IceCube
HAMAMATSU 10 inch PMT Calibration

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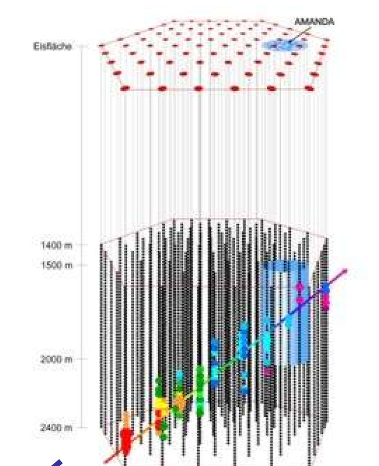


Introduction

IceCube is the high energy cosmic neutrino detector with 4800 PMTs(Photo Multiplier Tube) using the ice on the surface of the South Pole. The huge glacial ice at the South Pole is the cleanest and the most transparent naturally occuring substance. And its stronger scattering and weaker absorption make it a better calorimeter than water. Therefore, the IceCube detector can be an ideal high energy neutrino telescope on the earth with PMTs which detect the Cherenkov light from neutrino-induced charged leptons. Each PMTs are enclosed in a transparent pressure sphere to comprise an Optical Module(OM). In the IceCube design, 80 strings are regularly spaced by 125 m over an area of approximately one square kilometer, with OMs at depth of 1.4 to 2.4 km below the surface.

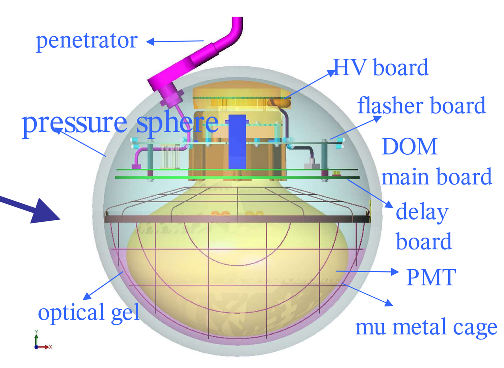
PMT Calibration

IceCube detector uses the HAMAMATSU 10 inch R7081-02 photomultiplier tube with 10 dynodes inside. It has a spherical surface of the photocathode to enlarge its collection area.
We must learn at least about these three parameters of the PMT below in the event reconstruction.

Signal = QE ⊗ CE ⊗ Gain

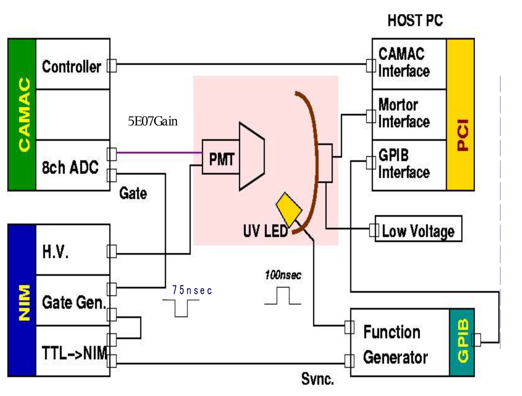
PMT R7081-02

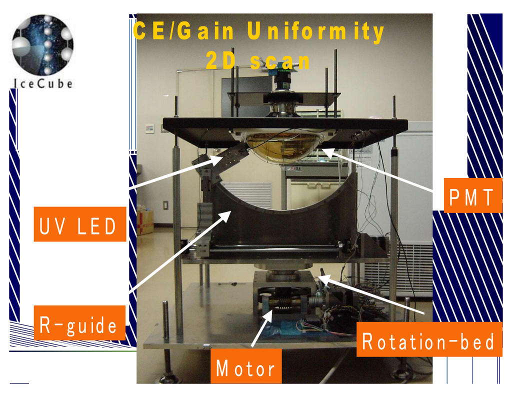
Digital Optical Module



- records timestamps
- digitizes waveforms
- transmits to surface at request via digital communications
- important design requirement
  Noise rate < ~1.5 kHz
  SN monitoring within our Galaxy

2D uniformity and 2D Gain scanning measurement

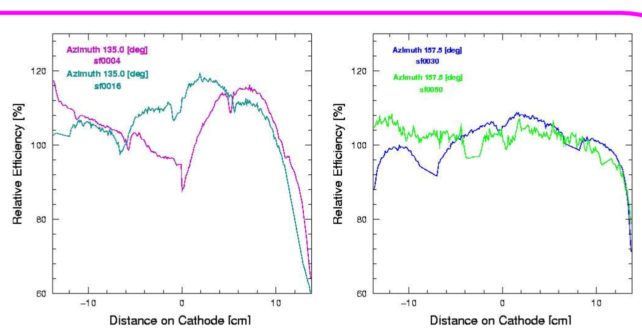


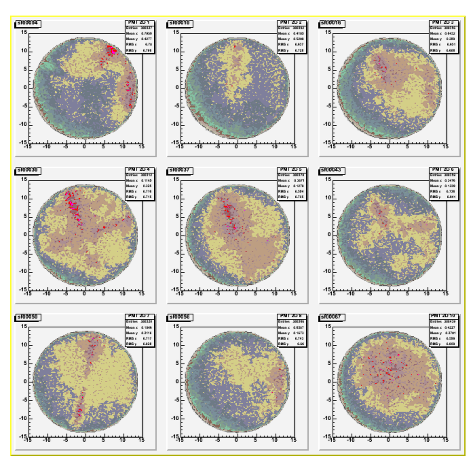


2D uniformity scanning

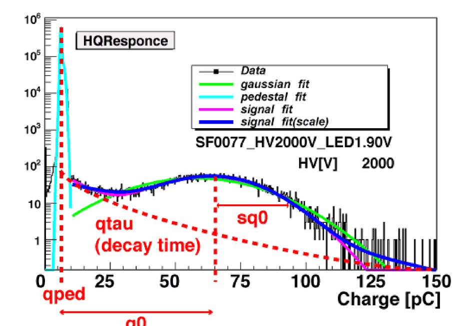
Two figures in the upper panel show the relative efficiency in two azimuthal angle slices (135deg and 157.5deg) for 4 tubes, SF0004, SF0016, SF0050 and SF0030. The efficiencies plotted here are normalized so that the average efficiency over entire photocathode is 100 %. You can see the efficiency varies photon locations to locations by +- 20 %. The difference between different tubes is also visible. We have implemented these effects to the IceCube detector MC.

The collection efficiency depends on where a photo-electron is emitted on the photo-cathod surface. The lower figure shows our scan results of 9 IceCube PMTs.





2D Gain scanning



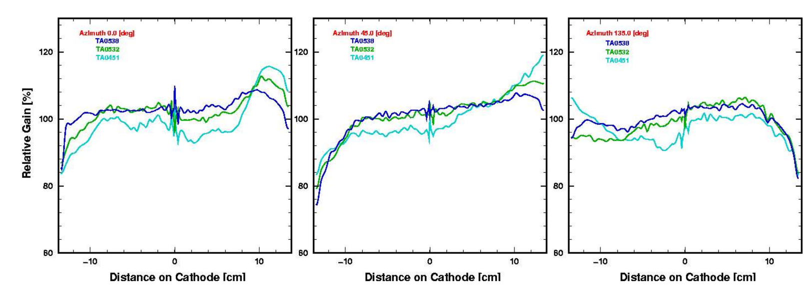
$$f = \frac{P\_ex}{qtau}\,Exp\left(-\frac{q-qped}{qtau}\right) + (1-P\_ex)\frac{1}{\sqrt{2\pi}\,sq0\,N}\,Exp\left(-\frac{(q-(q0+qped))^2}{2\,sq0^2}\right)$$

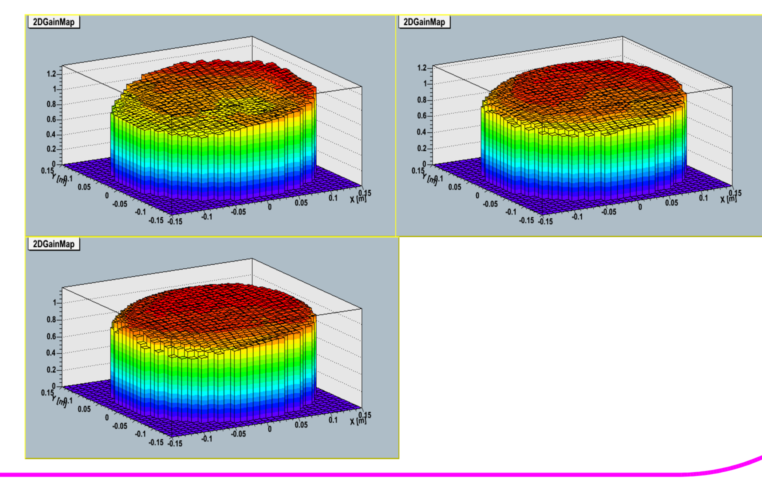
Charge response of the PMT

The most simplest formula to represent the signal part of ADC spectrum (single p.e.) can be easily supposed to be a gaussian function. However, our data shows the existence of another component: exponential-like component appears together with the main gaussian feature and dominates especially at lower ADC range. This behavior probably arises from the instability of first dynode gain.
We thus sum up both components and assumed it to be a model function of our data. Reduced fitting chi-square between our data and model were below 1.0, which justify our model assumption.

The plots shows the gain variance along the three slices with different rotation angles on the photo-cathode. The vertical axis represents the relative gain normalized as 100% in the overall average. The actual (absolute) gain in this data taking is approximately 4.4E7 (at room temperature). The spikes in the center is caused by an interpolation of the data points and you should neglect it.
Although there are slight pmt-by-pmt variances, but the trend is quite same, in contrast to the case of the collection efficiency.

Three figures below are lego plots of the gain map for three different tubes. You can see they share the same general behavior.





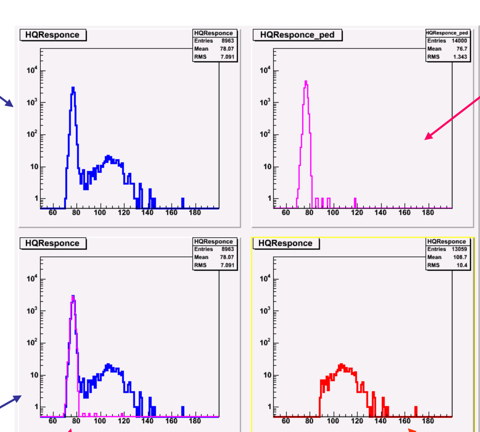
Absolute Efficiency (CE⊗ QE)

Data Analysis

I. Estimate the photoelectron per laser shot. Supposing Poisson distribution of the charge response, photoelectron number can be described by the number of pedestal events and the all the event as bellow.

$$\text{photoelectron \#} = -\ln(N_{ped} / N_{all})$$

Signal Subtraction



II.Estimate incidental photon #.

cathode hit photon # ~ initial photon# x aperture x Cross Section

Energy meter — Numerical calculation

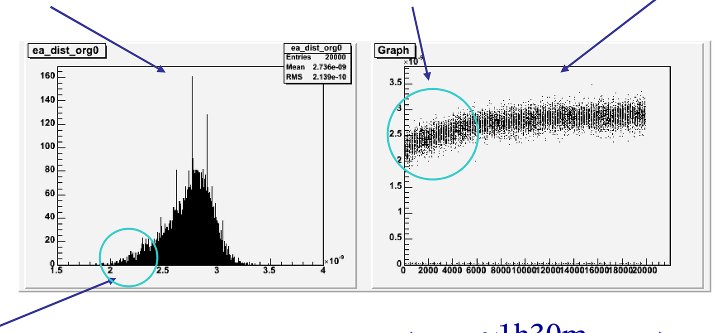
Typically,

~ 2E10 x 4.8E-11 ~ 1

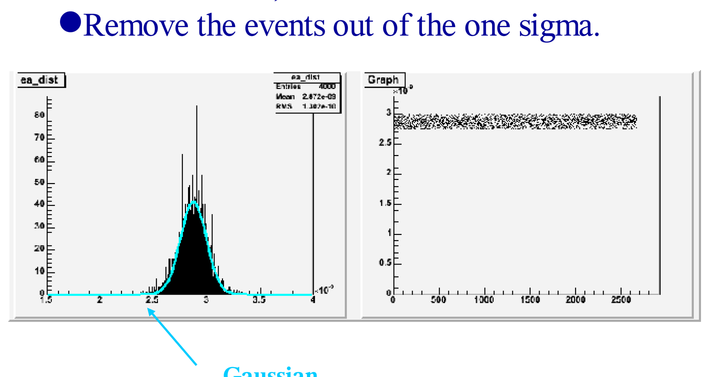
QE(absolute efficiency)
= photoelectron # / cathode hit photon #

For more accuracy….

Distribution of Initial Photon #

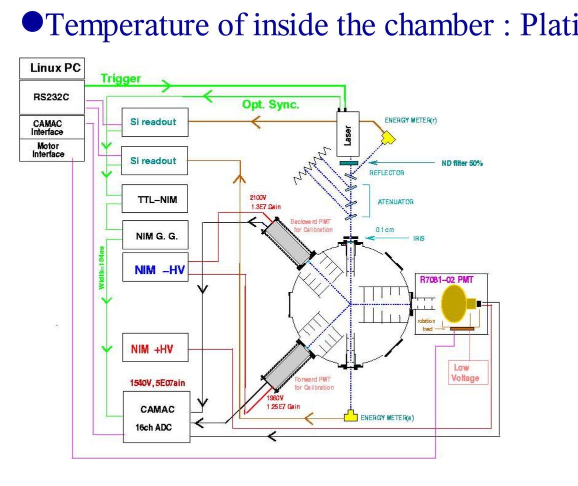


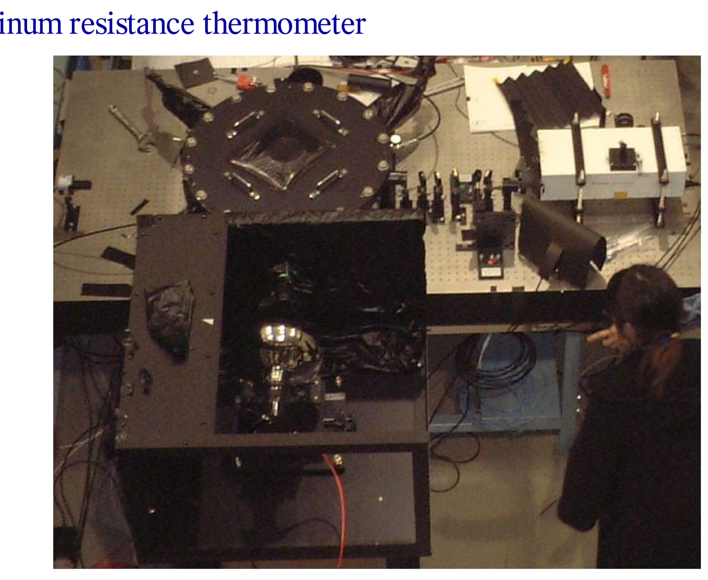
- Remove first 6,000 events.
- Remove the events out of the one sigma.



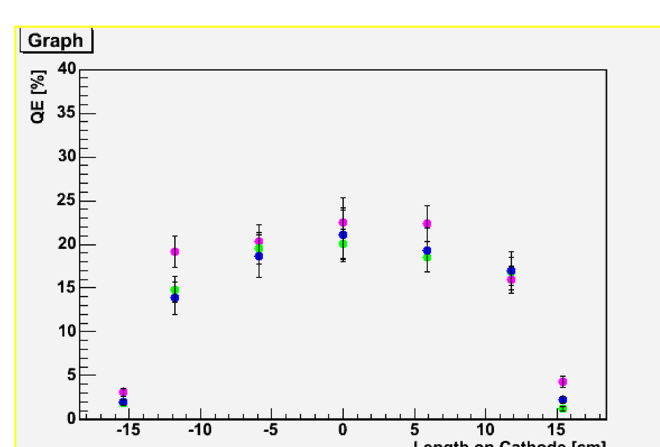
Measurement Setup

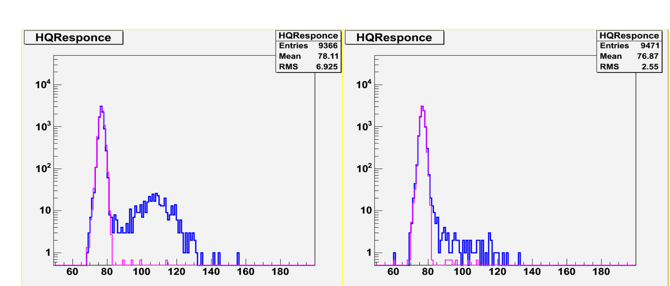
We use N2 laser (Laser Science VSL-337BD-S), the wavelength of the shot is 337.1 nm.
Each parameters are monitored as bellow.
- Absolute energy of the laser shot : Si energy probe (Laser Probe Inc. RjP-465)
- Pressure of inside the chamber : Pressure meter
- Temperature of inside the chamber : Platinum resistance thermometer





Results

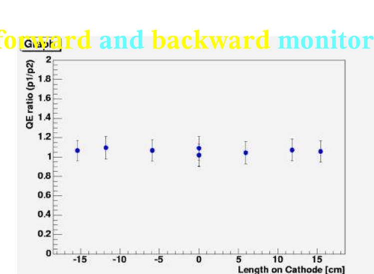




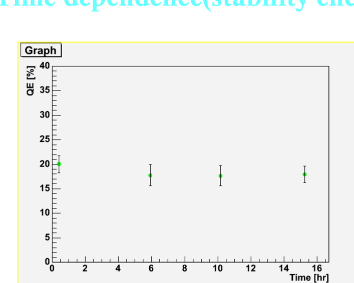
Horizontal axis is the length on cathode. 0 corresponds to the center of the photocathode, while the edge does about 15 cm off from the center. You can see the efficiency doesn't change so much around center and the asymmetry of efficiency distribution. There's almost no efficiency outside area at more than 15 cm from the center.
The data of these three PMTs look like similar distribution, but trend of individual tubes starts to appear.

Verification

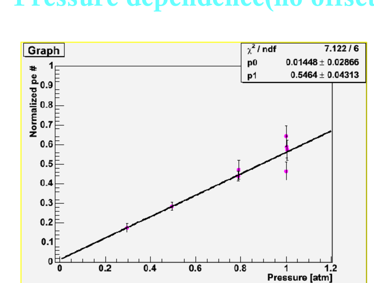
Check air condition(Rayleigh dominant)
by forward and backward monitor PMT



Time dependence(stability check)



Pressure dependence(no offset)



Error budget

-- Statistics --
- photoelectron # : 10 %

-- Systematics --
- photoelecton # : 1 %
- Light Yield (aperture) : 4 %
- Initial photon fluctuation : 4 %
- Pressure : 1 %
- Photon energy probe : 5 %

Total Error Budget : 12.7 %