Improvement and Modelling for the Output Linearity of the Photomultiplier-Tube for High-Precision Neutrino Measurement

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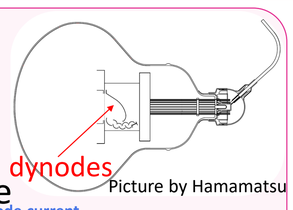
Motivation:
Hyper-Kamiokande (HK) is a water-Cherenkov detector with 40,000 photomultiplier-tubes (PMT), which plans the operation in 2027.
Photon counting performance of the PMTs is important for high-precision measurement.
The charge output of PMT is not perfectly linear to the number of photons, which is difficult to be corrected if it is varied by some factors.

Two approaches { **1. To suppress the individual differences**: **Improvements of PMT base bleeder circuit**
2. To calibrate the individual non-linearity: **A trial of modelling non-linearity response**

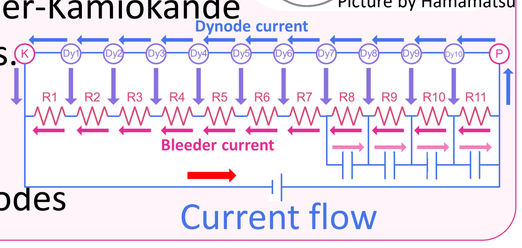
Purpose: To improve energy reconstruction for high-precision measurement → aiming at 1 % of photon counting accuracy

20-inch HK PMT (R12860 by Hamamatsu):

* 20-inch HK PMT has 10 dynodes with a typical gain 1×10^7 at 2000 V.
* The linearity of HK PMT is worse than Super-Kamiokande PMT due to different structure of dynodes.



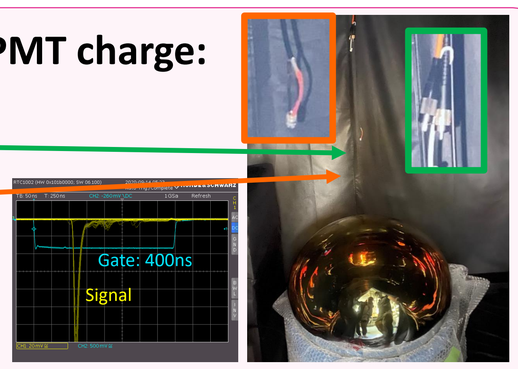
Picture by Hamamatsu



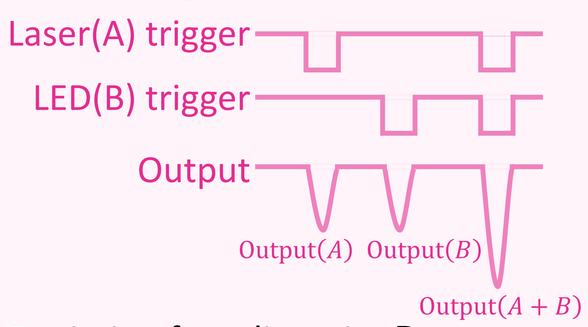
Sources of the non-linearity[*1]:
1. Deviation of voltage at each dynode
2. Saturation of space charge between dynodes

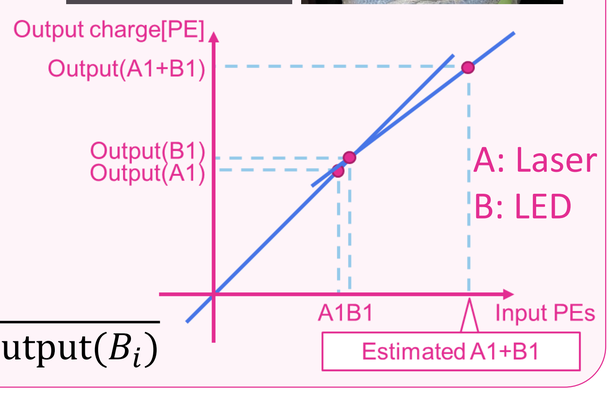
Setup of evaluating non-linearity by PMT charge:

* Used two light sources:
  Laser (λ: 405 nm, pulse width: 1 ns)
  LED (λ: 465 nm, pulse width: 2.5 ns)



Data taking:



