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Expected Performance of the CDF Plug Upgrade Calorimeter at TeV33

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ABSTRACT

We have evaluated the performance of the CDF plug tile/fiber calorimeter under the radiation environment at a luminosity of 1×10^{33} cm^{-2}s^{-1} at TeV33. The issues covered are the radiation damage, the anode current of photomultipliers, and the energy miss-measurement due to the minimum bias event pile-ups. The plug calorimeter is expected to perform as precision calorimetry in the pseudorapidity range up to ~2.3.

I. RADIATION LEVEL IN THE PLUG REGION

The CDF plug calorimeter is a sampling calorimeter based on the tile/fiber technique where the scintillating light emerging from the scintillating plates (tiles) is trapped by the wavelength shifting fibers embedded in the tiles and re-emitted light is extracted through clear fibers to photomultipliers (PMT's) located behind the calorimeter [1]. The CDF plug calorimeter covers a pseudorapidity η range from 1.1 to 3.5. Fig. 1 is a schematic drawing of the 15° tile/fiber unit consisting of 20 towers with the tower segmentation of approximately 0.1 in η. The ϕ segmentation is 15° for Towers 1–4 and 7.5° for Towers 5–20. The configuration of the preshower (PS) tile/fiber systems is similar to that of the EM calorimeter tile/fiber systems except that the tile thickness is 10 mm (the EM tiles are 4 mm thick) and the tile/fiber signals are readout individually with multi-channel phototubes (MCPMT's).

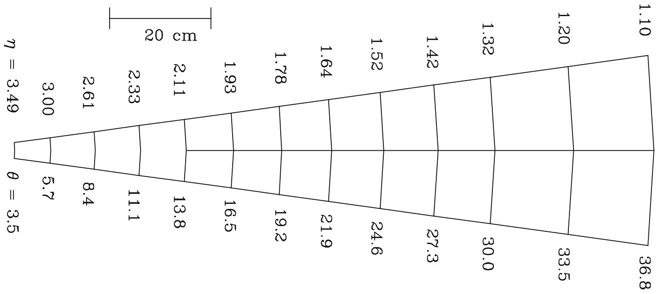

Figure 1: Tower segmentation of the 15° tile/fiber unit.

The radiation level in the plug calorimeter was evaluated using a GEANT simulation where the $P_{\rm T}$ spectrum and charged multiplicity measured by the CDF [2] were used. The results are summarized in Table I where the charged particle flux, the dose rate at the PS counter and that at the shower maximum (SM) detector are shown on a tower-by-tower basis. In the calculation we assumed that the charged particles are all π^+'s and neutrals are π^o's which are produced at half the rate of charged particles, and that the mean momentum given by $P = 0.46/\sin\theta$ (GeV/c) is substituted for the momentum spectrum of minimum bias (MB) events. The validity of this substitution was verified by comparing the distributions of the two cases. The dose evaluated here is consistent to 20% with that given in the PDG booklet.

For five years of running at 1×10^{33} cm^{-2}s^{-1}, the dose at the SM will be less than 500 krad for Towers 4 to 20 ($|\eta| < 2.33$). However, Tower 1/2/3 accumulates 7.4/2.5/1.0 Mrad, respectively. The dose at the PS counter is smaller than that at the SM by a factor of 2.5–1.5 depending on the tower number. The SM detector consists of two layers of 5 mm wide scintillator strips crossing at 45°. The strips are divided into two segments in η. The average dose in the same running period is 5 Mrad (180 krad) in the high (low) η strips which covers η from 2.6 to 3.5 (from 1.1 to 2.6).

