Calibration For Hyper-K

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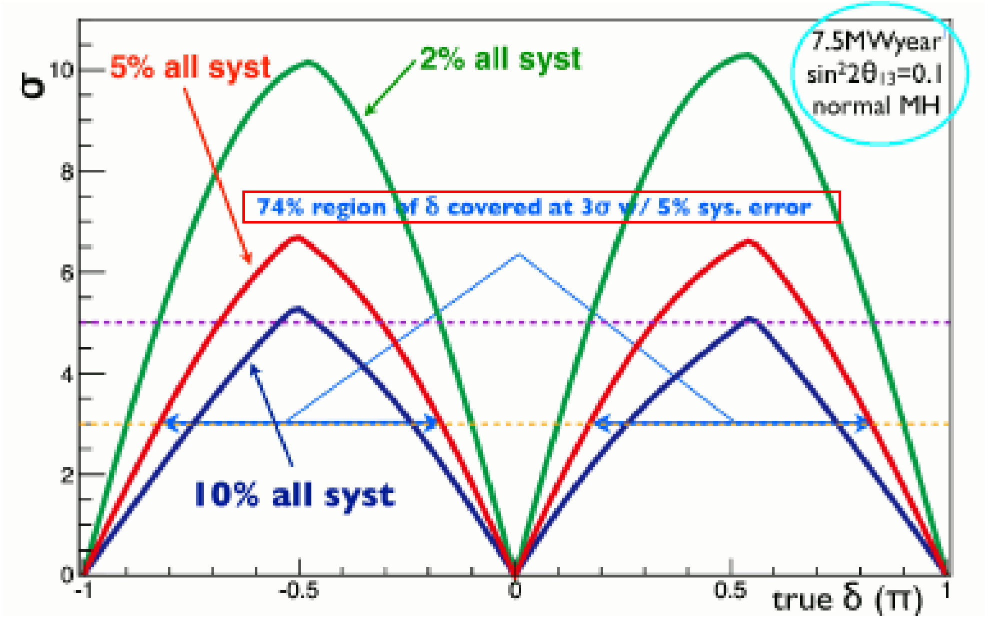
Measurement of oscillation parameters

Sensitivity of HK dependant on total systematic uncertainty

SK detector systematics are significant for T2K

- We will need to do better in HK.



Source of error for ν_e appearance arXiv:1311.4750

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

Source of error for ν_μ disappearance PRL, 111, 211803

Source of uncertainty (number of parameters)	$\delta n_{SK}^{exp} / n_{SK}^{exp}$
ND280-independent cross section (11)	6.3%
Flux and ND280-common cross section (23)	4.2%
Super-Kamiokande detector systematics (8)	10.1%
Final-state and secondary interactions (6)	3.5%
Total (48)	13.1%

What do we need to measure?

Electronics

PMT Response

- Timing
- Gain
- Angular Response
- Faulty PMTs
- Relative PMT efficiency
- Overall detector gain
- Multi and single photon effects

Detector Properties

- Water Attenuation/Extinction
- Scattering
- Reflections from surfaces
- Detector Asymmetries

Physics sources

- Energy scale
- Reconstruction
- Event shapes
- Neutrons

Calibration Strategies

Deploy sources
- Light sources
- Radioactive sources

Collect data for calibration insitu
- Michel Electrons
- Cosmic muons
- Atmospheric neutrinos

Build sources into the detector
- Optical fibres
- Embedded sources

Precalibraton
- Careful measurements before/during assembly

Precalibration

Magnetic field measurement

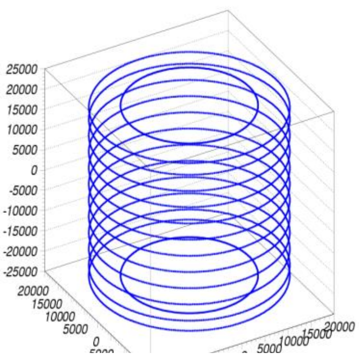
A Suzuki et al. NIM A329 299-313 (1993)

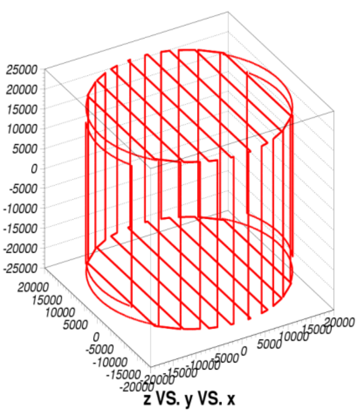
<100mG is necessary for <10% effect on PMT gain.

Compensation coils for the geomagnetic field exist.

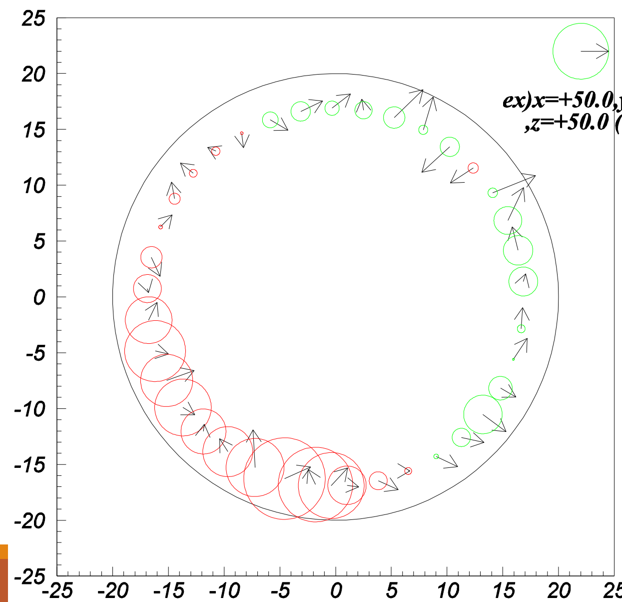
Residual magnetic field was measured during reconstruction and found to be less than 100mG.

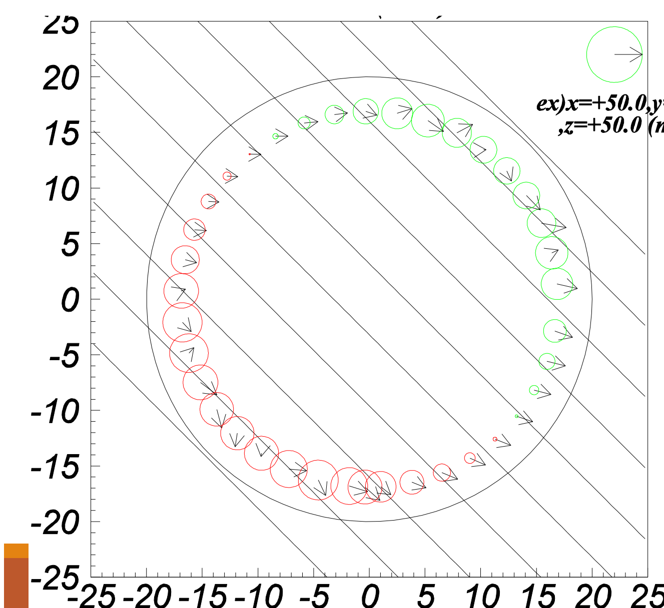
At the same time, tank geometry was surveyed.



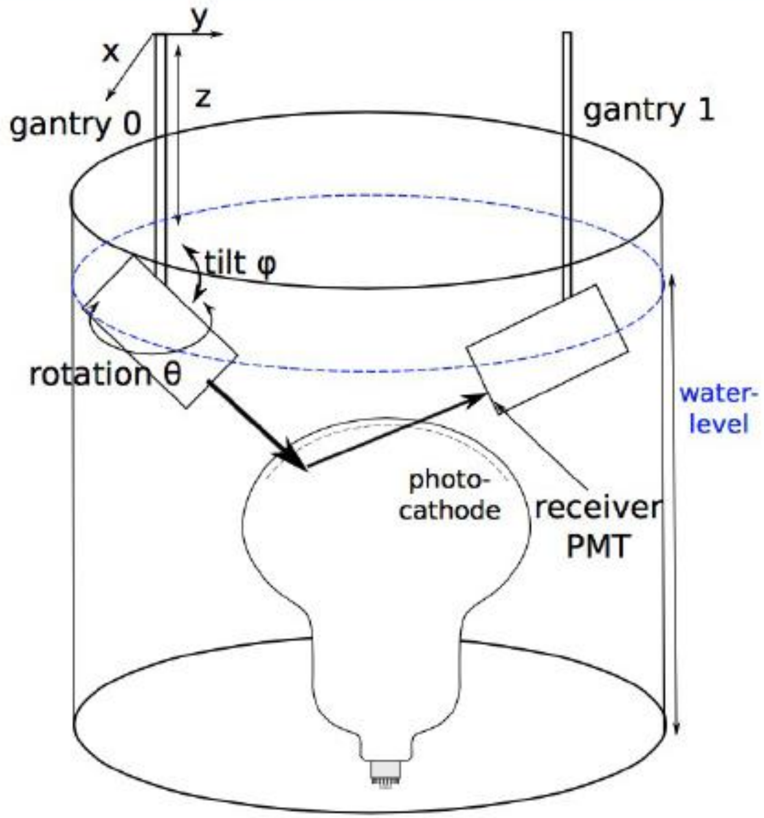


One example: data for central barrel part





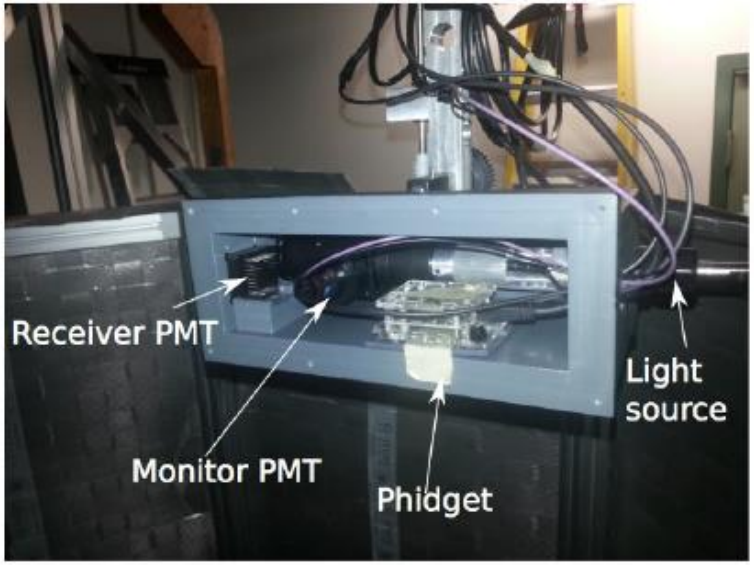
PMT Test Facility (PTF)

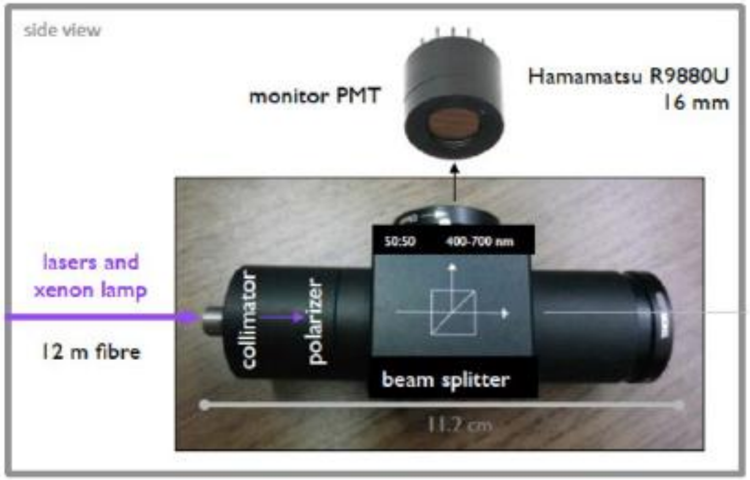


- PMT centered inside tank with ultrapure water.
- 5 stepping motors for each of two manipulator arms (gantries) ⇒ 5D (x,y,z, rotation, tilt)
- Waterproof optical box with laser, monitor and receiver PMT attached to the head of the gantry arm.
- Position accuracy: ∼1 mm (x,y,z) and ∼1° (rotation and tilt).

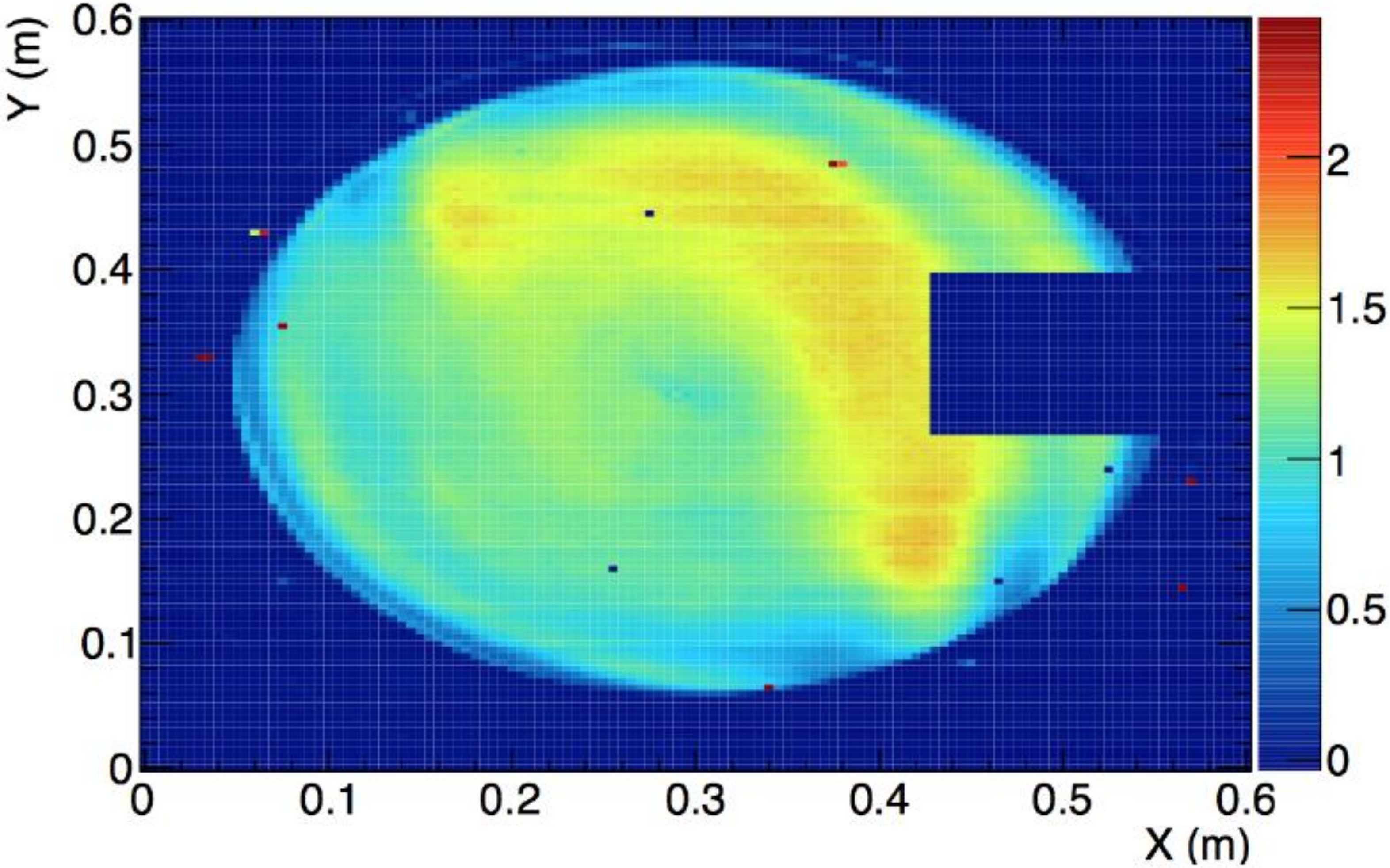
PMT Test Facility II

Optical system





- Light sources: 405/467nm pulsed laser and Xe lamp with filters.
- Connected through fiber to optical boxes.
- Collimator, polarizer, beam splitter.
- Monitor PMT and receiver PMT.
- USB powered board with 3-axis magnetometer, accelerometer and gyroscope (*Phidget*).