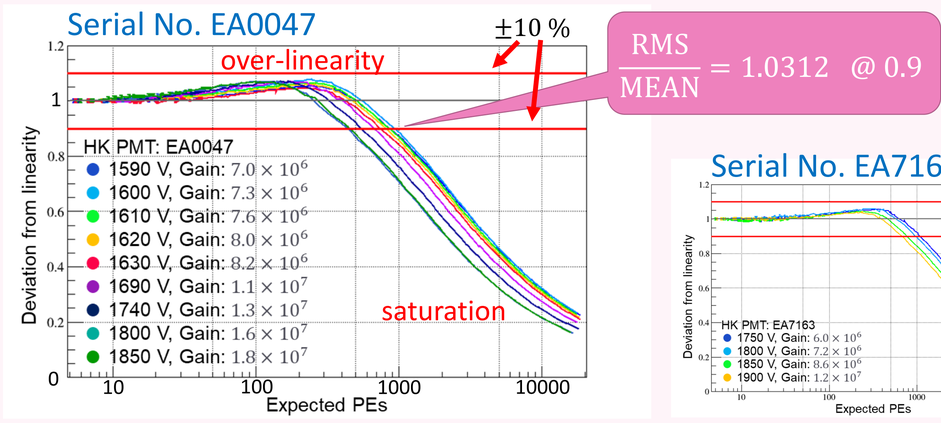


Deviation from linearity D_i

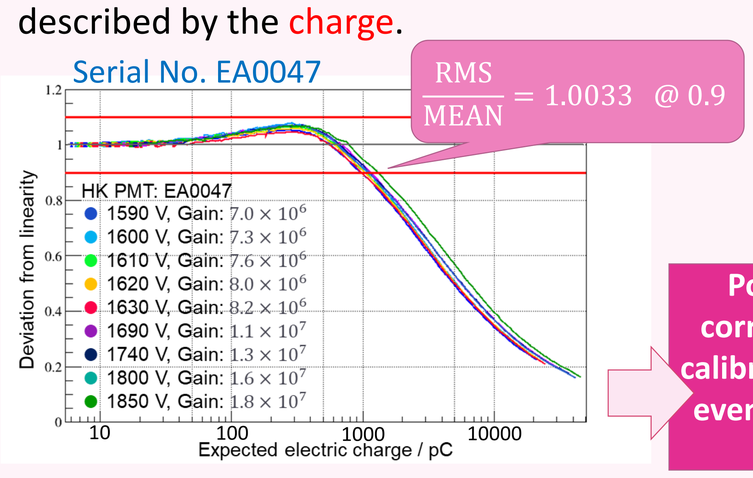
$$D_i = \frac{\mathrm{Output}(A_i + B_i)}{D_{i-1} \times \mathrm{Output}(A_i) + D_{i-1} \times \mathrm{Output}(B_i)}$$

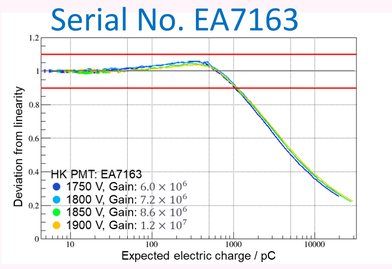
Linearity of different HV:

* Measured the deviation from linearity at two 20-inch HK PMTs
* Deviation from linearity has over-linearity and saturation.



* The non-linearity curves as a function of photo electrons (PEs) are varied among different HV set, that can be more uniform if it is described by the charge.





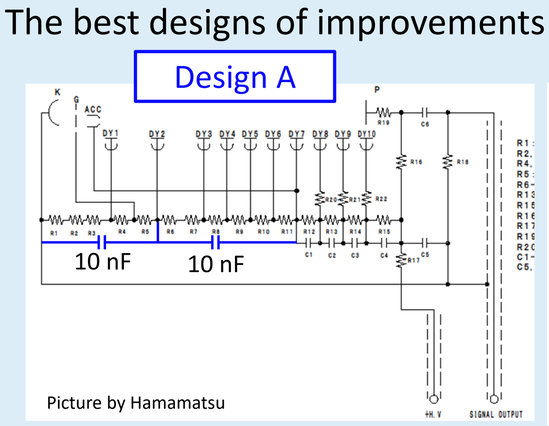
Possibility to improve the correction of non-linearity by calibration using charge amount even with as a single response curve

If the non-linearity is varied by each PMT, it is difficult to correct non-linearity to achieve the 1 % of accuracy.

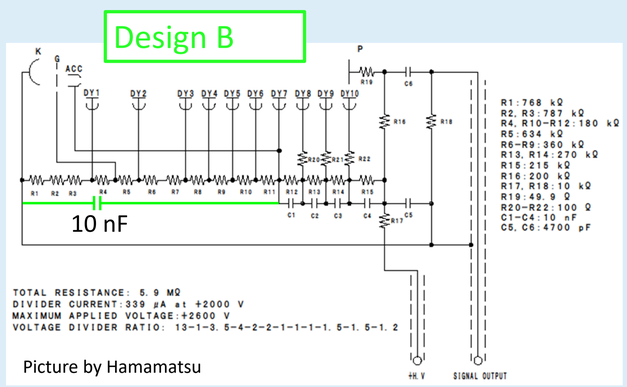
To suppress the individual differences…

Improvements of bleeder circuit:

* Motivation
  * To suppress the individual differences of over linearity
* Bleeder circuit:
  current through bleeder resistors determines the voltage at each dynode
* The best designs of improvements in 10 trials

