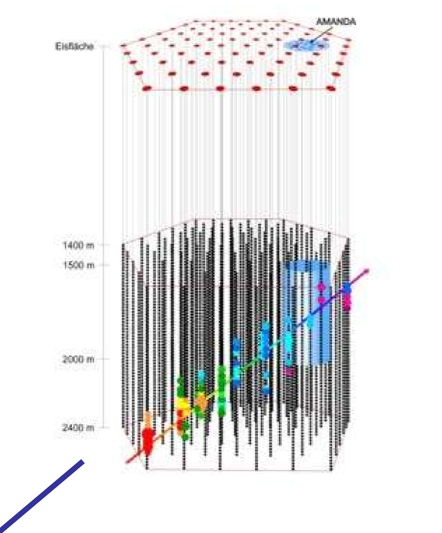
Calibration and Characterization of Photomultiplier tubes of the IceCube Neutrino Detector

Hiroko Miyamoto
Dept. of Physics
CHIBA University

千葉大学 Chiba University



Introduction

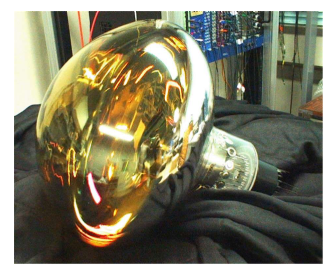
The IceCube neutrino observatory will consist of an array of 4800 Digital Optical Modules (DOMs) located in the deep ice at the South Pole, and also an IceTop air shower array of 320 DOMs in 160 ice tanks located on the surface. A 10 inch PMT is housed in each DOM for the detection of Cherenkov light. This poster describes the methods of calibration and characterization of the IceCube PMTs in the laboratory, which are germane to improving the detector resolution and reducing systematic uncertainties. Two dimensional scans on the entire photocathode to map out photon conversion efficiency have been carried out for 60 PMTs. The quantum/collection efficiency has been calibrated in an absolute manner using the Rayleigh scattered light from our newly built chamber filled with nitrogen gas. The charge response of the PMTs at temperatures below freezing has been extensibely studied and found to be well represented by the analytical model. All these results have been combined and implemented in the detector Monte Carlo simulation.

PMT Calibration

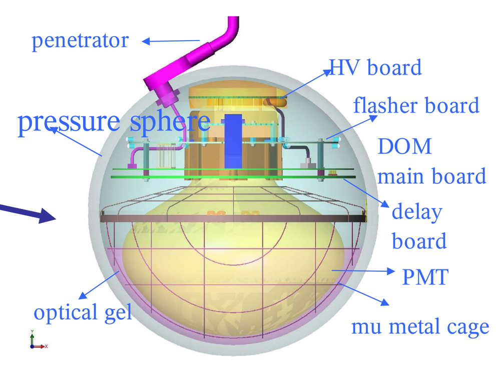
IceCube detector uses the HAMAMATSU 10 inch R7081-02 photomultiplier tube with 10 dynodes inside. It has a spherical surface of the photocathode to enlarge its collection area.
We must learn at least about these three parameters of the PMT below in the event reconstruction.

Signal = QE ⊗ CE ⊗ Gain

PMT R7081-02



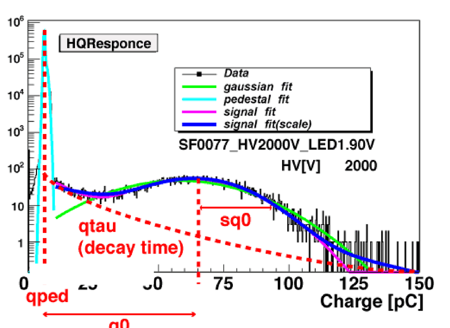
Digital Optical Module



- 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

Charge response of the PMT

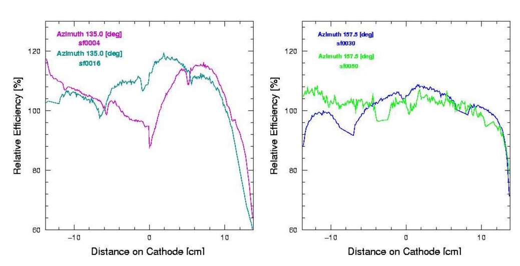


$$f = \frac{P_{ex}}{qtau} Exp\left(-\frac{q - qped}{qtau}\right) + (1 - P_{ex}) \frac{1}{\sqrt{2Pi}\, sq0\, N} Exp\left(-\frac{q - (q0 + qped)}{2\, sq0^2}\right)$$

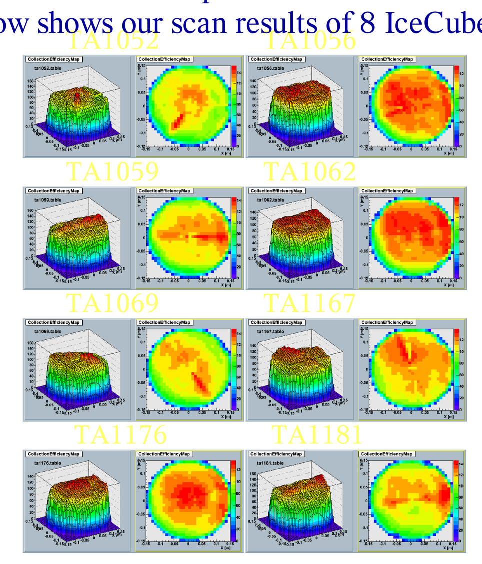
The most simplest formula to represent the signal part of ADC spectrum (single p.e.) can be easily supposed to be a gaussian function. However, our data shows the existence of another component: exponential-like component appears together with the main gaussian feature and dominates especially at lower 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.

2D uniformity scanning

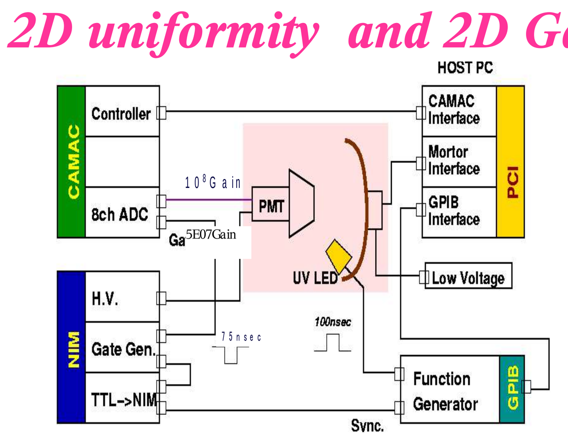
Two figures in the panel below show the relative efficiency in two azimuthal angle slices (135deg and 157.5deg) for 4 tubes, SF0004, SF0016, SF0050 and SF0030. The efficiencies plotted here are normalized so that the average efficiency over entire photocathode is 100 %. You can see the efficiency varies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

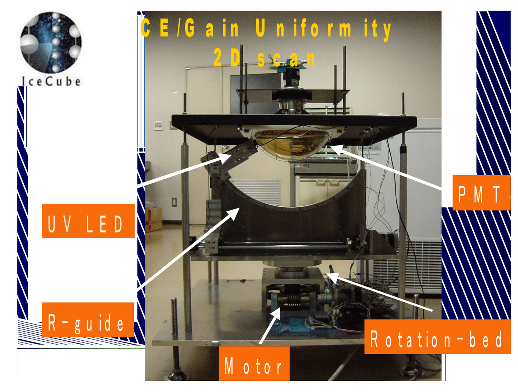


The collection efficiency depends on where a photo-electron is emitted on the photo-cathod surface. The figure below shows our scan results of 8 IceCube PMTs.



