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PERFORMANCE OF THE "SHASLIK" ELECTROMAGNETIC CALORIMETER

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Dedicated to Professor Mladen Paić on the occasion of his 90$^{\mathbf{th}}$ birthday

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In 1994, extensive tests were carried out to evaluate shashlik prototype calorimeter as a candidate for the electromagnetic calorimeter (ECAL) for the Compact Muon Solenoid (CMS) detector. The measured energy resolution is characterized by a stochastic term of $8.5\%/\sqrt{E}$, a noise term of $0.33/\ E$ and a constant term of 0.5% (E in GeV). Reproducibility of performance of the towers and the uniformity of the calorimeter response have been studied across a large 25 cm × 25 cm area. Effects of radiation damage on the shashlik tower have also been studied.

1. *Introduction*

The future Large Hadron Collider (LHC) at CERN has been designed to collide protons at a centre-of-mass energy of 15.4 TeV every 25 ns at a luminosity of $1.7 \cdot 10^{34}$ cm^2 s^{-1} [1]. CMS is a general purpose detector designed to run at the highest luminosity at LHC. The CMS detector aims to detect signatures of electroweak symmetry breaking or any new phenomena by identifying and precisely measuring muons, electrons and photons over a large range of energy and solid angle, at very high collision rates, while also exploiting the lower luminosity initial running for top quarks and B-mesons. The CMS design emphasises precision electromagnetic calorimetry for identifying and measuring photons and electrons. A possible light Higgs boson (or the lightest MSSM Higgs) should be detected via its decay into photon pair or via $\mathrm{H} \to \mathrm{ZZ}^* \to 4$ charged leptons. The electromagnetic calorimeter must assure excellent energy resolution with good rapidity (η) coverage, as well as a good photon direction determination. To reduce background, a good π^0 rejection is required. The design parameters of the CMS shashlik electromagnetic calorimeter are: energy resolution given by stohastic term of $9\%/\sqrt{E}$, constant term of 1% and noise term of $0.3/E$, and angular resolution of 70 mrad$/\sqrt{E}$ (E in GeV) [2].

With these performances, a Higgs di-photon signal would be observable with a statistical significance of more than 5 sigma for a different Higgs boson mass of more than 85 GeV, with 10^5 pb^{-1} integrated luminosity. Figure 1 shows the expected results for a single Monte Carlo experiment, for an integrated luminosity 10^5 pb^{-1}, after background subtraction [3].