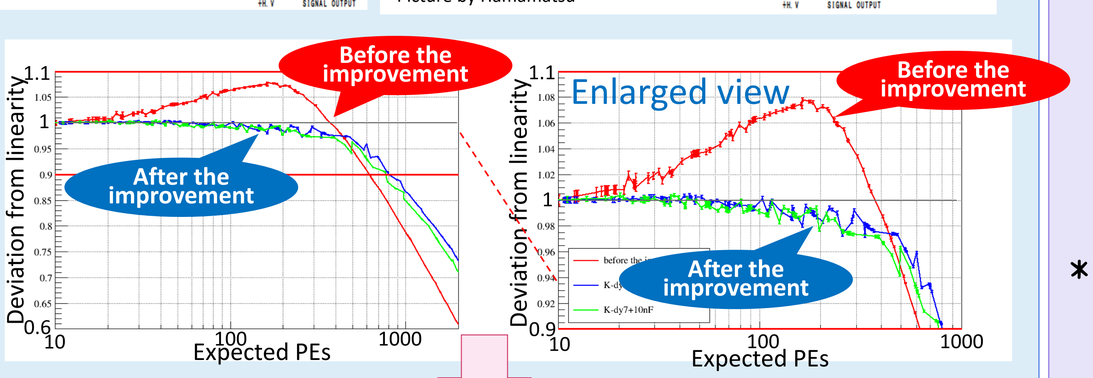


Picture by Hamamatsu



Picture by Hamamatsu

* Result
  * EA0047
  * 1690 V



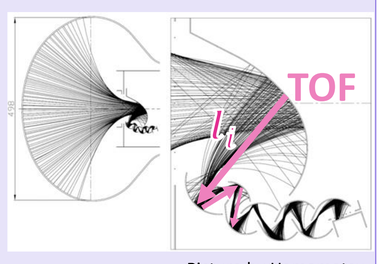
Suppressed the over linearity

* Ongoing investigation to decide adoption to the HK PMT
  * The effect of electromagnetic field and position of incidence
  * The individual differences of degree of improvement

To calibrate the individual non-linearity…

Trial of modelling of non-linearity responce:

* Motivation
  * To predict the individual variation
* Assumptions
  * The amplification factor at i-th dynode ($\mu_i = aV_i^k$) is changed by the voltage which is varied by bleeder and dynode current.
  * The parameter a and k: estimated by fitting EA0047 measured data
  * TOF: $t_i = l_i\sqrt{m_e/(e \times V_i)}$ l_i: dynode distance
* LTSpice



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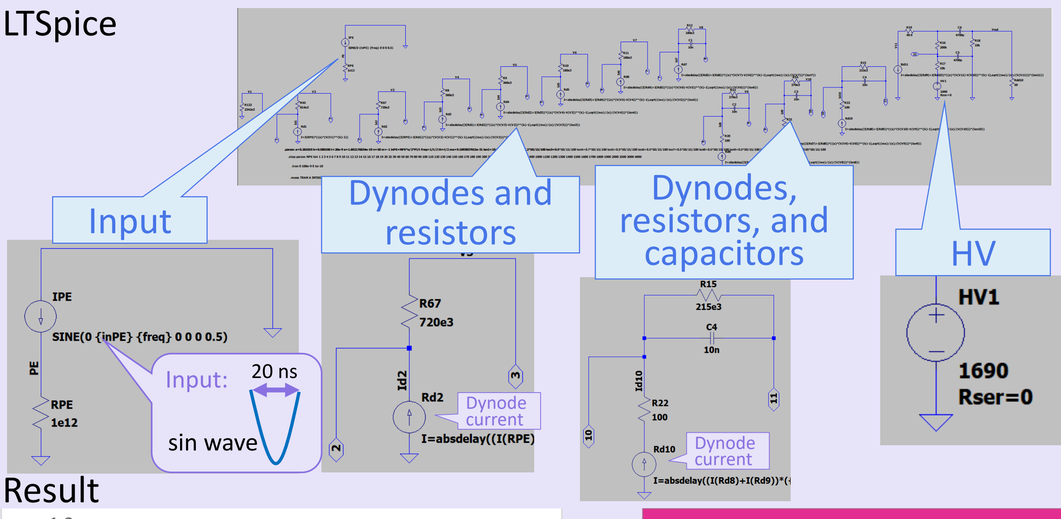
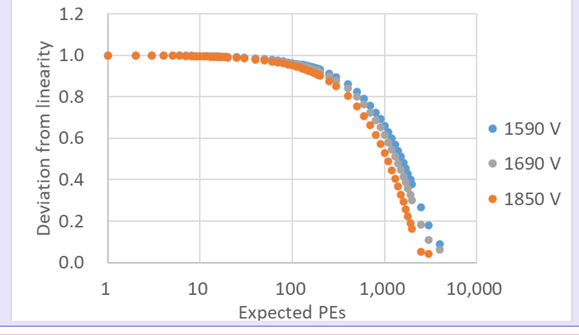


* Result



Confirmed saturation, but need tuning

1. Taking account of space charge saturation
2. Trying more realistic model

Summary:
* Suggested the possibility to improve the correction of non-linearity by calibration using charge amount
* Suppressing the over-linearity by adding capacitors to the bleeder circuit, for example, over-linearity of 8 % was suppressed at one PMT sample
* Confirmed saturation on the non-linearity curve of output by LTSpice, but need tuning such as taking account of space charge saturation

Reference:
*1: Hamamatsu Photonics K.K., PHOTOMULTIPLIER TUBES -Basics and Applications-, 5.1.3.Voltage-divider current and output linearity, Third Edition, URL: https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf.