Development and evaluation of 10-inch Photo-Multiplier Tubes for the Double Chooz experiment

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What is the Double Chooz experiment?

- The Double Chooz experiment is a neutrino oscillation experiment.
- The goal of this experiment is a precise measurement of the last unknown angle θ_{13}.
- It is located at Chooz nuclear power plant in France.

How are the neutrinos detected?

- Anti-electron neutrinos are detected through inverse β-decay process: $\overline{\nu}_e + \mathrm{p} \ \rightarrow \mathrm{e}^{+} + \mathrm{n}$
- Positron deposits its energy in the liquid scintillator, then annihilates with electron.
- The Gd captures neutron and generates γ-rays.

the Double Chooz detector

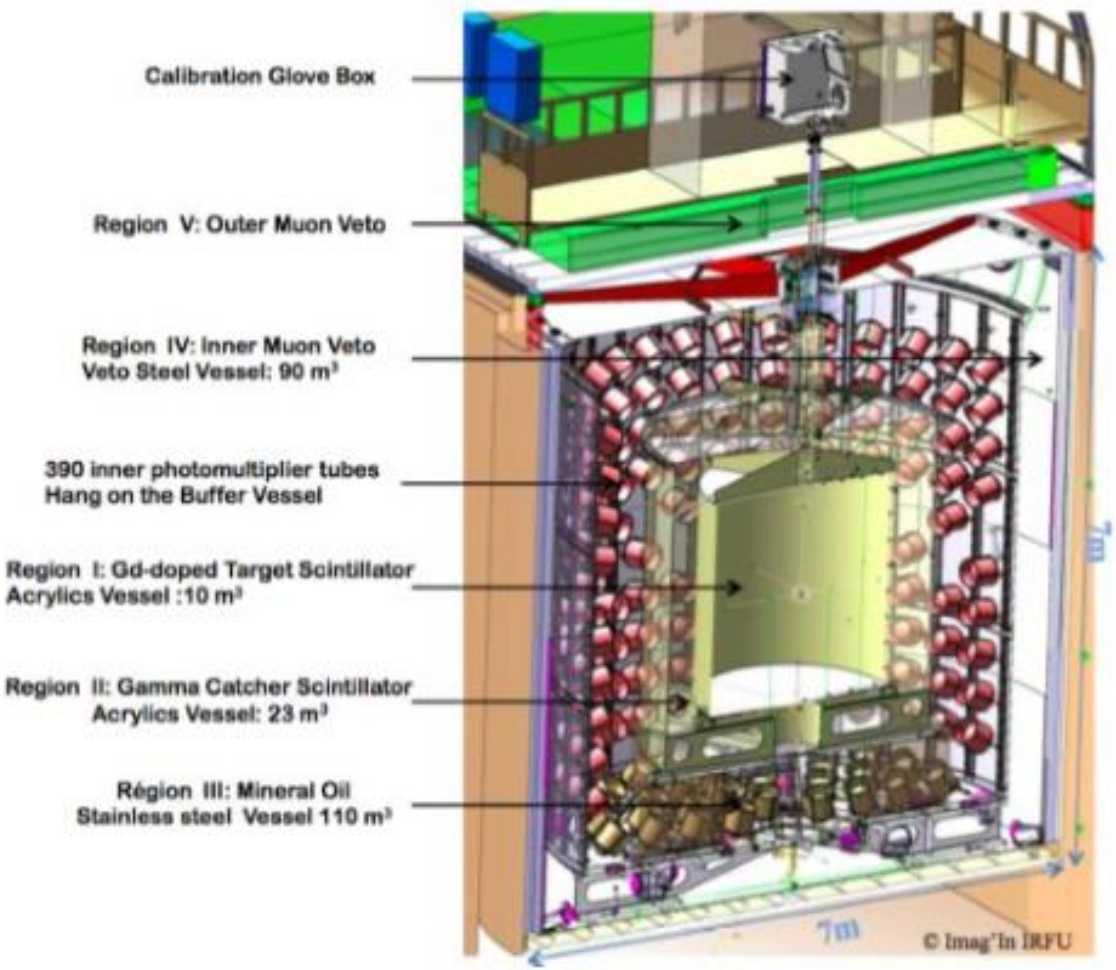

Figure 1: Double Chooz detector structure.