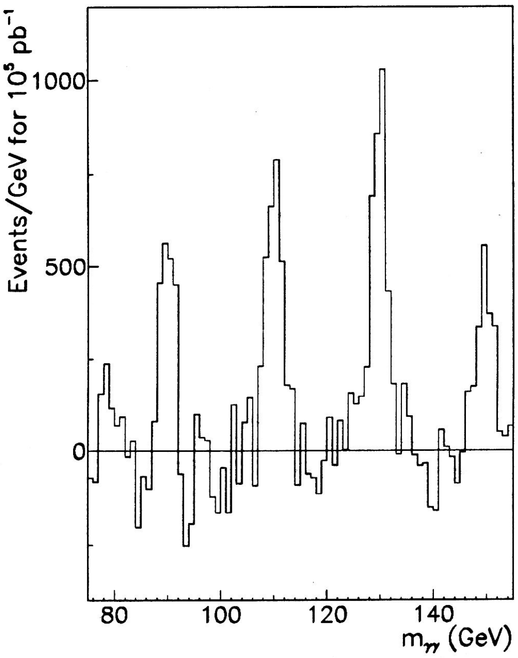
2. *Cobalt test results*

The possible shashlik option for the ECAL at CMS would be an assembly of about 3×10^4 shashlik towers of about 4.5 cm × 4.5 cm front face and each about 45 cm long, 27 X_0 deep [4]. It is extremely important to achieve a high level of reproducibility by the production of high quality towers (shown in Fig. 2). As a measure of tower quality, the response to ^{60}Co gamma source is measured, and the distribution of mean response for different towers indicates a reproducibility level of production. Data were taken along the tower every 2 cm from the front to the rear of the tower. The response is measured with a photomultiplier (PM). Figure 3 gives the distribution of the mean light response versus tower number (the mean here is the average response between $z = 6$ cm and $z = 36$ cm, see Fig. 4). The overall dispersion for all towers, taking out towers 33 and 36 which have a different mechanical design, given by fit on the constant, is 7%. Figure 4 gives the light response of each tower normalized to the own mean as a function of longitudinal ^{60}Co source positions. The above results indicates the very good (inside 5%) quality of towers and the high reproducibility level of tower production.

3. *Beam test results*

A shashlik calorimeter prototype equiped with a preshower detector has been tested in electron, muon and pion beams at CERN - SPS during July - September 1994. All towers were read out by 10 mm × 10 mm silicon PIN photodiodes (S3590

Hamamatsu), followed by a low noise amplifier [2]. Figure 5 shows the standard



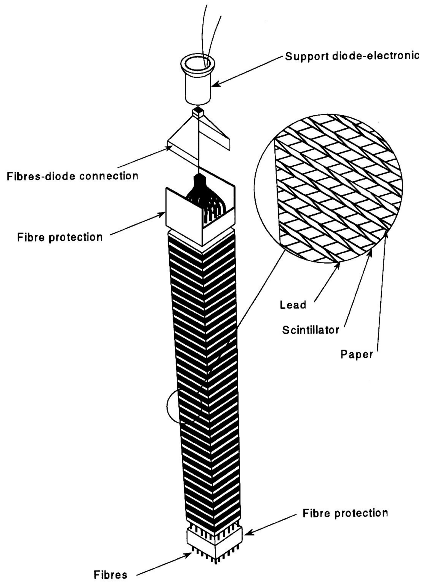
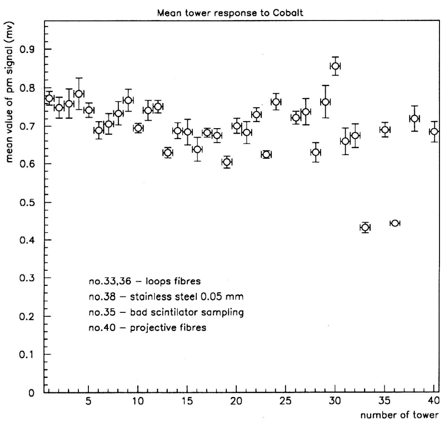


Fig. 1. Result of a single Monte Carlo experiment of $H \to \gamma\gamma$ (background subtracted) for 10^5 pb^{-1}, with Higgs peaks at 90, 110, 130 and 150 GeV.
Fig. 2. Shaslik tower (right).



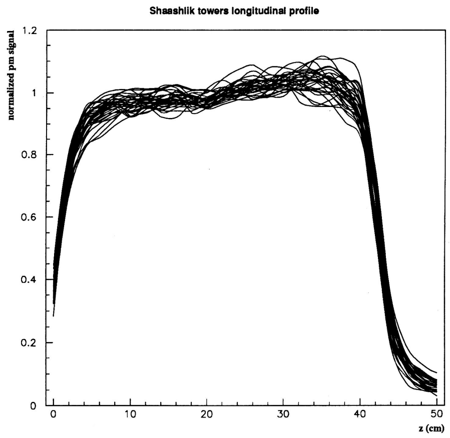
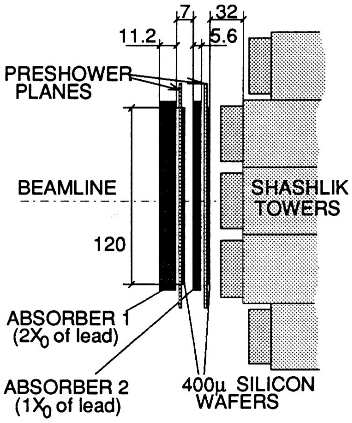


Fig. 3. Mean light response for the 36 new IHEP shashlik towers.
Fig. 4. Longitudinal light response for the 36 new IHEP shashlik towers (right).