Table I: Tower-by-tower charged particle flux N_{ch} and the dose rates at PS and SM. The luminosity is 1×10^{33}cm^{-2}s^{-1}. The dose rate is in krad/yr, where 1 yr is 1×10^7 sec.

tower	η range	N_{ch} [Hz]	$\langle P\rangle$(GeV)	$\dot{D}_{\rm PS}$	$\dot{D}_{\rm SM}$
1	3.49–3.00	5.01×10^6	5.93	581	1472
2	3.00–2.61	4.29×10^6	3.83	222	490
3	2.61–2.33	3.19×10^6	2.74	106	198
4	2.33–2.11	2.54×10^6	2.14	56	96
5, 6	2.11–1.93	1.04×10^6	1.77	32	53
7, 8	1.93–1.78	0.87×10^6	1.51	20	31
9, 10	1.78–1.64	0.81×10^6	1.31	13	20
11, 12	1.64–1.52	0.69×10^6	1.16	8	13
13, 14	1.52–1.42	0.57×10^6	1.05	6	9
15, 16	1.42–1.32	0.57×10^6	0.96	4	6
17, 18	1.32–1.20	0.67×10^6	0.88	3	4
19, 20	1.20–1.10	0.56×10^6	0.80	2	3

II. RADIATION DAMAGE OF THE PLUG CALORIMETER

The radiation damage of SCSN81/Y7 tile/fiber systems is reported elsewhere. [3] The light yield degradation induced by 2.5-GeV electrons is measured in the dose range from 4 krad to 5 Mrad as shown in Fig. 2. The data points can be fitted to a function:

$$R = 0.6365\exp(-0.1794D) + 0.3325\exp(-2.64D), \quad (1)$$

where R is the ratio of the tile/fiber light yield after to that before irradiation. The dose D is expressed in Mrad. Since the radiation hardness of SCSN38/Y11 and BC408/Y11 tile/fiber systems used in the EM calorimeter and in the PS, respectively, is roughly equal to that of SCSN81/Y7[4], the performance degradation was evaluated using this function. Using the GEANT simulation results for the longitudinal energy depositions and the light yield drop accounting for the radiation damage, we evaluated the response drop and the degradation of the energy resolution.

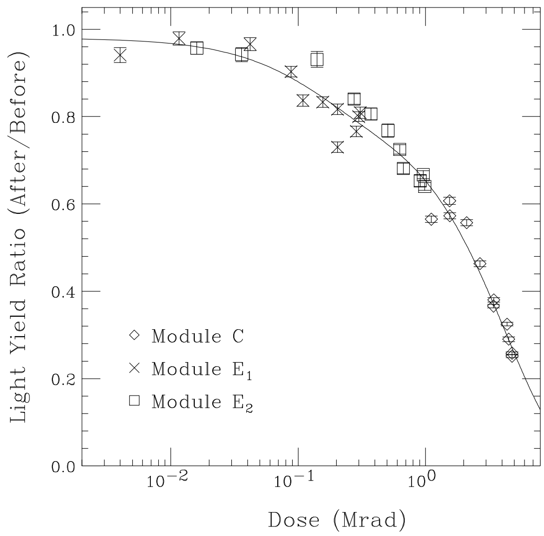

Figure 2: Light yield drop of tile/fiber systems as a function of the dose.

A. EM Response Drop and In-situ Calibration

Figure 3 shows the EM, PS, and SM response for 40 GeV electrons. The response normalized by that at no damage is plotted against the dose at the SM layer.

For five years of running, Towers 4–20 will receive less than 500 krad, and the EM calorimeter response will drop by $<30\%$. The response of Towers 1, 2, and 3 will drop by approximately 75%, 50% and 35%.

