Optimization study of scintillator shape of electromagnetic calorimeter for Higgs factories

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THE UNIVERSITY OF TOKYO

ICEPP The University of Tokyo

Outline

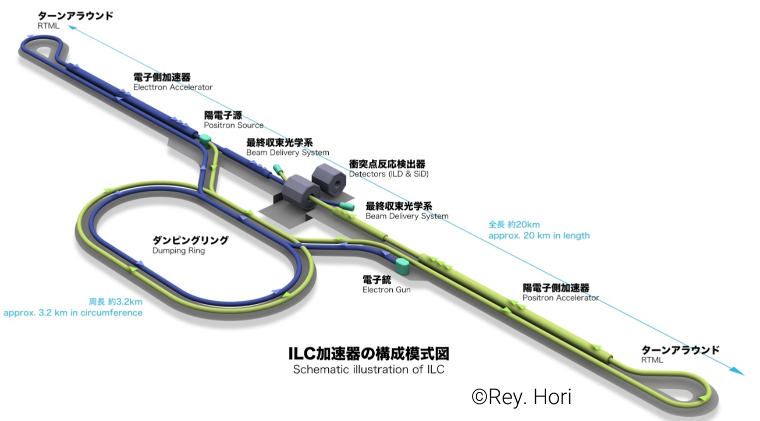
- Introduction
  - Higgs factories
  - Scintillator ECAL
  - Scintillator with SiPM
- Dimple readout scintillator
  - Measurement of light yield and uniformity
  - Simulation with Geant4
  - Optimization of scintillator shape
- Plans for next measurements
  - 2-dimensional measurement of dimple readout scintillator
  - Parameter determination of optical properties
- Summary and Outlook

ECAL for Higgs Factories

Higgs factory makes a lot of Higgs boson to measure a feature of them and search new physics beyond the standard model

These collider experiments need **high granular calorimeters** for Particle Flow Algorithm (PFA)

- Planned Higgs factories
  - **International Linear Collider (ILC)**
    $\sqrt{s}$ = 250 GeV – 1 TeV, site: Kitakami Mountains, Japan
  - **Compact Linear Collider (CLIC)**
    $\sqrt{s}$ = 380 GeV – 3 TeV, site: CERN
  - **Circular Electron Positron Collider (CEPC)**
    $\sqrt{s}$ = 240 GeV, site: China
  - **Future Circular Collider (FCC-ee)**
    $\sqrt{s}$ = 365 GeV, site: CERN



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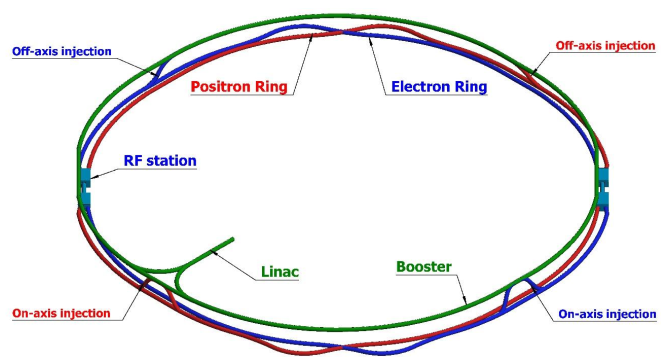


Layout of CEPC

CEPC Conceptual Design Report Vol.1, 2018

ECAL for Higgs factories is a sampling calorimeter, and there are two options for readout:

SiECAL (silicon pad) and **ScECAL** (scintillator strip + SiPM)

Scintillator ECAL (ScECAL)

- Sensor layers of ScECAL consists of segmented scintillator strip with SiPM
  - **Scintillator strip**

    Plastic scintillator wrapped by reflector film

    Size: 45 mm x 5 mm x 2 mm

  - **SiPM** (MPPC®, PPD, GAPD, …)

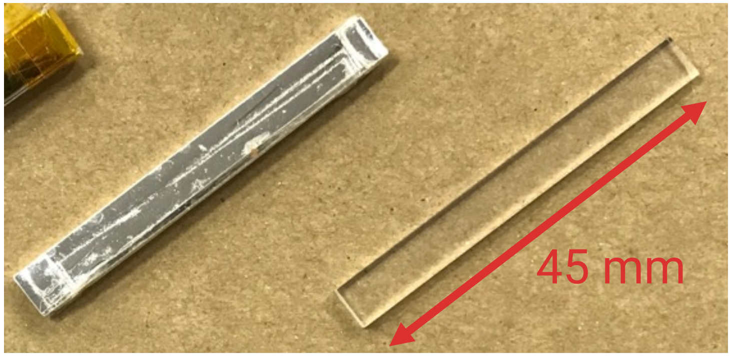
    Photosensitive area : 1 mm x 1 mm

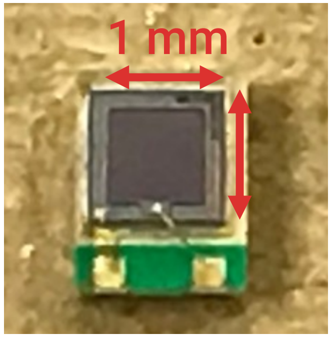
    Gain: **10^5** (PMT : 10^6–10^7)

    Pixel pitch: **10 um** or **15 um**

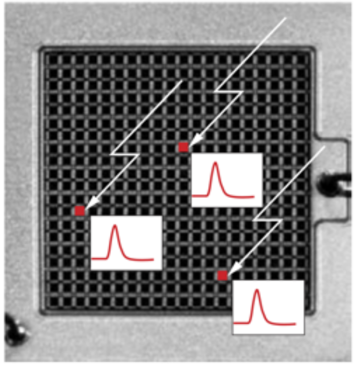
    - The smaller pixel pitch SiPM has, The larger dynamic range it has. So small-pitch SiPM has less effects of saturations.

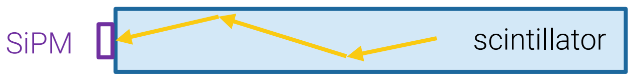
Advantage: low operation voltage (<100 V), high magnetic filed resistance





SiPM: S12571-015P (HAMAMATSU)


HAMAMATSU, Opto-semiconductor hand book



$E_{loss} \propto$ # of detected photon

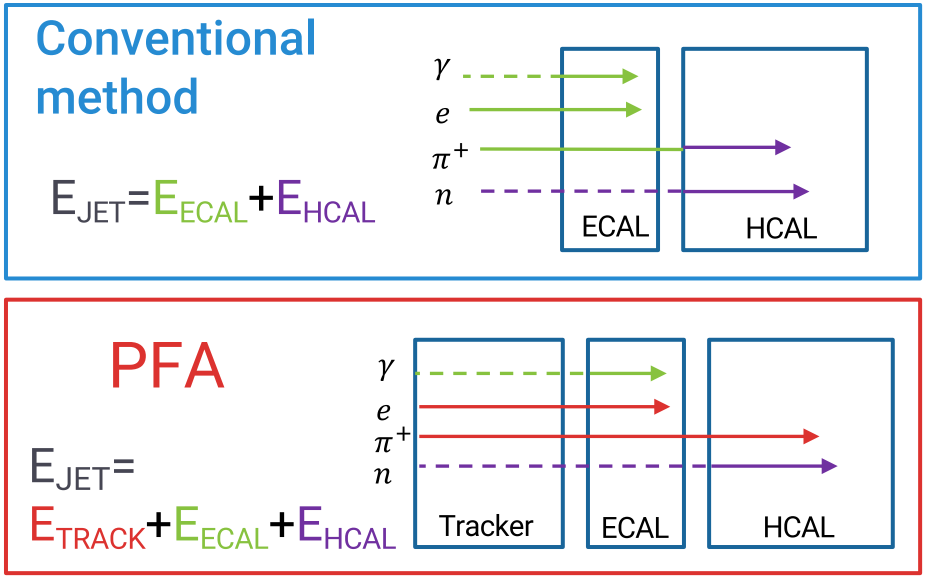
Scintillator ECAL

- Particle Flow Algorithm (PFA)