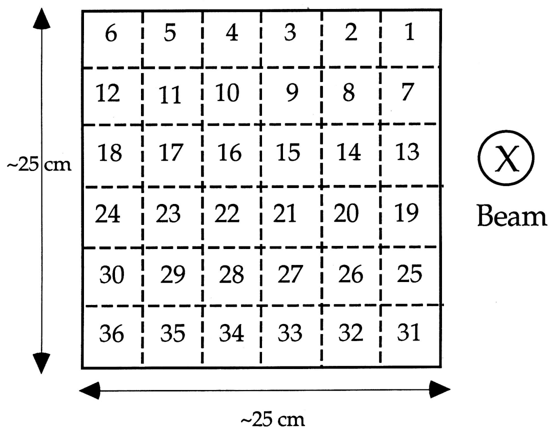
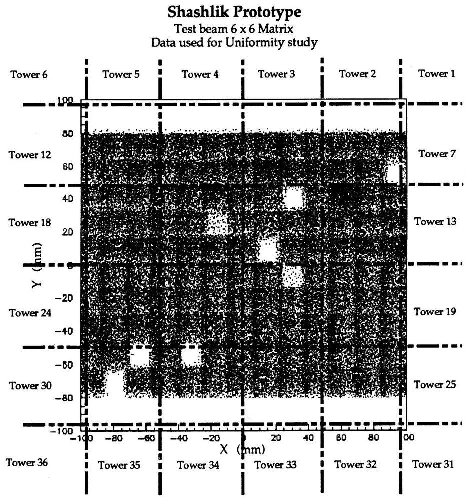


Fig. 5. Test beam setup. Shashlik towers with preshower detector in front (dimensions in mm*).*

Fig. 6. The 6 $\times$ *6 shashlik tower matrix tested in the H4 SPS beam line. The towers front dimensions area is 42* mm $\times$ *42* mm*, giving at the shower maximum an apparent size of 48* mm $\times$ *48* mm *(right).*



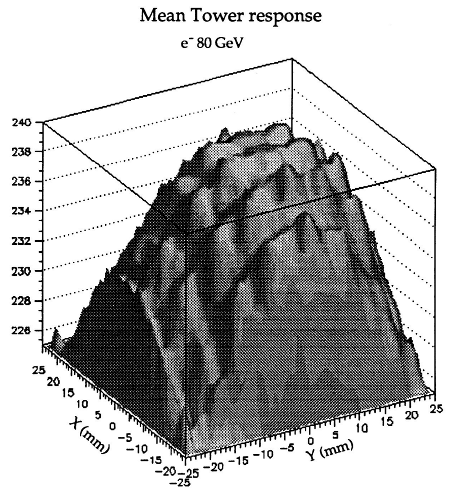


Fig. 7. Sketch of the 6 $\times$ *6 test beam shashlik matrix and the 80* GeV *electron data impact points* ($5 \cdot 10^6$ *triggers) taken for the uniformity study. The empty squares correspond to unusable data files.*

Fig. 8. Mean response (sum of 9 towers) for the 16 central towers of the 6x6 matrix exposed to 80 GeV *electrons. The dispersion of all the data is 3% (right).*

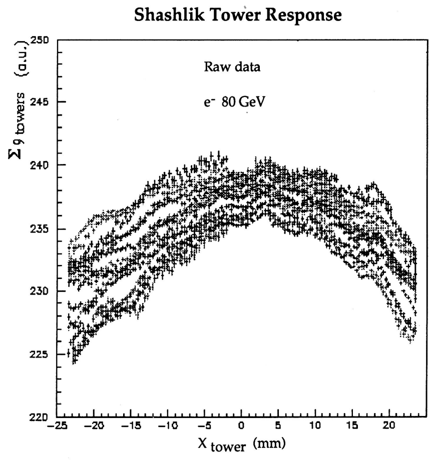
setup we have in the beam, a matrix of shashlik towers in front of which there is a preshower detector equiped with 2 planes of silicon strip detectors. Each layer (400 μm thick) consisted of 4 wafers, each of 6 cm $\times$ 6 cm with 29 strips of 2 mm pitch. In front of each plane, we have placed $2X_0$ and $1X_0$ of absorber (lead), respectively. The preshower signals were read by a 16-channel AMPLEX - SiCAL signal processor [5]. The shashlik tower matrix placed in the H4 beam line at SPS is shown in Fig. 6. Towers 15, 16, 21 and 22 were exposed to an electron beam of variable energy to study the energy resolution. For the study of uniformity of response, the full area of a 6×6 tower matrix was scanned with an 80 GeV electron beam.