The EM energy has to be measured to a 1% precision and the calorimeter response has to be calibrated accordingly. Electrons from Z decay are useful for this energy scale calibration. In Table II we list the number of electrons per tower calculated using ISAJET, where one of the Z electrons is required to be central. By measuring the momentum of the central electron with the central tracker, the momentum of the plug electron can be derived from the Z mass without relying on the momentum measurement. Since the energy resolution is $\sim 2\%$ for electrons at $\sim$50 GeV $P_{\rm T}$, a sample of 10 electrons is enough to calibrate the energy scale to a 1% level. 10 electrons will be accumulated in any tower in 150 pb^{-1}, or 2 days at 1×10^{33} cm^{-2}s^{-1}. The energy resolution of tower 1/2/3 will degrade to 6.5%/3.5%/3.1% for 40 GeV electrons after five years of running, as described in the next section. Though, for example, the number of electrons necessary should be increased to $\sim$40 for Tower 1 after the damage, it can be still accumulated in 3 days. The above numbers do not account for the detector efficiency nor the electron quality cut efficiency. Taking these contributions into account, a dataset for calibration is reasonably available weekly. We could possibly merge the towers in the same ϕ to increase the statistics if required. Note that the response drop is a fraction of 1% per 10 krad as can be derived from Fig. 3 and that the number of electrons accumulated per 10 krad is larger than that accumulated per 100 pb^{-1} as shown in the table (except for Tower 1). Therefore such a weekly calibration is indeed in effect to calibrate the calorimeter response to a 1% precision.

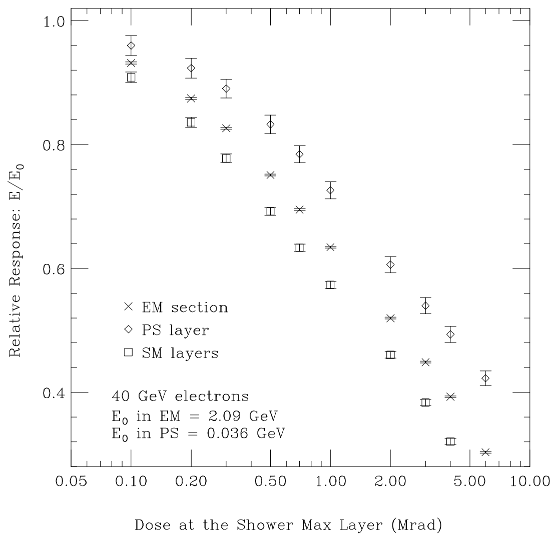

Figure 3: Degradation of the calorimeter response (crosses), PS response (diamonds) and SM response (squares) as a function of the dose at the SM layer.

Table II: Number of electrons from the Z decay (ISAJET) in the plug calorimeter. Shown are the (number of electrons per tower)$\times$(number of towers in the same plug) for 100 pb^{-1} and for accumulation of 10 krad at the SM detector.

tower	#e's/(100 pb^{-1})	#e's/(10 krad)
1	15×24	10×24
2	18×24	36×24
3	20×24	100×24
4	19×24	200×24
5, 6	10×48	190×48
7, 8	9×48	290×48
9, 10	9×48	440×48
11, 12	9×48	710×48
13, 14	7×48	>1000×48
15, 16	8×48	>1000×48
17, 18	10×48	>1000×48
19, 20	10×48	>1000×48

B. Energy Resolution Degradation

The radiation damage induced energy resolution degradation is defined as

$$\Delta = \sqrt{(\sigma_D/E_D)^2 - (\sigma_0/E_0)^2}, \quad (2)$$

where σ_0/E_0 and σ_D/E_D are the energy resolution at no damage and at dose D, respectively. The simulation results for 40 GeV electrons are plotted in Fig. 4. After five years of running, the EM resolution of Tower 1/2/3 will degrade by 6%/2.5%/2%, and vary from:

$$\sigma_0/E_0 = 2.5\% \rightarrow \sigma_D/E_D = 6.5\%/3.5\%/3.1\% \quad (3)$$

for 40 GeV electrons. For Towers 4–20, the energy resolution degradation Δ is less than 1.5% and will be negligible in most cases.