- Double Chooz places two detectors of same structure, i.e. far and near detectors.

the Double Chooz detector

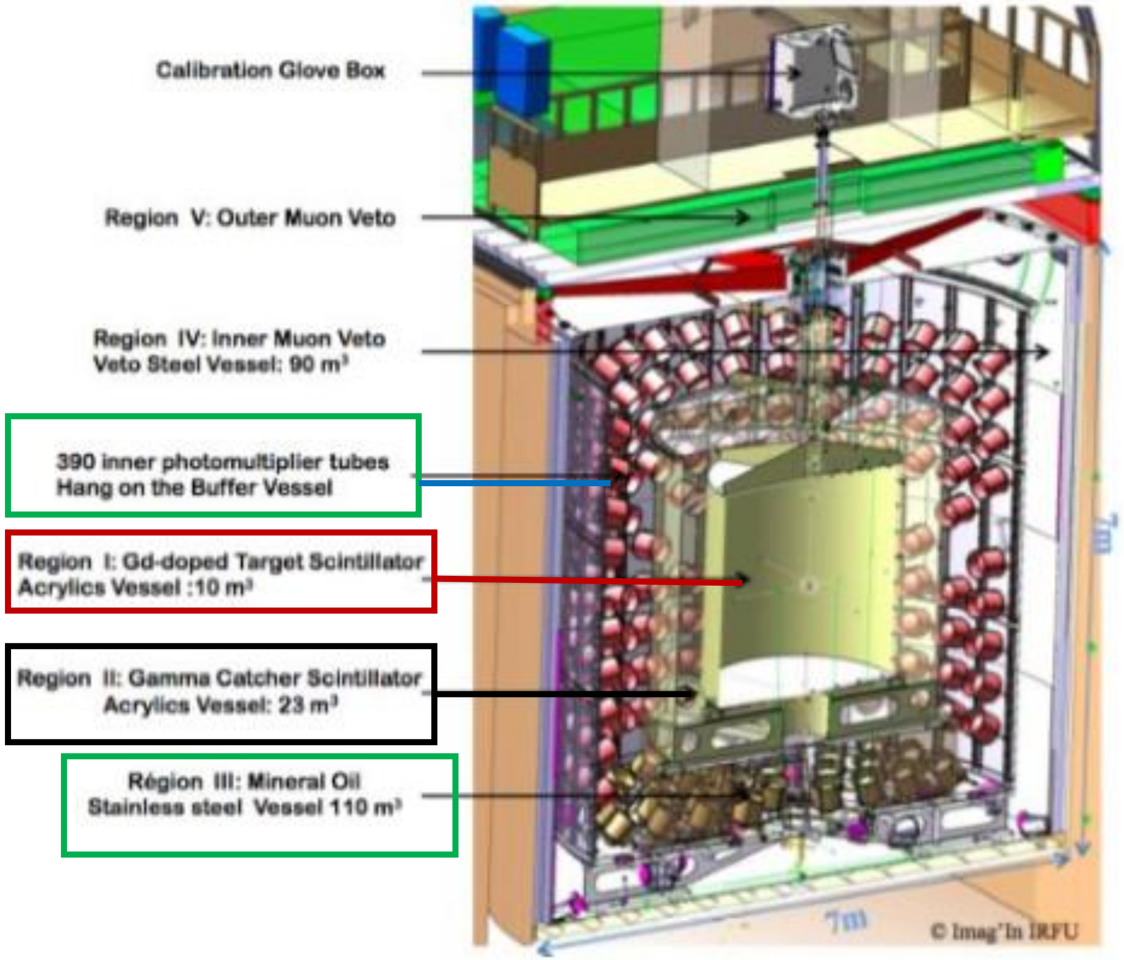

Figure 1: Double Chooz detector structure.

- The target and the γ-catcher vessels are built with acrylic material.
- The target region is filled with Gd doped liquid scintillator.
- The γ-catcher region is filled with un-doped liquid scintillator.
- The buffer tank is made of stainless steel.
- The buffer region is filled with non-scintillating mineral oil.
- A total of 390 10-inch PMTs are mounted at the wall of the buffer tank.

the Double Chooz detector

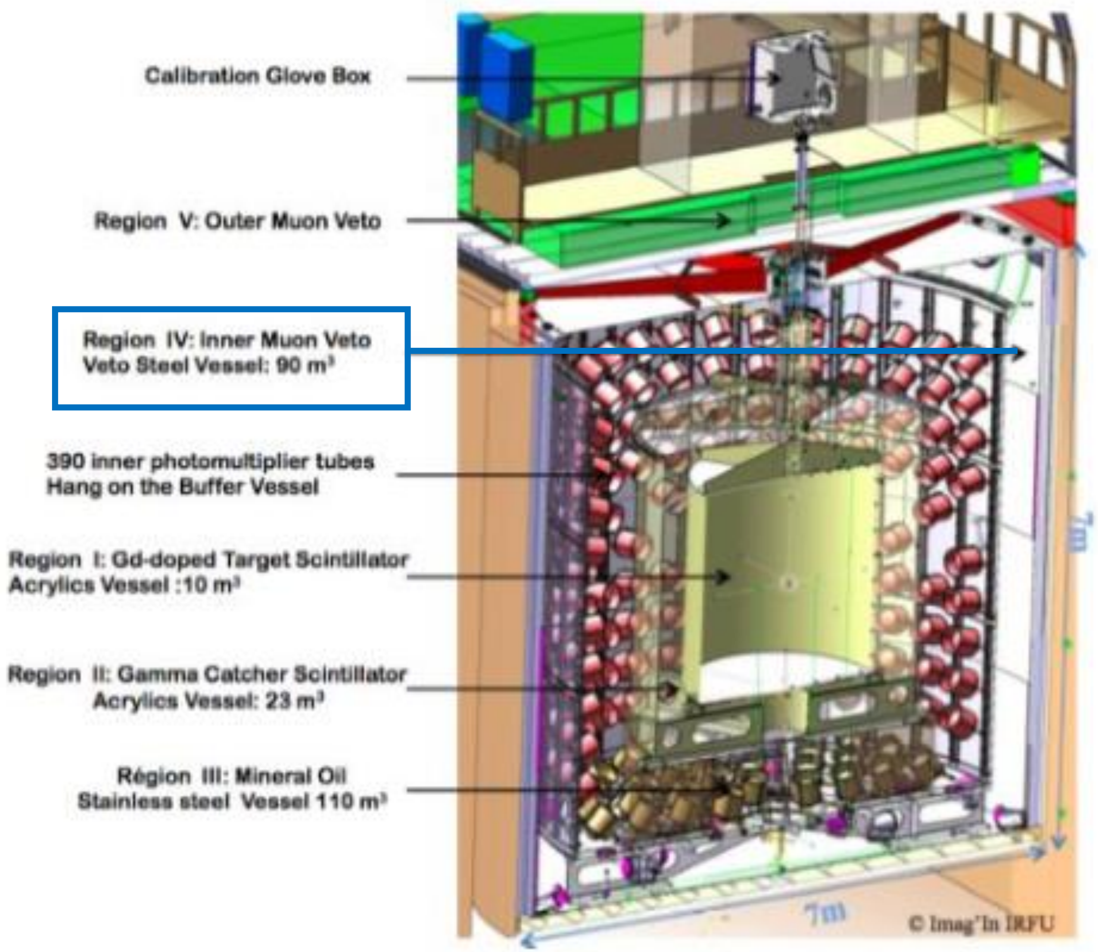

Figure 1: Double Chooz detector structure.

- Inner veto tank is filled with liquid scintillator.
- Inner veto tank is surrounded by steel shield.
- The scintillation light generated in inner-veto region is monitored by 8-inch PMTs.

gain

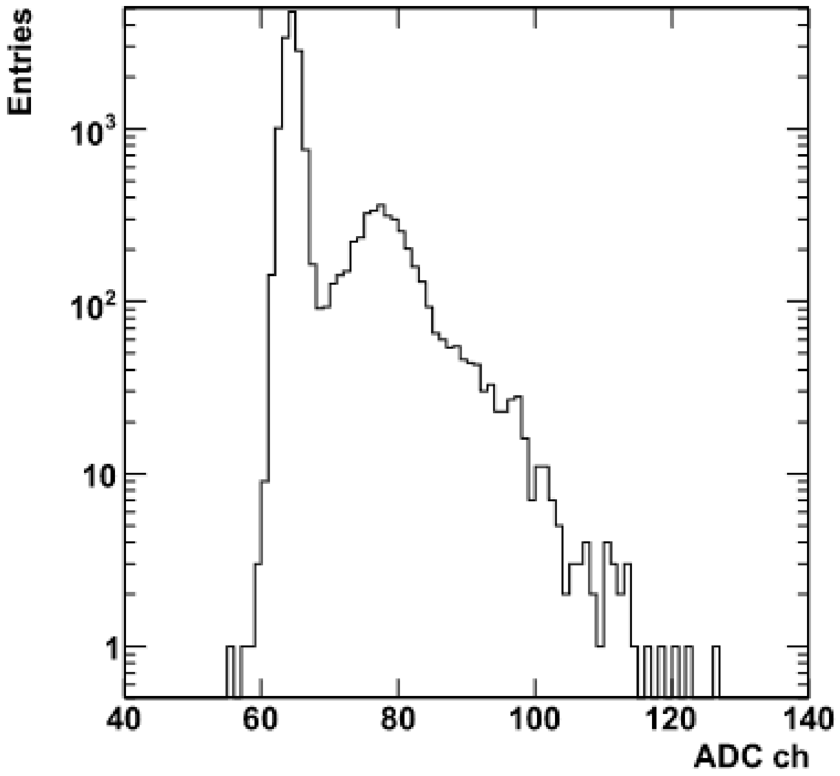

Figure 7: Charge distribution obtained using laser pulse with an intensity of 0.25 P.E. and supplying HV with 1,200 V. The 1 P.E. peak is seen at ADC counts of 80.

- The figure shows the charge distribution obtained by using a laser pulse with an intensity of 0.25 p.e. and supplying HV with 1200 V.
- $Gain = a^n \left(\frac{V}{n+1}\right)^{kn} = \alpha V^{\beta}$
- *A* is a constant parameter.
- *K* depends on the material of electrode.
- *N*(=10) is the number of dynodes.

peak to valley ratio

- Peak to valley ratio is an index value for significance of 1 p.e. signals relative to the pedestal.
- $P/V\ ratio = \frac{height\ of\ 1\ p.e.peak}{valley\ between\ the\ pedestal\ and\ 1\ p.e.\ peak}$

transit-time spread

- Timing information is crucial to determine the vertex position in the detector.
- Transit time is the time difference between the light injection and the signal output.
- TTS is defined as the FWHM of the transit-time distribution.

efficiency

- Quantum efficiency(QE) is a conversion probability from photon to photoelectron at PMT cathode.
- Collection efficiency(CE) is defined as dynode collection efficiency of converted photoelectron.
- QE and CE are difficult to measure separately.
- Only the product of two values, QExCE can be measured.

evaluation systems

- They took two steps on evaluation: before and after the transportation to Germany(Max Planck Institute).
- They measured the HV value to give 10^7 gain, peak to valley ratio, time specifications, dark count rate and QExCE.

step-1 evaluation system

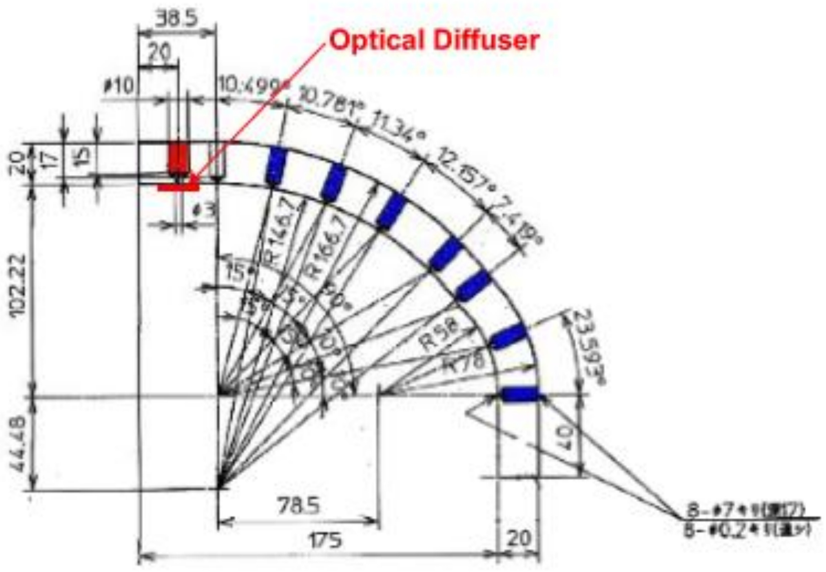

Figure 9: The light arm for the PMT evaluation. The top port is to insert the optical fiber for laser and 7 other ports are to insert LEDs.

