonally in the two planes. The signals were readout by a 16-channel AMPLEX-SiCAL signal processor [8]. Each detector was connected to a printed board circuit containing two AMPLEXs.

2.2. SPS-H2 beam line

The trigger is generated by the coincidence of three scintillation counters, S1 ($10 \times 10 \times 0.5$ cm^3), S4H ($2 \times 2 \times 1$ cm^3) and S4 ($4 \times 4 \times 1$ cm^3), defining the beam spot size of 2×2 cm^2 at the Shashlik matrix center. The tracking of the particle is obtained with two delay line wire-chambers (DWC), which had 300 μm intrinsic resolution [9].

Based on the experience of previous beam tests, special attention has been paid to reduce the amount of material in front of the calorimeter as the energy resolution is degraded due to bremsstrahlung. This is especially important for tests in a magnetic field. While the major contribution arose from the three scintillation trigger counters (5.9% X_0), the thickness of air was not negligible (2.6% X_0). The total amount of material is 9.8% X_0. Monte Carlo simulation shows that this extra material does not induce a significant tail in the energy resolution.

2.3. The EHS magnetic field

The Shashlik and preshower detectors have been placed at the center of the EHS magnet [10]. The magnetic field map is shown in Fig. 2. The beam direction is taken along the z-axis. The field is along the x-axis, perpendicular to the beam. The largest side of the Shashlik 3×5 matrix is then in the bending direction (y-axis). The peak field value is 3 T, and the full bending power is $\int B \, dl = 5.7$ T m. The Shashlik matrix center was placed at the EHS magnet center ($x = y = z = 0$). The fully equipped Shashlik tower is about 65 cm long and the entrance is at $z = -30$ cm. When the preshower detector is installed, the beam impact point (at the front surface of the first radiator material of $2X_0$) is at $z = -35$ cm. The 40 GeV electrons along the z-axis hit the Shashlik surface 6 mm below the tower center, making an angle of 0.8 degree with respect to the normal incident.

Monte Carlo simulations show that due to the transverse magnetic field it is important to have a compact preshower detector, i.e. to keep the distance from the lead plate and the following silicon layer as small as possible (1.5 mm in the

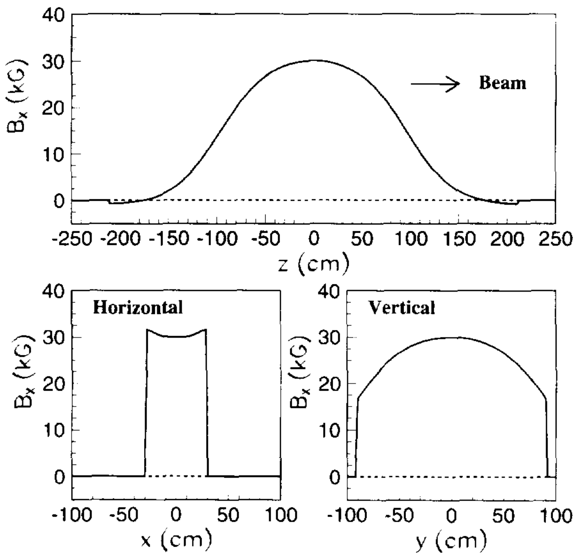

Fig. 2. EHS magnet field map. The magnetic field is along x-axis, and the field strength B_x is drawn along each axis.

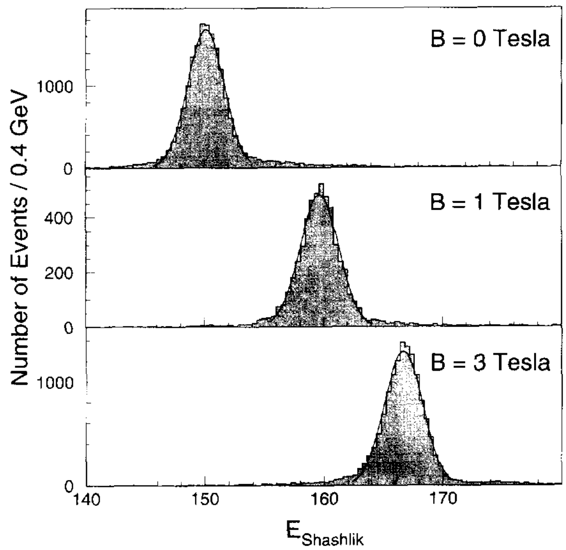

Fig. 3. Energy distributions for 150 GeV electrons, for B = 0, 1 and 3 T without preshower detector. The calibration constants are kept to those values obtained at 0 T.

test setup). The distance between preshower detector and Shashlik must also be kept small to avoid any shower leakage due to low energy electron/positrons which are swept away by the strong magnetic field.