  Particles in jet are reconstructed, taking advantage of the best measurements available for the type of particle

  - Charged particle → Tracker
  - Photon → ECAL
  - Neutral hadron → HCAL

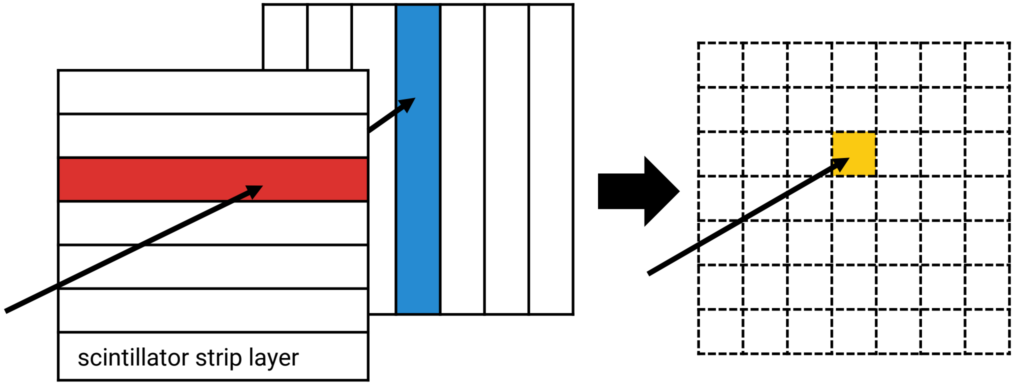
  PFA requires **position resolution of 5 mm x 5 mm** in the ECAL



- Strip Splitting Algorithm (SSA) Kotera et al., NIM A789 (2015) 158

  Method to **reconstruct scintillator strips (e.g. 5 mm x 45 mm) as virtual tiles (e.g. 5 mm x 5 mm)** by resolving the hits from perpendicularly stacked strips.

  Using SSA, the number of readout channels for ScECAL is 1/10 that for SiECAL.



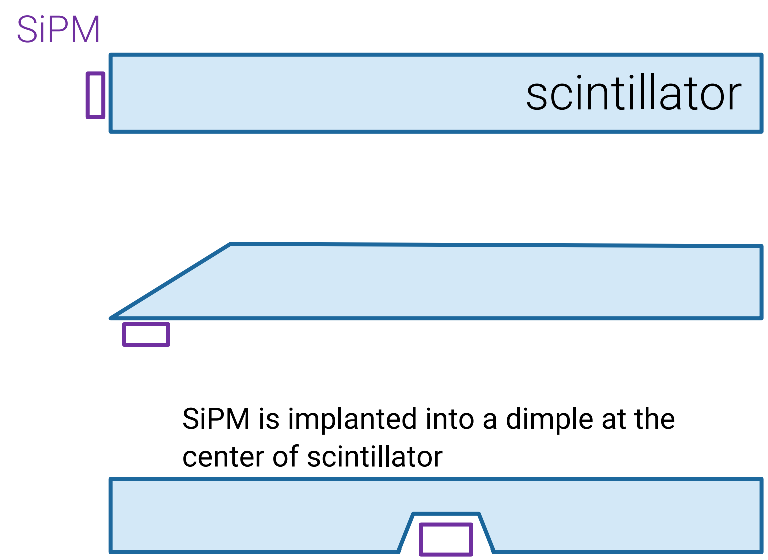
Readout Methods

- Requirement for scintillator strip with SiPM is that photon detector can detect **enough light yield for MIP** and **uniform light yield for incident position**

- **Side readout**
  - Good light yield for MIP
  - Dead space about 2%, bad light yield uniformity

  Bottom readout
  - No dead space, good light yield uniformity
  - Less light yield for MIP

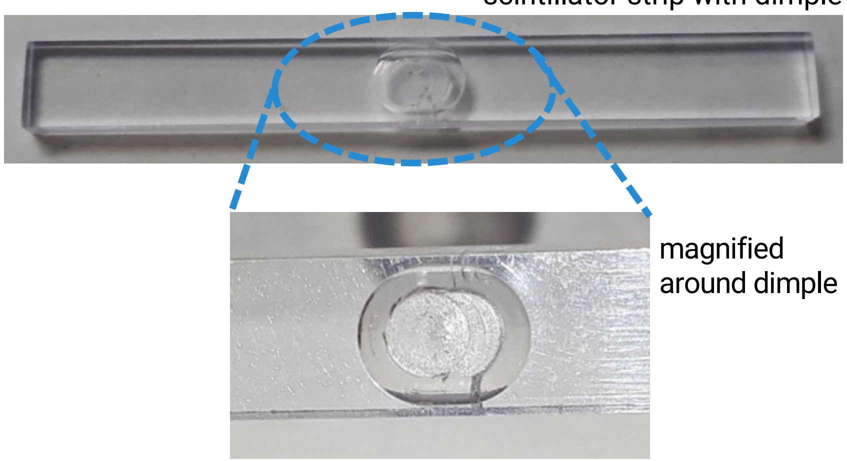
  Dimple readout (NEW: proposed by USTC & IHEP)
  - **No dead space**
  - **Easy to mass-produce**

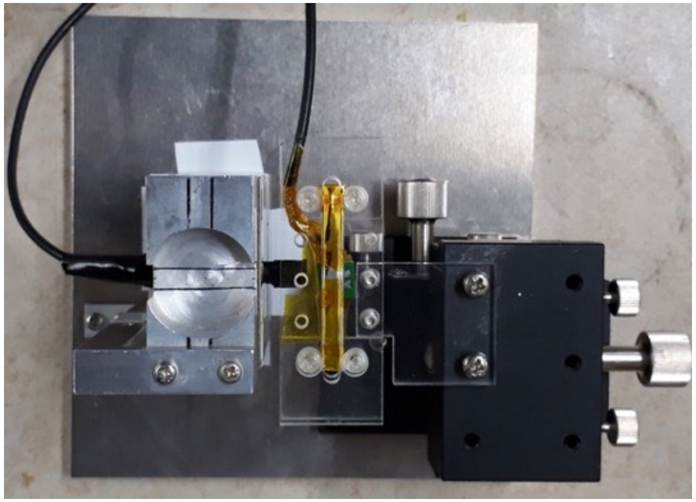


In this talk, we confirm the characteristics of the **dimple readout** method through light yield measurements and simulation.
These results will be used for **optimizing the strip shape**.

