IV. EMC Calibration Systems Design

IV.1 Overview of Calibration

The physics requirements of calibration and the practical implementation are described here. The Calibration and monitoring systems and methods for the EMC towers are generally a superset of those for pre-shower and shower maximum detector (SMD). The main goal of EMC calibration is to establish the energy scale of each tower. However, a full calibration using physics events in STAR may occur on time scales which are long compared to a physics run. It is therefore important to monitor the stability of the entire optical system chain including phototubes on shorter time scales. For example, a scan of the towers with radioactive sources may occur only a few times per year. This method calibrates the overall system, scintillator, fiber, and phototube. The light diodes which will feed into the cookies on the phototubes via fibers can monitor the phototubes alone for each run. This independence is useful, because the light output of the scintillator is expected to increase by about 5% when the magnetic field is on, the light transmission through fibers could change, etc. This can be monitored by comparing the LED and source calibrations.

There are several aspects to calorimeter calibration. One is knowing the absolute energy scale. Another is knowing the relative scale of all the towers (and relative scale of depths of towers). Another is setting the scale of all the towers for the trigger. Another is following the time variation of each tower, where phototubes, fibers, and scintillators all drift in time.

We can ask how big a constant term in the resolution we can tolerate, and what tower to tower calibration accuracy is needed to achieve this. The tile to tile response will affect the constant term in the resolution and could affect the energy linearity if there were systematic differences from front to back in the tower. In STAR the highest expected energy in a single tower is about 50 GeV. With $16\%/\sqrt{E}$ resolution the stochastic term will be 2.25%. We would not be able to distinguish a 1.5% constant term. Also, in high-p_t heavy ion physics, for moderate energy signals there is an effective broadening of the resolution due to energy deposition by the high multiplicity of low energy particles. Within towers of 0.05 by 0.05 this effect is small (~ 200 MeV), but is quite significant for summed towers.

Another restrictive requirement for the absolute EMC calibration in STAR arises from the measurement of differential cross sections that fall steeply with p_p. Fits to the SPS data[1] for inclusive direct-γ and π^o spectra at p_t > 10 GeV/c give the dependence of $d\sigma/dp_t \propto p_t^{-(5-5.5)}$. To measure these kind differential cross sections with systematic errors of no more than ~10 %, the EMC absolute scale in the region of interest has to be known at the accuracy of better than ~2%.

The issue of the relative response of the scintillator layers in a sampling calorimeter can be largely separated from the above issues. It can be dealt with by quality control measurements during construction and the relative gain of the photomultipliers.

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[1] C. Albajar, et al (UA1), Phys. Lett. **B209** (1988) 385; J. A. Appel, et al (UA2), Phys. Lett. **B176** (1986) 239.

The calibration of the shower maximum detector poses different issues. We must find the absolute calibration in known conditions, and then monitor the gas gain with temperature and atmospheric pressure and high voltage variations. We will calibrate the electronics separately. The gas gain must be normalized to electron showers of known energy in the calorimeter with known gas mixture, high voltage, pressure, temperature and magnetic field.

The following techniques have been found to be effective and cost-effective in similar calorimeters in other experiments. We will use them in STAR EMC:

1) Calibration of a sample of modules in a test beam.
2) Cosmic ray testing and calibration at the time of construction.
3) Penetrating charged particles close to minimum ionizing.
4) LED light flashers (green) for the phototubes.
5) Radioactive sources near shower max depth.
6) Conversion electrons
7) 2 body decays
8) Electronics / Charge injection

For the pre-shower, the objectives of calibration are to establish a scale in minimum ionizing particles (mips), to understand this scale relative to EMC energy, and to calibrate the channel-to-channel gain variations in the multi-anode PMTs. Much of this is done with bench measurements of the PMTs, and the rest with test beam, cosmic rays, mips, and conversion electrons as in the EMC.

For SMD, the objectives are to establish the energy scale relative the EMC towers, to establish a scale at particular values of atmospheric pressure, HV, etc so that gain can be tracked; and to calibrate the channel to channel variation of the 30k channels caused by different strip to wire capacitances and different transmission lines. Clean cosmic ray signals require that the HV (and gain) be increased, so this is not completely adequate for the absolute scale, but will provide the channel to channel gain variation measurement. The EMC methods of test beam, conversion electrons, and two body decays provide the rest of the calibration.

For the EMC level 0, there are a couple of calibration issues. The trigger signals from the PMT channels come from separate 6 bit ADCs and 4 bit ADCs. The analog pedestal of the gated integrator should be small compared to a least bit from these. However, the 6 bit signals are added 16 at a time on the PMT card with analog combination. 300 of these signals are added digitally. Ultimately, 4800 PMT integrator pedestals are involved, so we have a pedestal for ET of 4800 times the individual PMT pedestal. Even if every pedestal is below 1 bit at the point where 16 signals are digitized to 6 bits, the amplitudes that get digitized are shifted by the sum of analog integrator pedestals. Furthermore, the individual PMT pedestals may vary from channel to channel.

Another issue is to establish the absolute scale of the trigger signals. The details of this can be measured in data by setting a threshold, and reading out the data to see what energy it corresponds to. However, the electronics must be built so that the appropriate physics scales are covered with the few bits available.

IV.2 Some General Features of this Approach

In the long run the absolute calibration comes from physics events such as J/ψ. However, a rather long time (on the order of a year) is needed to obtain statistics and do the required analysis. Electrons are used to tie the EMC calibration of each tower to measurements of magnetic field and track curvature. An abundant source of electrons is from conversions of gammas from π^o's in the beam pipe and the SVT. This material constitutes about 5% of a radiation length. The resolution of the calorimeter and the tracking are comparable at about 15 GeV if the vertex is used in fitting the track. The means can be found well if a number of events are used, in any case.

It is very useful to cross-calibrate test beam data, cosmic ray response, radioactive source response, and LED response on a few calorimeter modules. This method allows reasonable absolute initial calibration of similar modules with cosmic rays and/or radioactive sources. The initial calibration of all the calorimeter would come from this approach.

The effect of the magnetic field on the scintillator can be measured and tracked if we have one system to inject light into the scintillator, the radioactive source, and another system to inject green light into the phototube, the LED's. The magnetic field may increase the light output of the scintillator by about 5%.

A system of green LED's can provide a crude (10%) calibration of the number of photoelectrons due to the narrow spread in pulse height compared to photostatistics. This system is good for debugging the electronics chain. It is also useful for creating events in adjacent RF buckets to look for pileup effects. The tube-to tube variation of light is typically large, so that this is not a good means to do absolute calibration unless it is tied to the test beam in an individual module.

IV.3 Analysis of Needs and Practical Implementation

It is helpful in analyzing the requirements to break the requirements up into 3 time periods or situations:

I) Ultimate use in STAR

II) Early days of EMC and when Modules are added

III) Test beam run before day 1

Ultimately we need the calibration of the EMC both globally and for individual towers over the full energy range. There are reasons for this in various physics regimes.

For identifying electrons and reducing background, we use the relative calibration of EMC and TPC to make E/p cuts. This is needed from 1.5 GeV for J/ψ to 50 GeV for W or Z. Any relative error in the calibration at a particular energy or as a function of energy will reduce the effectiveness of this cut and/or reject good electrons.

For combining thousands of small energy contributions from the towers to make a Global measurement in Au-Au collisions, we need to know the scale of each contribution to understand the scale of the sum.

For reconstructing asymmetric decays of π^o which are a background to direct gammas. The relative calibration of low and high energy scales determines the mass resolution (along with the angles) which has a big contribution to the background level.

A relative mis-calibration of nearby towers contributes to a constant term in the overall resolution, which leads to bigger backgrounds because cuts have to be looser.

Realistically, we can determine the scale of each tower in the detector in a couple of energy regions using physics processes in RHIC, and also measure the underlying non-linearities on some average basis by test beam measurements and bench-top tests of phototube linearity.

We know the energy resolution as a function of energy, and aside from cases where we combine energy from large numbers of towers, there is no point (and no method) in trying to calibrate very much beyond the level of the resolution. The resolution of delta E/E = 16%/root(E) gives 30% at 280 MeV which is where minimum ionizing, penetrating particles appear, 3% at about 30 GeV, which is the limit of direct photon sensitivity in the barrel, and 2% at 60 GeV which is the highest single tower energy expected in our physics at RHIC. Furthermore, the TPC resolution gets worse with momentum, about 12% at 50 GeV/c, so that we do not need anything like 2% resolution of the EMC in the E/p cut.

As explained later, we do have a large sample of events in the equivalent of 280 MeV region from mips, so that the calibration there will be significantly better than the resolution, just where it would be needed for combining many towers with relatively small signals.

One issue in this particular case is that mips deposit energy uniformly in depth, while low energy photons deposit energy toward the front of the calorimeter.

In actually calibrating for electromagnetic showers, we must take into account that in most cases there is significant energy sharing among adjacent towers. The sharpness of the trigger threshold and therefore the number of background events leaking into the trigger depends on the overall resolution, including the tower to tower variation.

Different parts of the EMC system may have different time scales for changes in calibration. Thermal effects changing gain through HV changes or changes to phototubes may occur over hours. Decay of optical components may occur over years. Voltages on ADC cards may change as new modules are added over months. The magnet temperature may change both over 1/2 day and over months.

Calibrations relevant to Phototube gain drift will be done on the time scales at which gains can drift. Calibrations relevant to other changes shall be done on timescales relevant to these changes. Calibrations done during a run shall be written to the data tape for that run.

1) LED signals (with temperature corrections to the LEDs done offline) can be measured hourly.

2) Measurements with minimum-ionizing signals can be done run by run more than once a day.

3) Measurements with two-body decays can be done over months.

4) Measurements with radioactive sources can be done over months and years.

IV.4 Calibration Systems and Methods:

IV.4.1 Test Beam

For the first Module, the test beam will provide absolute calibration of towers within 3% at 280 MeV and at 8 GeV without relying on other STAR detectors. This can later be transferred to other EMC modules when they are understood and when software exists to utilize them for EMC.

EMC needs a calibration adequate to do early physics before there is time to accumulate and digest data which relies on other detectors. Even if some types of calibration by minimum ionizing tracks can be done quickly without tracking, this does not cover the entire energy scale.

High voltages must be set relatively accurately (~0.3% in V for 3% in signal) when a module is installed if it is to be used in any kind of trigger.

Calibration is be done in the test beam, and then carried to other modules with Sources and Cosmic rays and minimum ionizing particle signals in order to establish absolute scale. The scale of the individual module calibrated in the test beam can also be carried by LED.

The test beam can establish the correlation between SMD and EMC signals vs. energy and establish that both tower and SMD maximum signals are within the range of the electronics (both high and low end).

IV.4.3 Penetrating Charged Particles (mip)

Extensive GEANT simulations have been done on calibrating by means of penetrating charged particles which are approximately minimum ionizing. This method has been used by other experiments to find the relative calibrations of a ring of EMC towers at constant eta. Our simulations indicate that it will work over a range in eta, with sin(theta) corrections, and also that mips in the test beam give the same signal as pions from AuAu collisions (with magnetic momentum cut over about 1 GeV) within about 1%.

Studies have been made of implementing this in stages of increasing complexity. The first stage can be done with no TPC tracking and the magnetic field off, so that all tracks go straight into the EMC. Second, with the magnetic field on, without momentum and angle cuts using tracking, the high side of the pulse height distribution will still correspond to the test beam distributions. The lower side is not usable because the lowest momentum tracks (over about 150 MeV/c) hit the EMC at an angle and do hot hit all the tiles in one tower. Third, the method is most applicable when TPC tracking is used both to put about a 1 GeV/c momentum cutoff, and to select tracks that penetrate all the way through EMC towers.

IV.4.4 LED

A system of green LED's can provide a crude (10%) calibration of the number of photoelectrons, due to the narrow spread in pulse height compared to photostatistics. It is also extremely useful for debugging the electronics chain. It is also useful for creating events in adjacent RF buckets to look for pileup effects. The tube-to tube variation of light is typically large, so that this is not a good means to do absolute calibration except for carrying the calibration of the one test beam module.

An LED box with 15 LEDs , each driving 7 fibers, will be mounted in each PMT box. This will provide signals to the 80 PMT tubes and 5 pre-shower tubes, with cross correlations to be used in case an LED fails. LED signals (with temperature corrections to the LEDs done offline) can be measured hourly.

To take an LED event, EMC must request a calibration trigger from STAR, and then flash the appropriate LED in synch with the event that the trigger issues to EMC.

This will depend upon the STAR trigger issuing a calibration trigger a fixed number of rhic clocks after the request is made or else sending some kind of pre-trigger signal.

The LED signal will be at about 3 GeV in each phototube (within a factor of 2). This is near the crossover point for the dual slope ADCs. There is a mechanism through slow controls to force the ADC to utilize one slope or the other, so that EMC response with both slopes can be calibrated with one LED amplitude.

IV.4.5 Source

The distribution of energy in the layers of scintillator in a lead/scintillator sampling calorimeter can be crudely approximated by the energy distributed by a radioactive source near the shower maximum for EM showers. This method makes the source particularly useful for calibration in that the weighting given to each layer resembles the weighting it has in measuring physical events. This approach is used in the CDF detector as the best long-term calibration.

The individual strengths of a few (1 to 8) radioactive sources can be measured adequately, to a percent or two, with simple means. This measurement allows absolute calibration of all modules when only a few have been calibrated in a test beam. A calibrated detector at a calibrated distance is needed. The metal containers of the sources are similar so that the ratio of numbers of electrons to gammas or the ratios of numbers of gammas of different energies is not significantly affected.

The front end electronics, FEE, for the photomultipliers has a separate slow integrator on each channel for integrating the current from the calibration sources.

Error in the source calibration may come from:

- the dark current in the phototubes. We expect roughly 100 na from the source and roughly 2 na from the dark current, with some tubes having more dark current. (We have measured a factor of 4 increase in dark current in raising the phototube temperature from 23 deg C to 33 deg C.)
- variations in the time constant of the integrators from channel to channel, due to capacitor variations.
- the range of gammas from ^{60}Co has tails larger than a tower size. The peak seen will depend slightly on the width of the tower. We can both sum and compare adjacent towers to control this effect.
- position of the source in the source tube with respect to the scintillator and lead changes the solid angle and intermediate absorber slightly. We use a small source and a small tube to minimize this effect ($\leq$ 1 mm diameter).

Estimate of Source Strength for STAR EMC Calibration

^{60}Co has two gammas per decay, one about 1.17 MeV and one about 1.33 MeV. The absorption length in grams/cm^2 for Pb and scintillator are both about 10 at about 1 MeV. This means we can calculate the energy deposition just from the mass. Also, it gives about 1/2 of the gammas absorbed per Pb-Scint pair. So the attenuation goes like 1/2, 1/4, 1/8, 1/16 in calorimeter layers.

A minimum ionizing particle puts about 2 MeV/cm in scintillator. Our scintillator is about 1/2 cm, so we have a scale of 2 photoelectrons per 1 MeV.

- 1 milli Ci is 3.7×10^7 decays / second.

- I assume PMT gain of 2×10^5.
- The fraction of energy in scintillator vs total is mass(scint)/mass(Pb + scint) = .083
- We then get for 1 mCi $3.7 \times 10^7 * 4*10^5$ electrons * .083 x 2 = 4×10^{-7} Amp out of the phototube.

If the maximum dark current is 10 na, then this is 40 times the dark current. If dark currents varied from tube to tube from 0 to 10 na, and we could not do a subtraction, then there would be 2.5 % errors (+- 1.25 % if all dark currents were really < 10 na) on the measurement. Actually, we can run the system so that we do some background subtraction .

The half life of ^{60}Co is 5.7 years, so to have some signal in 6 years we need to multiply this by about 3.

There are slight complications to this picture because the source illuminates one layer of scintillator without any lead in front of it and shower max materials may have a small effect.

Calculations of noise as well as comparison to experience in other experiments indicate that the PMT card slow integrators must integrate for a fixed time which is more than 10 ms but less than 100 ms.

Assume the source is in continuous motion, and that we want 100 points measured within a tower. Then with 100 ms integration time, the time to cross a tile would be 10 seconds. If we try to do all 4800 towers with 1 source driver, it would take over 13 hours, not including setup time. We expect to ultimately use 8 source systems, and we expect that the measurement time will be dominated by setup time for the sources, data acquisition programs, file handling, etc.

The source drivers mount on the outside of the STAR magnet, outside of the phototube boxes. The drivers can be dismounted and moved so that fewer are required, and also for radiation safety reasons.

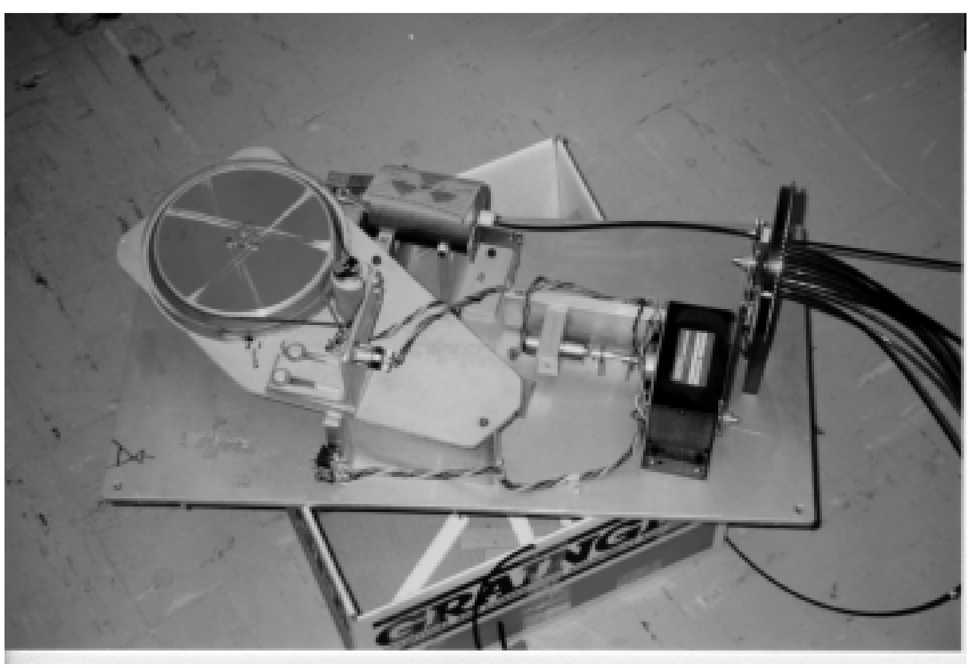

Fig. 1: photograph of reel of operating Gatling gun here from ANL

Approximate cost for Source system for EMC

8 gattling guns (from Purdue, or copy	@ 15 k each =	120k
2 PCs with interfaces for controls	$5k * 2 =	10k
programming labor 1 month		12k
tubing in module	$20 ea * 240 =	4.8k
machine shop for tubing	$1 each =	0.3k
G-10 plate in module $200 ea (with machining)		24. k
assembly labor		
tube and G-10 1 hour/module	$45 * 120 =	5.4k
		176.5k

IV.4.6 Conversion Electrons

Electrons are used to tie the EMC calibration of each tower to measurements of magnetic field and track curvature. An abundant source of electrons is conversions of gammas from _^{o}'s in the beam pipe and the SVT. This material constitutes about 5% of a radiation length. The resolution of the calorimeter and the tracking are comparable at about 15 GeV if the vertex is used in fitting the track. The means can be found well if a number of events are used, in any case.

When using electrons from either physics at the vertex or conversions of gammas, we depend on the TPC plus Magnet plus vertex calibrations to do our energy calibration. This will probably improve as a function experience in STAR.

TPC resolution is worse at high energy. Most of the TPC momentum resolution comes from knowing where the vertex is or where the beam is with respect to the TPC very well. We need cross checks that we get the same result with both polarities of the magnetic field.

Calibration in 1 to 2 GeV region must be good enough to make the J/psi to 2 electron peak sharp to reduce background. This is mainly relative tower to tower. Calibration over a broad scale of energies must be good enough so that tails on resolution do not affect background to gammas from lower energy feed-up. Resolution for jets has a component from tower-to-tower calibration, and a smaller contribution from linearity calibration.

We can also use conversion electrons to set the relative scale between calorimeter and shower max. and between calorimeter and Pre-shower.

IV.4.7 Two Body Decays

Very good calibrations of both the EMC and tracking detectors can be done with $e^+ e^-$ decays of particles of definite mass such as J/ψ and Z^o. The EMC can also be calibrated with 2 photon decays such as π^o or η. The energy range for these 2 photon calibrations is restricted to be low enough that the spatial separation measurement can be made with the precision of the desired energy measurement.

IV.4.8 Electronics and Charge Injection

Electronics cards for PMT, SMD , pre-Shower., and trigger shall be calibrated electronically, independent of the detector, so that they are interchangeable. If the pedestals and gains and linearities are not sufficiently uniform on all cards, then a record will be kept that travels with each card. We want to make it easy to exchange cards because we do not want to lose calibration for large numbers of EMC channels when part of one card with many channels fails.

Different cards will be used in both the test beam and cosmic ray calibration set-ups than in the calorimeter in place, so the scales must be measured and documented.

Some aspects of electronic calibration are:

1) Charge injection on PMT cards.
2) Voltage signal on SMD cards, and either sufficient uniformity of preamplifiers or charge injection of preamplifiers.
3) downloading of pedestals and gains to the data collector, level 3, and offline. (pedestals and gains include both slopes and both pedestals of dual slope ADCs)

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IV.5 EMC calibration data sets:

We define the EMC calibration data sets for use in the STAR data stream and storage. Simple ASCII files of numbers for the following are sufficient. We should include text headers and comments inside these files. Note that most ADC's are dual-slope and require 2 pedestals and 2 slopes. This is to get 14 bit dynamic range from 2 x 10-bit ADCs for PMT and 10 bit dynamic range compressed into 8 bits for SMD. Note also that there may be multiple historical versions of the data sets to be saved for cross checking, to see how the system changes in time. There is extensive documentation in STAR concerning the readin times required for EMC calibration, and the amount of computer analysis required.

INPUT CALIBRATION DATA SETS	APPLICATION CALIBRATION DATA SETS
PMT	PMT data collector ped. sub.
--------------------------------------	Trig LVL 0 pedestals and gain
cosmic ray	SMD data collector ped. sub.
(2 gain + 2 ped) * (4800 + 720)	
source	PMT ped, gain LVL 3
(1gain+1ped+1dark-c.) *(+)	
(multiple sets)	
LED	SMD ped, gain LVL 3
(2 gain + 2 ped) * (4800 + 720)	
(multiple sets)	
pion/muon no TPC	PMT offline
(2 gain + 2 ped) * (4800 + 720)	
(multiple sets)	
pion/muon with TPC	SMD offline
(2 gain + 2 ped) * (4800 + 720)	
(multiple sets)	
charge injection - card	PRE-SHR LVL 3

(2 gain + 2 ped) * (4800 + 720)	
test beam	PRE-SHR offline
(2 gain + 2 ped) * (4800 + 720)	
pi-0 recon mass	Pre-SHR collector ped. sub.
(2 gain + 2 ped) * (4800 + 720)	
eta recon mass	
(2 gain + 2 ped) * (4800 + 720)	
J/psi-recon mass	
(2 gain + 2 ped) * (4800 + 720)	
electron mom in TPC	
(2 gain + 2 ped) * (4800 + 720)	
SMD	
---------------------------------------	
charge injection-card	
(2 gain +2 ped)*(30k + 10k)	
test beam	
(2 gain +2 ped)*(30k + 10k)	
pre-amp bench calib	
(2 gain)*(30k + 10k)	
capacitances?	
pi-0 recon mass	
(2 gain + 2 ped) * (30k + 10k)	
eta recon mass	
(2 gain + 2 ped) * (30k + 10k)	
J/psi-recon mass	
(2 gain + 2 ped) * (30k + 10k)	
electron mom in TPC	
(2 gain + 2 ped) * (30k + 10k)	
PRE-SHOWER	
-------------------------------------	
cosmic	
(1 gain + 1 ped)*(4800+720)	
led	
(1 gain + 1 ped)*(4800+720)	
pion/muon no TPC	
(1 gain + 1 ped)*(4800+720)	
pion/muon with TPC	
(1 gain + 1 ped)*(4800+720)	
charge injection-card	
(1 gain + 1 ped)*(4800+720)	
test beam	
(1 gain + 1 ped)*(4800+720)	
pi-0 recon mass (in EMC twr)	

(1 gain + 1 ped) * (4800 + 720) |
eta recon mass (in EMC twr.) |
(1 gain + 1 ped) * (4800 + 720) |
J/psi-recon mass (in EMC twr.) |
(1 gain + 1 ped) * (4800 + 720) |
electron mom in TPC |
(1 gain + 1 ped) * (4800 + 720) |

|
OLD Application Data Sets |
to be adjusted |
-------------------------------------- |
3 sets (PMT,SMD,PRE) |
each in 3 formats |