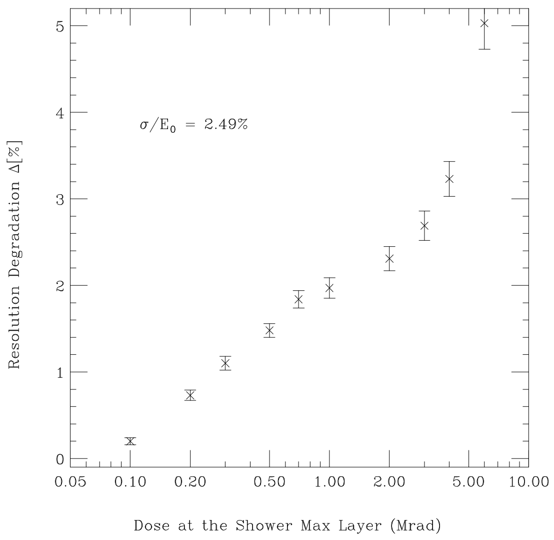

Figure 4: Radiation induced degradation of the energy resolution simulated for 40 GeV electrons.

Although only 40 GeV electrons were used for the performance study, we expect that both the response drop and the damage induced energy resolution degradation are weakly dependent on the energy, as demonstrated in Ref. [3]. The radiation damage is manageable for Towers 4 through 20 ($|\eta|$ <2.33), provided that the energy response is calibrated using electrons from Z's.

C. Hadron Calorimeter Performance

The hadron energy is determined from a linear sum of the HAC and EM energy deposits with a weight factor α:

$$\mathbf{Energy} = HAC + EM/\alpha. \quad (4)$$

Fig. 5 shows the energy resolutions for GEANT 100 GeV pions as a function of α. At no radiation damage, the minimum energy resolution 8.3% is given at α ~3.7 (we assumed that the response of the tile/fiber systems is equal in the calorimeter depth). Since the radiation damage of the EM part is larger than that of the HAC part, the factor α at the minimum energy resolution becomes smaller with the dose. The energy resolution will be 13.9% at 1 Mrad if α is kept at 3.7 throughout the experiment while it will be 10.1% if α is set at the energy resolution optimum. The induced resolution degradation Δ is 11.1 GeV and 5.8 GeV for 100 GeV π's, respectively.

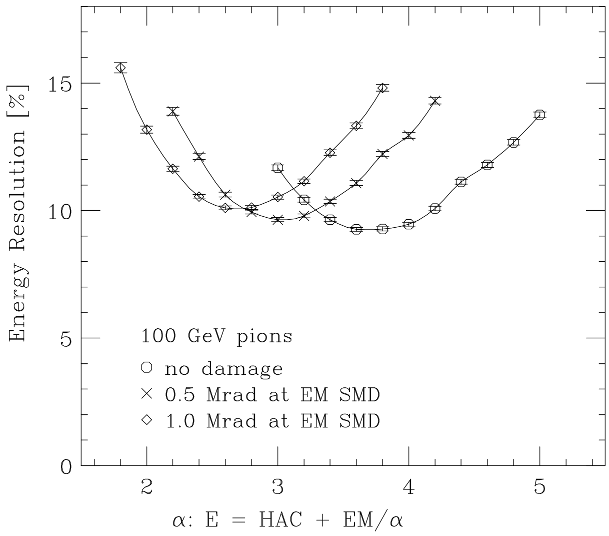

Figure 5: Energy resolution of 100 GeV π's as a function of the EM weight factor α. The data are shown for the doses of 0, 0.5 Mrad and 1 Mrad at the EM shower maximum detector.

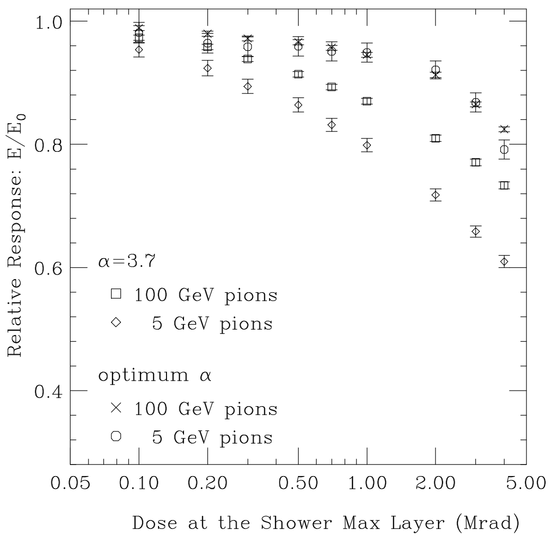

Figure 6: Normalized response for 100 GeV and 5 GeV π's as a function of the dose at the shower maximum detector. The response was calculated using constant α or α that minimizes the resolution for 100 GeV π's.

Fig. 6 shows the calorimeter response for 100 GeV and 5 GeV

π's as a function of the dose at the shower maximum detector. The response is normalized at no damage. The plots are given for two sets of the EM weight factor, $\alpha = 3.7$, and α that minimizes the energy resolution for 100 GeV π's. We note that the response drop at 1 Mrad is 13% (20%) for 100 GeV (5 GeV) π's if the constant α is used. The drops are smaller (5% at 1 Mrad) and the energy dependence is weak if the response is calculated using the resolution optimizing α. Since the response drop is moderate, it should not be hard to correct for the response drop.

III. PMT ANODE CURRENT

Since the particle flux is high, the PMT gain has to be kept as small as possible while maintaining the sensitivity to minimum ionizing particles (mips). At a PMT gain of $\sim 1 \times 10^4$, the mip charge per tile is 10 fC for a light yield of 6 photoelectrons/mip/tile measured for EM tile/fiber systems. The muon charge is then visible at 220 fC, which should be compared with the typical noise charge 40 fC of the present readout electronics of the CDF calorimeter. A guideline in determination of the PS MCPMT gain is to separate 1 mip signals from the pedestals. Since the light yield of the PS tile/fiber is 10 photoelectrons/mip/tile, the PS MCPMT gain should be $\sim 1.3 \times 10^5$ to have a mip charge of ~200 fC.

The evaluation of the PMT anode current due to MB events can be done similarly to the dose rate evaluation described in Section I. The results are summarized in Table III for the two PMT gains described above.

Table III: Average anode current expected at 1×10^{33} cm^{-2}s^{-1}.

tower	EM at G = 1×10^4 with 6 PE's/mip	PS at G = 1×10^5 with 10 PE's/mip
1	9.26 μA	7.4 μA
2	5.12 μA	5.6 μA
3	2.72 μA	3.6 μA
4	1.70 μA	2.5 μA
5, 6	0.58 μA	0.9 μA
7, 8	0.40 μA	0.7 μA
9, 10	0.34 μA	0.5 μA
11, 12	0.26 μA	0.4 μA
13, 14	0.18 μA	0.3 μA
15, 16	0.18 μA	0.3 μA
17, 18	0.18 μA	0.3 μA
19, 20	0.14 μA	0.2 μA

The EM calorimeter PMT current will be less than 2 μA for Towers 4–20, but it is nearly 10 μA for Tower 1. The lifetime of Hamamatsu R4125, the PMT's for RUN II, is guaranteed to be larger than 100 Coulomb photocathode charge, which corresponds to 3 calendar years at 1 μA anode current. Note that the gain setting of EM PMT's is 5×10^4 for RUN II.

The signals of the PS are read out with 16-ch MCPMT's. The current sum over Towers 5–20 is 9 μA. Assuming that Towers 1–4 and those in another module at the neighbor are read out with the same MCPMT, the current sum will be ~40 μA.

For the SM detector, the anode current at a gain of 1×10^5 (RUN II setting) will be 0.28 (1.1) μA per low (high) η strip, and the sum over 16 channels per MCPMT will be 5 (18) μA for low (high) η strips.

Since such anode currents are larger than the level manufacturers recommend, typically 1 μA for long term operation, it is essential to establish the long term stability of both PMT's and MCPMT's. Depending on the results, we may have to reduce the gain of the (MC)PMT's at high η, which reduces the sensitivity to mip signals.

IV. ENERGY MEASUREMENT UNDER MINIMUM BIAS EVENT PILE-UPS

At TeV33, the number of minimum bias (MB) events per crossing is anticipated to be 10 on the average. ISAJET event generator was used to evaluate the energy miss-measurement due to MB event pile-ups. The number of events per crossing was picked up according to a Poisson probability with the mean of 10, and the vertex positions of these events were distributed along the beam line as measured by the CDF. The energy of EM particles was smeared with $16\%/\sqrt{E}$. The energy of other particles was smeared with $60\%/\sqrt{E}$ and then the EM energy fraction was evaluated from a EM/HAD ratio distribution obtained using a GEANT simulation. The transverse energy sum in the EM part was histogramed as a function of the cluster size. The mean and rms spread of the distributions are plotted in Fig. 7. The clustering assumed here is a rectangular summation of neighboring tower energies, and the cluster size refers to the side length of the rectangle ($\Delta\eta = \Delta\phi$). Typically 3×3 tower summation corresponds to the cluster size of 0.3. The mean shift of the transverse energy is 0.3 GeV and its rms spread is 0.42 GeV at the cluster size of 0.3. The η dependence of these numbers is weak in the η range from 1 to 2.2, as expected from constant multiplicity density $dN/d\eta$. In measuring electrons with transverse energy of 10 GeV, the mean shift of 0.3 GeV corresponds to 3% of the transverse energy, which can not be ignored in view of the nonlinearity. This shift is also dependent on the luminosity. On the other hand, the rms spread of ~0.4 GeV hardly degrades the performance, since the energy resolution for $E_{\rm T}$= 10 GeV electrons expected from $16\%/\sqrt{E}$ is 0.78 GeV at η=1.0 and 1.57 GeV at η=1.8: The effect is larger at lower η and the energy resolution will be 0.89 GeV at η=1.0.

V. INFLUENCE OF RADIATION DAMAGE ON MISSING ENERGY MEASUREMENT

As we discussed in Section II.B, the response of the hadron calorimeter will drop due to radiation, the amount of drop depending on the EM weight factor α. We assume here that the response drop is not corrected at all and evaluated the influence of the response drop on missing energy measurement.

In Fig. 8a we plot the distribution of the transverse energy of ISAJET MB events. As in the previous section, 10 MB interactions on the average are overlaid. Particles in $\eta < 3.5$ are used in the calculation of the transverse energy but no other de-

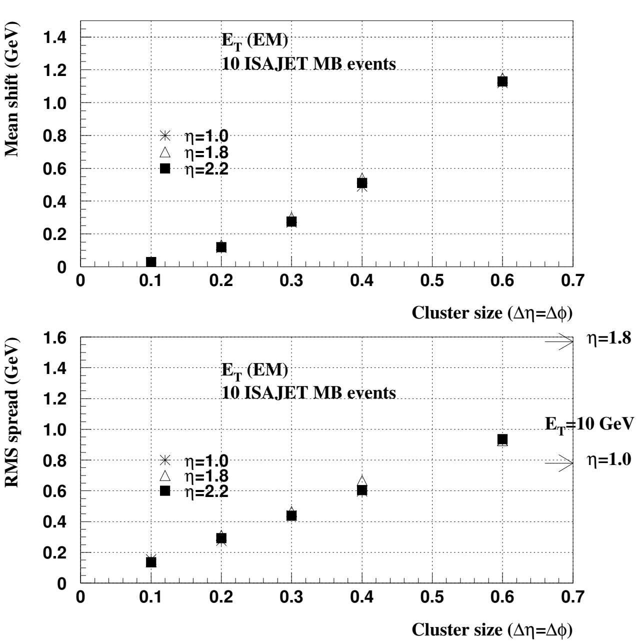

Figure 7: Effects of 10 MB event pile-ups in energy measurement. (top) Mean shift and (above) rms spread of the transverse energy as a function of the cluster size.

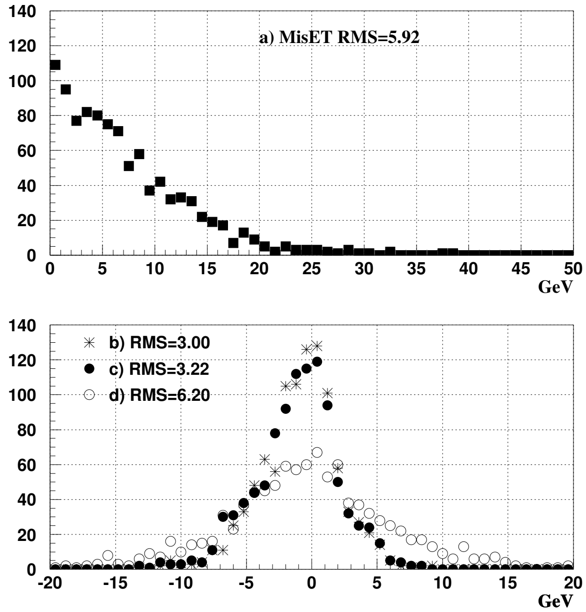

Figure 8: a) Missing transverse energy distribution in GeV for MB events (10 interactions on the average). No detector effect is included except that particles in $\eta < 3.5$ are summed. b–d) Differences of the transverse energy measurement from a) if the response drop is not corrected: b) the response calculated using the resolution minimizing α, c) the response calculated using the constant α, and d) same as c) but particles in $\eta > 2.6$ are excluded from the missing energy measurement.

tector effects (response drop and energy smearing) are considered. The transverse energy sum extends to $\sim$12 GeV (63% of the events are included in this region). If the response drop is not corrected the transverse energy is mis-measured with an rms spread of about 3 GeV as shown in Figs. 8b and c for the two sets of the EM weight factor α. In the above calculation, we assumed an integrated luminosity of 50 fb^{-1}. In the case where Towers 1 and 2 are excluded from the sum, the spread will be 6.2 GeV as shown in Fig. 8d. Since these spreads are small compared to the intrinsic spread of Fig. 8a, the missing energy measurement is barely degraded.

VI. SUMMARY

We have evaluated the performance of the CDF plug tile/fiber calorimeter under the radiation environment at a luminosity of 1×10^{33} cm^{-2}s^{-1}. The results are summarized as follows:

- For five years of running (50 fb^{-1}), the plug calorimeter will perform precision energy measurement up to $|\eta|$=2.3 (Towers 4–20), provided that the energy scale is calibrated using electrons from Z's. For Towers 1–3 the energy response will drop by 75%–35% and the EM energy resolution will degrade by 6%–2% for 40 GeV electrons.
- The hadronic response drop of Tower 3 will be 12–20% for 100–5 GeV π's. The response drop and the energy resolution degradation are made substantially smaller by adjusting the EM weight factor.
- The current in the Tower 4 PMT will be $\sim$2 μA. The current in MCPMT's used for the Preshower and the Shower Max Detector will become 20–40 μA at higher η. We need to understand the performance and lifetime of both PMT's and MCPMT's at such high anode current.
- Pile-ups of 10 MB events will cause a pulse height shift of $\sim$0.3 GeV for 3 $\times$ 3 clustering of the EM towers. It is essential to measure the pedestals as a function of luminosity to correct for the shift. The energy resolution broadening is about 0.4 GeV in E_{T} and small compared to the stochastic contribution.
- The missing transverse energy measurement is hardly degraded due to the radiation damage.

VII. REFERENCES

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[3] F. Funaki et al., NIM A317 (1992) 123.

[4] K. Hara et al., SDC note 93-526. The difference between SCSN38 and SCSN81 is small in the dose range smaller than 1 Mrad.