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RADIATION INDUCED ENERGY RESOLUTION DEGRADATION AND RESPONSE NONLINEARITY OF THE TILE/FIBER EM CALORIMETER WITH TWO-PMT READOUT

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Radiation induced energy resolution degradation and response nonlinearity of the tile/fiber EM calorimeter with two-PMT readout

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Abstract

Longitudinal EM segmentation can help correct for radiation induced longitudinal nonuniform response. We study this correction procedure using a GEANT simulation and assuming various damage profiles. Measured damage vs dose relation is employed in the calculation to model realistic damage profiles. The correction is found to make the calorimeter lifetime about two times longer, although the correction becomes dependent on the detailed damage profile and on the electron energy at above a certain damage. The response nonlinearity becomes small with 2-PMT readout. The radiation induced lateral nonuniformity induces a change in response map, and the calorimeter lifetime using SCSN81/Y7 will be limited by the lateral nonuniformity to 2.5–5 Mrad, provided that the longitudinal nonuniformity is corrected for by masking.

1. Introduction

The effectiveness of 2-PMT readout in correcting for radiation induced longitudinal nonuniformity has been demonstrated successfully in Ref. 1. We repeat the calculation using the measured damage vs dose curve [2] and choosing various longitudinal dose profiles. From this study we understand the sensitivity of the correction procedure to the detailed damage profile, which could vary according to η and due to amount of hadron contribution to the damage.

The response linearity is also degraded by radiation damage as pointed out in Ref. 2. Although it seems not to difficult to correct for those nonlinearities, the nonlinearity could become small if we employ 2-PMT readout.

The longitudinal nonuniformity could be corrected for by calibration and masking as proposed in Ref. 3. After all if we correct for the longitudinal nonuniformity and if the light yield after masking is high enough (which would be the case for the forward calorimeter where the light yield is high for the same E_{T} by $1/\sin\theta$), the calorimeter lifetime could be limited by radiation induced lateral nonuniformity in a tile. Such a radiation induced lateral nonuniformity is reported in Ref. 4. This contribution to the additional error to the resolution and change in the response map are estimated.

2. Simulation of 2-PMT Readout

The endcap EM calorimeter is used as a model in the GEANT simulation. As shown in Fig. 1, the EM calorimeter consists of 6 mm thick lead absorber plates and 4 mm thick scintillating tiles. A polystyrene plate of 2 mm thickness is interleaved between the tile and lead plate for fiber routing. As for the massless gap, two sets of the tile and polystyrene plate are included, following a 2.5 mm thick aluminum top cover. The shower max detector equivalent to 12 mm thick polystyrene is inserted between the 6th and 7th lead/tile/polystyrene cells. The tower size is enlarged so that all the shower particles are contained.

Electrons with energies of 0.5, 2, 5, 10, 20, 50, 100, and 200 GeV are injected to the calorimeter. The procedure for evaluating the damage induced error to the resolution is essentially the same as the one described in Ref. 2. The energy deposit in each tile is summed and recorded on an event by event basis. The cutoff energies for photons and electrons are set to 1 MeV. For a given value of "peak damage", the light yield loss at the shower maximum tile, the damages for the other tiles are calculated using the damage curve given in Ref. 2 and the average shower profile calculated for 0.5–10 GeV electrons. The energy deposit in the tiles are reduced according to the damages. The reduced energy deposits in the tiles from 1 to 6 and those from 7 to 24 are summed separately to account for the longitudinal segmentation in the EM calorimeter. Here the energy deposit in the massless gap tiles is not included, but that in the shower max tiles is included to minimize the energy resolution at no damage. Each of the energy sums is converted to the number of photoelectrons using the relation 2 photoelectrons/0.8 MeV (i.e. 2 PEs/tile/mip) with a Poisson fluctuation included.

3. Results and Discussions

3.1 Energy resolution with 2 PMT readout

The idea of 2-PMT readout is to weight the responses of the two EM longitudinal segments according to the damage. Since the radiation damage is induced mainly by low energy γ's from π^{o}'s and hence the first EM segment receives more dose than the second, the response of the first segment has to be multiplied by a factor greater than that for the second. The weighted energy can be written as;

$$E = A[(1 + X)\mathrm{Seg1} + (1 - \mathrm{X})\mathrm{Seg2}], \tag{1}$$

where X represents the relative weight, A is the overall calibration factor, and Seg-i is the response of the i-th EM segment. The optimum X can be dependent on the damage profile and the electron energy. The dependence on the electron energy is, however, expected to be small above a certain energy we are interested in, since the shower profile changes slowly with energy E like $\log E$. The optimum X can be determined *in situ* by minimizing the resolution for electrons of known energy, or by measuring the damage profile with a source scan and using a Monte Carlo simulation.

Fig. 2a shows the energy resolution as a function of X for 200 GeV electrons at a given peak damage from 10% to 70%. The data points are fitted to a polynomial function. The damage profile is calculated using 2 GeV shower profile and the damage vs dose curve measured for SCSN81/Y7 combination. The optimum X can be determined by minimizing

the energy resolution. Note that the additional error to the resolution is substantially reduced with 2-PMT readout compared to with 1-PMT readout, which corresponds to the case $X = 0$. Fig. 2b is a similar plot for 20 GeV electrons.

The damage induced additional error to the energy resolution is plotted as a function of peak damage for the electron energy from 20 to 200 GeV in Fig. 3. The hadron contribution (see below for detail) and the damaging electron energies, that determine the damage profile, are fixed to 20% and 2 GeV, respectively.

In Figs. 4a and 4b the minimum energy resolutions are compared with the resolutions obtainable with 1-PMT readout at two electron energies 200 GeV and 20 GeV. For 200 GeV electrons the energy resolution degrades to 2% (radiation induced additional error is 1.5%) at peak damage of 25% with 1-PMT readout, and at peak damage of 45–60% with 2-PMT readout depending on the detailed longitudinal profile of the damage. Therefore, the calorimeter lifetime will become about two times longer with 2-PMT readout. The lifetime becomes longer with decreasing the energy of damaging electrons. The damaging electron energy is varied from 0.5 to 10 GeV in this simulation. Since the average E_T of γ's is 0.3 GeV and hence E varies up to 3 GeV at $\eta = 3$, the simulation covers the electron energy range in the endcap region. For 20 GeV electrons this tendency becomes more distinct. The calorimeter lifetime is about 1.5 times for 10 GeV damaging electrons and about 2 times for 0.5 GeV. In Fig. 4 the "hadron contribution" is also varied from 10% to 30% with fixing the damaging electron energy at 2 GeV. According to Ref. 3, the contribution of charged pions amounts to as much as 20% of the total dose. In addition, neutrons may increase this contribution further. Although we can simulate the hadron shower profile assuming the average hadron energy, the hadron contribution is, instead, set to be constant in the EM tiles in this study. To be precise, 20% hadron contribution means the EM and hadron contributions at the shower maximum layer are 48% and 12%, respectively, for 60% peak damage. Fig. 4 shows the dependence on hadron contribution is weak in the range from 10% to 30%.

3.2 Optimum weight ratio

We have shown that the calorimeter lifetime will be about two times longer with 2-PMT readout for the two electron energies 20 and 200 GeV, which corresponds to 2 and 20 GeV in E_T at $\eta = 3$. The lifetime will be longer for higher energy electrons. In practice, however, the calibration would be time consuming if the optimum weight ratio is strongly dependent on the damage profile, or on the average damaging electron energy and the hadron contribution in this study; and on the electron energy. If it is the case, the detailed damage profile has to be measured by source scan (for each tower), and the calibration using high energy electrons from W/Z can not be extended to lower energies.

The optimum X varies with the peak damage almost linearly as shown in Fig. 5, where the optimum X is plotted for the electron energies from 10 to 200 GeV. At the peak damage below 30% the optimum X is almost independent to the energy. At higher peak damage, however, the optimum X becomes dependent on the energy. At 50% peak damage the optimum X is 0.23 for 10 GeV electrons whereas it is 0.37 for 200 GeV electrons. According to Fig. 2 the resolution changes slowly with the ratio X at higher energies. Although 0.23 is not the optimum for 200 GeV electrons at 50% peak damage, it gives 2.3% energy resolution which should be compared to 4.2% obtainable with 1-PMT readout and 2.0%, best achievable

with 2-PMT readout. In summary it is preferable to optimize the weight as a function of the energy, but it is not catastrophic even if such an energy dependent calibration is not available – in the case only the high energy electrons from W/Z are used for calibration.

Next, the optimum X is plotted for different damage profiles in Fig. 6. For 200 GeV electrons the optimum X is weakly dependent on the damage profile for peak damage below 30%. The optimum X for 50% peak damage can be different by 0.05 due to different damaging electron energies and by 0.08 due to different hadron contributions for the central value of 0.35. As mentioned above, however, this much of difference is small in terms of the achievable energy resolution. For 20 GeV electrons the correction seems to be complicated. The optimum X can be different by 0.12 for the central value of 0.25 at 50% peak damage. By changing the weight ratio by 0.12 the resolution will be 5.8% whereas the minimum resolution is 5.2%, and 6.6% for the case of 1-PMT readout; The energy resolution is improved moderately with 2-PMT readout. To take full advantage of 2-PMT readout, we have to measure not only the peak damage but also the longitudinal damage profile by source scan.

3.3 Response linearity with 2-PMT readout

The response linearity is degraded due to radiation damage, since the EM shower profile is dependent on the energy while the damage profile is specific in a give tower. The response linearity obtainable with 1-PMT readout is shown in Fig. 7, where the response is normalized by the response at no damage. The damage profile is calculated using 2 GeV electron shower and assuming 20% hadron contribution. At 30% peak damage, the response is reduced to 84% for 100 GeV electrons and the nonlinearity in the range from 5 to 200 GeV is 6.3%. The nonlinearity is, however, a smooth function of the energy and seems to be corrected for.

The response linearity after the correction with 2-PMT readout is plotted in Fig. 8. Here the correction is made using the optimum X that minimizes the energy resolution. For the same damage profile as for the case with 1-PMT readout, the nonlinearity in the range from 5 to 200 GeV is 3%/75.8% at 30% peak damage and is 6%/56% at 50% peak damage, where the numbers in the denominator are the reduced response for 100 GeV electrons. Note although the response reduction is apparently large for the case with 2-PMT readout, it is due to weighting and the photostatistics is not degraded of course. The nonlinearity becomes smaller with 2-PMT readout.

4. Resolution degradation due to radiation induced lateral nonuniformity

The radiation induced response nonuniformity in a tile has been measured using ^{60}Co γ rays [4]. Nonuniformity is observed above 1 Mrad for the tile/fiber combination SCSN81/Y7. When the responses are normalized at the tile center, the response around the fiber is 8% higher after 5 Mrad irradiation. It is suspected that the light attenuation in the tile becomes short due to radiation, which enhances the response around the fiber relatively. This lateral nonuniformity has been measured to be roughly proportional to the dose.

The calorimeter could be usable with 2-PMT readout up to about 50% peak damage, which corresponds to 2 Mrad for SCSN81/Y7 tile/fiber combination and about 1 Mrad for SCSN38/Y7 combination [4]. We could correct for the radiation induced longitudinal nonuniformity by means of masking, provided that the light yield is high after masking. In

this case the lateral nonuniformity would instead limit the calorimeter lifetime. We compare the longitudinal and lateral nonuniformity contributions to the resolution degradation taking SCSN81/Y7 as a model. For the forward region, we may have to use different tile/fiber combination or even new plastics, which may show completely different lateral nonuniformity. To deal with this case, we show an estimation in more general way.

4.1 For the case of SCSN81/Y7 combination

The energy resolution degradation including the longitudinal nonuniformity can be evaluated using the data shown in Fig. 3. The resolution on the nonuniformity peak should be similar to the one at 47% peak damage instead of at 50%: The peak damage is effectively smaller by about 3% on the lateral nonuniformity peak at 2 Mrad. The resolution is "recovered" by 0.2% for 200 GeV electrons. Since the limit of 50% peak damage comes from 1.5% increase in resolution for 200 GeV electrons, the lateral nonuniformity does not contribute much to the resolution degradation. The energy resolution degradation around the nonuniformity peak is calculated, which results that the degradation is maximum on the peak. Therefore, the contribution of the lateral nonuniformity is small as far as the resolution degradation is concerned. The effect on the change in the response map can be estimated from Figs. 7 and 8. With 2-PMT readout the response at optimum X would change by about 3% for a 3% change in the peak damage at 200 GeV. With 1-PMT readout the response would change by 1.5% for the same condition. The response would be over-corrected at the nonuniformity peak with 2-PMT readout. These numbers are calculated without taking the lateral shower spread into account. As will be described in the following, the actual response changes by about 1/2 of these numbers due to lateral shower spread. Therefore, at 2 Mrad this change in the response map due to lateral nonuniformity has to be considered seriously for the case with 2-PMT readout and if the longitudinal nonuniformity is not corrected.

Electrons of 100 GeV were injected to the endcap calorimeter with recording the position and energy deposition at each interaction. In total 180 events were generated. The event-by-event response is a sum of energy depositions weighted by the local response accounting for the lateral nonuniformity. The measured lateral nonuniformity [4] at 5 Mrad is modeled such that the response on the fiber is enhanced by 8% and that 1.5 cm inside the fiber is reduced by 4% at the shower maximum tile. The magnitude of the nonuniformity for the other tiles are set to be proportional to the dose. The fibers in depths are placed projective to the beam; The simulation assumes the worst case. Hereafter we assume that the longitudinal nonuniformity is corrected for by masking.

In Fig. 9 the response and the energy resolution degradation are plotted as a function of the impact point. The response is enhanced near the fiber. While the nonuniformity peak is set high by 8% at the shower maximum layer, the response for 100 GeV electrons is high by 2%. The nonuniformity is averaged over both longitudinally and laterally. These two averagings are calculated to reduce the nonuniformity almost equally. In order to maintain the response map unchanged within 1% (2%), we have to keep the radiation induced lateral nonuniformity to be smaller than 4% (8%). The corresponding dose is 2.5 Mrad (5 Mrad). On the other hand, the resolution degrades by 0.6% even for 8% peak nonuniformity. In the calculation, the number of photoelectrons/mip/tile is set to 2. If this number becomes small due to intensive masking, the contribution of the lateral nonuniformity becomes less

significant but the overall resolution should start to see the effect of photoelectron statistics. If the number of PEs is set to 2 at no damage, the masked number of PEs will be about 0.9 (0.5) PEs/tile/mip after 2.5 Mrad (5 Mrad) [2]. The contribution of radiation induced lateral nonuniformity is compared with this reduction in the number of PEs in the following.

4.2 In general case

So far the discussion is based on the nonuniformity measured for SCSN81/Y7. The lateral nonuniformity shape could be different for other types of tile/fiber combination. For example, the nonuniformity is measured to be less than 2% at 5 Mrad for SCSN3HF/O2 combination. In order to extend the discussion for more general cases, we approximate the lateral nonuniformity to be a gaussian in shape. The response and the energy resolution degradation are plotted in Fig. 10 as a function of the "nonuniformity sigma", width of the assumed gaussian. The magnitude of the nonuniformity is taken to be 5% or 10% in the shower maximum tile. The nonuniformity in the other tiles is assumed to be proportional to the dose, but the longitudinal nonuniformity at the tile center is not included assuming that it is corrected for by masking. Since the local nonuniformity is smeared, the response nonuniformity becomes small for smaller nonuniformity sigma, as shown in the figure. In order to keep the response map unchanged within 1%, the nonuniformity can be as much as 5% if the nonuniformity sigma is smaller than 3 mm. If the response map can be measured *in situ* (summing the modules at the same η to increase statistics), all the problems would be solved; the effect of the lateral nonuniformity is small, since the energy resolution degradation is less than 0.6% even for 10% peak nonuniformity.

Masking longitudinal nonuniformity reduces the number of photoelectrons. The shower fluctuation contributes to the stochastic term by $17\%/\sqrt{E}$ for the endcap calorimeter. In order to keep the stochastic term below $15\%/E_{\mathrm{T}}$, the number of photoelectrons has to be maintained to be more than those numbers listed in Table 1.

Table 1. The stochastic term in E to achieve $15\%/\sqrt{E_{\mathrm{T}}}$, the maximum allowed contribution from photostatistics and the corresponding number of photoelectrons/GeV (GeV in E).

η	stochastic term	photostat. contribution	PEs/GeV in E
1.5	$23.0\%/\sqrt{E}$	17.4%	33
2.0	$29.1\%/\sqrt{E}$	24.9%	16
2.5	$37.1\%/\sqrt{E}$	33.9%	8.7
3.0	$47.6\%/\sqrt{E}$	45.2%	4.9

The number of PEs can be small at higher η as shown in the table. If the light yield of a tile/fiber (after masking) is 1 PE/mip, the corresponding calorimeter light yield is 68 PE/GeV for the endcap calorimeter.

For the case of SCSN81/Y7 for which the initial light yield is assumed to be 2 PEs/tile/mip, the calorimeter after masking could be usable up to about 3 Mrad, 10 Mrad, and beyond 10 Mrad (no data available) [2] in view of the photostatistics at $\eta = 1.5$, 2 and above 2, re-

spectively. However as described previously, SCSN81/Y7 shows lateral nonuniformity. The critical doses are 2.5–5 Mrad depending on the requirement to the change in the response map. Therefore, the lateral nonuniformity determines the calorimeter lifetime for the case of SCSN81/Y7 at above $\eta \sim 1.5$.

For the case of SCSN2HF/O2 for which the initial light yield is about 1/5 of SCSN81/Y7 (0.4 PEs/tile/mip), the calorimeter after masking could be usable up to 40% (68% and 80%) damage at $\eta = 2$ (2.5 and 3.0). The corresponding dose is [4] 2 Mrad (7 Mrad and 9 Mrad, data extrapolated). Lateral nonuniformity is measured to be small to induce a change in the response map up to 5 Mrad. Probably no significant contribution would be seen with this combination up to about 10 Mrad. For this combination, therefore, the lateral nonuniformity would not limit the calorimeter lifetime, but the photostatistics limits the lifetime; This combination can not be employed for the endcap calorimeter around $\eta =$ 1.5 because of small light yield.

In summary the calorimeter lifetime using SCSN81/Y7 combination will be limited by the radiation induced lateral nonuniformity, and could be usable up to 2.5–5 Mrad. SCSN3HF/O2 would perform fine at higher η up to nearly 10 Mrad. Any tile/fiber that shows as much light yield as SCSN81/Y7 and small nonuniformity as good as SCSN3HF/O2 (by special fiber path, or by red sensitive photodetector) will be usable in the endcap calorimeter up to beyond 10 Mrad, provided that the longitudinal nonuniformity is corrected for by masking. The data shown in Fig. 10 and in Table 1 are usufull for judging the lifetime.

5. Summary

The energy resolution degradation due to radiation induced longitudinal nonuniformity can be reduced by longitudinal EM segmentation. Although the optimum weight for the two segments is dependent on the detailed damage profile and electron energy above a certain damage, the calorimeter lifetime could become about two times longer by employing 2-PMT readout. The response nonlinearity is also reduced with 2-PMT readout.

The radiation induced lateral nonuniformity observed for SCSN81/Y7 combination changes the response by at most 2% locally on the fiber at 5 Mrad, but the contribution to energy resolution degradation is substantially smaller than that caused by the longitudinal nonuniformity.

After correcting for the longitudinal nonuniformity by masking, radiation induced lateral nonuniform response and photostatistics are the main sources that limit the calorimeter lifetime. For SCSN81/Y7 tile/fiber combination with 2 PEs/tile/mip light yield, the radiation induced lateral nonuniformity limits the calorimeter lifetime to 2.5–5 Mrad if the response is not mapped after that much dose. Although SCSN3HF/O2 could be usable to ~10 Mrad, it can be employed only in a very forward region since photostatistics limits the application at above $\eta \sim 2$.

References

[1] D. Green, A. Para and J. Hauptman, "Radiation damage, calibration and depth segmentation in calorimeters", Fermilab Note 565 (1991).

[2] S. Funaki et al., "Beam test of radiation hardness of a scintillating tile/fiber calorimeter", NIM A317 (1992) 123.

[3] SDC Tile/Fiber Calorimeter Group, "Calorimeter Conceptual Design Tile/Fiber Scintillator Option", Volume I, Sept. 3, 1991.

[4] K. Hara et al., "Radiation hardness study of scintillating tile/fibers", SDC note 92-186.

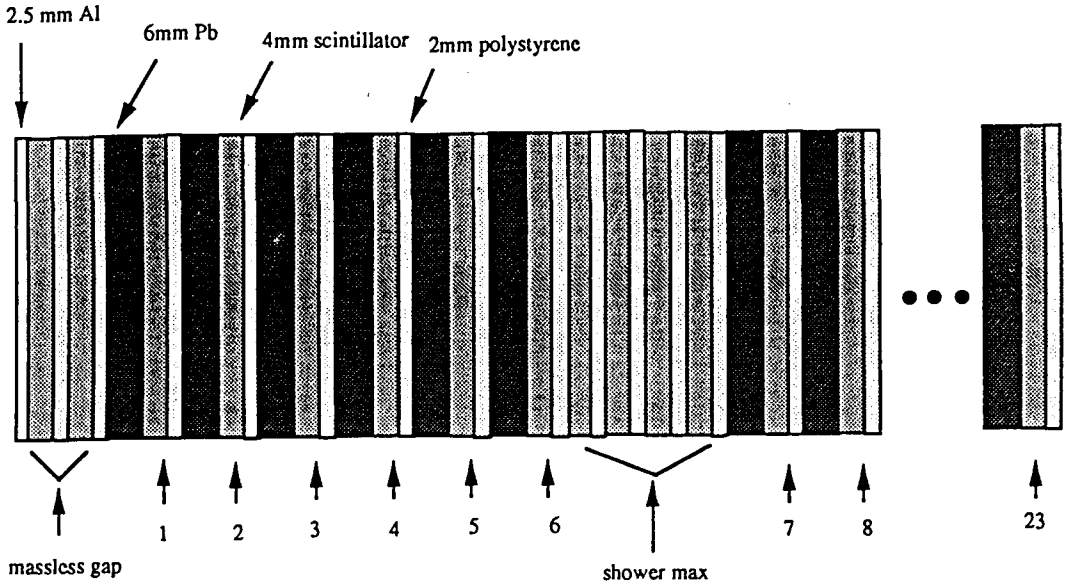

Fig. 1 The geometry of the endcap calorimeter used in the simulation.

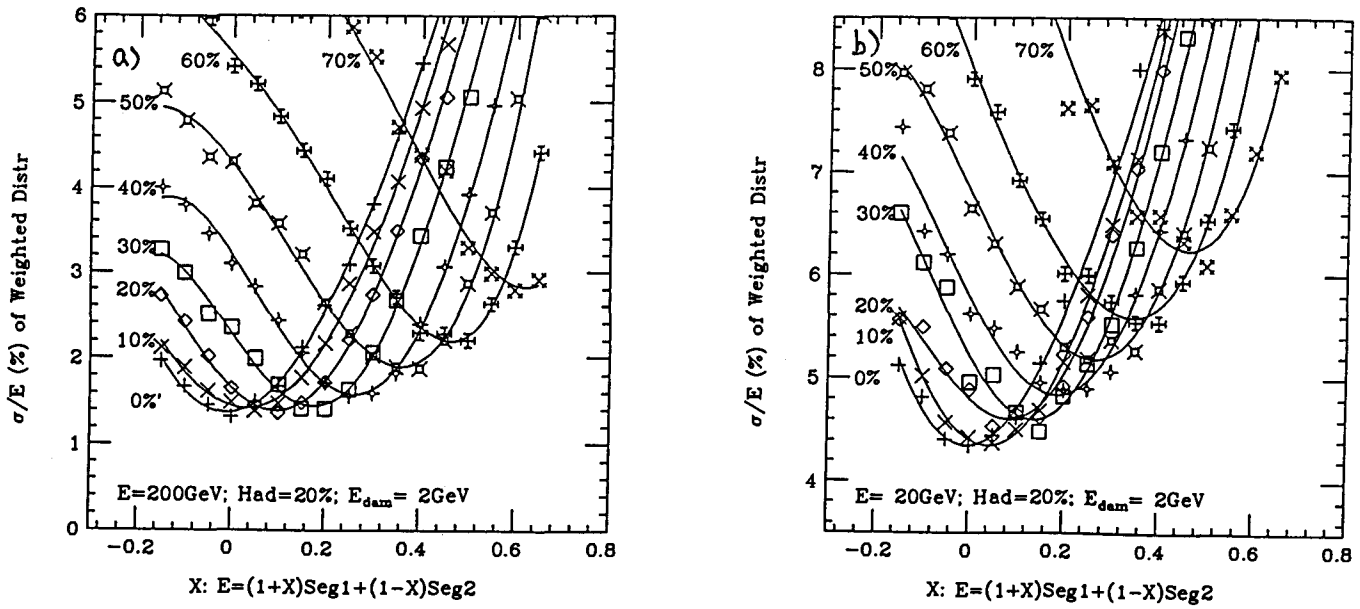

Fig. 2 Energy resolution as a function of the weight X. The data are shown for (a) 200 GeV and (b) 20 GeV electrons with changing peak damage from 0 to 70% .

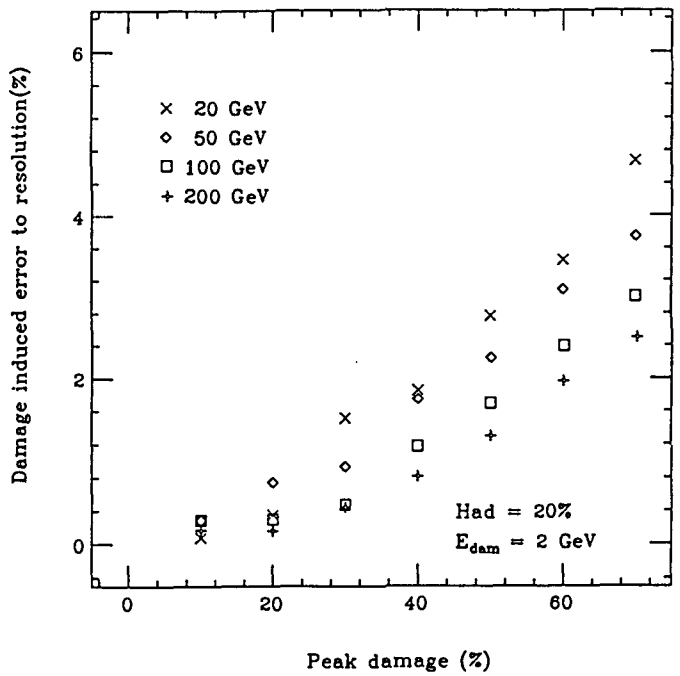

Fig. 3 Damage induced additional error to resolution as a function of peak damage. The data are shown for electrons from 20 to 200 GeV.

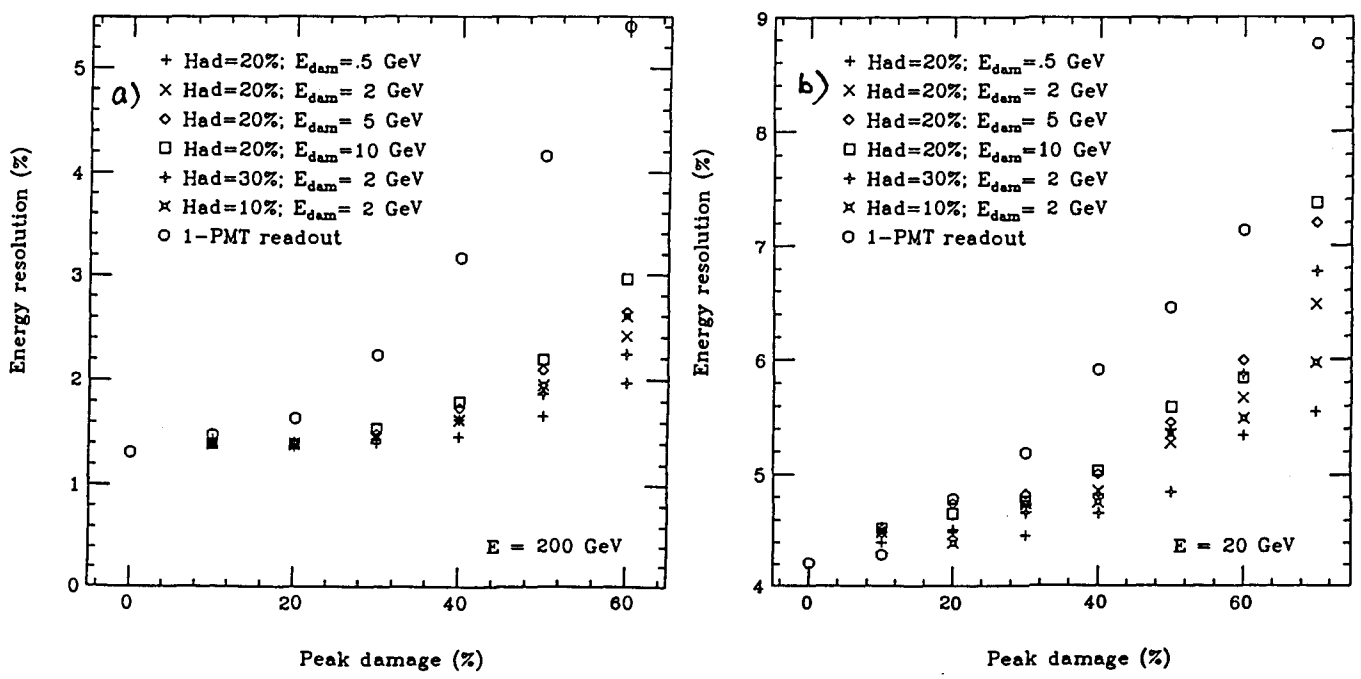

Fig. 4 Energy resolution as a function of the peak damage for (a) 200 GeV and (b) 20 GeV electrons. The damage profile is changed, and the data with 1-PMT readout are shown (circle) as a comparison.

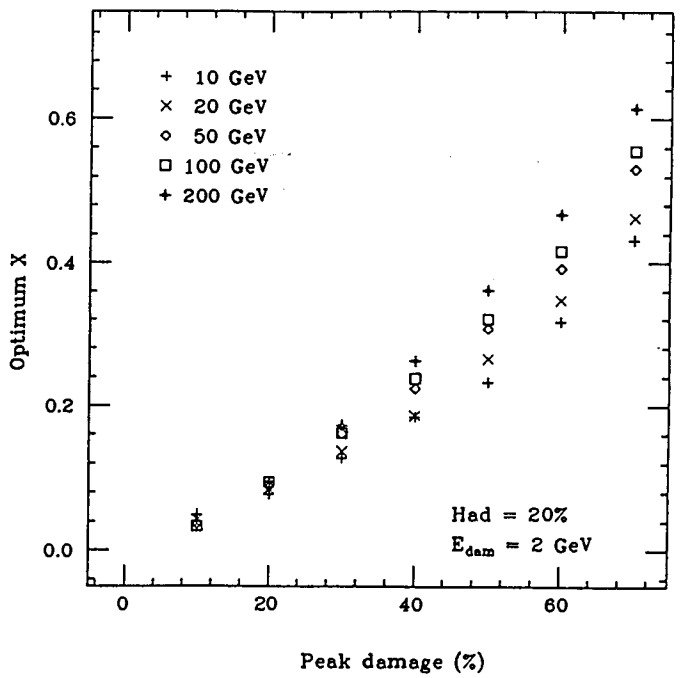

Fig. 5 The optimum weight ratio as a function of peak damage. The data are shown for electrons from 10 to 200 GeV.