3.1. Shashlik response uniformity

Without the preshower in front, an extensive study of bare shashlik uniformity was performed with the 80 GeV electron beam. An area of 20 cm $\times$ 15 cm was illuminated with a density of about 150 hits/mm^2. Figure 7 shows the tower edges and the area exposed to the beam and used for the energy measurements. Uniformity of response, both in lateral and longitudinal directions, is the crucial issue for the calibration of a calorimeter involving more than 10 thousands towers. It is impossible to construct towers with uniform response for any impact point. The aim of this study is to find the law governing the response non-uniformity and by its parametrization to perform uniformity corrections. This is done by studing the reconstructed shower energy, summing the energy deposited in the central tower (hit by electrons) and the 8 surrounding towers, collecting the sidewise leaking energy. Figure 8 gives the averaged response of the 16 towers for which the deposited energy can be reconstructed. Figure 9 shows the superimposed response of 16 individual towers. From Fig. 9 it is clear that a 2nd order polynomial provides a satisfactory description of the observed non-uniformity. The observed lateral non-uniformity is mainly caused by tower geometry, the non-uniform reflectivity at the sides of the towers, and by the choice of parallel fibres and projective geometry of the towers, implying that the distance between the fibres and the scintilator edges changes (increases) from the front to the rear of the tower. This can be compensated by an appropriate choice of the fibre attenuation length. A local non-uniformity is also present around fibres due to Cherenkov photons for particles travelling in the fibres. This local non-uniformity can be avoided by tilting the tower a few degrees with respect to the incident beam direction. Having all this in mind, the $x(y)$ lateral projections of the tower response can be parametrized by a second order polynomial modulated by a cosine wave with the periodicity of fibres:

$$f(E) = a_1 \cdot [1 - a_2(x - x_c) - a_3(x - x_c)^2] \cdot [1 - a_4 \cdot \cos \frac{2\pi(x - x_c)}{d}]$$

where a_1 is tower response at its centre, $a_2(a_3)$ the global non-uniformity correction (linear + quadratic term), a_4 the amplitude of the ondulation due to the fibre position, d the distance between the fibres and x_c are the tower centre positions.



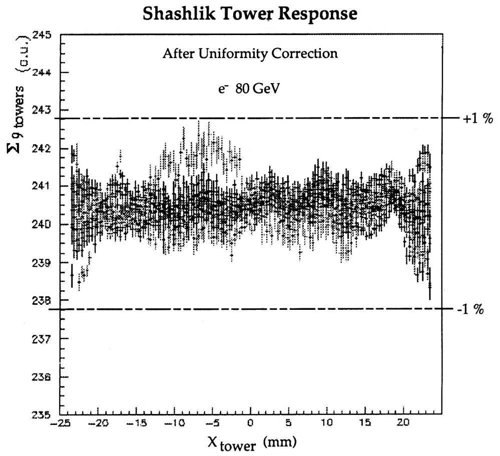
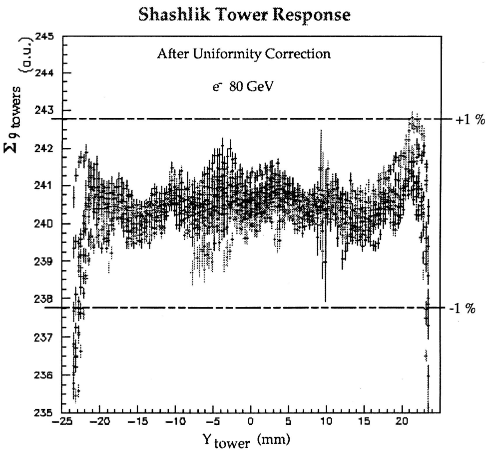


Fig. 9. Superimposed response of 16 shashlik towers exposed to 80 GeV *electrons. Data for the full tower are used (*ΔY*= 47* mm*). A similar distribution is obtained for the Y projection.*

Fig. 10. Superimposed response of 16 shashlik towers exposed to 80 GeV *electrons. Data for the full tower are used (*ΔY*= 47* mm*). The dispersion of all the data relative to the mean response has* σ*= 0.14% (right).*



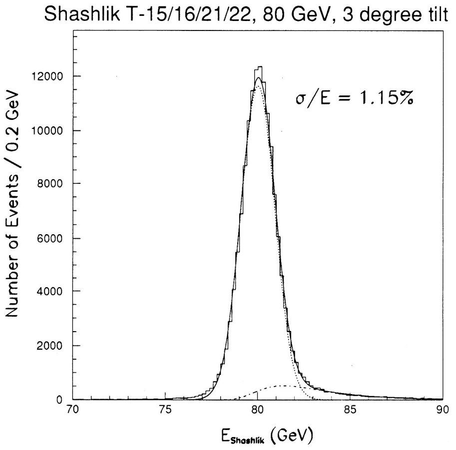


Fig. 11. Superimposed response of 16 shashlik towers exposed to 80 GeV *electrons. Data for the full tower are used (*ΔX*= 47* mm*). The dispersion of all the data relative to the mean response is* σ*= 0.16%.*

Fig. 12. Reconstructed energy in shashlik towers-15, 16, 21 and 22 for 80 GeV *electrons in the tower centre 2* cm $\times$ *2* cm*. The solid curve is the result of the fit with Gausssian (doted line) plus Landau distrubution for the nuclear counter effect (dot-dashed line) (right).*

The quadratic term represents the main correction to be applied to the data. The response after these corrections for the mentioned 16 towers is shown in Figs. 10 and 11 for x and y projections, respectively. The overall response fit to the constant shows small dispersion, $\sigma = 0.14\%$ [6]. One can notice in Fig. 11 (Y slice) that the effect of edges due to the non-tilted tracks is more pronounced than for the tilted directions (X slice).

3.2. Energy resolution

The energy resolution of a calorimeter is generally parametrized as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

where a parametrizes the "stochastic term", b the "noise term", c the "constant term", (E is the energy in GeV) [7, 8]. The signals summed over 9 towers (the central one + 8 surrounding ones) were used to study the energy resolution. The data used were events with the e-beam falling onto the central 2 cm $\times$ 2 cm area of a tower, corrected for the lateral non-uniformity as described above. The reconstructed energy in shashlik towers is shown in Fig. 12 for 80 GeV electrons. The tail on the high-energy side is due to the "nuclear counter effect" (leakage of electromagnetic shower is present due to a limited longitudinal depth of tower of $27X_0$, which degrades the energy resolution). To extract the intrinsic resolution, the fitting with Gaussian plus Landau distribution has been made [9]. A summary of shashlik energy resolution results is shown in Fig. 13 for 4 towers (T-15,16,21 and 22). Tower 21 has a special geometry and the wave-length-shifting (WLS) fibres were also projective. The average resolution of the 4 towers is:

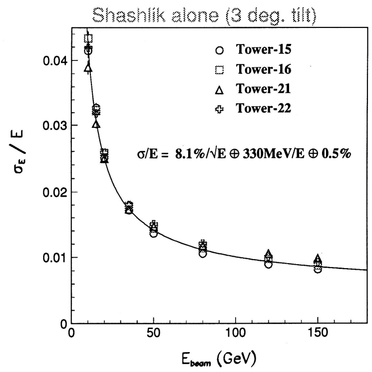
$$\frac{\sigma_E}{E} = \frac{8.1\%}{\sqrt{E(GeV)}} \oplus \frac{0.33}{E(GeV)} \oplus 0.5\%$$

which is within the design requirements for the CMS detector [1,3].

In order to test influence of magnetic field, the shashlik calorimeter prototypes equiped with a preshower detector have been also tested in a 3 T magnetic field. The light response was as much as 11% greater than in the case of test without magnetic field, but no significant effect on the energy resolution nor on the preshower performance has been found [10].

3.3. Energy resolution for a large area

For 80 GeV and 150 GeV electron data, the energy resolution has been measured over the 16 central towers. Results for 80 GeV data, corrected for non-uniformity, are shown in Fig. 14. The dispersion on the energy resolution for the 16 individual towers is small (about 0.1%) and compatible with the results obtained at the tower center (2 cm × 2 cm). When all data are used (20 cm × 15 cm), the overall resolution (1.29%) is also compatible with the one obtained for individual towers.



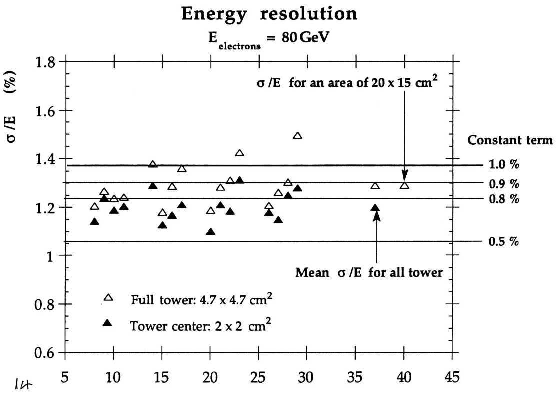


Fig. 13. Energy resolution of the new shashlik prototype (shashlik alone with 3° tilt).

Fig. 14. Energy resolution for all 16 shashlik towers, after uniformity corrections, at tower center (2 cm × *2* cm *area) and for the full towers (4.7* cm × *4.7* cm *area) (right).*

3.4. Angular resolution

For the Higgs boson diphoton decay H $\to \gamma\gamma$ at high luminosity, when event pile-up is present in the bunch crossing, the measurement of the angle of emission of the photons is required to preserve satisfactory mass resolution. In order to reconstruct this angle, the photon shower position has to be measured at two depths in the electromagnetic calorimeter. The first point along the EM shower is obtained from the preshower detector, whilst the second one is the shower barycenter in the calorimeter itself.

With the preshower ($\sigma_{x,y}(\mathrm{mm}) = 2.0/\sqrt{E(\mathrm{GeV})} + 0.2$) and shashlik tower position resolutions ($\sigma_{x,y}(\mathrm{mm}) = (8.3 \pm 0.4)/\sqrt{E(\mathrm{GeV})} + (0.17 \pm 0.06)$), obtained by measurements [2], assuming that the shower barycenter is located at the shower maximum (about 6-8 X_0), one can estimate the photon direction angular resolution for the combined measurements. Figure 15 shows the dependence of the angular resolution as a function of the electron energy at the tower center. From the fit, we obtained:

$$\sigma_\theta = \frac{70\ \mathrm{mrad}}{\sqrt{E(\mathrm{GeV})}}.$$

Few two-bundle and three-bundle shashlik towers have also been produced and tested in the beam, and it was confirmed that the position resolution is improved by the expected factor in comparison with the same type of tower equiped with a single channel readout [11].