2D uniformity and 2D Gain scanning measurement

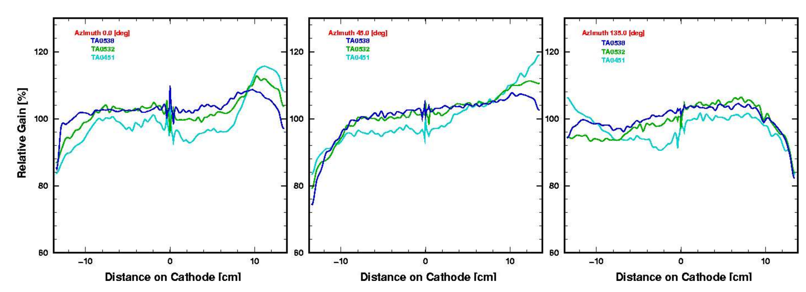


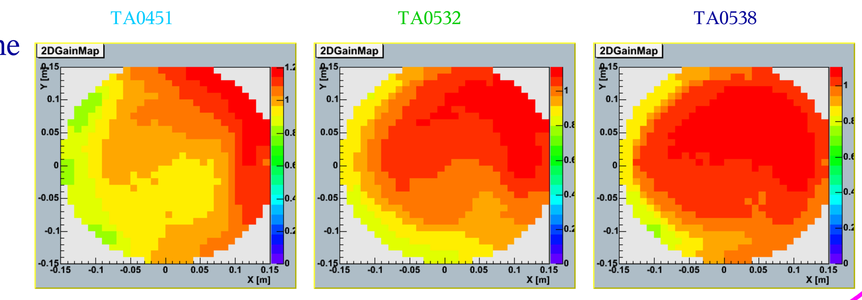


2D Gain scanning

The plots of the right panel shows the gain variance along the three slices with different rotation angles on the photocathode. 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 to pmt variances, but the trend is quite same, in contrast to the case of the collection efficiency.

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





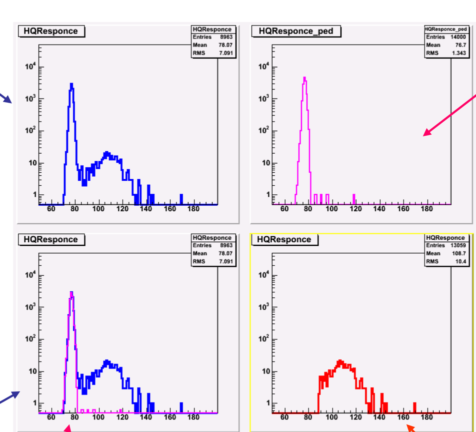
Absolute Efficiency (CE⊗QE) Measurement

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 #.

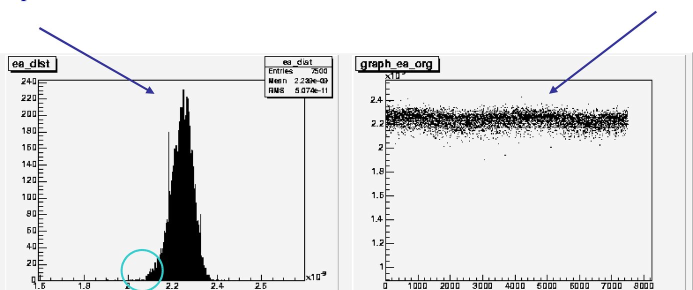
cathode hit photon # ~ initial photon# x aperture x Cross Section

Energy meter
Numerical calculation

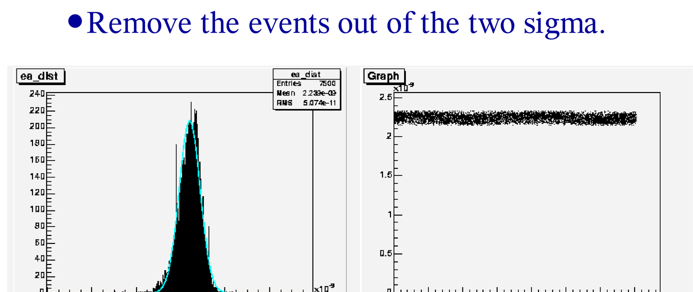
Typically,
~ 4E9 x 5E-11 ~ 0.2

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

Distribution of Initial Photon #

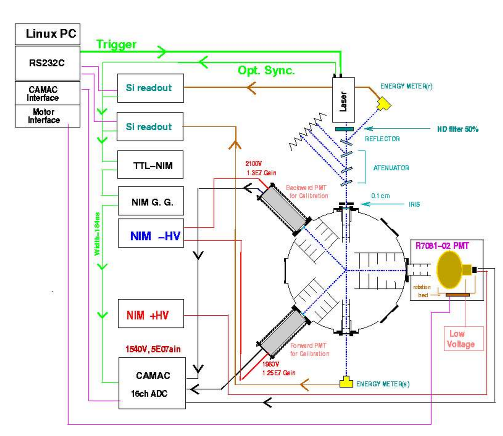


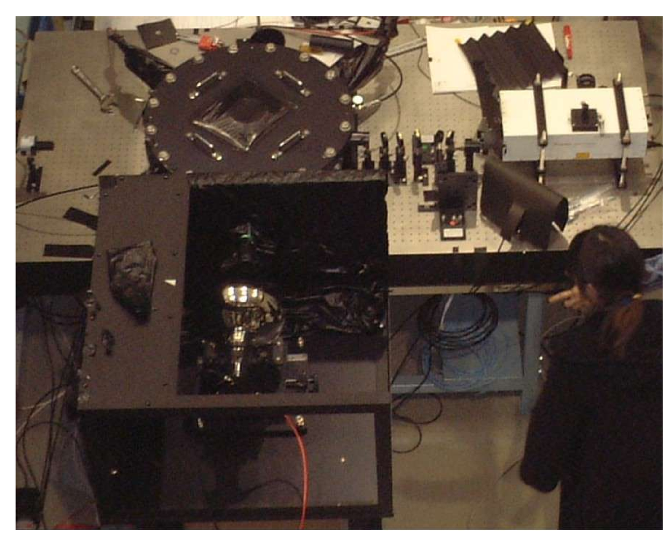
● Remove the events out of the two sigma.



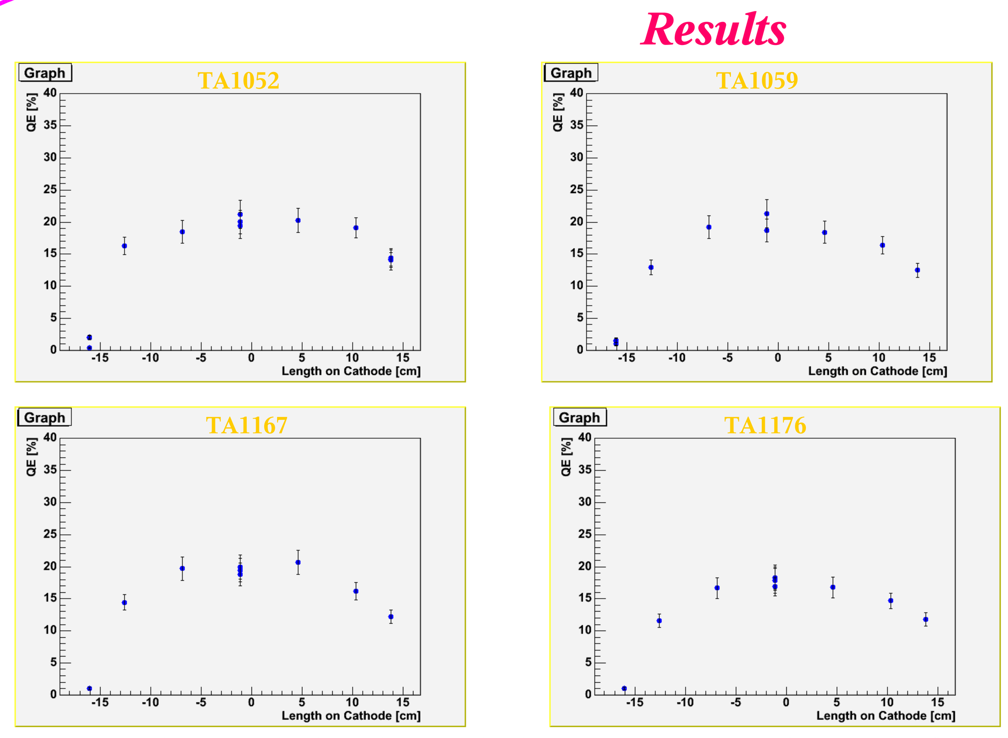
Measurement Setup

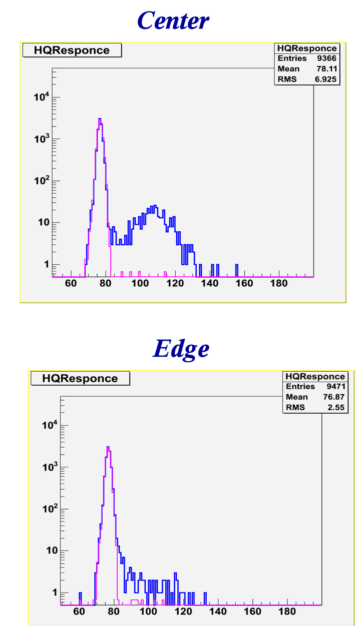
We use N2 laser (Laser Science VSL-337BD-S), the wavelength of the shot is 337.1 nm.
Each parameters are monitored as bellow.
- ●Absolute energy of the laser shot : Si energy probe (Laser Probe Inc. RjP-465)
- ●Pressure of inside the chamber : Pressure meter
- ●Temperature of inside the chamber : Platinum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