3. Shashlik and preshower detector in a magnetic field

As the Shashlik calorimeter is intended to operate in the strong CMS magnetic field, it is important to study its possible consequences on the electromagnetic shower energy measurement. The signal distribution, the energy resolution together with longitudinal and transverse profiles are studied. The central tower of the Shashlik matrix is used to study energy resolution in a 0–3 T magnetic field with and without the preshower detector.

3.1. Shashlik response in magnetic field

The Shashlik energy response without the preshower detector is shown in Fig. 3 at 0, 1 and 3 T for 150 GeV electrons. One sees a displacement of the peak when the field increases. The tail on the high-energy side is due to the "nuclear counter effect" in the silicon photodiode due to shower leakage from the rear of the calorimeter. Charged particles traversing the PIN photodiode leave an energy equivalent of a few GeV due to ionization energy loss. In addition, there can be some shower leakage via the holes in the scintillator plates not converted by the WLS fibre. Cherenkov light in WLS fibres may also contribute to the non-Gaussian tail.

The response in the magnetic field for Shashlik alone or with $3X_0$ of passive material in front is plotted in Fig. 4 as function of the magnetic field. The calibration constants were kept at the values obtained at 0 T. The response for 150 GeV electrons is obtained by summing signals in 9 towers. Parametrizing the light increase as $S = S_0(1 + \alpha\sqrt{B})$, we can extrapolate to the 4 T CMS field where we expect a signal increase of about 13% compared to 0 T. Such an increase will have to be taken into account for the calibration of the Shashlik modules when used in the magnetic field. When there is passive material $(3X_0)$ in front of calorimeter, the variation is slightly smaller. The reason is probably due to low energy electrons/positrons which are stopped or swept before reaching the Shashlik detector.

Using pedestal and test pulse data, we can exclude the

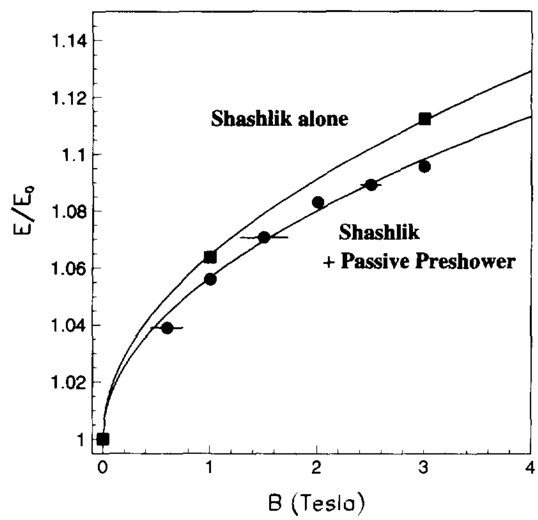

Fig. 4. Shashlik response for 150 GeV electrons in the magnetic field for Shashlik alone (square) and with passive preshower detector, i.e. $3X_0$ material in front of Shashlik (circle). Data are normalized to the response in 0 T. The curves are to guide the eye.