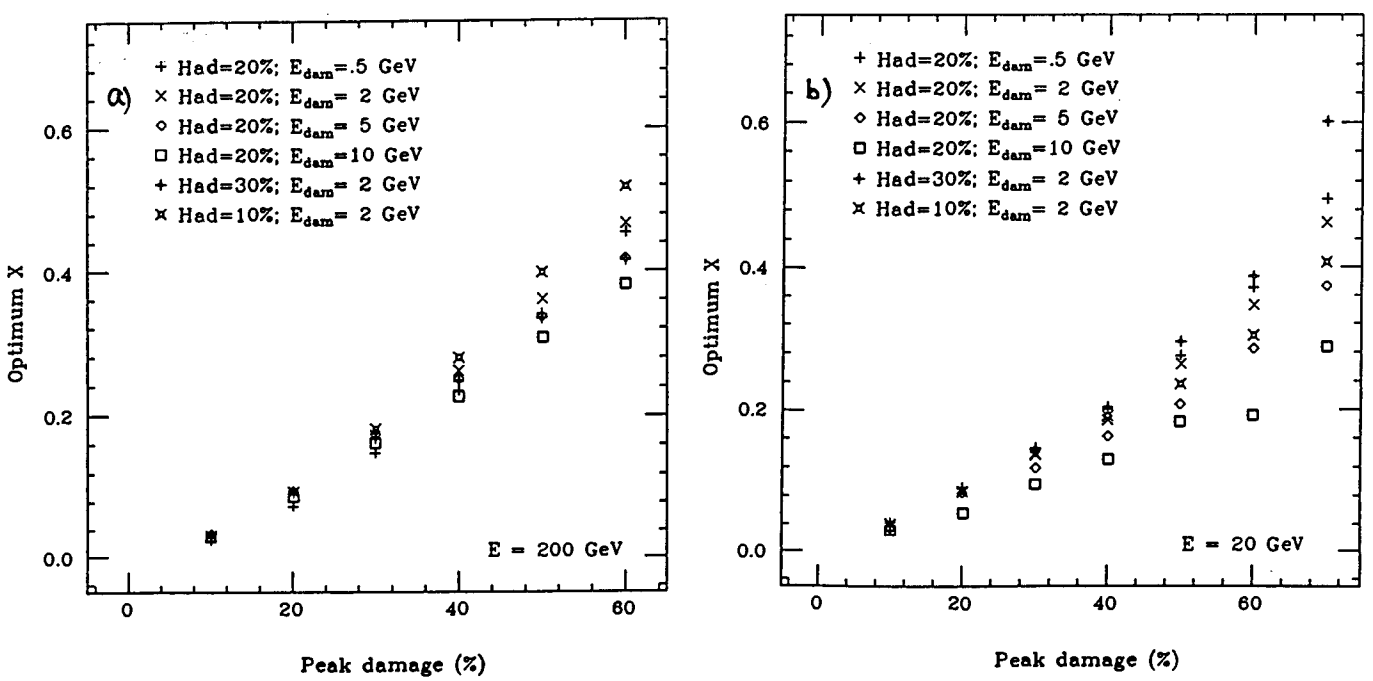

Fig. 6 The optimum weight ratio as a function of peak damage for (a) 200 GeV and (b) 20 GeV electrons. The damage profile is changed.

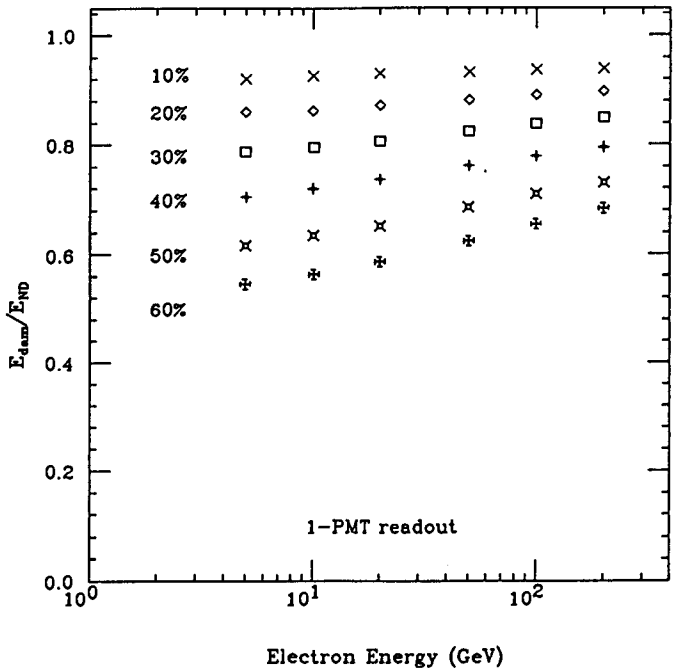

Fig. 7 Response linearity achievable with 1-PMT readout.