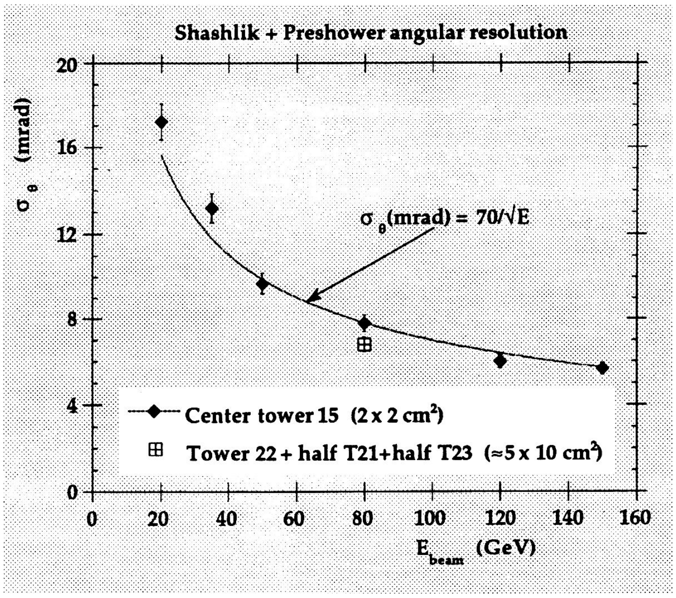
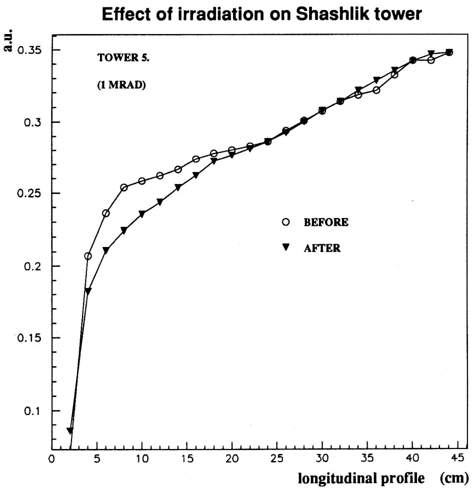


Fig. 15. Photon angular resolution of the shashlik + preshower assembly.

4. Radiation damage tests

One of the basic requirements for the electromagnetic calorimeter of CMS is to be radiation hard. The expected radiation dose (from simulation), due to the electromagnetic energy deposited in the CMS barrel calorimeter over a ten year data taking period, varies from about 0.2 Mrad at η =0.0 to 1 Mrad at η=1.5 [1]. The effect of radiation damage on shashlik performance has been studied by realistic modelling and experimentaly by irradiation of complete towers. A study of the effects of radiation damage on light yield collection [12 – 14] shows that in addition to the overall decrease in light collected, the non-uniformity of response across a calorimeter tower increases. This leads to an increase of the contribution of the constant term to the energy resolution.

Irradiation of complete shashlik towers using the LINAC injector at LEP (intensity of up to 10^9 electrons of 500 MeV per second) was carried out [15]. Figures 16 and 17 show the effects of 1 Mrad and 5 Mrad doses on the longitudinal response of a tower to ^{60}Co photons. One sees that the damage is maximum at the shower maximum. Test of the energy resolution using 150 GeV electrons shows that no significant effects occurs for a dose up to 1 Mrad.



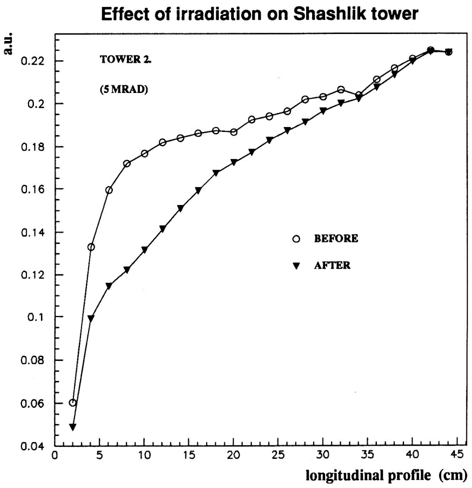


Fig. 16. Effect of an irradiation of 1 Mrad *produced at LiL by 500* MeV *electrons on a shashlik tower. The longitudinal response profiles of the tower before and after irradiation are shown.*

Fig. 17. Effect of an irradiation of 5 Mrad *produced at LiL by 500* MeV *electrons on a shashlik tower. The longitudinal profiles of the tower before and after irradiation are shown (right).*

5. *Conclusion*

A WLS technique has been developed to read-out the light from a lead/scintillator sampling calorimeter. The use of optical fibres enables a fine lateral segmentation to be achieved with a minimum of dead spaces.

Several prototypes have been built and tested in electron beams at CERN [2]. The energy resolution measured on projective towers is

$$\frac{\sigma_E}{E} = \frac{8.1\%}{\sqrt{E}} \oplus \frac{0.33}{E} \oplus 0.5\% \ (E \text{ in GeV}).$$

It is estimated that an irradiation of 1Mrad (corresponding to 10 years of LHC operation at nominal luminosity in the CMS barrel) produces a loss of light of about 10%. The resultant loss in energy resolution has been found to be small. In conclusion, the measured performances of shashlik detectors satisfy the basic requirements for a sampling calorimeter at the LHC. A higher performance crystal calorimeter, however, provides a large safety margin for the observation of such difficult signals as the H $\rightarrow \gamma\gamma$ [4].

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References

1) *Letter of Intent*, CERN/LHCC 92-3, LHCC/I1, 1 October 1992;
2) L. Dobryznsky et al., *A Shashlik + Preshower Detector as Electromagnetic Calorimeter For LHC*, CERN/DRDC 94-47, RD36 - Status Report, 9 January 1995;
3) C. Seez et al., *Proc. Large Hadron Collider Workshop*, Aachen, 1990, eds. G. Jarlskog and D. Rein, CERN 90-10, vol. III, 474;
4) *CMS Collaboration Technical Proposal for CMS*, CERN/LHCC, 94-38, LHCC/P1, 1994;
5) E. Beuville et al., Nucl. Instr. and Methods **A288** (1990) 157;
6) L. Dobryznski et al., *Study of Shashlik Uniformity Response.* CMS TN/94-311;
7) H. Fessler et al., Nucl. Instr. and Methods **A254** (1987) 26;
8) L. Dobryznski et al., *A Combined Shashlik+Preshower Detector for LHC*, CERN/DRDC 93-28(1993)
9) P. Aspell et al., *Beam Test Results on Shashlik Projective Tower and Preshower*, CMS-TN/95-064 (Submitted to Nucl. Instr. and Methods.);
10) L. Dobryznski et al., *Shashlik Beam Test Results in High Magnetic Field*, CMS-TN/95-002 (Submitted to Nucl. Instr. and Methods);
11) J.Badier et al., Nucl. Instr. and Methods **A354** (1995) 328-337;
12) V. Vasil'chenko, *New Results on Plastic Scintillators Radiation Damage*, CMS TN/94-220;
13) V. Bolotov et al., *Radiation Hardness of WLS Fibres*, CMS TN/94-221;
14) B.V. Semenov, *Gamma Irradiation Tests of Shashlik ECAL Injection Molding Type Scintillators*, CMS TN/94-225;
15) J.P. Merlo et al., *Radiation Hardness Tests Using LiL Beam Facilities*, CMS TN/94-262.

REZULTATI ISPITIVANJA SHASHLIK ELEKTROMAGNETSKOG KALORIMETRA

Sveučilište u Splitu, kao član CMS kolaboracije, sudjeluje u razvoju olovno/scintilacijskog elektromagnetskog kalorimetra "sandwich"-tipa (shashlik), u okviru RD36 projekta. Tijekom 1994. provedeni su detaljni eksperimentalni testovi svojstava prototip-tornjeva shashlik kalorimetra, kao jednog od kandidata za elektromagnetski kalorimetar u CMS detektoru na LHC-u. Izmjereno energijsko razlučivanja odredeno je stohastičkim članom iznosa $8.5\%/\sqrt{E}$, šumom iznosa $0.33/E$, te konstantnim članom iznosa 0.5% (E u GeV). Razmatrana je reproducibilnost proizvodnje tornjeva jednakih svojstava, uniformnost odziva kalorimetra na površini 25 cm $\times$25 cm, te kutno razlučivanje. Procijenjen je i utjecaj radijacijskih oštećenja na shashlik tornjeve.