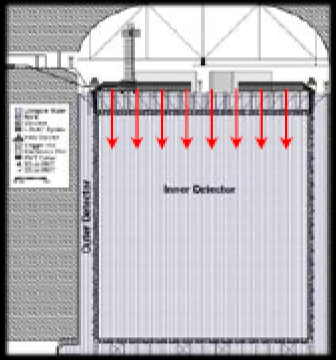
Y (m)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
X (m)
2
1.5
1
0.5
0

Detector Calibration

Deploying sources

Current Deployment Systems

Super-K

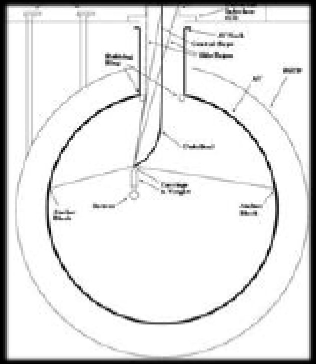


Semi-automatic

1D calibration
System (manual)

Volume Calibrated:
~ 50k m^3

SNO

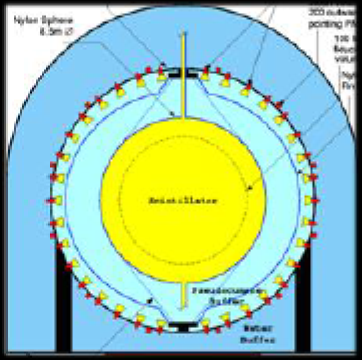


Semi-automatic

2D calibration
System (manual)

Volume Calibrated:
~ 1k m^3

Borexino



Fully manual

3D calibration
System (manual)

Volume Calibrated:
~ 0.3k m^3

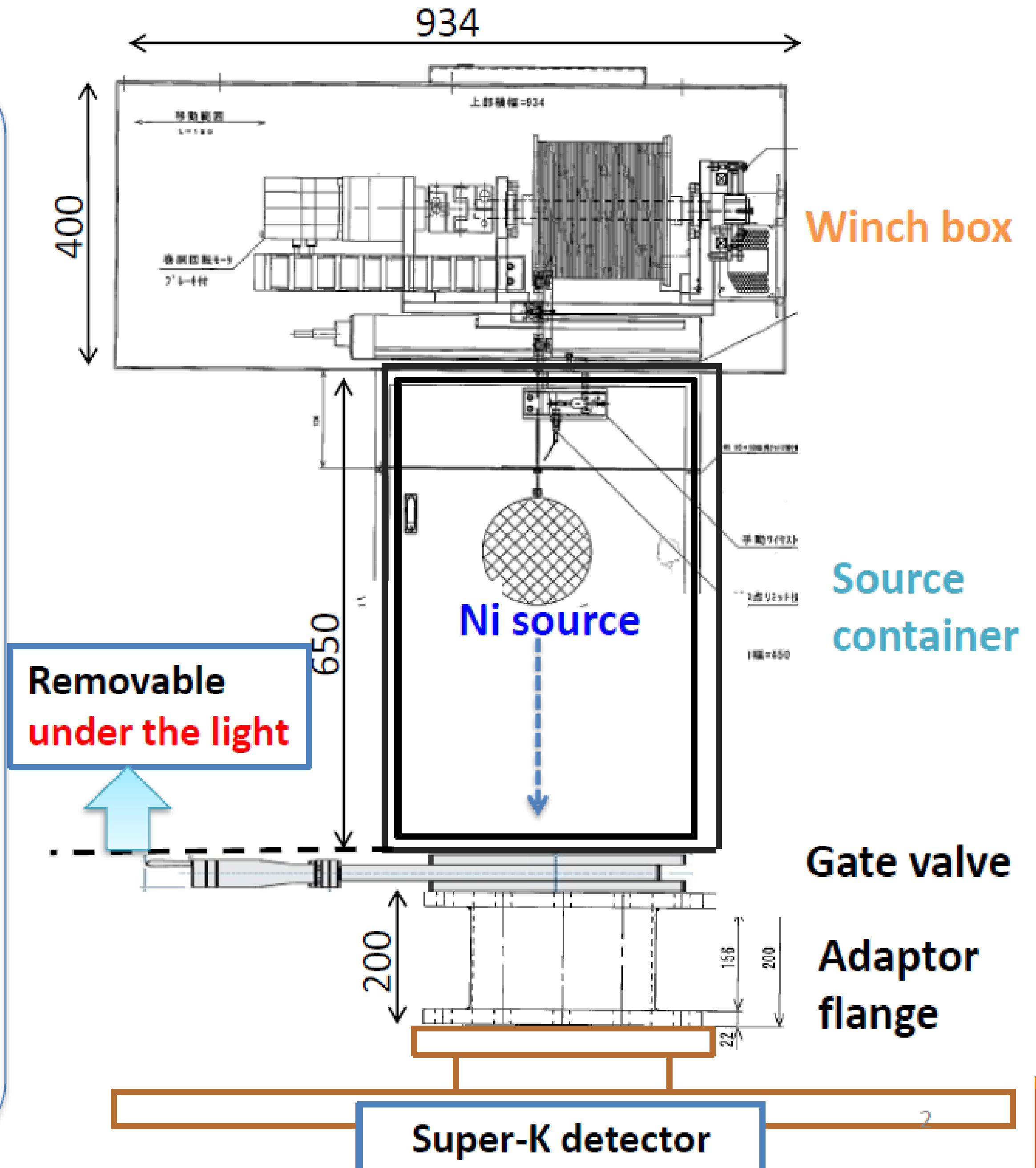
Automated source deployment system

Purpose:

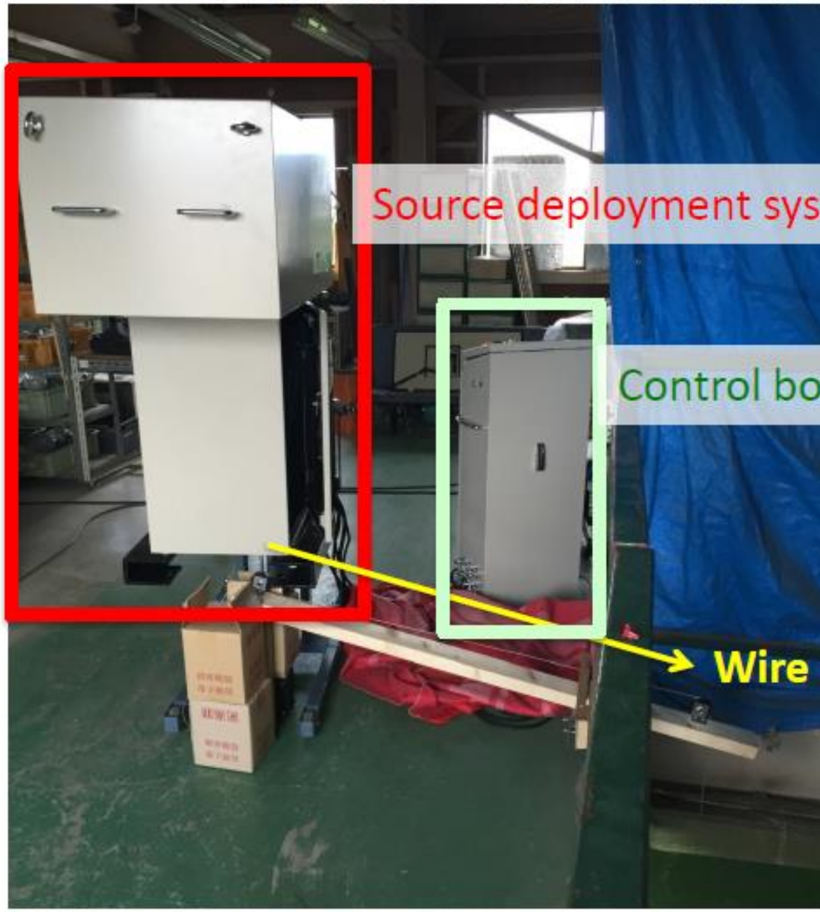
To automate calibration (Ni)

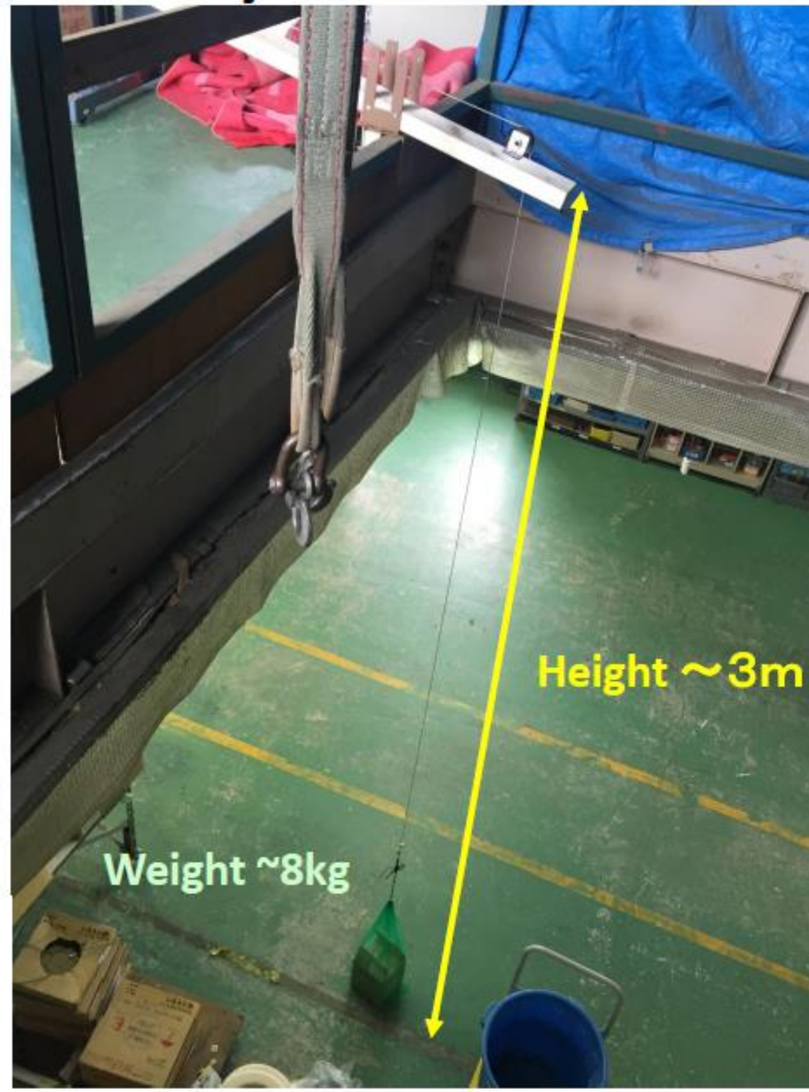
Design requirements

- **Safe for the detector**
- **Automated source deployment.**
- **Movable only in Z (vertical) direction.**
- **Position precision < ±5mm.**



Basic function & safety tests





Basic functions (lSep. 2015)
- **pull up/down weights (～8 kg)**
- **position precision < ±1 mm**

Further safety tests (planed Apr. – Jun. 2016)
- **urgent stop by emergency button & recovery**
- **Cooperation w/ tension sensor & gate valve**
- **speed control**

How do SK do it?