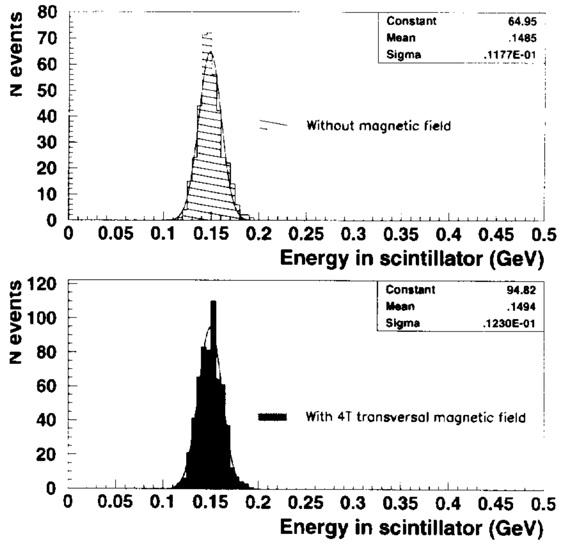

Fig. 5. Energy deposited in the scintillator for 1 GeV electrons without magnetic field and with a 4 T transversal field, as predicted from full Monte Carlo simulation. The full lines are the results of Gaussian fit.

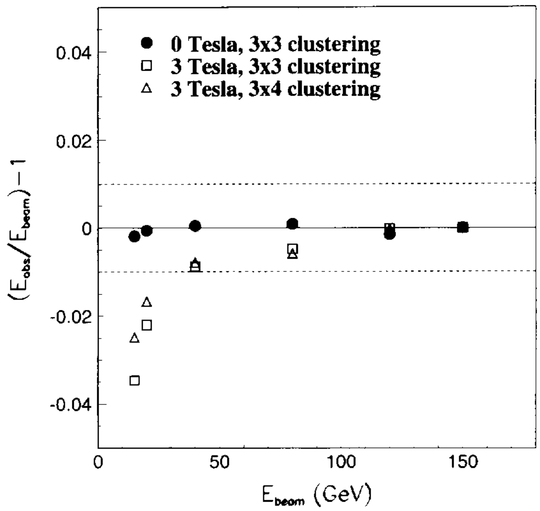

Fig. 6. Shashlik signal linearity at 0 and 3 T as a function of the electron beam energy. Data are normalized at 150 GeV. For 3 T data, the results for different clustering method are shown.

possibility that the change in response is due to a variation of the gain of the readout system. On the other hand, one may expect a modification of the electron sampling fraction due to the curvature of low energy electrons in the field. A Monte Carlo simulation (GEANT 3.21) of the full sampling structure has been performed down to a cutoff of 10 keV for the energy of electrons and gammas. The result is presented in Fig. 5 where signal distributions for 1 GeV electrons without and with a 4 T transverse field are shown. The difference in mean signal response between 0 and 4 T data is less than 1%. Similar results have been obtained for 10 GeV electrons as well. We then conclude that the observed signal increase is due to a light yield increase. Such an effect has already been reported [11] for SCSN-38 Kuraray type scintillator, although at a lower field intensity (1.5 T). A detailed study concluded that this phenomenon can probably be explained by the effect of magnetic field on base molecules excitation or energy transfer to the first fluor in the scintillator [12].

The energy resolution at 150 GeV is listed in Table 2 for 3 different field values. It is found that the resolution is independent of the field. Similar results are obtained with the preshower detector in front of the calorimeter.

Table 2
Energy resolution for 150 GeV electrons for the magnetic field intensity of 0, 1 and 3 T

Beam energy E_{beam} [GeV]	Magnetic field B [T]	Energy resolution σ_E/E [%]
150	0	0.89 ± 0.03
150	1	0.89 ± 0.03
150	3	0.84 ± 0.03

3.2. Shashlik signal linearity

To study the linearity and the intrinsic energy resolution, a correction for lateral non-uniformity was applied to the data [13]. The global response is corrected with the 2nd order polynomial function. The local fibre effect due to Cherenkov light or due to shower leakage around the fibres is also corrected with a cos-wave function superimposed to the polynomial. The linearity of response in 0 and 3 T is shown in Fig. 6. In the absence of magnetic field, the linearity is better than $\pm 0.2\%$. In magnetic field, the linearity at low energy is poor. Low energy electrons hit the lower boundary region with a large incident angle so that the electromagnetic shower is shared almost equally between the central tower and the lower adjacent tower of the Shashlik matrix. Due to the air gap between these two towers (~ 500 μm), part of the energy is lost. Although we find a slightly better linearity with a shower clustering in a larger zone (3×4 instead of 3×3), we observed exactly the same energy resolution with the 3×3 and the 3×4 clustering method.

3.3. Effect of rear leakage

As seen in Fig. 3, we observe for high energy showers an excess of events above the peak value. Such a high energy tail is due to charged particles leaking out at the rear of the Shashlik modules ($27X_0$ long) and giving a signal in the photodiode (see also Ref. [6]). This tail has been studied as a function of the calorimeter depth and of the field intensity. The excess of events is defined as the fraction of events that give a signal greater than 2σ above the peak value. The results are shown in Fig. 7. The points at $30X_0$ correspond to data with the preshower detector in front of the Shashlik. We observe that the tail is reduced, as expected, when increasing

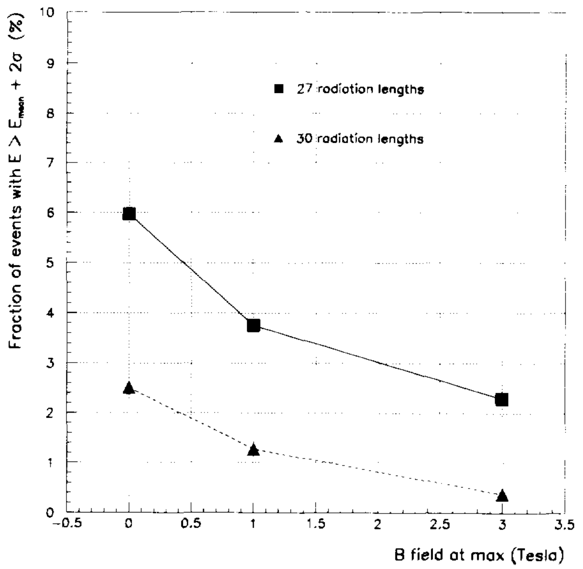

Fig. 7. Excess of high response events as a function of the calorimeter depth and of the magnetic field intensity. The excess is defined as the fraction of events with a signal greater than the Gaussian peak + 2 sigma. The points at depth equal to $30X_0$ correspond to data with preshower detector in front.

the calorimeter depth, but also by a factor three (for $27X_0$) or six (for $30X_0$) when going from 0 to 3 T magnetic field. This can be understood by the trapping in the field of the low energy electrons exiting the rear of the Shashlik tower.

3.4. Effect on transverse profile

The position resolution without magnetic field has already been reported elsewhere [6]. In the magnetic field, one may expect a deformation of the shower profile and therefore a modification of the position resolution.

In Fig. 8 is presented the transverse profile for 80 GeV electrons in the direction parallel to the field. The energy in each tower is normalised to the sum of energies deposited in 9 towers and expressed in percent, in order to unfold the effect of increase in light. Monte Carlo predictions are also shown in Fig. 8 and are in good agreement with data. The precision of the simulation is of the order of $\pm 1\%$. This uncertainty is due to the incomplete description of the exact tower geometry, and of the beam impact point and profile. As one can see from data points, the electromagnetic shower slightly shrinks in field direction.

The transverse profile in the direction perpendicular to the field is presented in Fig. 9 for $B = 0$ and 3 T. The data in 0 T is asymmetric due to the position of the incidence point of the beam being at -8 mm with respect to tower center. An increase of the lateral spread of the shower in the field is observed in the data and is well reproduced by Monte Carlo simulation. It appears to be symmetrical and amounts to a 40% increase of energy in towers neigbouring the central one. This implies that the dominant effect of the field on the

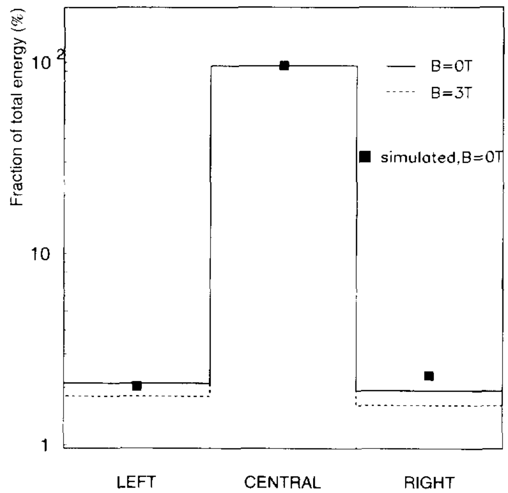

Fig. 8. Transversal profile in the direction parallel to the magnetic field for 80 GeV electrons hitting the central tower. Square black points give Monte Carlo simulation without field. Energy is expressed in % of the total energy contained in 3×3 matrix.

shower is on electrons/positrons pairs.

The position resolution is shown in Fig. 10, without and with magnetic field, as a function of the distance to tower center. No significant difference in position resolution between the two configurations (with/without preshower detector) is observed for 0 T. A resolution of 1.5 mm is achieved at the tower center and 0.5 mm at the tower edge. The resolution obtained with field is slightly better (by ~15%) than with field off, due to the modification of the energy sharing between central and next to central towers.

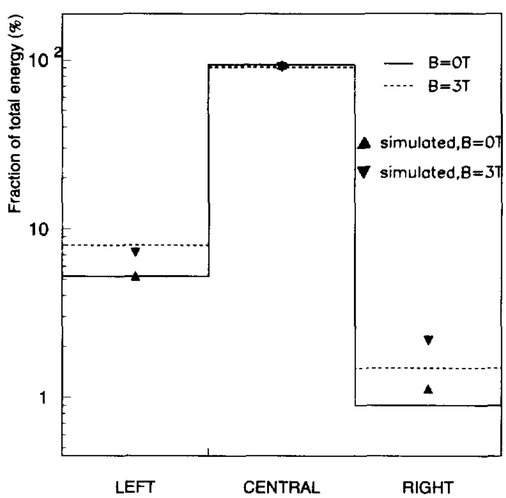

Fig. 9. Transversal profile in the direction perpendicular to the magnetic field for 80 GeV electrons. Also shown are Monte Carlo predictions with and without field.

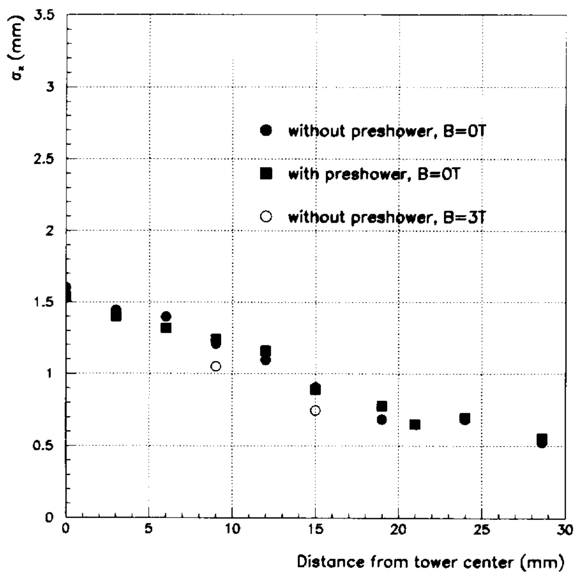

Fig. 10. Position resolution for 80 GeV electrons as a function of the distance to tower center with and without magnetic field.

4. Energy resolution

4.1. Bare Shashlik

The energy resolution of the calorimeter is generally parametrized as:

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

where a represents the stochastic term, b the electronics noise term, c the constant term and E is the energy in GeV.

The noise term has been studied using the width of the pedestals. No significant correlated noise between readout channels has been observed, i.e. the equivalent noise per channel was equal to the noise b divided by three for 3×3 clustering. The noise is equivalent to 173 MeV per channel for 0 T data. No change in noise is observed when magnet is on, and is 159 MeV per channel for 3 T data. This virtual improvement is due to the light output increase in the magnetic field. When fitting the energy resolution, the noise term, $0.519/E$ (0 T) or $0.476/E$ (3 T), is fixed and subtracted from the data.

The energy resolution of a bare Shashlik for an area of 2×2 cm^2 at the tower center is shown in Fig. 11. When the magnet is off (0 T), the energy resolution is found to be

$$\frac{\sigma_E}{E} = \frac{8.73\%}{\sqrt{E}} \oplus 0.70\%. \quad (2)$$

In the 3 T magnetic field, we measure the same resolution for energies above 40 GeV. The fit result is

$$\frac{\sigma_E}{E} = \frac{8.89\%}{\sqrt{E}} \oplus 0.62\%. \quad (3)$$

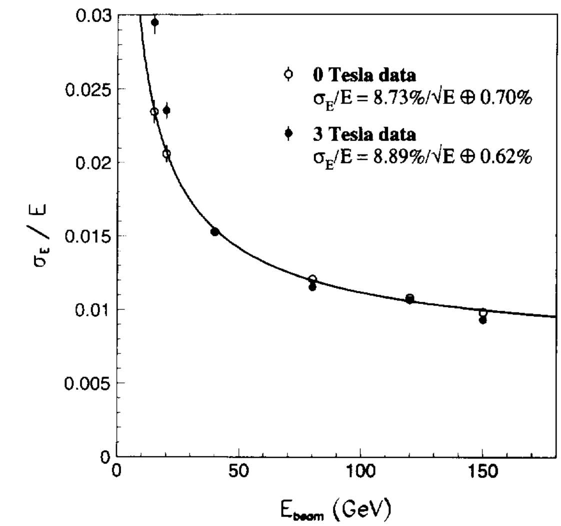

Fig. 11. The energy resolution of a bare Shashlik as a function of the beam energy of electrons incident in a 2×2 cm^2 region. Results in 0 T (open circles) and in 3 T (closed circles) are shown, where the noise term is subtracted. The curve is the result of the fit for 0 T data.

For lower energies, a slightly worse resolution is observed. This is due to the fact that lower momentum electrons hit the lower part of the central tower with an incident angle of a few degrees. The energy resolution at the tower boundary region is not as good as that at the tower center due to the shower leakage between towers.

4.2. Shashlik + preshower detector

The energy resolution of a Shashlik tower with the preshower detector in front is shown in Fig. 12 for a field

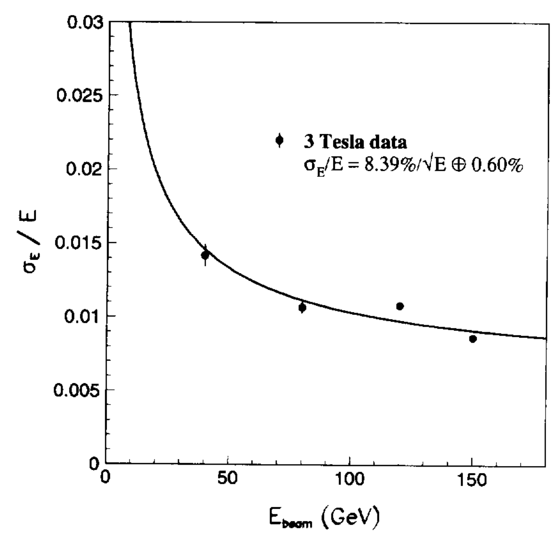

Fig. 12. Energy resolution of Shashlik plus preshower detector in 3 T magnetic field. Data correspond to a zone of 3×4 strips (0.6×0.8 cm^2) of the preshower detector. The noise term is subtracted. The curve is the result of the fit.

of 3 T. The energy resolution, fitted to data above 40 GeV, is given by:

$$\frac{\sigma_E}{E} = \frac{8.39\%}{\sqrt{E}} \oplus 0.60\%. \tag{4}$$

Due to fiducial cuts in the preshower detector, the data correspond to a smaller area of 0.6×0.8 cm^2. The slightly better resolution when compared with Shashlik alone can be explained by a smaller residual non-uniformity.

5. Conclusion

The Shashlik and an active preshower detector have been tested with electron beams of 15-150 GeV in 0 and 3 T magnetic field. The scintillation light yield increases in the presence of magnetic field by +11% at 3 T. No significant deterioration in the position and energy resolution has been observed at 3 T. When a preshower detector is placed in front of the Shashlik, the energy resolution is measured to be $\sigma_E/E = 8.4\%/\sqrt{E} \oplus 0.476/E \oplus 0.6\%$ above 40 GeV.

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