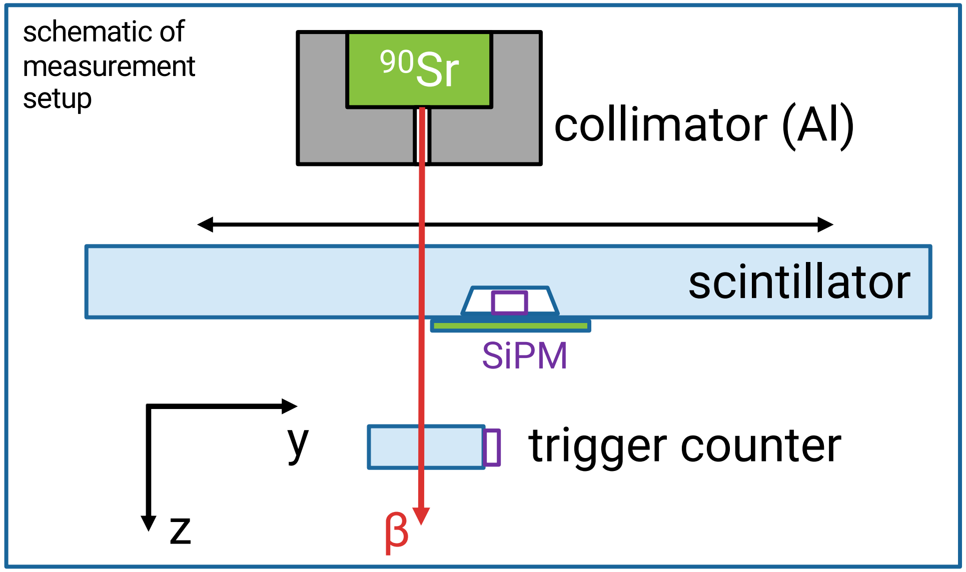
Measurement Setup [dimple readout]

- Measure light yield vs. incident position of beta ray
  - SiPM is placed inside the dimple
    - Scintillator strip: BC-404
    - Depth of dimple: 0.69 mm (design value: 0.85 mm)
  - SiPM: S12571-015P (HAMAMATSU), dV = 4 V
  - Checking source: ^{90}Sr
    - Collimator: diameter of 0.5 mm
  - Moving stage: ±20 mm

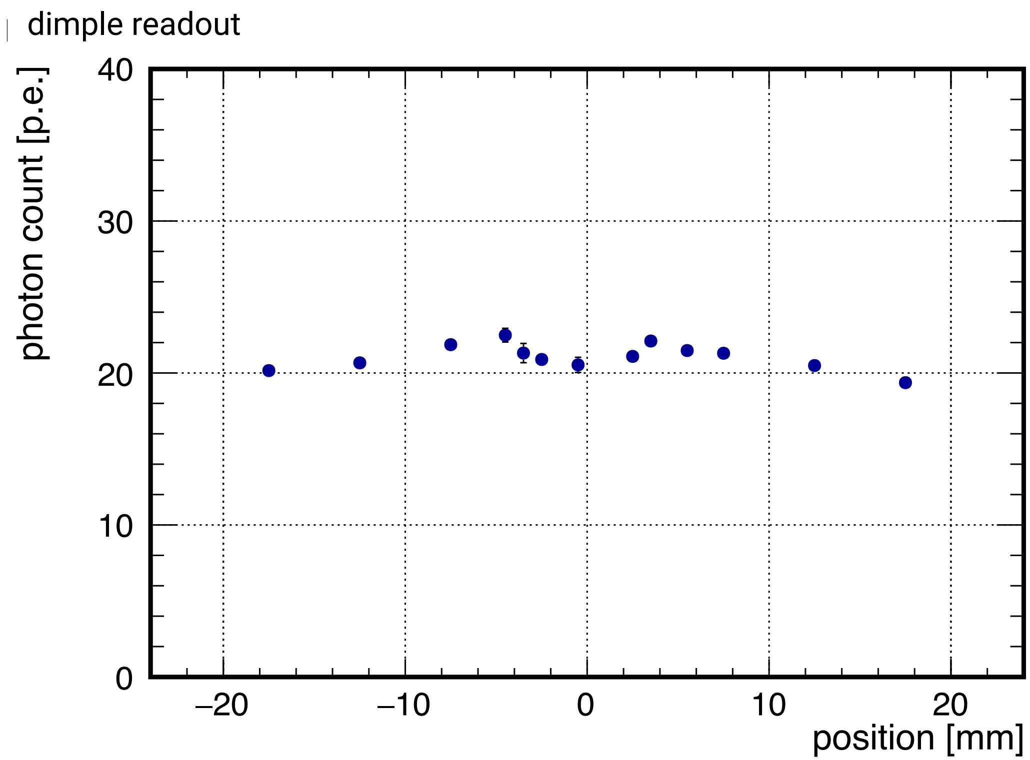


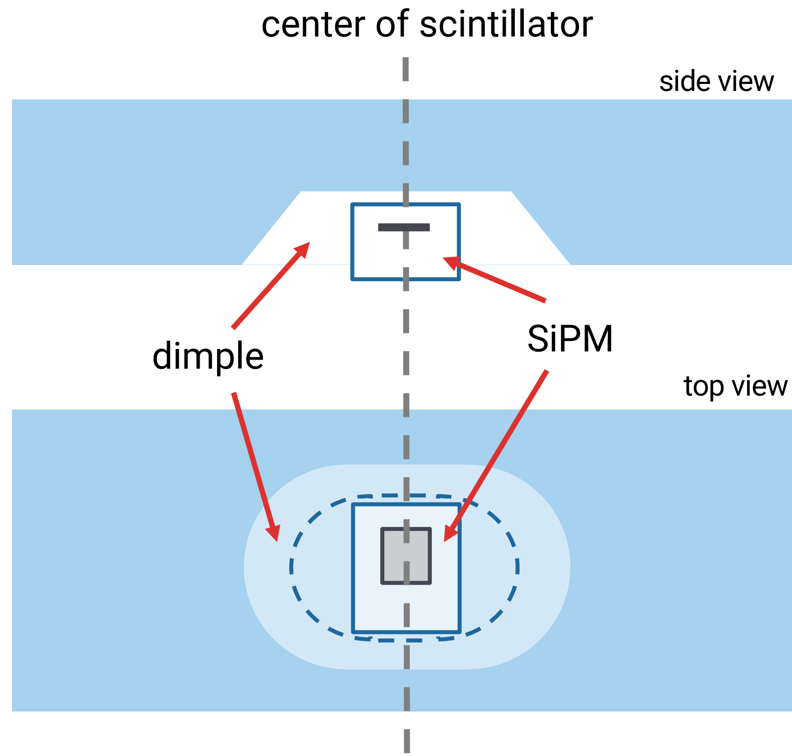


measurement setup



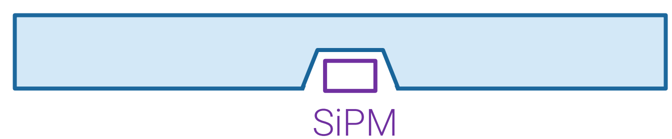
Light Yield vs. Position





Result for dimple readout:

- **Mean light yield ~ 21 photoelectron (p.e.)**
- **Good light yield uniformity**

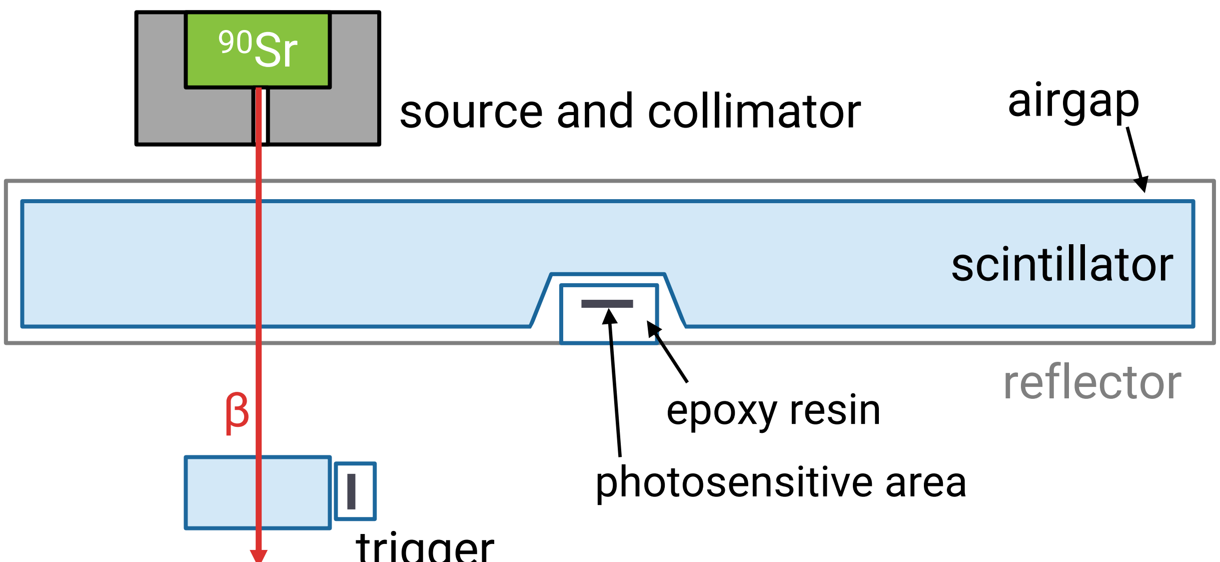


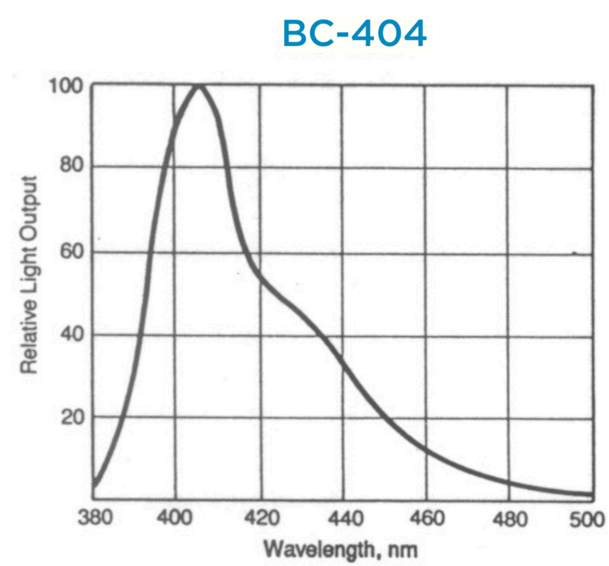
cf. mean light yield of bottom readout is ~10 p.e.

[S. Ieki, Master's thesis, U. of Tokyo, 2014]

Simulation for Photon Counting

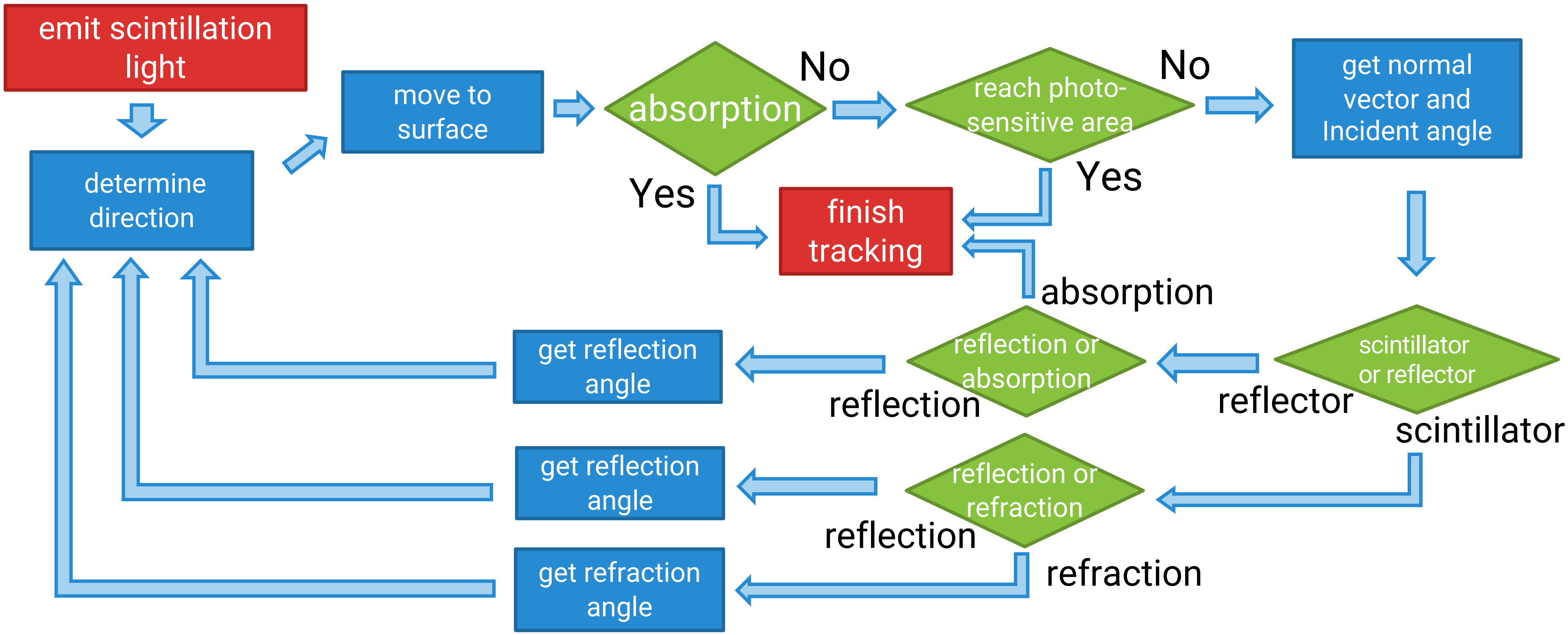
- Purpose of simulation is to **reproduce the result of measurements** and to **optimize the scintillator shape**
- Photon tracing simulation was developed using Geant4 (G4OpticalPhoton class library)
- The following sketch shows the elements implemented in the simulation.
- Photons are emitted inside the scintillator according to the characteristic emission spectra of the plastic.

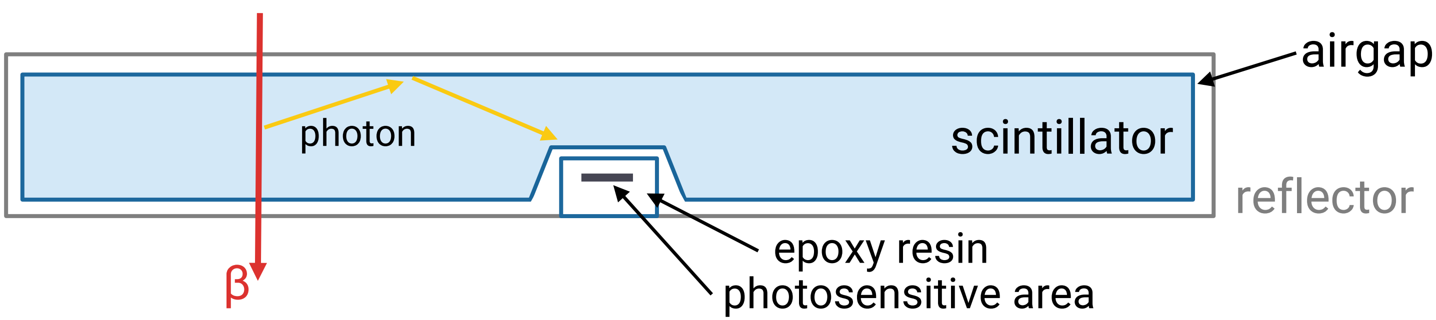




Photon Tracking in Geant4

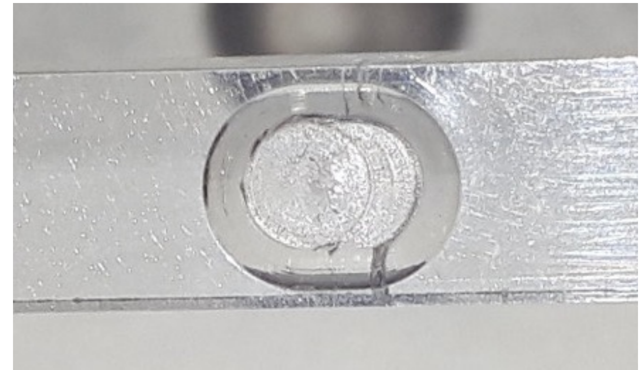
Flow chart of photon tracking



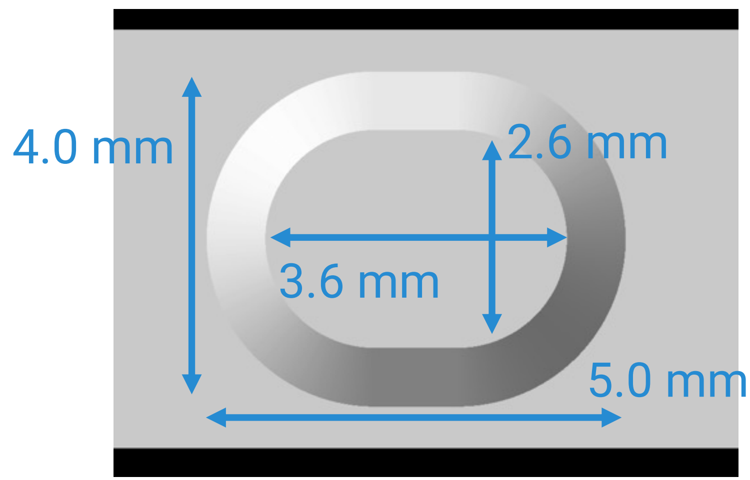


Simulation Parameters

- Scintillator
  - Dimple depth: 0.69 mm
  - Size: 45 mm x 5 mm x 2 mm
  - Light output: 10,000 photons/MeV
  - **Absorption length: 50 – 200 cm**
  - **Diffusion rate: 0.0 – 0.4**
- Reflector
  - **Reflectivity: 95 – 99%**
- SiPM
  - Size: 2.425 mm x 1.9 mm x 0.85 mm
  - Photosensitive area: 1 mm x 1 mm
  - PDE: 25% (S12571-015P)
- Collimator
  - Diameter of collimator: 1 mm
  - Depth of collimator: 3 mm
- Trigger
  - scintillator size: 5 mm x 5 mm x 2 mm



dimple of scintillator



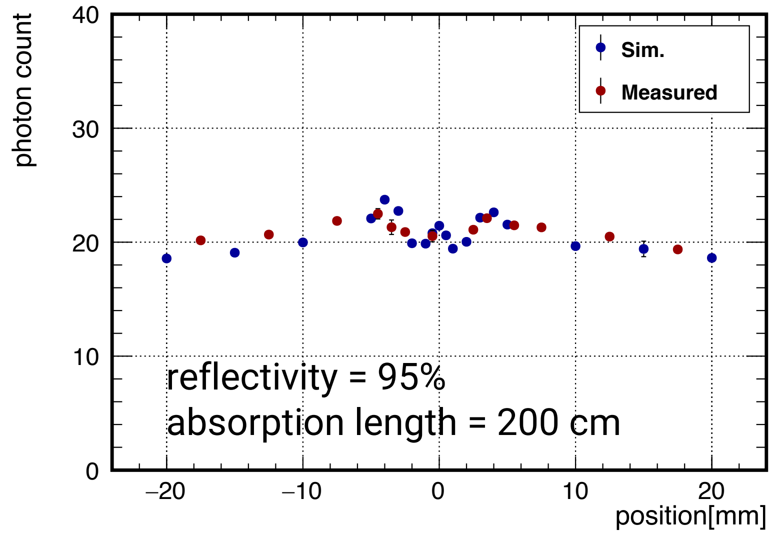
dimple implemented in Geant4

Current Best Simulation Results

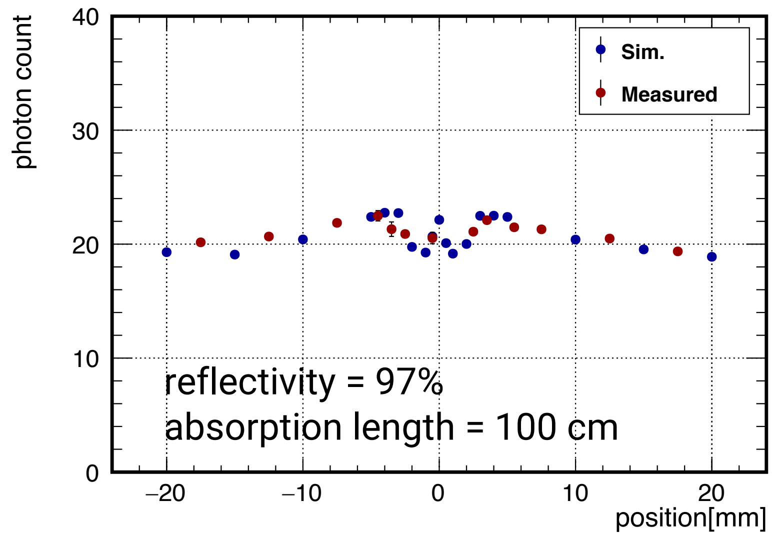
- Some simulation parameters, such as reflectivity of reflector or absorption length of scintillator, can be referred from datasheet.
- However, these values have uncertainty.

  e.g. reflectivity ~ 95 – 99%

  absorption length ~ 50 – 200 cm



- By tuning the parameters within the uncertainties, **the measurement result can be reproduced**
- However, different parameter values can also reproduce the result → **need dedicated measurement**