Results

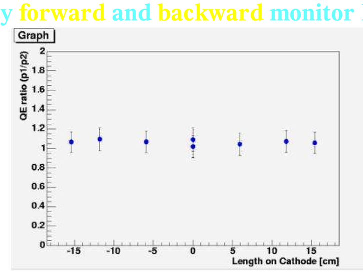




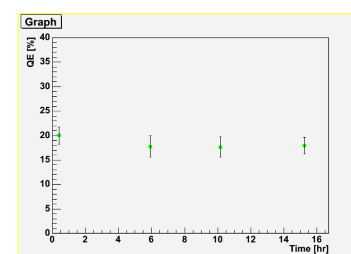
Horizontal axis is the length on cathode. 0 corresponds to the center of the photocathode, while the edge does about 15 cm off from the center. The light spot size is approximately 1.0 cm. You can see the efficiency doesn't change so much around center and the asymmetry of efficiency distribution. The detection efficiency in the central area of the photocathode is measured to be 18-20%. There's almost no efficiency outside area at more than 15 cm from the center.
The data of these four PMTs look like similar distribution, but trend of individual tubes starts to appear.

Verification

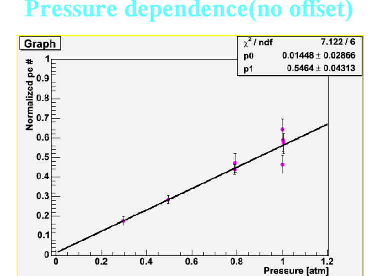
Check air condition(Rayleigh dominant)
by forward and backward monitor PMT



Time dependence(stability check)



Pressure dependence(no offset)



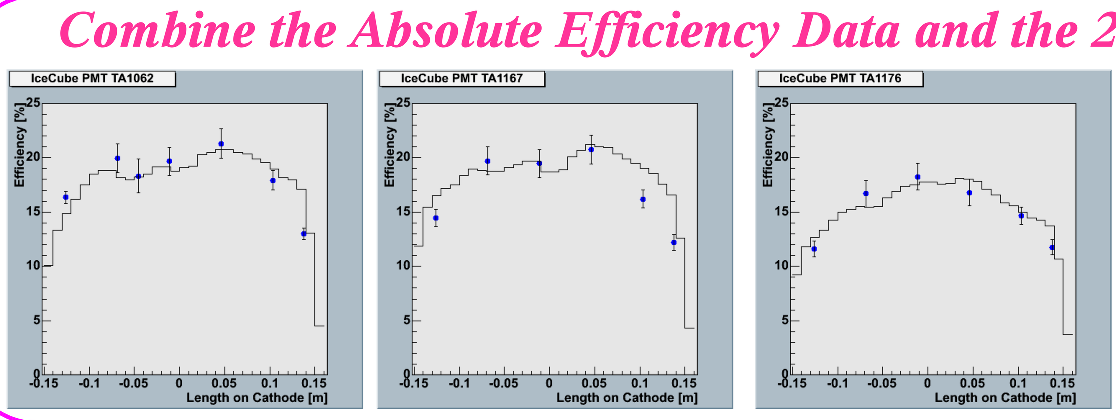
Error budget

-- Statistics --
- •photoelectron # : 6 %

-- Systematics --
- •photoelecton # : 0.4 %
- •Light Yield (aperture) : 4 %
- •Initial photon fluctuation : 0.02 %
- •Pressure : 1 %
- •Photon energy probe : 5 %

Total Error Budget : 10 %

Combine the Absolute Efficiency Data and the 2D Uniformity Data



The data points in the left panels show the determined detection efficiency as a function of the distance from the cathode center. The histogram shows the two dimensionally scanned relative collection efficiency described above, after applying the appropriate normalization.
The locally measured absolute efficiency data points agree very well with this histogram. Consequently, this allows us to estimate the those averaged over the entire photocathode.