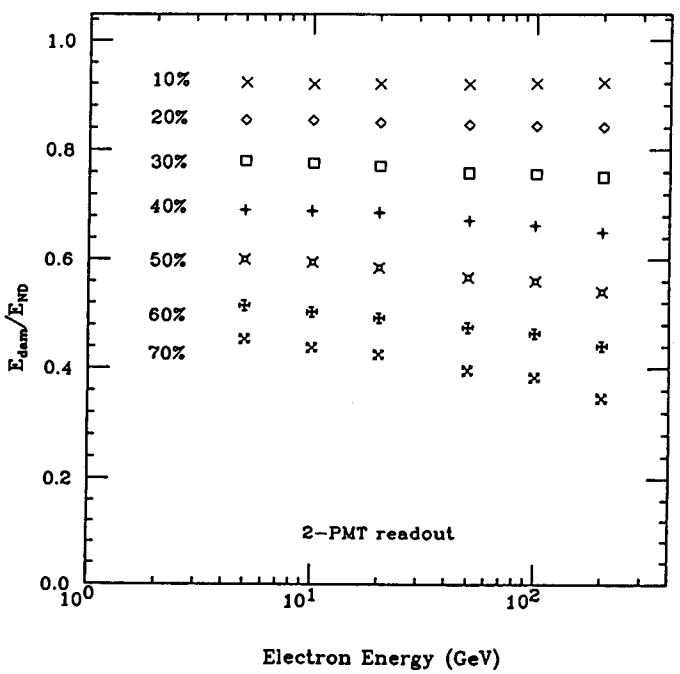

Fig. 8 Response linearity achievable with 2-PMT readout.

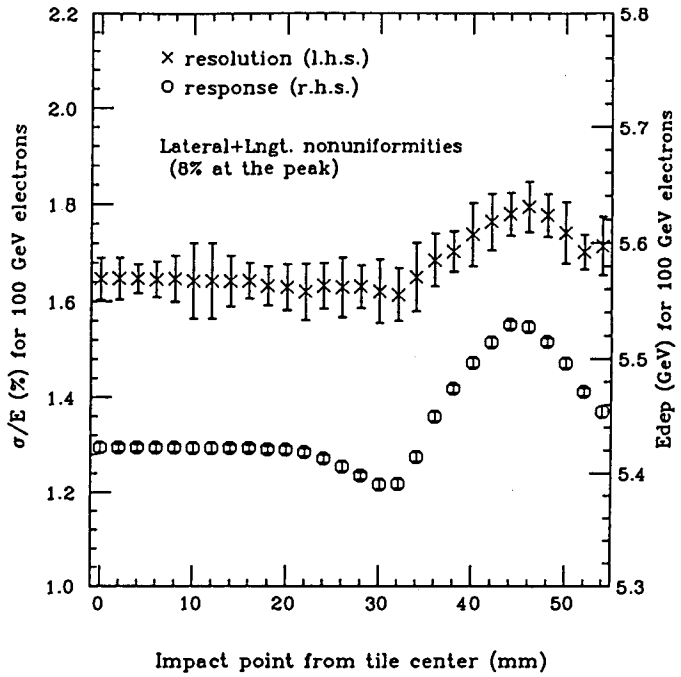

Fig. 9 Resolution degradation (l.h.s.) and response nonuniformity (r.h.s.) for SCSN81/Y7 combination at 5 Mrad. The longitudinal response at the tile center is assumed to be made equal by masking.

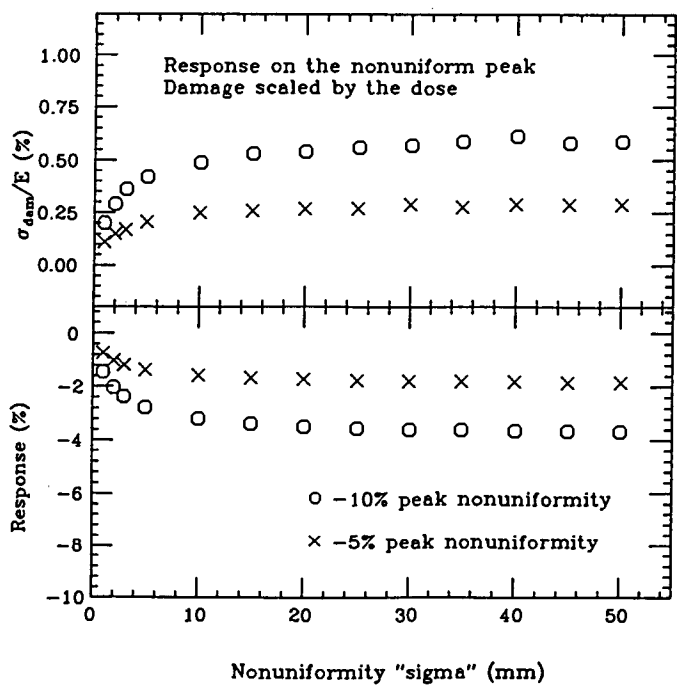

Fig. 10 Resolution degradation (top) and response nonuniformity (above) as a function of the width of the lateral nonuniformity. The magnitude of the nonuniformity is set to either 5% or 10%.