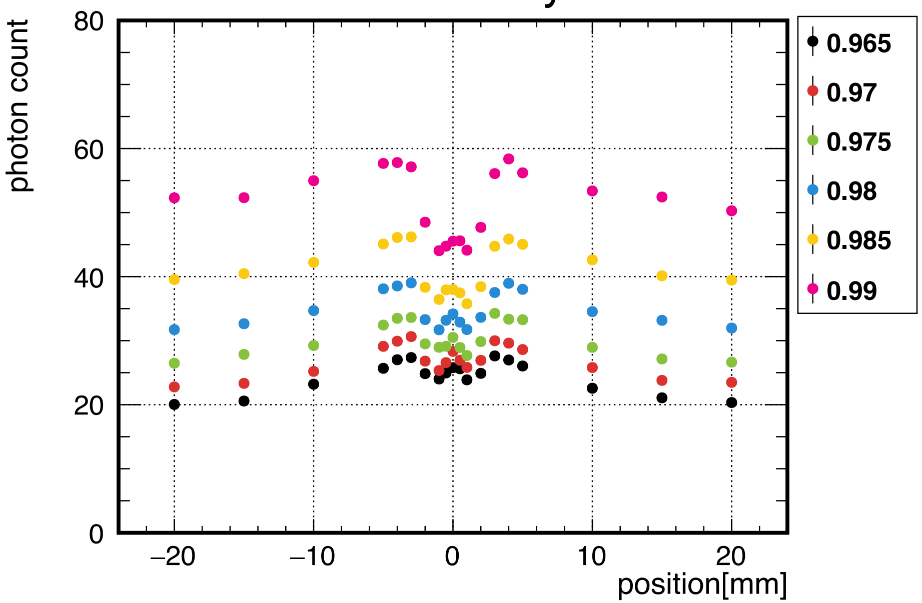


Simulation Parameters

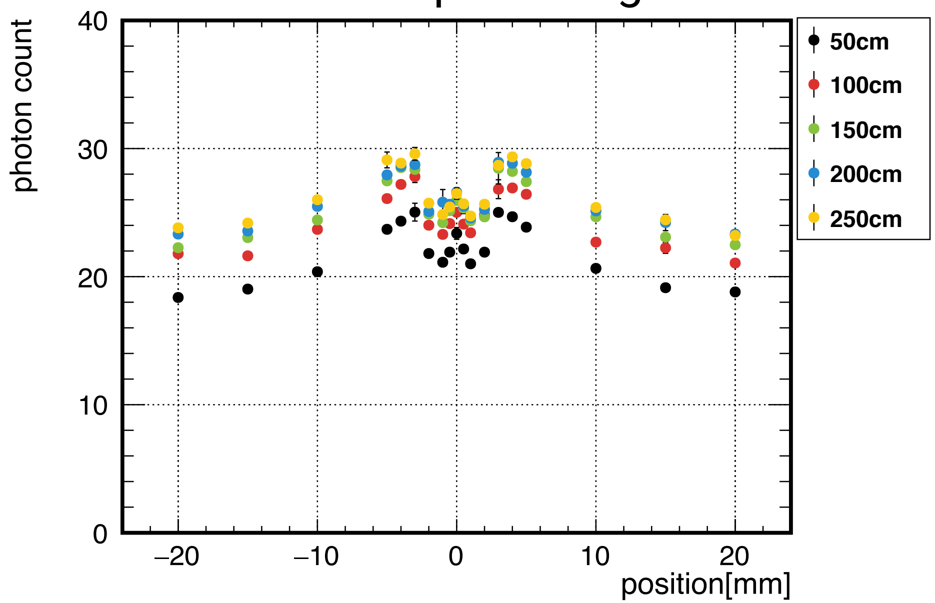
- Following parameters **based on type of materials** must be tuned
  - reflectivity of reflector film
  - light absorption length in scintillator
  - refractive index of scintillator
- **Small difference of these value has large effect on the result**

  For example, the light yield is reduced by half when changing reflectivity by 1%

ex. reflectivity



ex. absorption length

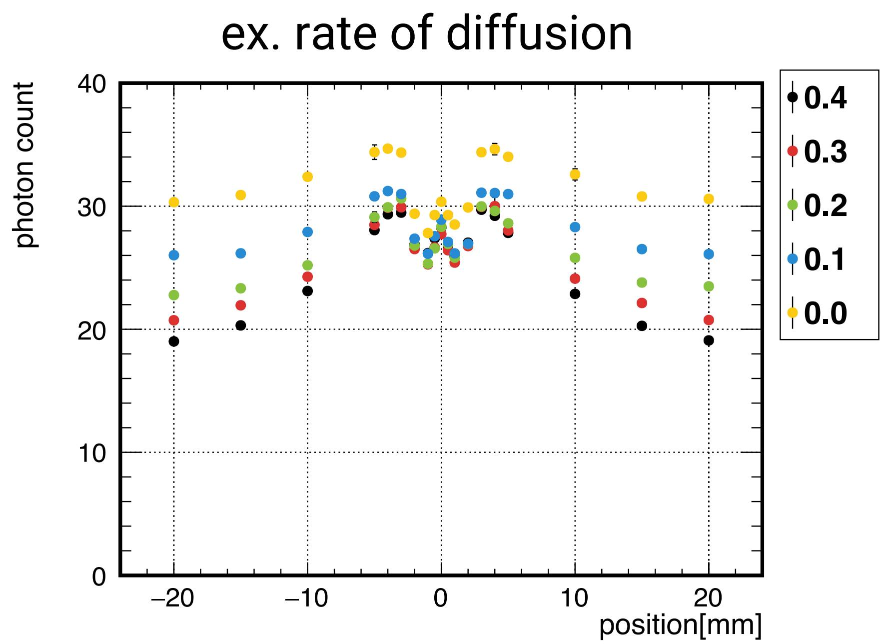


Simulation Parameters

- Some parameters **based on surface state of materials** must be determined
  - Rate of diffusion at surface
  - Roughness of surface

  Rate of diffusion means rate of reflection except Fresnel reflection and back scattering $(1-R_{Fresnel}-R_{back})$

  These parameters are not same under the different production process
- Difference of these parameters also has significant effect on the result

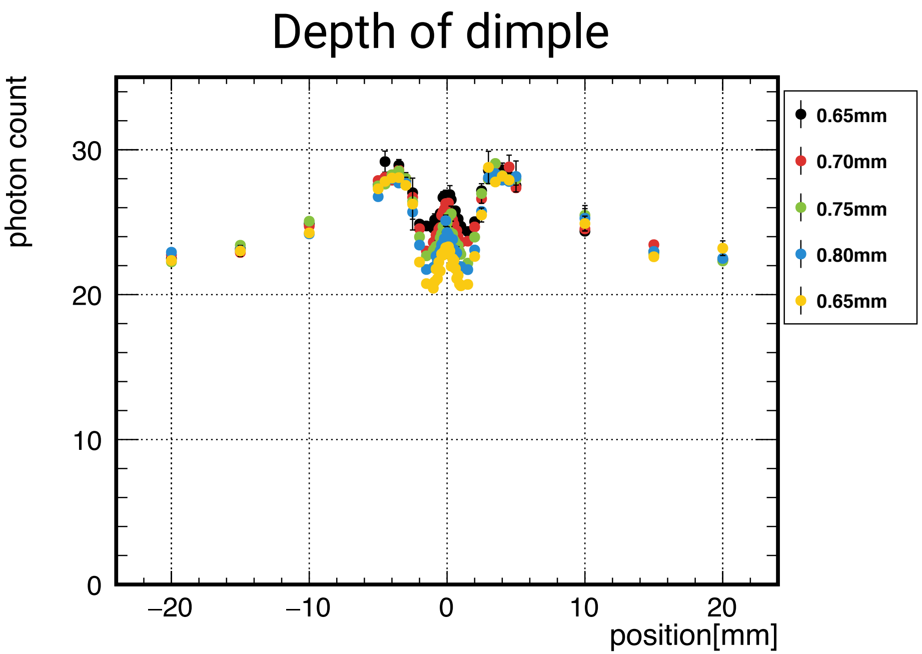


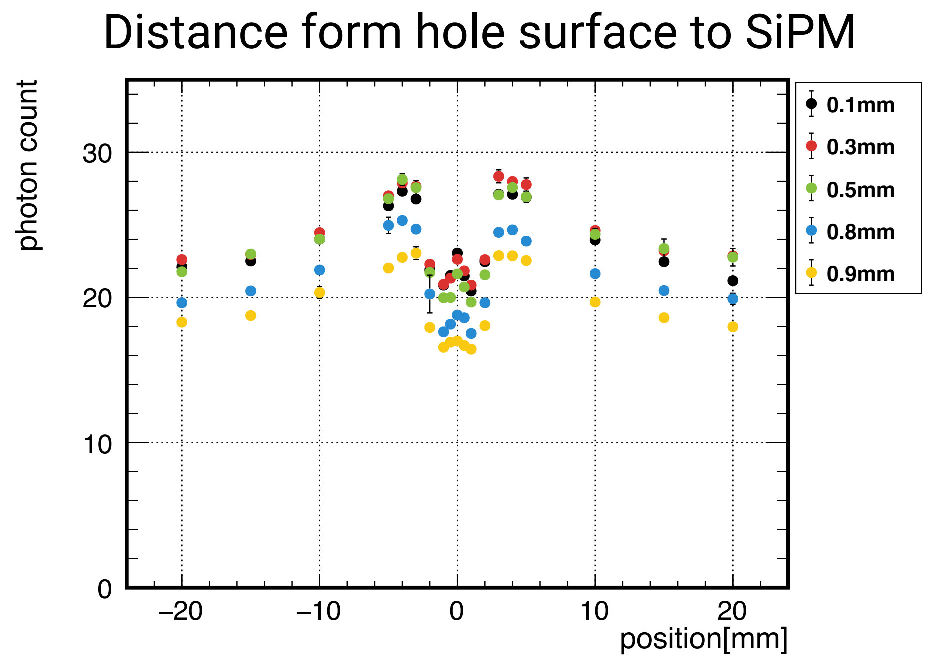
It is necessary to determine parameters about optical properties of scintillator and reflector

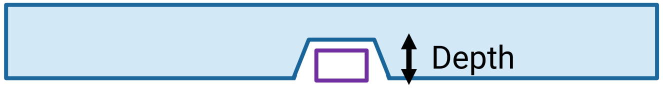
As reflectivity and refractive index depend on the photon wavelength, these values must be measured for several wavelengths

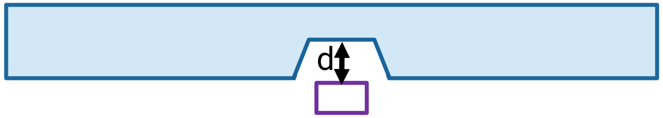
Toward Optimization of Scintillator Shape

- Effects of dimple size and position of SiPM







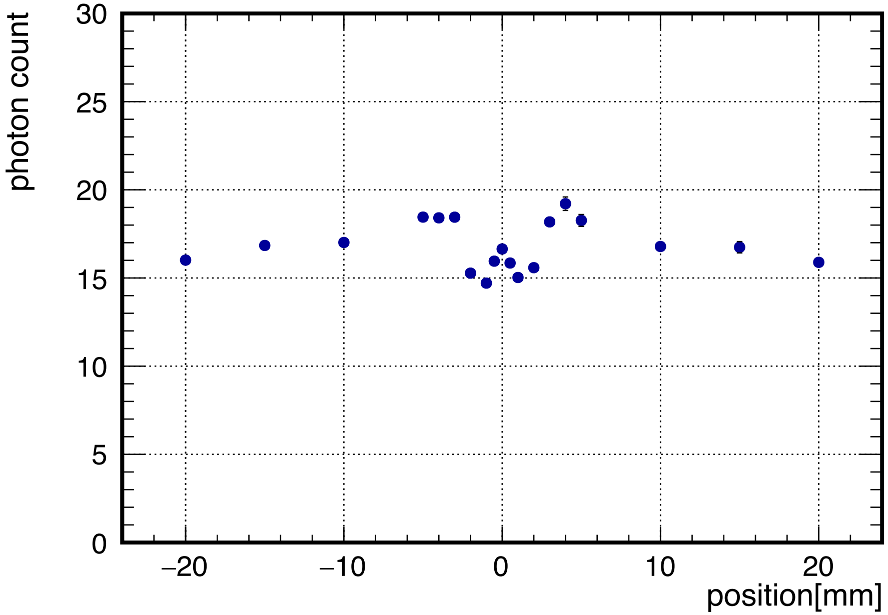


Light yield around the dimple decreases by shortening depth of dimple

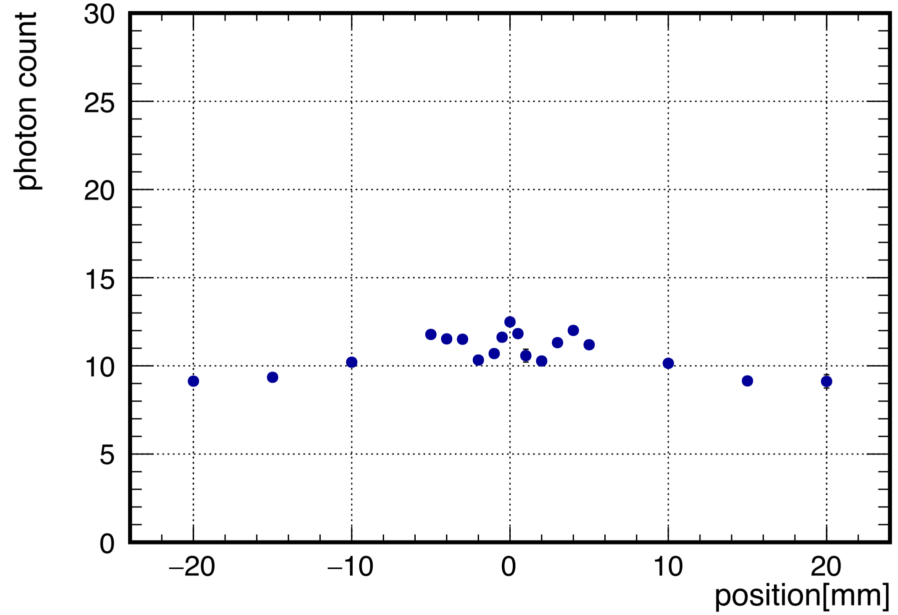
Entire light yield decreases by getting longer distance from the dimple surface to top of the SiPM

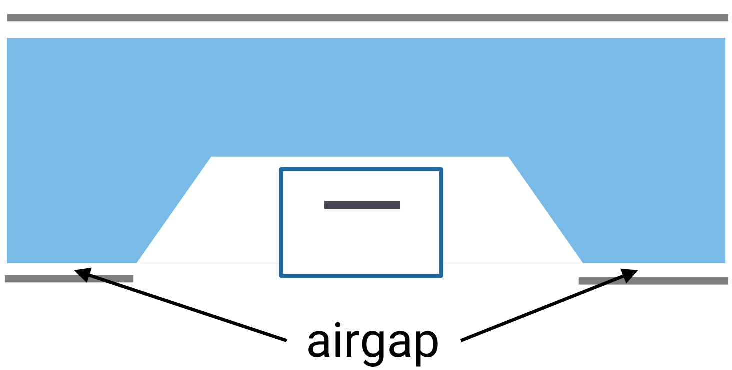
Toward Optimization of Scintillator Shape