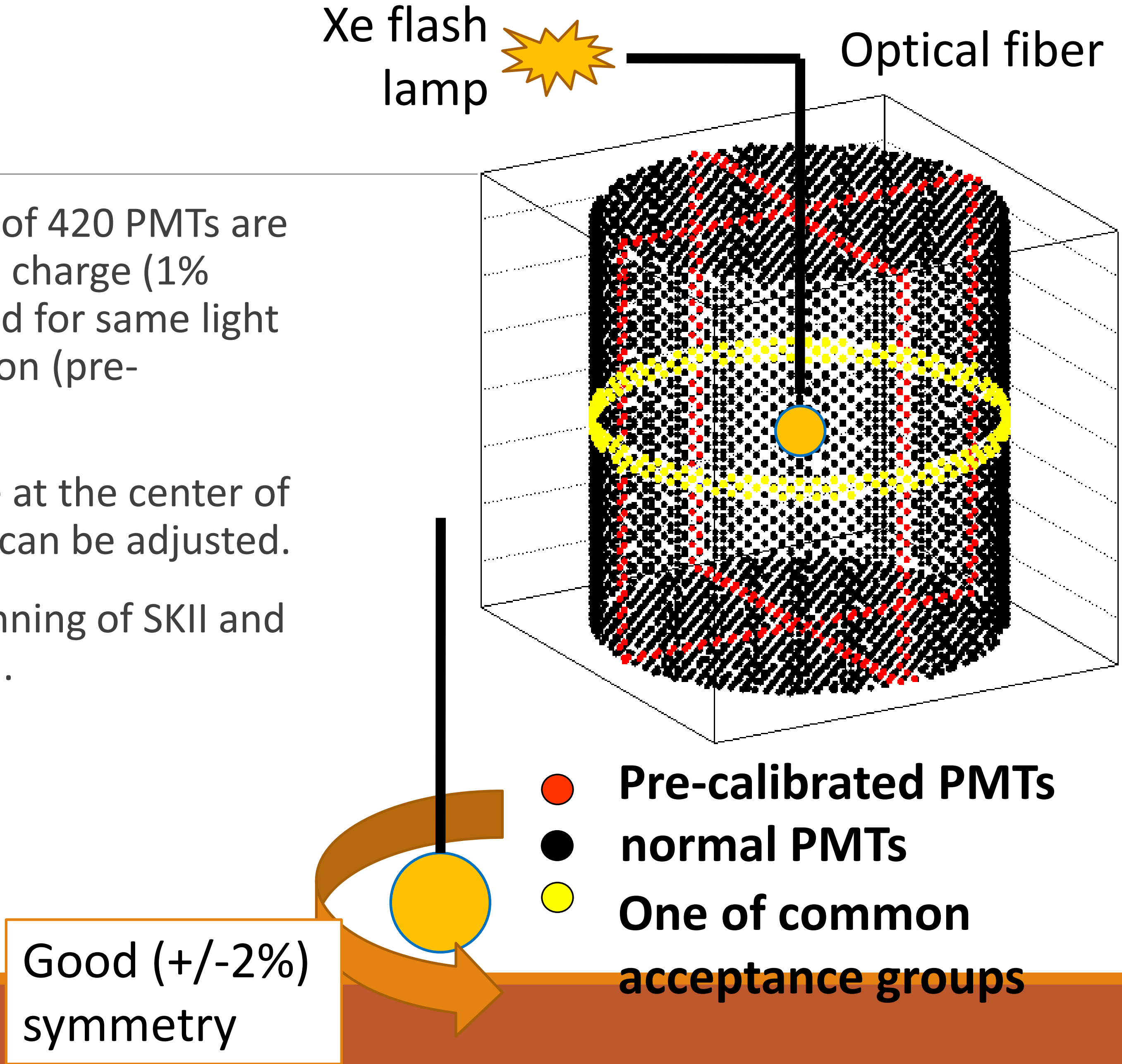
For more details see NIM A 737 (2014) 253-272

HV adjustment for each PMT

Among 11,129 PMTs, HV of 420 PMTs are determined so that same charge (1% accuracy) can be observed for same light intensity before installation (pre-calibration).

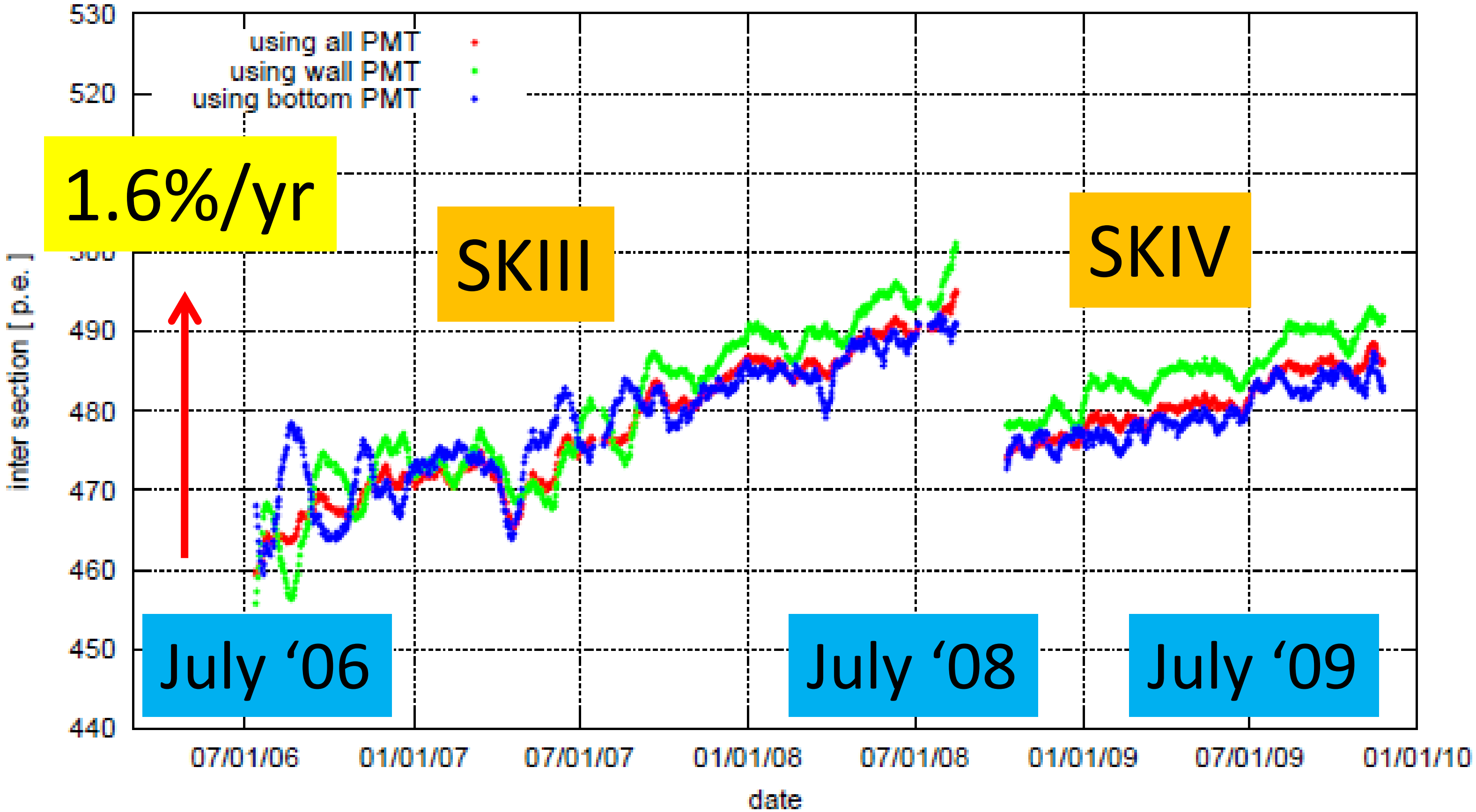
By flashing a light source at the center of the tank, other PMTs HV can be adjusted.

It was done once at beginning of SKII and once at beginning of SKIII.



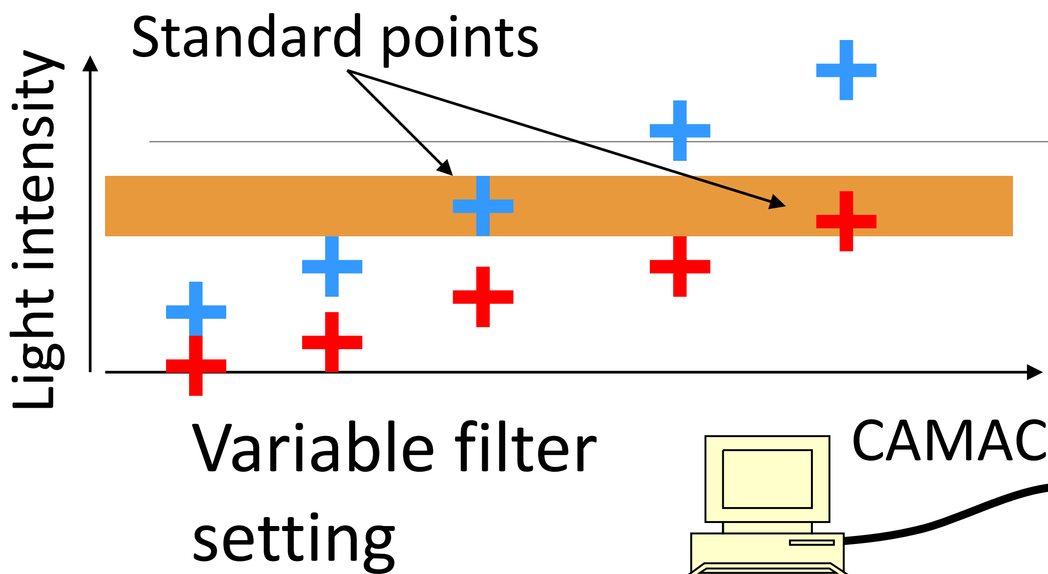
Gain drift over SKIII and IV

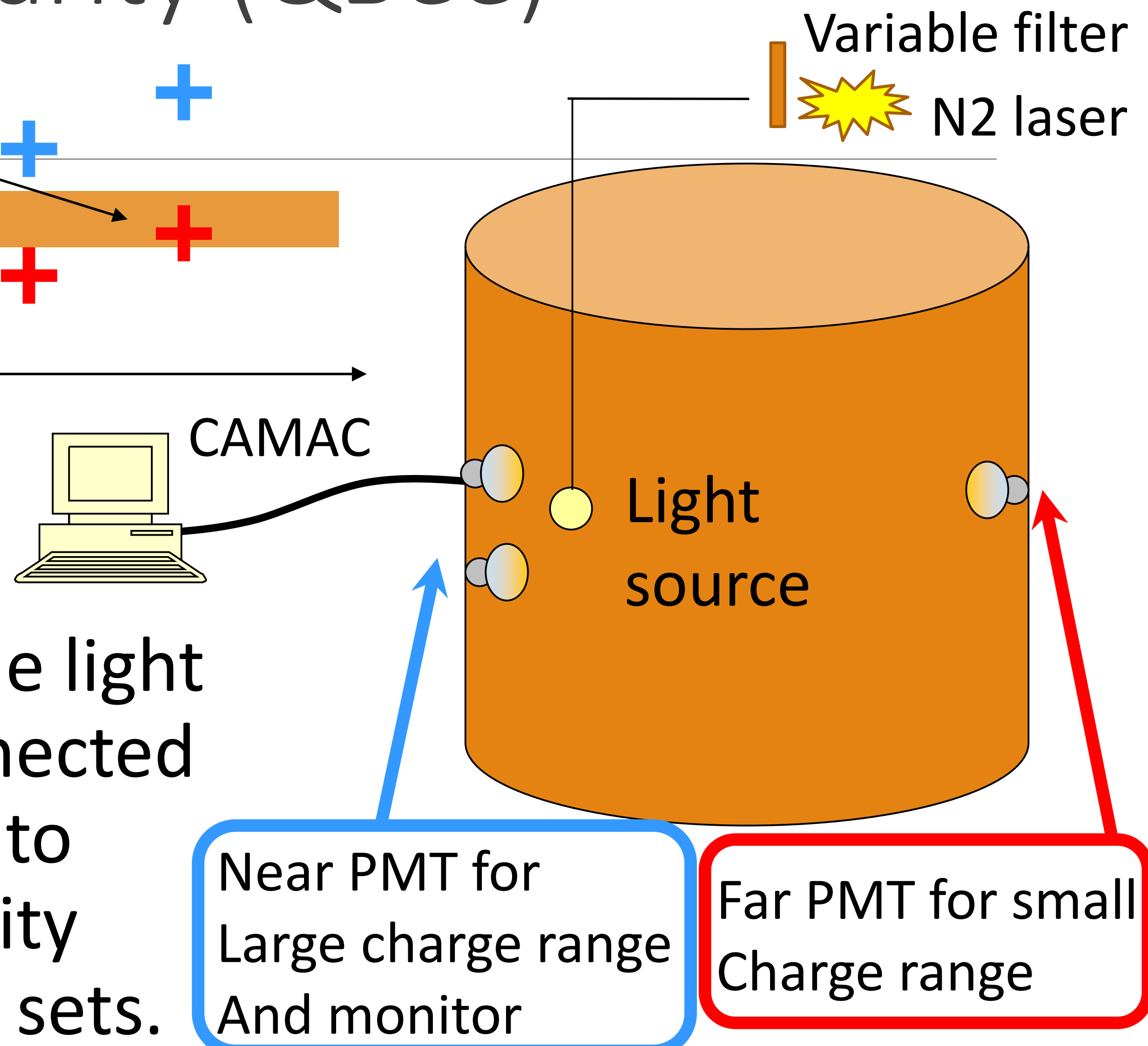
- Gain can be measured using cosmic rays.



No clear reason is known. Real data is corrected by water transparency and observed gain.

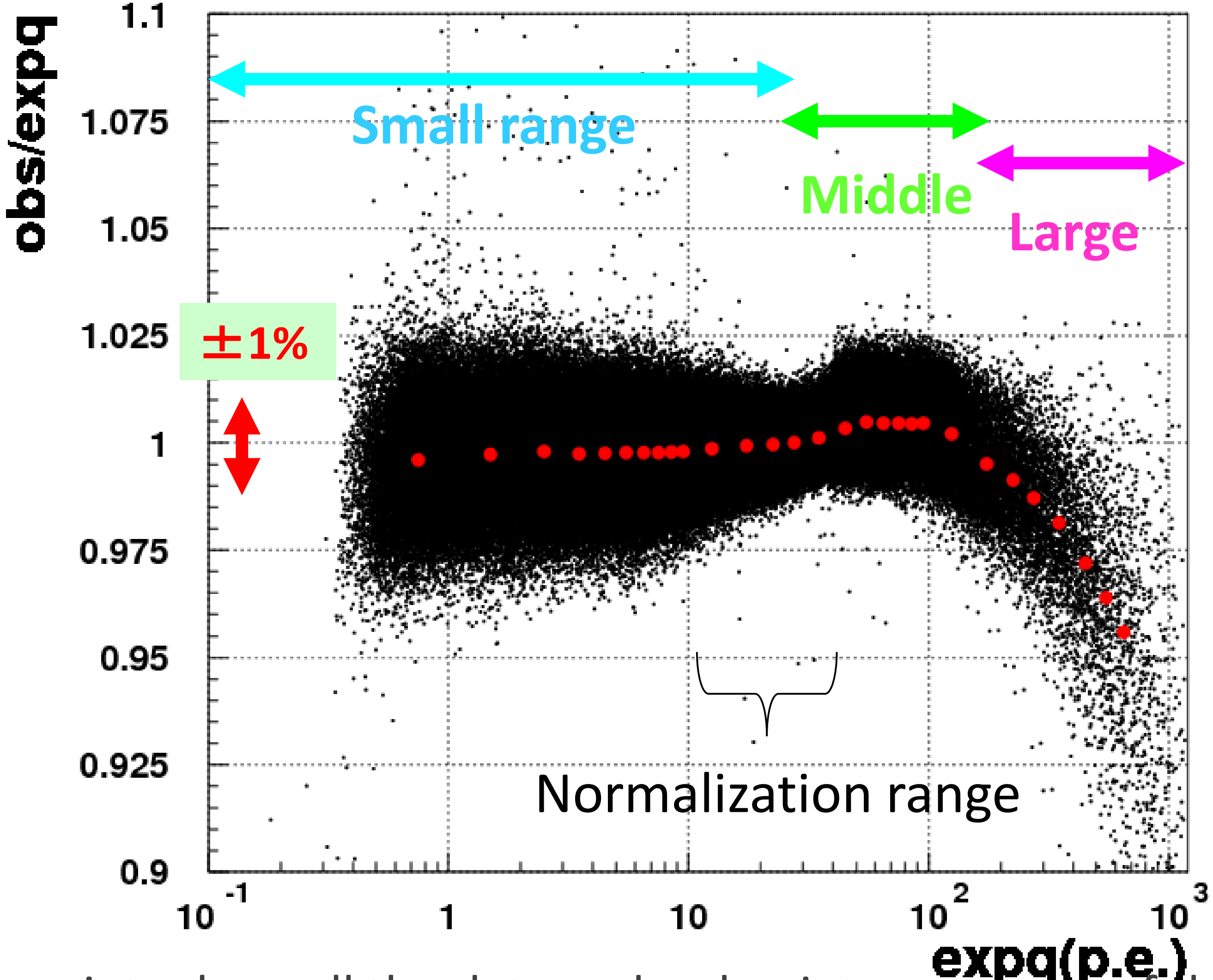
Charge linearity (QBee)





- 8 PMTs nearby the light source were connected to a CAMAC ADC to determine intensity ratio among data sets.

Results for all the channel and their mean

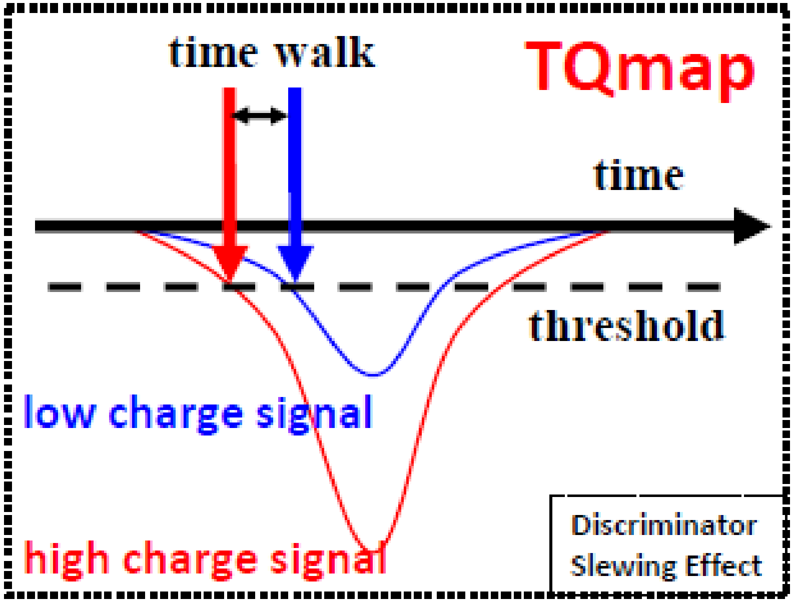


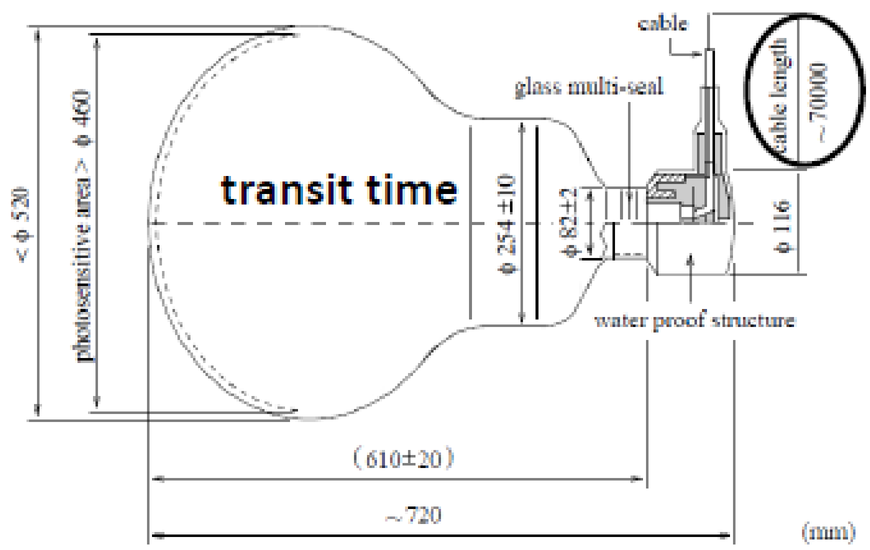
Black points show all the data and red points are mean of them.

Good linearity <100p.e. and PMT saturation can be seen above. PMT saturation is taken into account in the detector simulation.

TQ (Time and charge) mapping

- **Correction of "time offset + time walk"**
  1. **Time offset: PMT transit time and cable length**
  2. **Time walk: discriminator slewing effect**
  3. **TQmapping to get uniform timing response for each PMT**

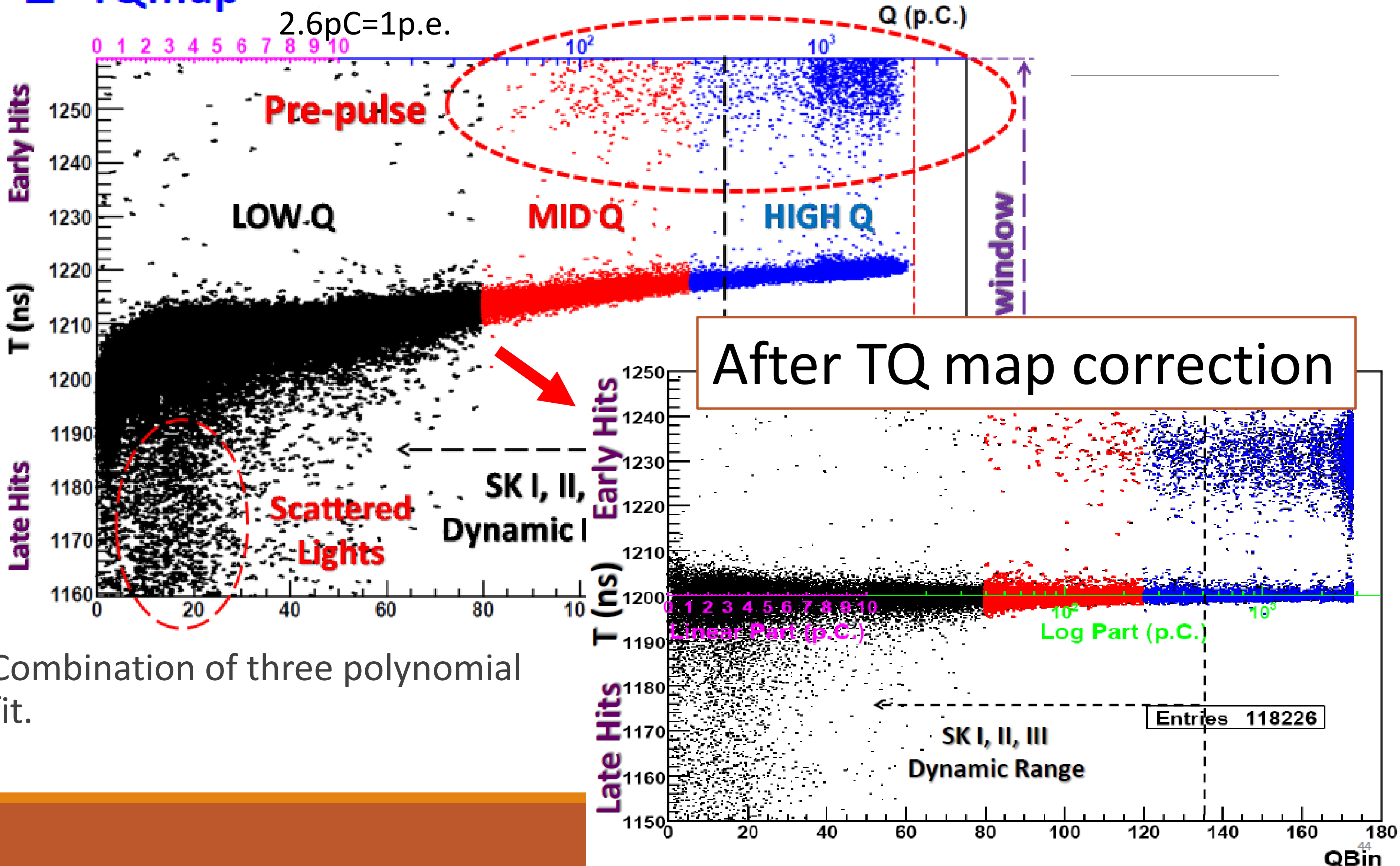




TQ map defined for each cable

- TQmap

2.6pC=1p.e.



Combination of three polynomial fit.

Relative gain measurement

Even we adjusted HV to have same charge for same intensity of light, number of p.e. is different because QE is different.

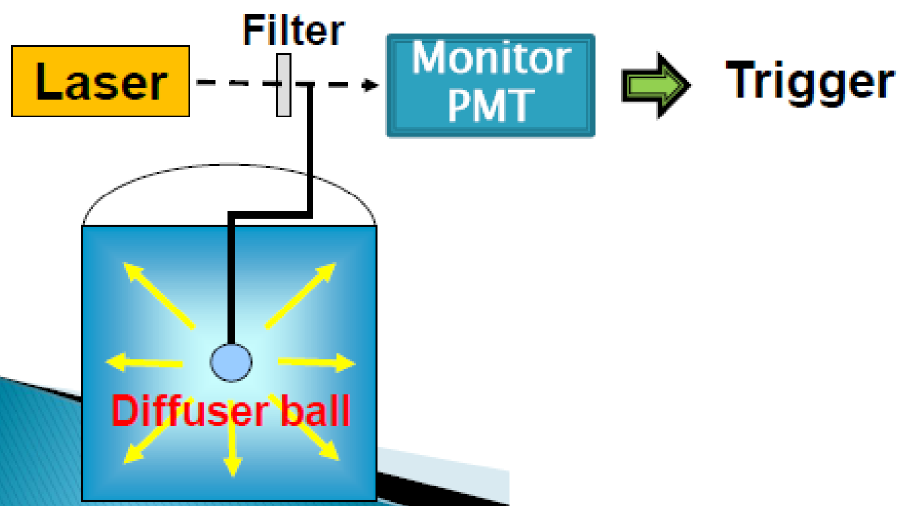
◎Method

$Qmean(i) \propto N^{photon}(i) \times QE(i) \times pC/pe \times gain(i)$

$Hit\ rate(i) \propto N^{photon}(i) \times QE(i)$

→ $gain(i) \propto Qmean(i) / Hit\ rate(i)$

◎Setup



By taking two data (one is with very dim light and one is with intense light) but same light pattern, we can measure gain for each PMT. (assuming same threshold eff.)

Ni+Cf ball

Gamma ray source

$$^{58}\mathrm{Ni}(n,\gamma)^{59}\mathrm{Ni}$$

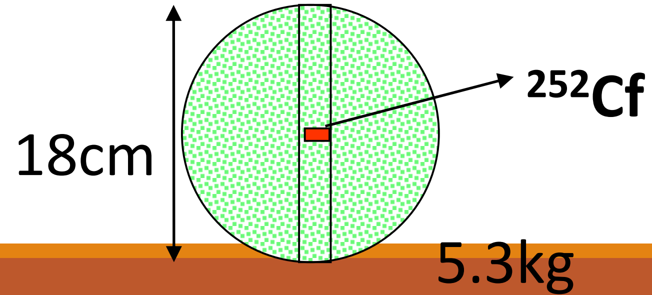
7, 8, and 9MeV γ

Symmetric source

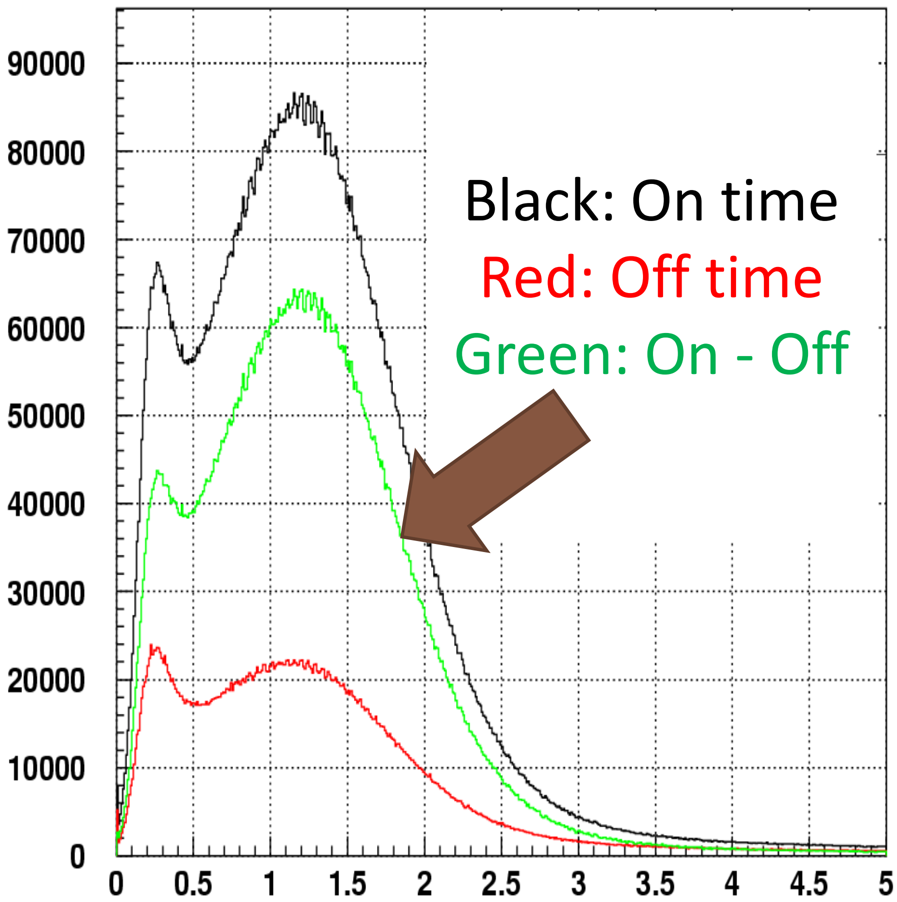
20-70hits/event

Reaction	natural abundance of Nickel (%)	capture cross section (barns)	γ energy (MeV)
^{58}Ni(n,γ)^{59}Ni*	67.88	4.4	9.000
^{60}Ni(n,γ)^{61}Ni*	26.23	2.6	7.820
^{62}Ni(n,γ)^{63}Ni*	3.66	15	6.838
^{64}Ni(n,γ)^{65}Ni*	1.08	1.52	6.098

Polyethylene pellet mixed with NiO powder bonded by Araldite epoxy resin.



Observed charge distribution



Left green distribution corresponds to the averaged SPE distribution over all the PMTs

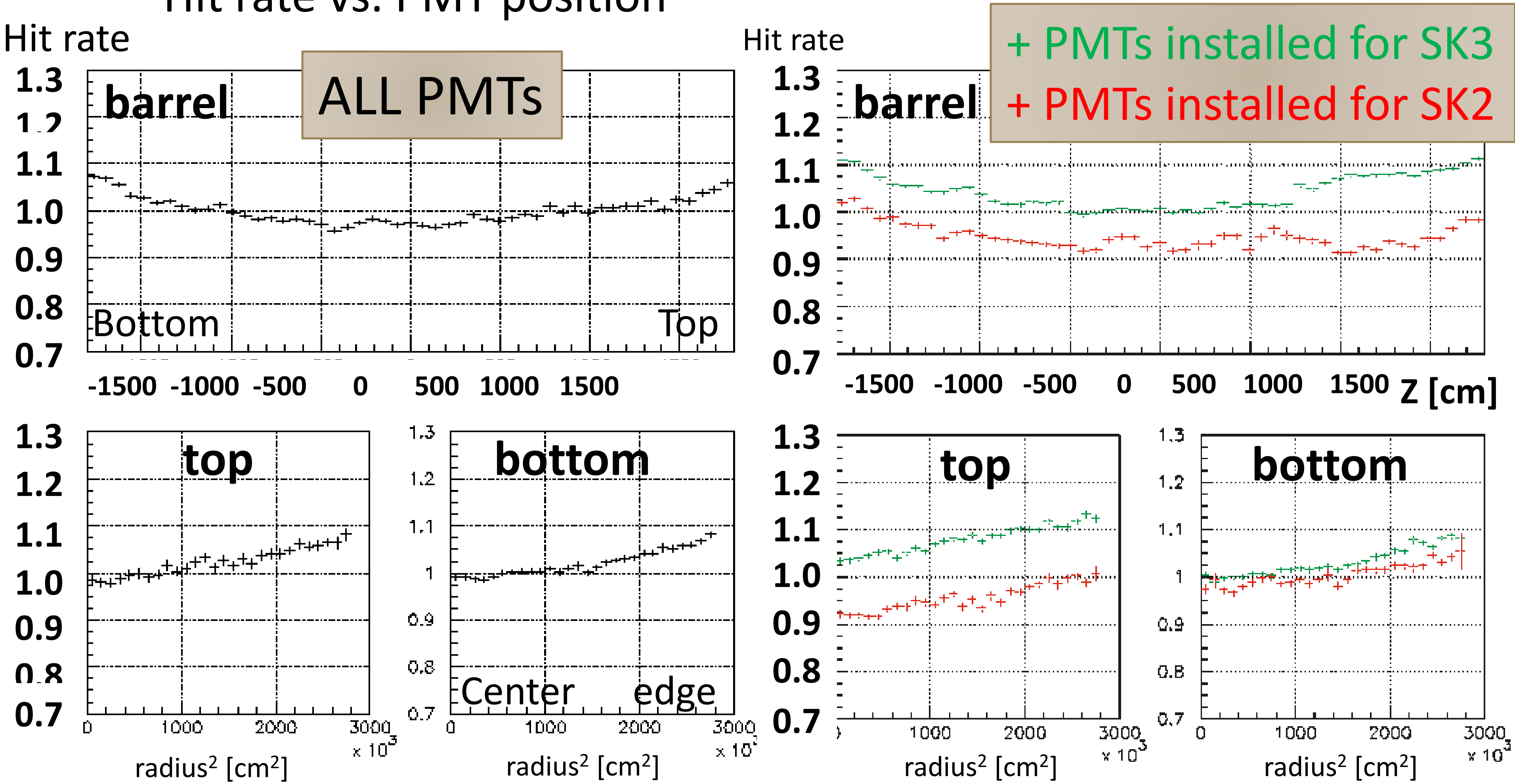
By applying higher voltage for PMTs and lowering threshold, distribution at lower part can be measured.

Extrapolation is needed for complete distribution.

Discrimination threshold is also modeled for MC input.

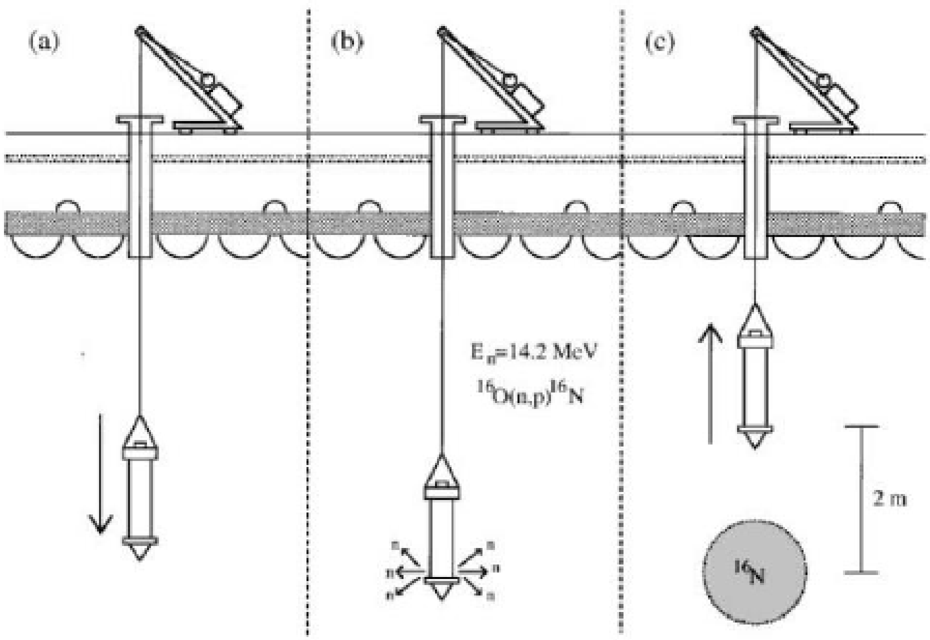
Result (SKIII, IV)

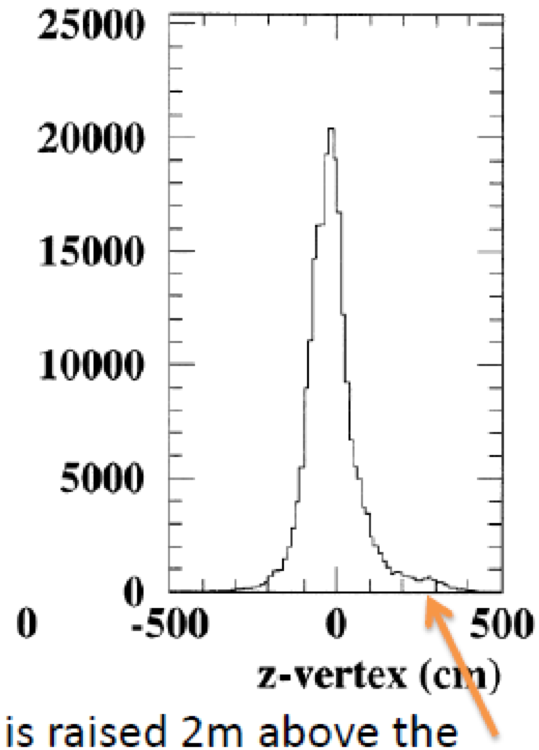
Hit rate vs. PMT position



Relative QE values are used for MC after correcting the effect of water absorption and reflection from wall.

The Super-K D-T generator : In action

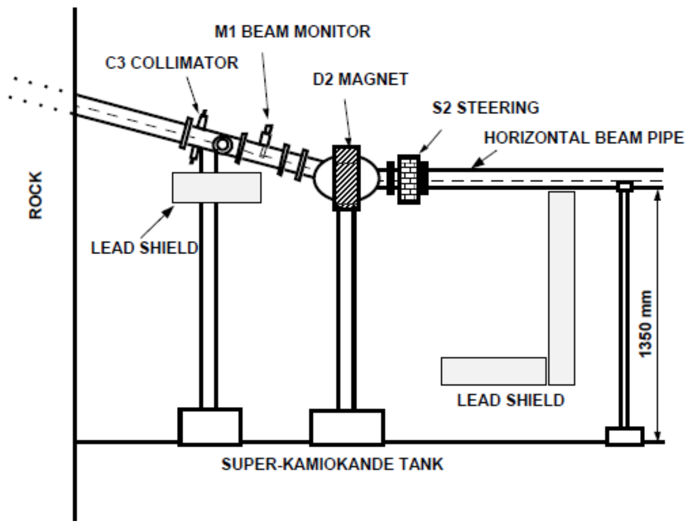


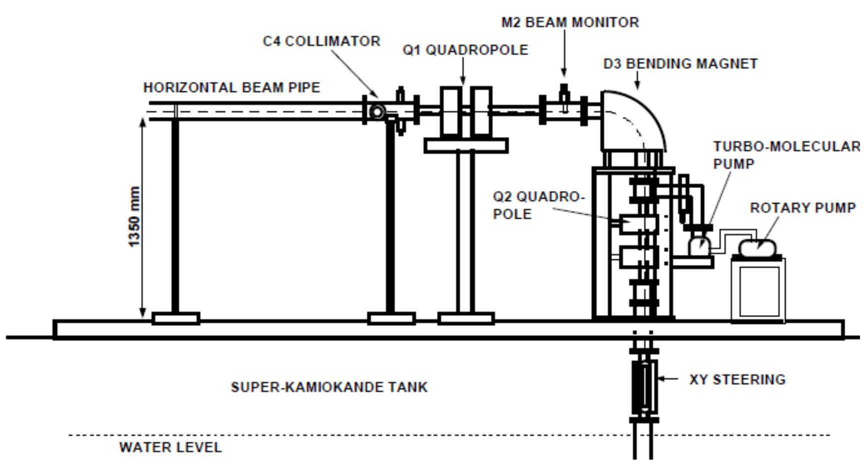


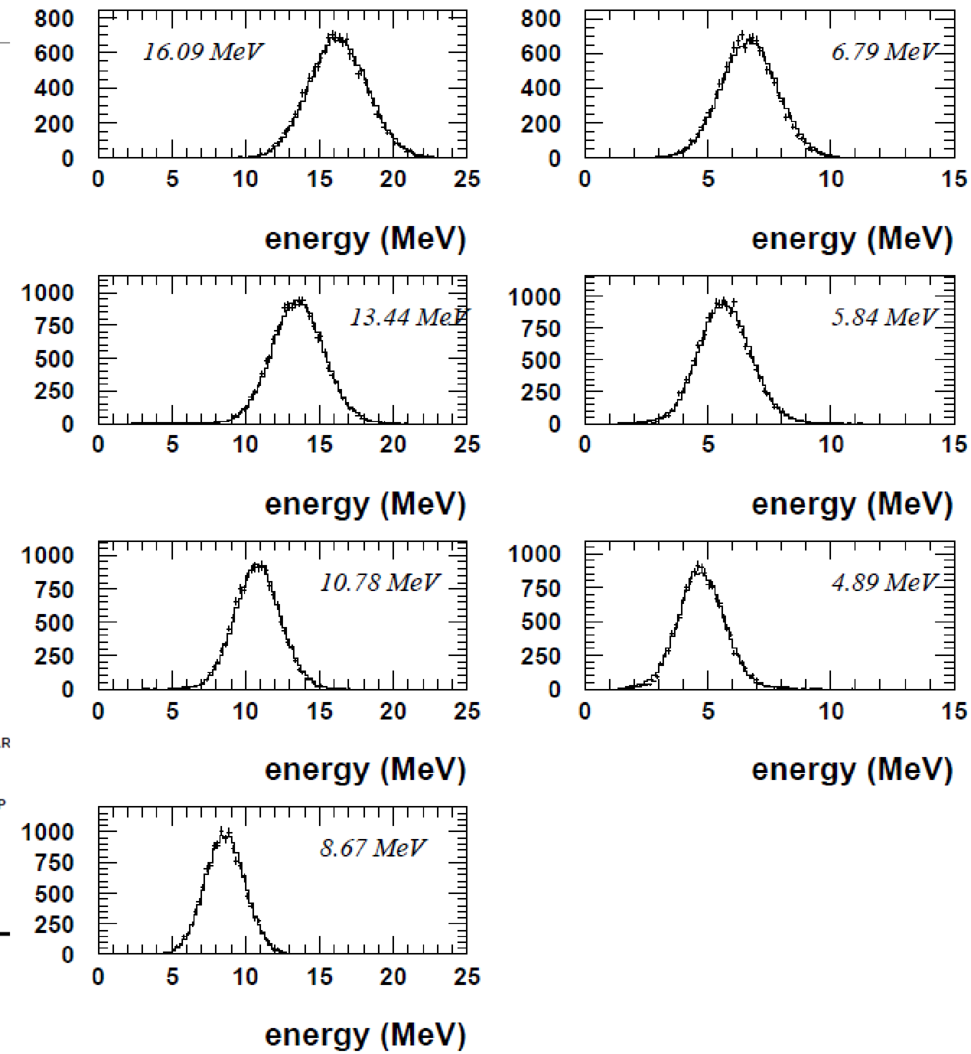
- During the calibration process the DT generator is raised 2m above the original fire position to reduce shadowing/interaction with the device
  - Basically unavoidable
- Causes diffusion of events along axis of this motion as water is displaced
- Range of utility in the vertical direction is limited
- Device is not so mobile

R. Wendell

LINAC


M1 BEAM MONITOR
C3 COLLIMATOR
D2 MAGNET
S2 STEERING
HORIZONTAL BEAM PIPE
ROCK
LEAD SHIELD
1350 mm
LEAD SHIELD
SUPER-KAMIOKANDE TANK


M2 BEAM MONITOR
C4 COLLIMATOR
Q1 QUADROPOLE
D3 BENDING MAGNET
HORIZONTAL BEAM PIPE
TURBO-MOLECULAR PUMP
Q2 QUADRO-POLE
ROTARY PUMP
1350 mm
SUPER-KAMIOKANDE TANK
XY STEERING
WATER LEVEL


16.09 MeV
6.79 MeV
13.44 MeV
5.84 MeV
10.78 MeV
4.89 MeV
8.67 MeV
energy (MeV)
energy (MeV)
energy (MeV)
energy (MeV)
energy (MeV)
energy (MeV)
energy (MeV)

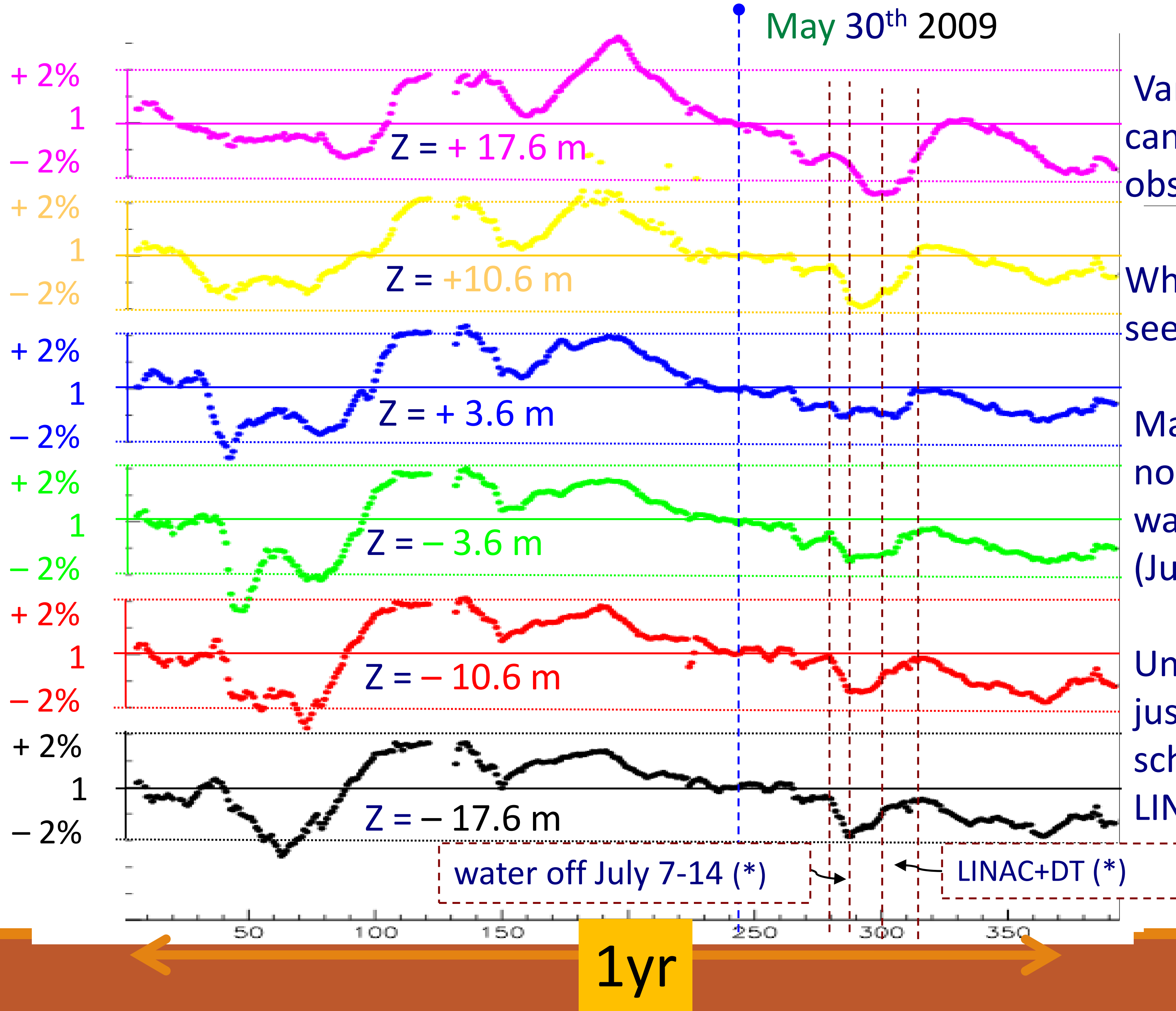
Auto calibrations and xenon/LED

Every ~1 second, TQ laser data, xenon flash, LED light, and water scattering laser lights are injected by turns even in normal runs.

Xenon/LED is important for finding anomalous PMTs, such as low gain, high gain, unstable PMTs and so on. It is also useful for monitoring position dependent water quality.

Since time variation and the position dependence of water quality is a big concern in the Super-K analysis, we utilize these data to derive useful information.

Auto xenon data shows detail behavior along the detector:



Variation +/-2% can be easily observed.

What we can see:

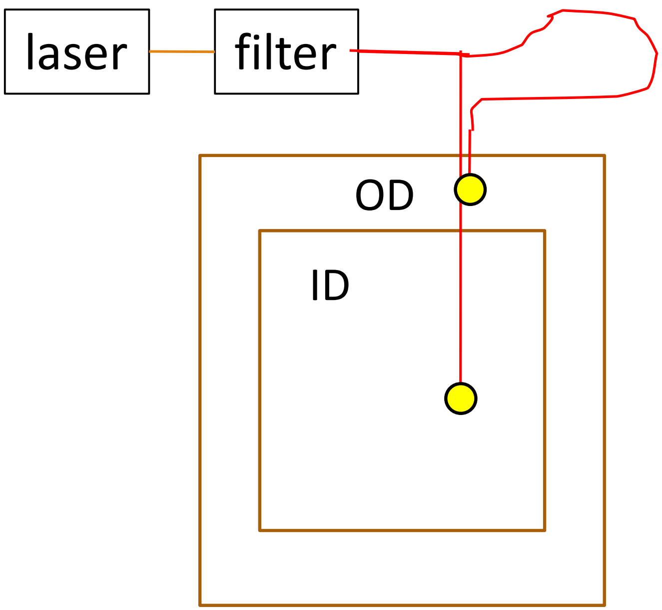
Main source of non-stability: water syst. off (July 7-14).

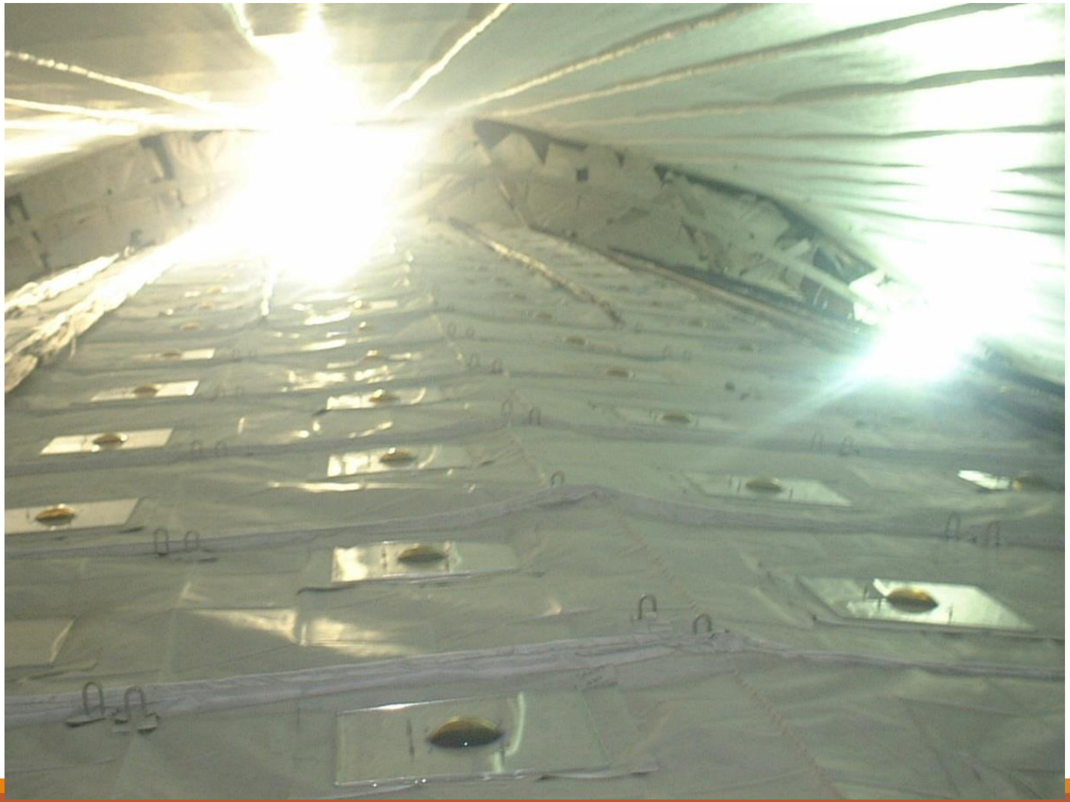
Unfortunately just before the scheduled LINAC calib.

OD calibrations (1,885 PMTs)

Timing offset adjustment: T(ID)-T(OD)~5ns

- Table of cable length
- Confirmation (with correction) with a laser ball





Improvements for HK

Potential new sources

^{16}N two options 6MeV γ + βs

- DTG neutron source deployed directly into the detector.
  - SK Style - may be a problem with Gd
- Activate CO_2 with DTG neutron source and flow gas into detector.
  - SNO style.
  - Tagged γs
- Neutron Sources
  - ^{252}Cf
  - AmBe
  - Neutristor
- Improved optical sources

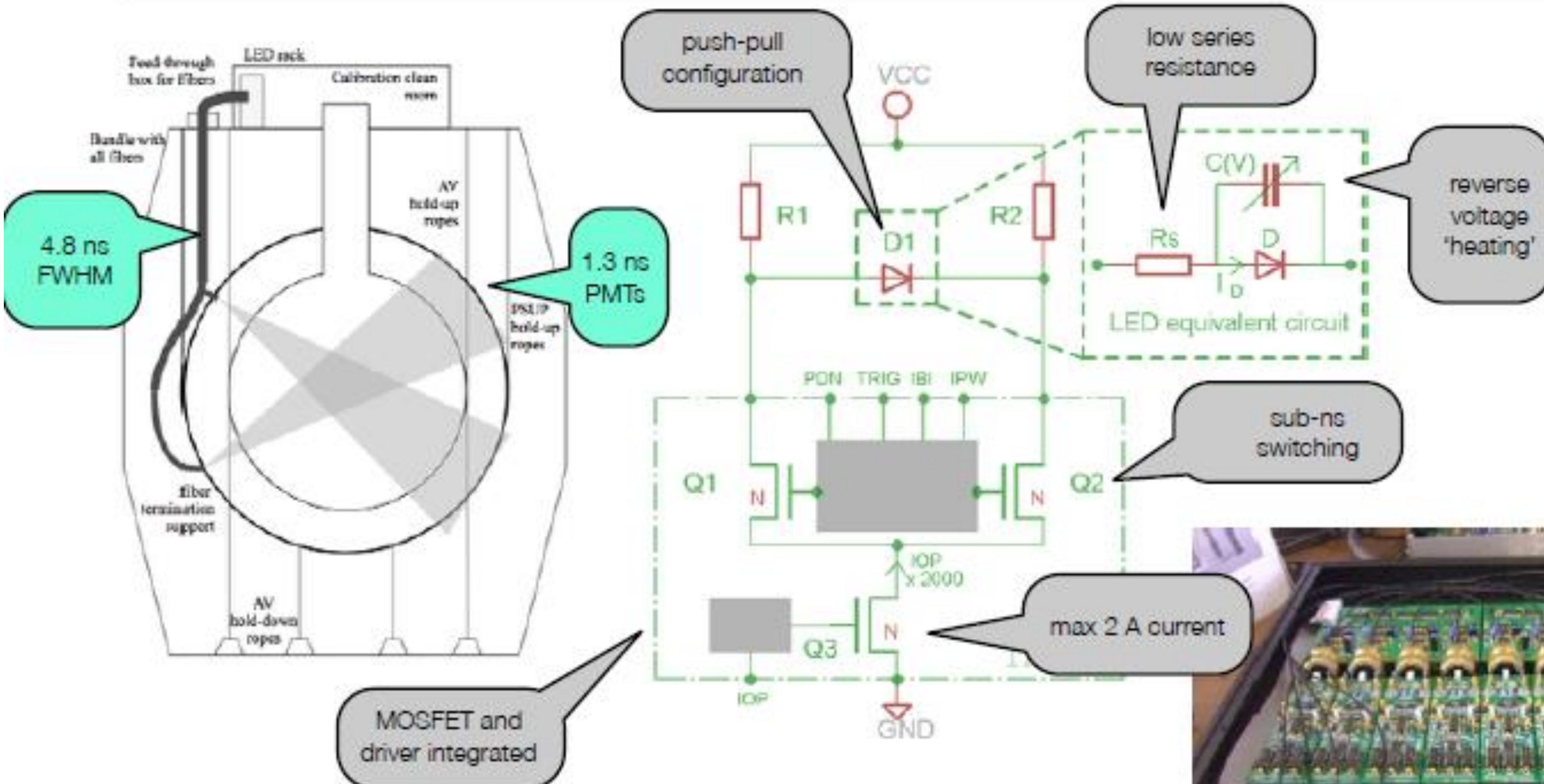
LED Pulsers

Use an LED rather than a laser as a light source.

Advantages
- Cheap per channel cost. (~£10 for LED and basic driver electronics)
- Compact device possible
- Stable wavelength distribution ~ 10 nm spread
- Wide range of wavelengths available
- ~1 ns pulses possible.
- Simple coupling to fibres

Disadvantages
- Higher current requirements
- Large light loss into fibres.

LEDs in SNO+



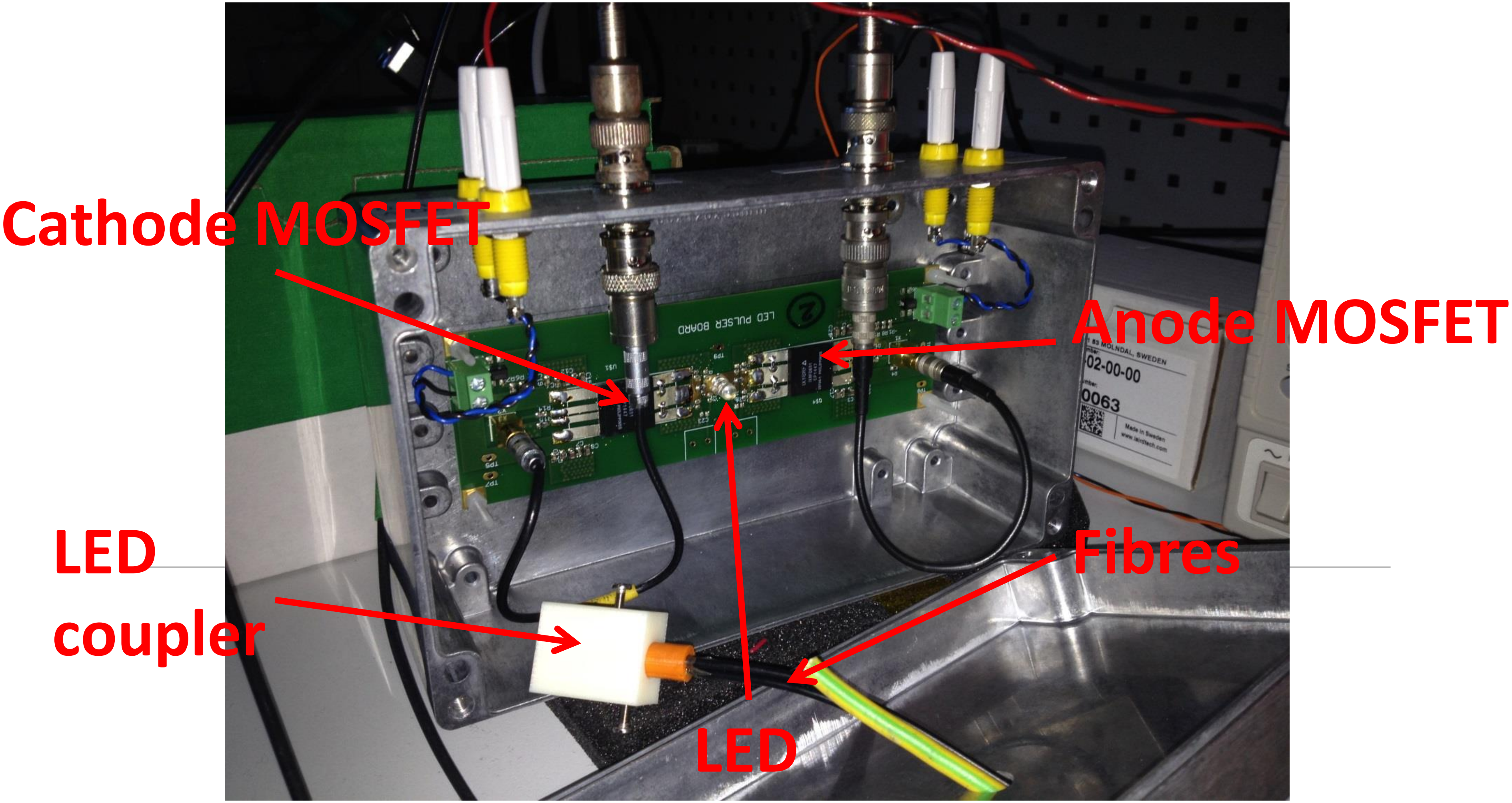
Original design requirement (LED end):
> **10^6 photons per pulse**
– **1 ns optical pulse width**

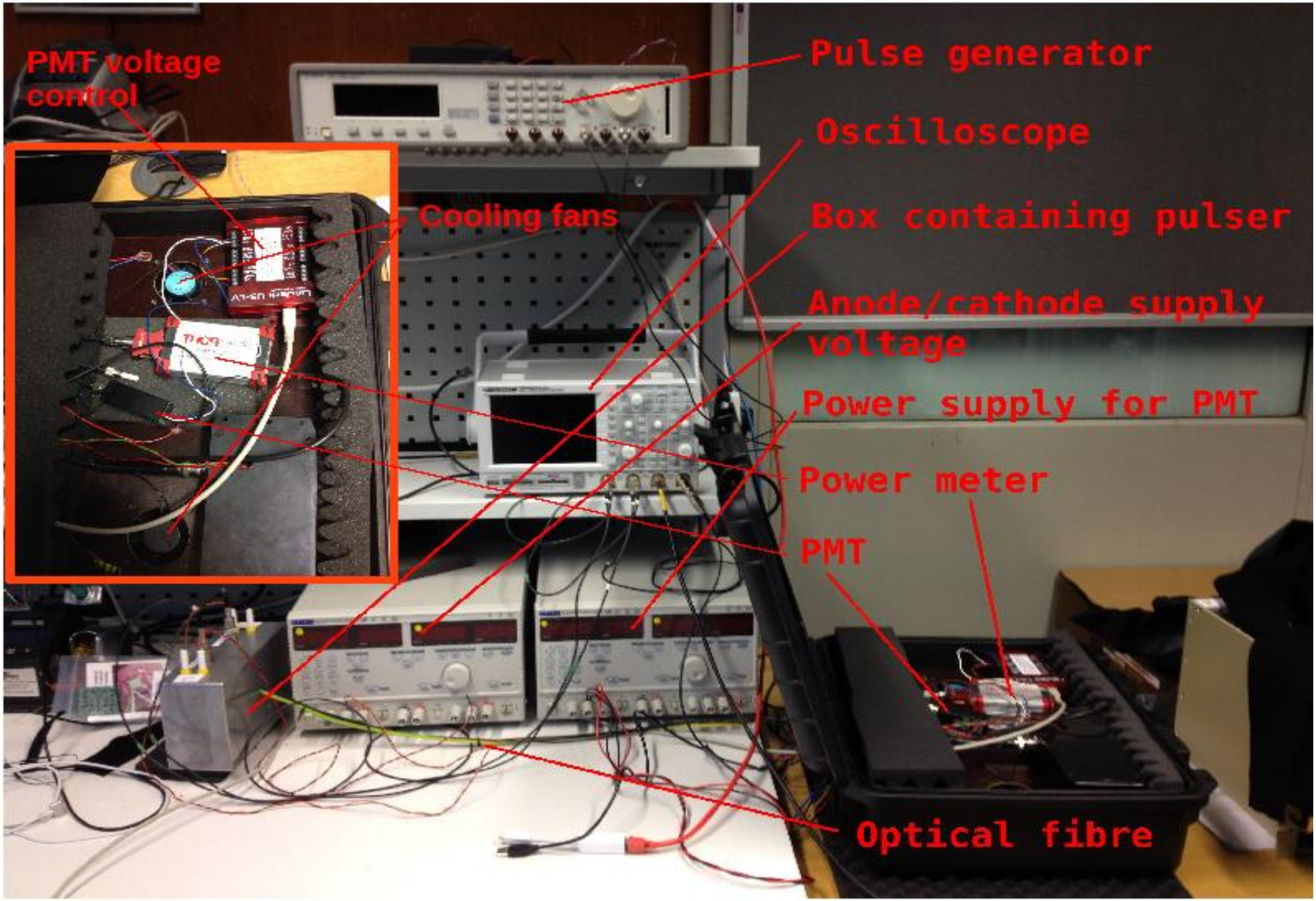
Later additional requirement (wet end):
10^3 photons per pulse (stable) at
1 pulse per second repetition rate

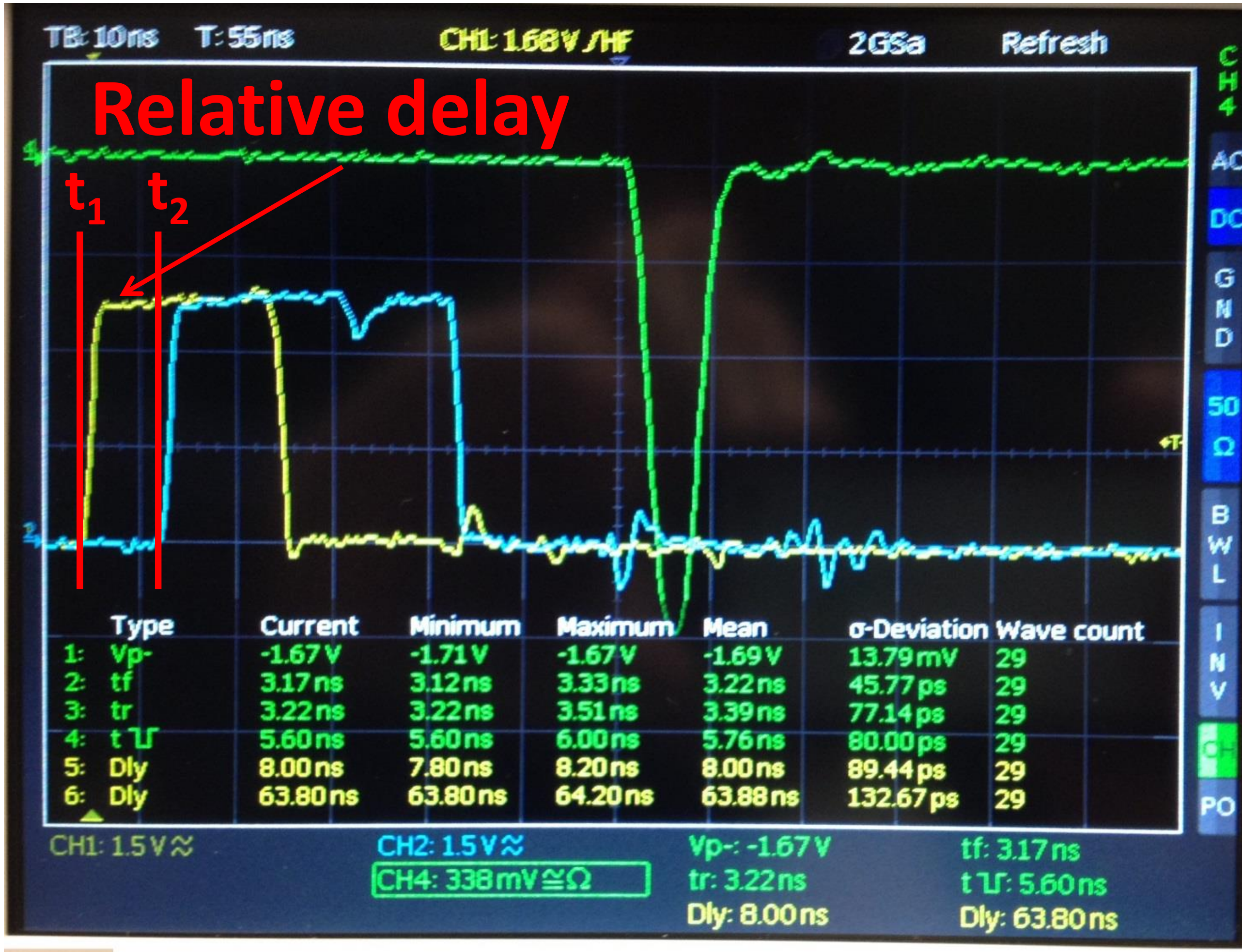
Updated LED drivers for HK

- Improved system for HK
- Longer fibre paths required
- Look for
  - Improved timing performance
  - Intensity control
  - Improved fibre coupling
    - Required as step index fibre will be necessary
  - Optical diffusers to control light into the detector

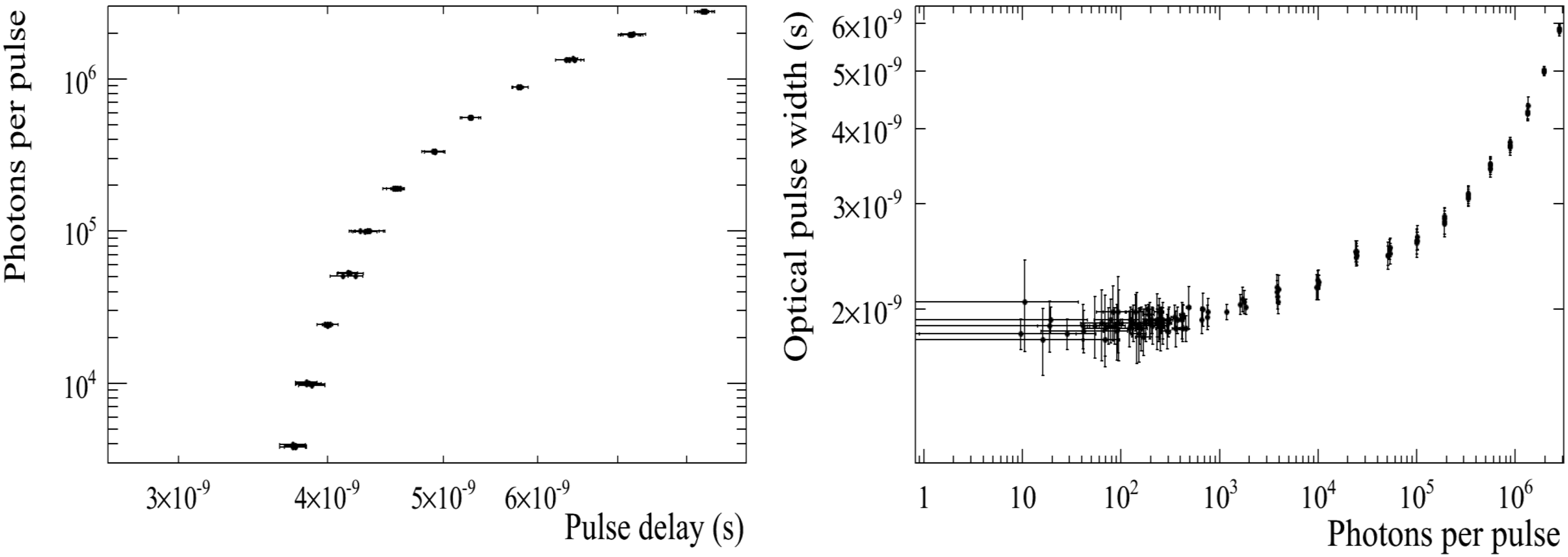
LED Quad-Mosfet Board




PMT voltage control
Cooling fans
Pulse generator
Oscilloscope
Box containing pulser
Anode/cathode supply voltage
Power supply for PMT
Power meter
PMT
Optical fibre