- μ-metal surrounds the side of the PMT to shield the geo-magnetic field.
- The wavelength of the laser pulser is 438.7 nm
- Time duration is less than 20 ps.
- The distance from the light source to the surface of a PMT was set to about 20 cm.

step-2 evaluation system

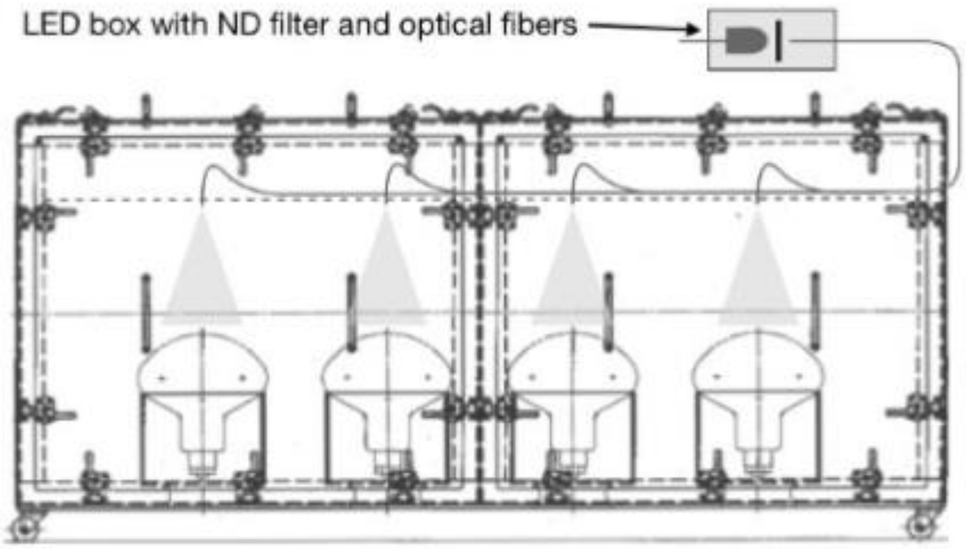

Figure 10: Design of Step-2 system. One can access 4 lanes from two front doors, and set 2 PMT at backward and forward in each line.

- 8 PMTs are evaluated simultaneously.
- Only one LED, the one used in step-1 evaluation system was used.
- The light is divided into 8 optical fibers with light injector.

the procedure of evaluation (step-1)

1. Turn on HV supply and wait for 1 hour to stabilize the PMT.
2. Measure the gain with 9 different HVs to define the HV obtaining 10^7 gain and set the HV for 10^7 gain.
3. Measure P/V ratio and TTS.
4. Record pulse shape with a digital oscilloscope.
5. Measure dark count rate.
6. Measure the QExCE map.

the procedure of evaluation (step-2)

1. Turn on the HV supply and illuminate PMTs with dozens of photoelectrons for 20 hours as aging operation.
2. Measure the gain supplying 9 different HVs to define the HV obtaining 10^7 gain.
3. Measure P/V ratio.
4. Measure dark count rate.

gain

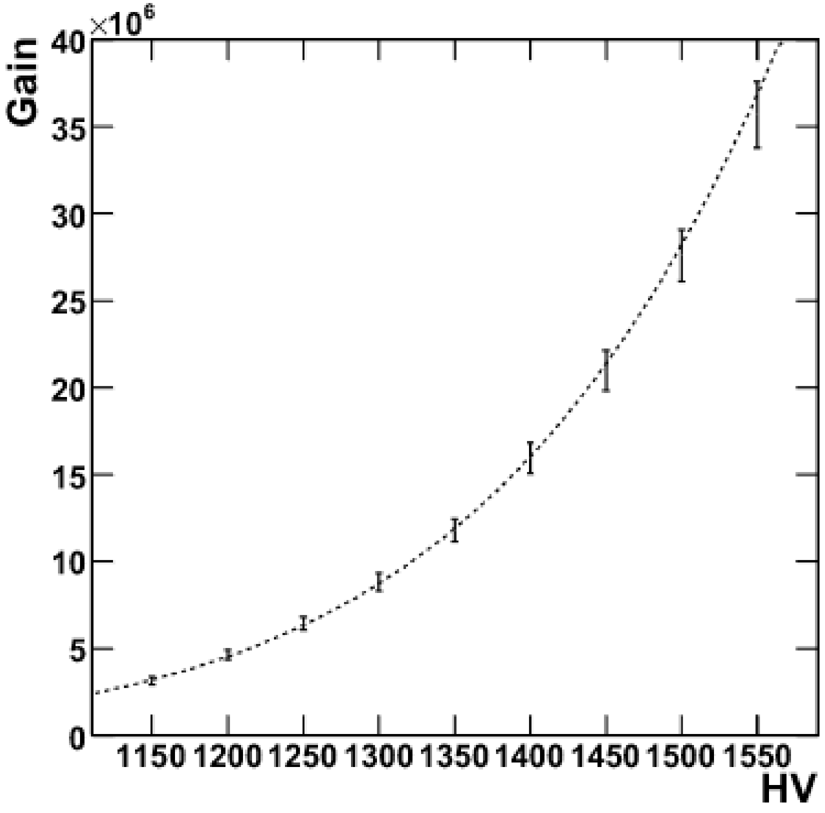

Figure 11: Gain as a function of high voltage. In this example, the HV obtaining 10^7 gain is 1,320 V.

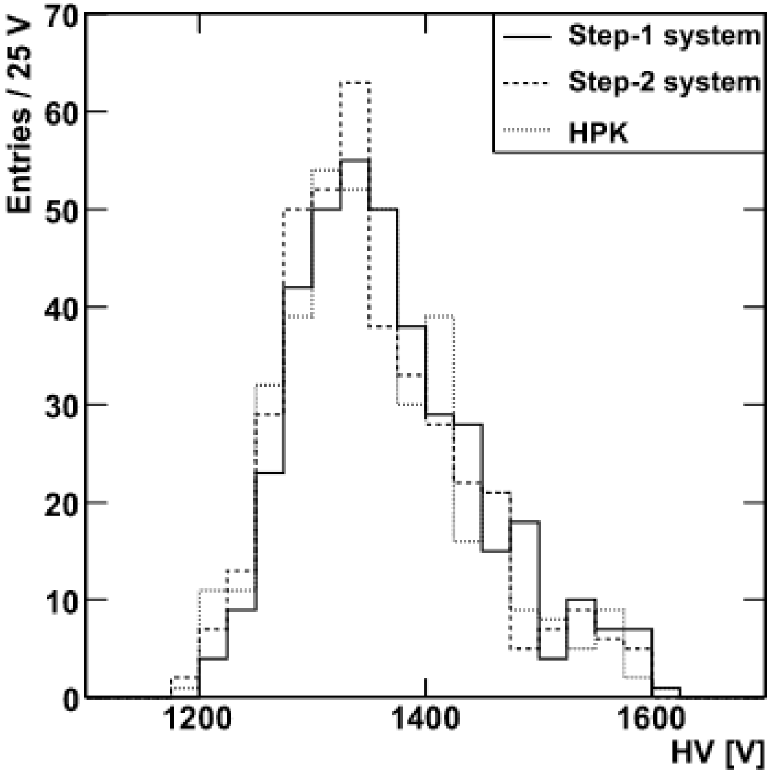

Figure 12: High voltage values for 390 PMTs which give 10^7 gain. Solid and dashed lines show the results obtained by Step-1 system and Step-2 system, respectively. Dotted line shows specification measured by HPK.

peak to valley ratio

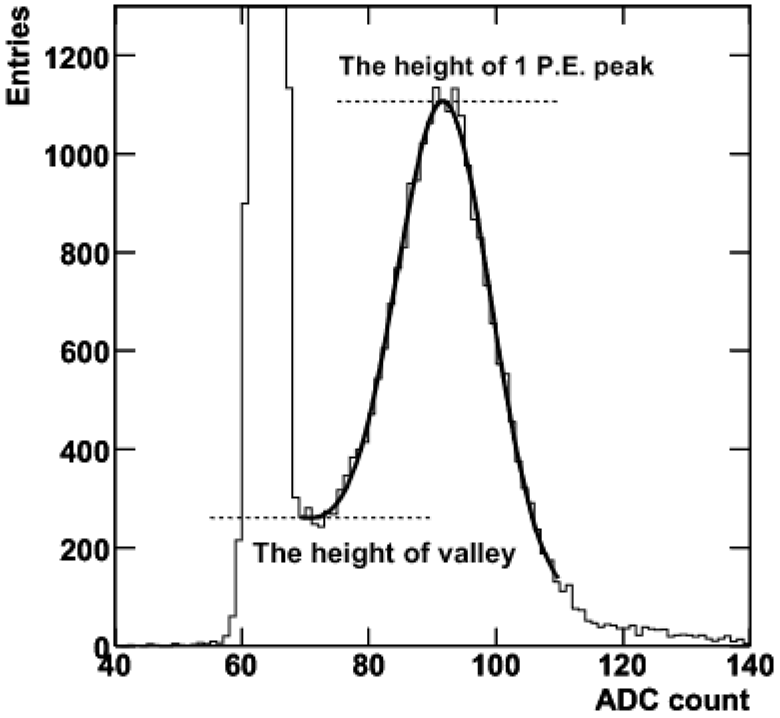

Figure 13: The charge distribution obtained using the laser pulse with an intensity for 0.1 P.E.. The height ratio of 1 P.E. peak to the valley between the pedestal peak and 1 P.E. peak is calculated as "Peak to valley ratio". In this example, P/V ratio is 4.2.

- An exponential + Gaussian function was used to fit and calculate the P/V ratio.

peak to valley ratio

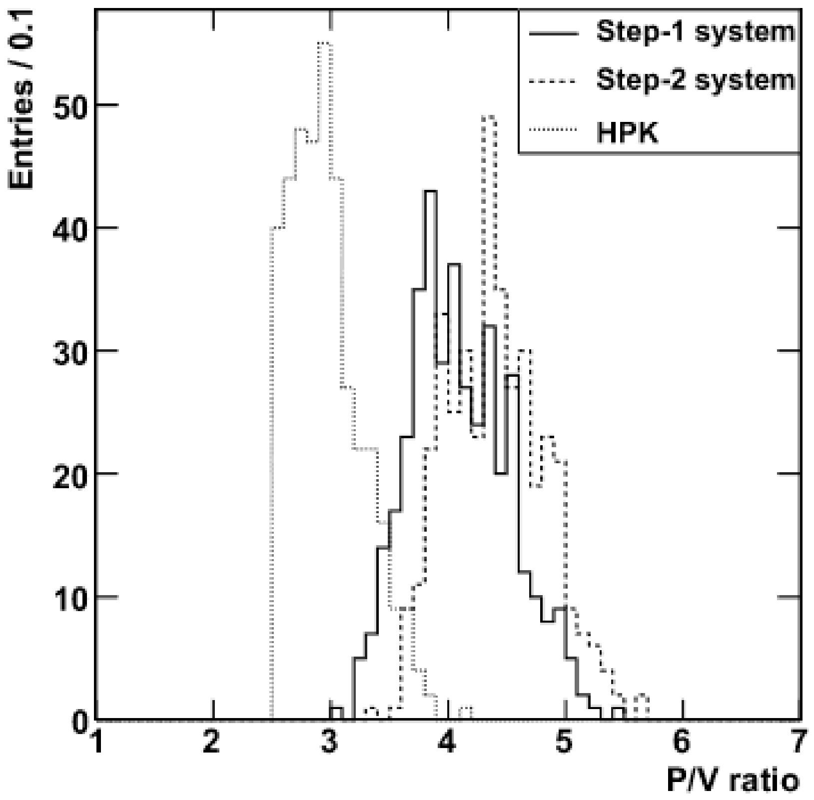

Figure 14: Evaluation result of peak to valley ratio for 390 PMTs. Solid and dashed lines show the results obtained by Step-1 system and Step-2 system, respectively. Dotted line shows the specification measured by HPK.

- There is a significant difference between HPK and their measurements.
- The difference may have caused by the difference of the setup such as the distance from the light source and use of μ-metal.

TTS

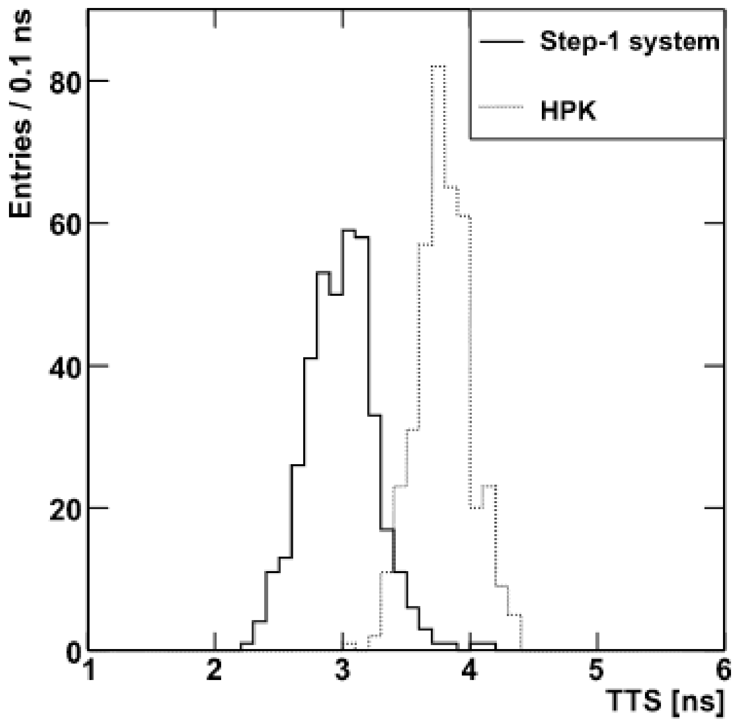

Figure 18: Evaluation result of TTS for 390 PMTs. Solid line shows the results obtained by Step-1 system. Dotted line shows the specification measured by HPK.

- The result of their measurement is better than HPK.
- The difference may have caused by the setup distance.

QExCE

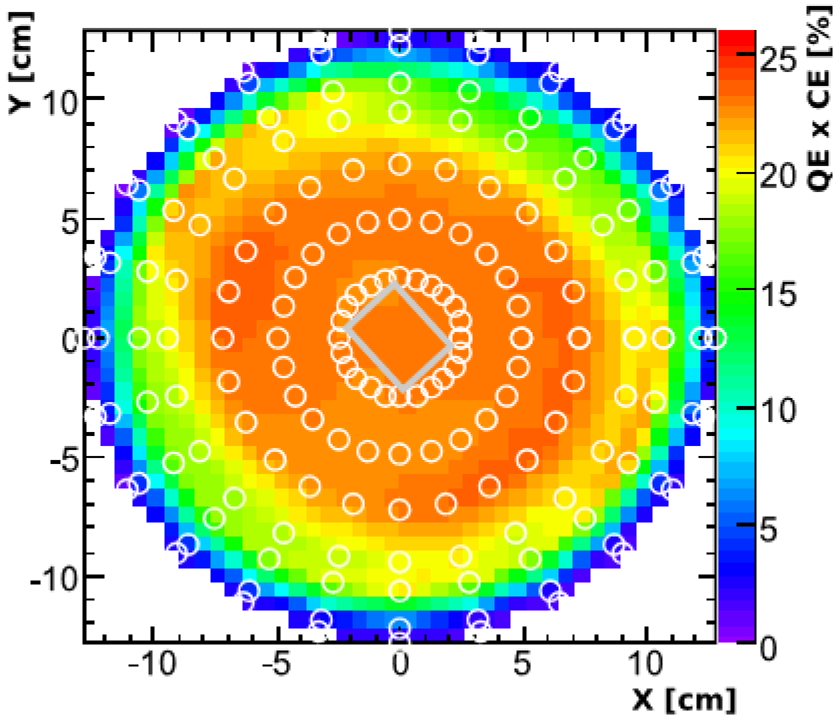

Figure 21: Result of QE×CE for a typical PMT. This PMT has 135 degrees of the first dynode direction with respect to cable output. Cable output is along the x-axis. The box at the center indicates the direction of the first dynode of the PMT. White circles show the measurement points.

- $QE \times CE = \frac{N_{pe}}{N_p}$
- N_{pe} is the number of measured photoelectrons.
- N_p is the number of injected photons calibrated with a reference PMT.

Works Cited

- Tokyo Institute of Technology "The Overview of the Double Chooz experiment"

  https://dchooz.titech.jp.hep.net/dc-experiment.html

Extra Information

- The experiment started in year 2010 with the far detector only.
- The near detector followed 1.5 years later.
- $f(x) = P_0 \times \exp\left(-\frac{x}{P_1}\right) + \frac{P_2}{\sqrt{2\pi}P_4}\exp\left(-\frac{(x-P_3)^2}{2P_4^2}\right)$