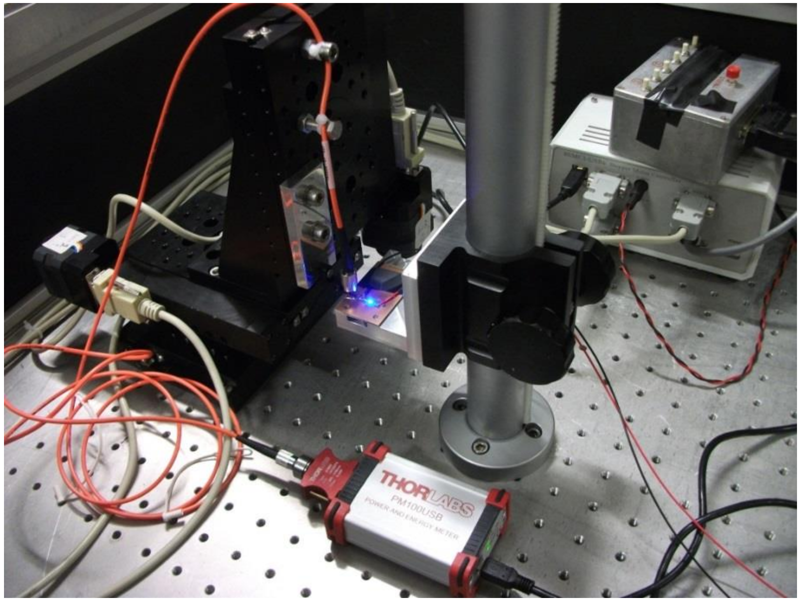


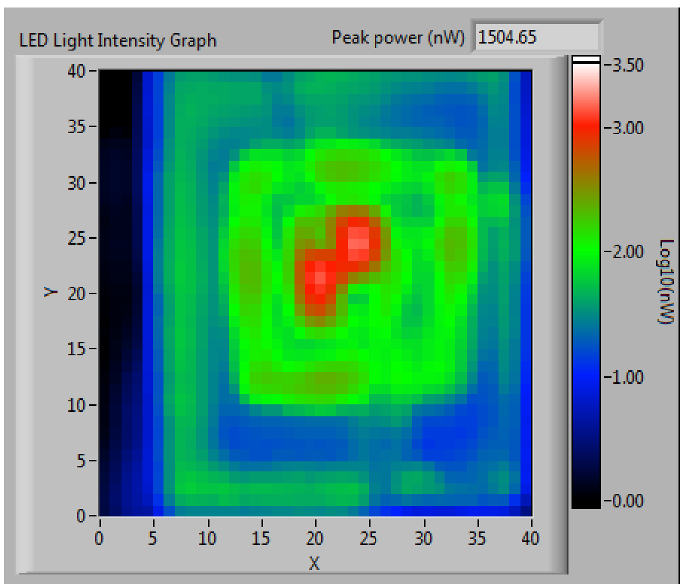
- Anode pulse at time t_1, forward current through LED, begins emitting photons
- Cathode pulse second at time t_2, reverse current through LED
- Charges swept out of depletion region, LED off
- Pulse width controlled by anode/cathode voltages



- Photons per pulse controlled by the relative delay between the anode and cathode pulses

- Generally good performance, pulse widths of <3ns at 100,000 photons/pulse





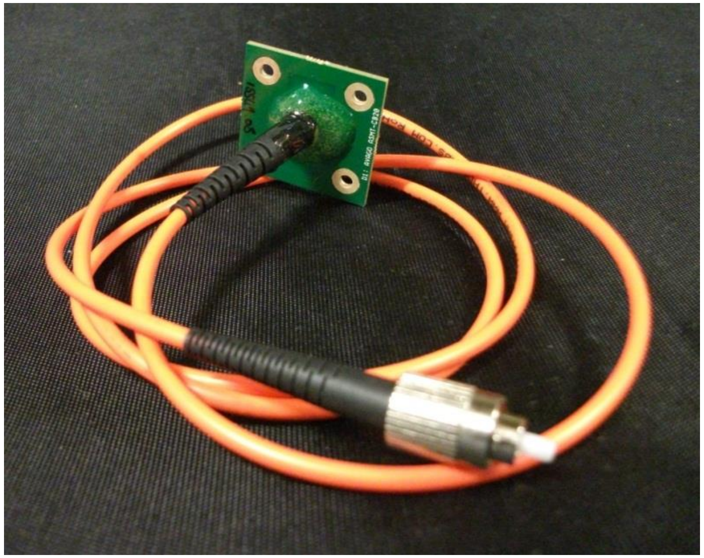
- LED light must be captured in fibre
- Fibre diameter is only 62 µm.
- LED chip is typically 200 µm square.
- Therefore must understand the emission from the chip and be close up and well aligned to capture a useful fraction of emitted photons

- Use 3 orthogonal rotary stages to scan fibre over LED
- Use a power meter to measure intensity profile

- Fibre must then be fixed in best location to capture light

Glued Version

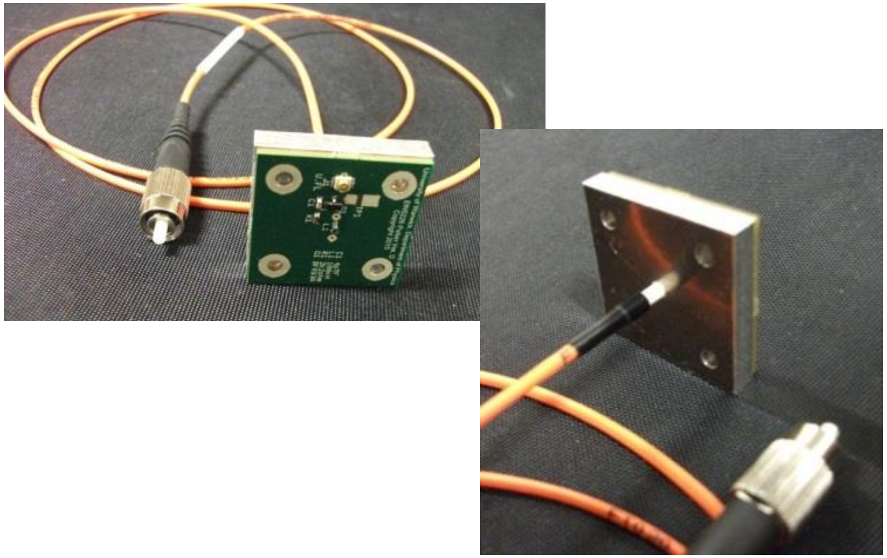
Align fibre to card with stages, searching for brightest spot, then glue in place.



The following results mostly used this version.

Template Version

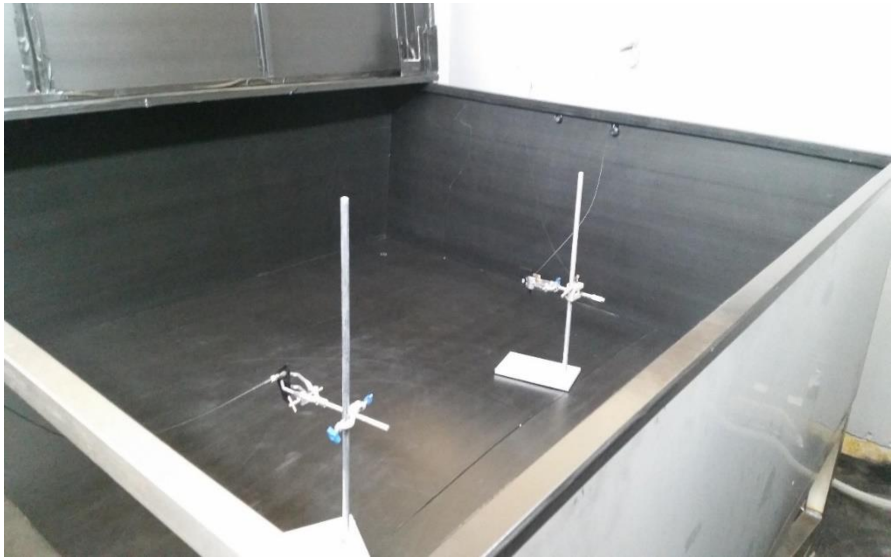
Use precise template to align fibre ferrule relative to LED using the four holes in the PCB.



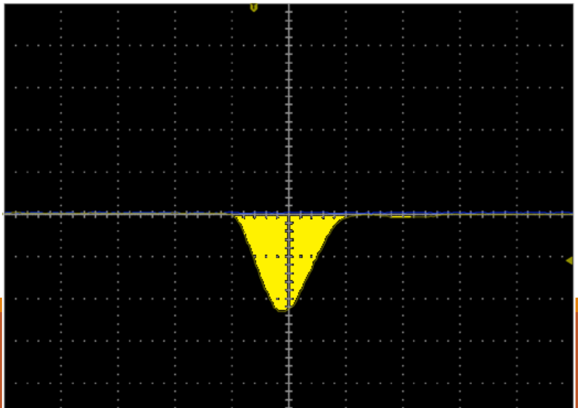
This version is probably more suitable for a large scale system.

Liverpool Test tank

Tank to test optical distribution from fibres and diffusers.



First light seen in air test

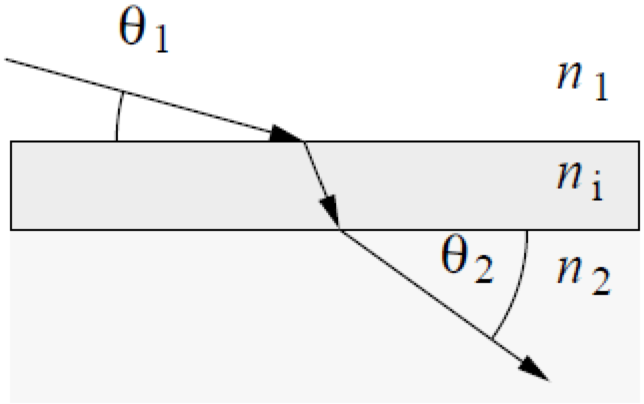


A fake muon source

A source to simulate muons and test reconstruction.

A narrow transparent tube with a light source producing almost parallel light at one end.

Light emitted at the Cherenkov angle.

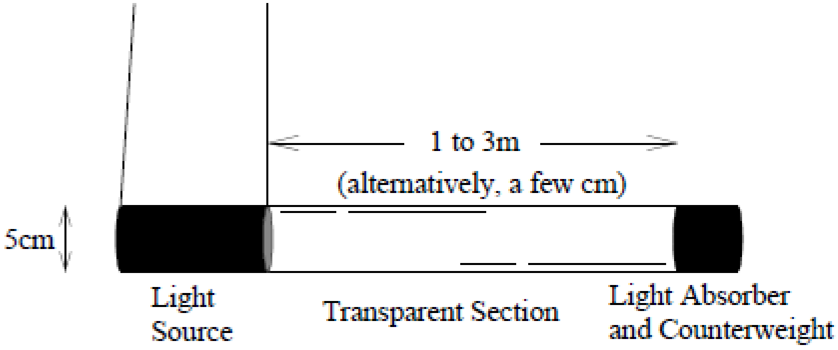


$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

independent of n_i

As $\theta_1 \rightarrow 90^\circ$ $\sin(\theta_2) \rightarrow 1/n_c$

Light emitted at Cherenkov angle.



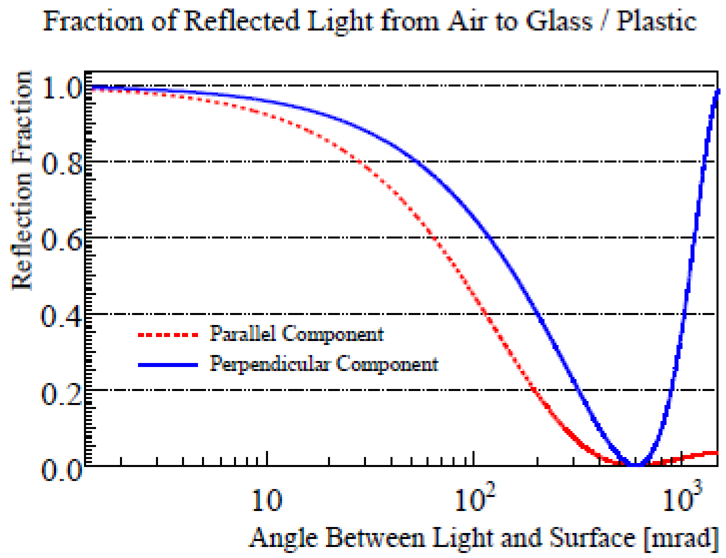
Plans for a muon source

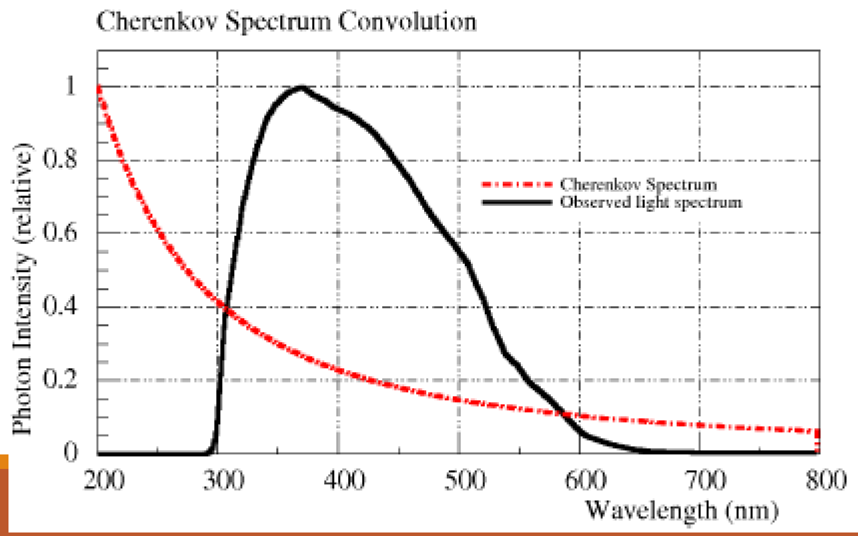
Produce a short source for testing.

Use multiple LEDs to "cover" range of Cherenkov spectrum

Plan to

- Test angular distribution
- Tune LED intensity
- Test light deployment and absorption methods.





Conclusions

Calibration will be critical to meet the physics goals of HK

A wide a varied program will be required

Light sources

- LED pulsers being pursed in the UK

Radio active sources

Calibration infrastructure

Plenty of scope for people to get involved involvement.