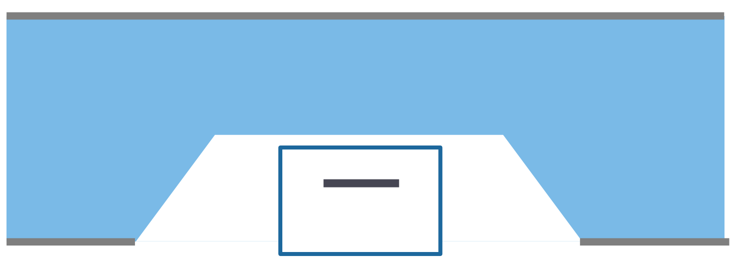
reflector film (w/ airgap)



painted (w/o airgap)







Next Measurements

- New 2-dimensional measurements of light yield is in progress

  Improve alignment of measurement such as position of trigger counter or position of SiPM

  Measure light yield **at intervals of 0.1 mm** using automatic moving stage

→The measurements will start next week

automatic moving X-Y stage

- Measurements of optical properties of scintillator and reflector are also ongoing
  - Reflectivity of reflector
  - Rate of diffusion at scintillator/reflector surface
  - Absorption length in scintillator
  - Roughness of surface

  Measure these parameters using spectrophotometer and laser microscope

→It will be taken until the end of November

Spectrophotometer: measure total reflectivity, diffuse reflectivity, and intensity of transmitted light

Laser microscope: measure roughness of surface

Summary and Outlook

- We are developing scintillator-based electromagnetic calorimeter for Higgs factories

  Ultimate goal of this study is to **determine best shape of scintillator strip** by simulation considering mass-production capability

- We confirm dimple readout scintillator has good light yield and good uniformity

- We are making simulation code for optimizing scintillator shape
  - Simulation can almost reproduce the behavior of the measurement
  - Some simulation parameters (e.g. reflectivity, absorption length and diffusion rate) have uncertainty

- To match results of simulation and measurement,

  We have updated the setup of light yield measurement. The data taking starts in next week.

  Measurement of parameters is also in progress.

- The final result will be presented by the end of this year (Master's thesis)

Back up

SiPM(S12571-010/015P)

Structure

HAMAMATSU, S12571-010, -015C/P Data Sheet

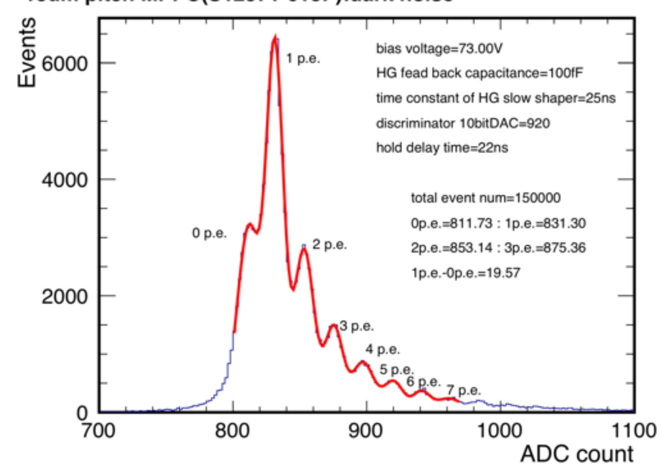
Parameter	Symbol	S12571				Unit
		-010C	-010P	-015C	-015P	
Effective photosensitive area	-	1 × 1		1 × 1		mm
Pixel pitch	-	10		15		μm
Number of pixels	-	10000		4489		-
Geometrical fill factor	-	33		53		%
Package	-	Ceramic	Surface mount type	Ceramic	Surface mount type	-
Window	-	Silicone resin	Epoxy resin	Silicone resin	Epoxy resin	-
Window refractive index	-	1.41	1.55	1.41	1.55	-

Electrical and optical characteristics (Ta=25 °C, unless otherwise noted)

Parameter		Symbol	S12571		Unit
			-010C / -010P	-015C / -015P	
Spectral response range		λ	320 to 900	320 to 900	nm
Peak sensitivity wavelength		λp	470	460	nm
Photon detection efficiency (λ=λp)*4		PDE	10	25	%
Dark count*5	Typ.	-	100	100	kcps
	Max.		200	200	
Time resolution (FWHM)*6		-	300	250	ps
Terminal capacitance		Ct	35	35	pF
Gain		M	1.35×10^5	2.3×10^5	-
Gain temperature coefficient		ΔTM	1.6×10^3	3.5×10^3	/°C
Breakdown voltage		V_{BR}	65 ± 10	65 ± 10	V
Recommended operating voltage		Vop	V_{BR} + 4.5	V_{BR} + 4.0	V
Temperature coefficient of recommended operating voltage		ΔTVop	60	60	mV/°C

*4: Photon detection efficiency does not include crosstalk or afterpulses.
*5: Threshold=0.5 p.e.
*6: Single photon level
Note: The above characteristics were measured the operating voltage that yields the gain listed in this catalog.
(Refer to the data attached to each product.)
The last letter of each type number indicates the package type (C: ceramic, P: surface mount type).

15um pitch MPPC(S12571-015P):dark noise



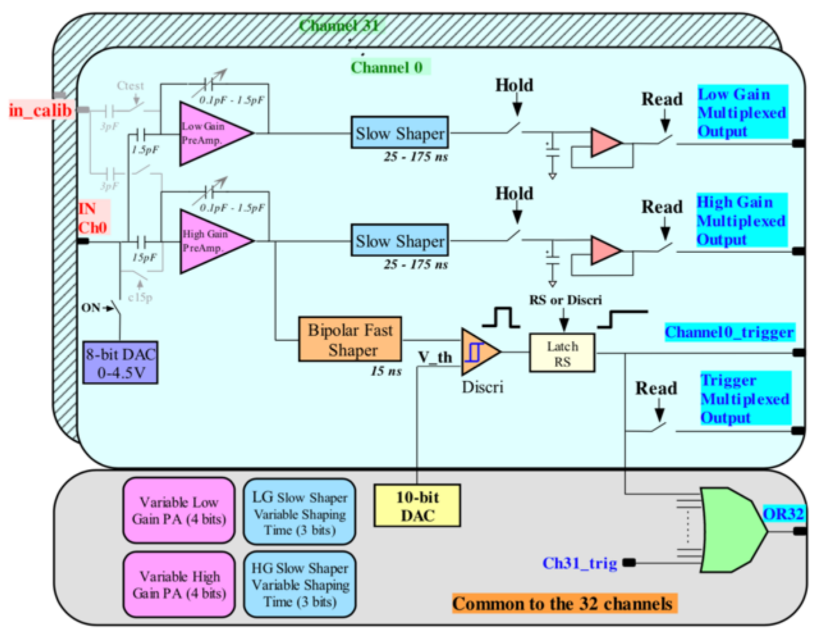
EASIROC Module

Use EASIROC module as readout module and power supply

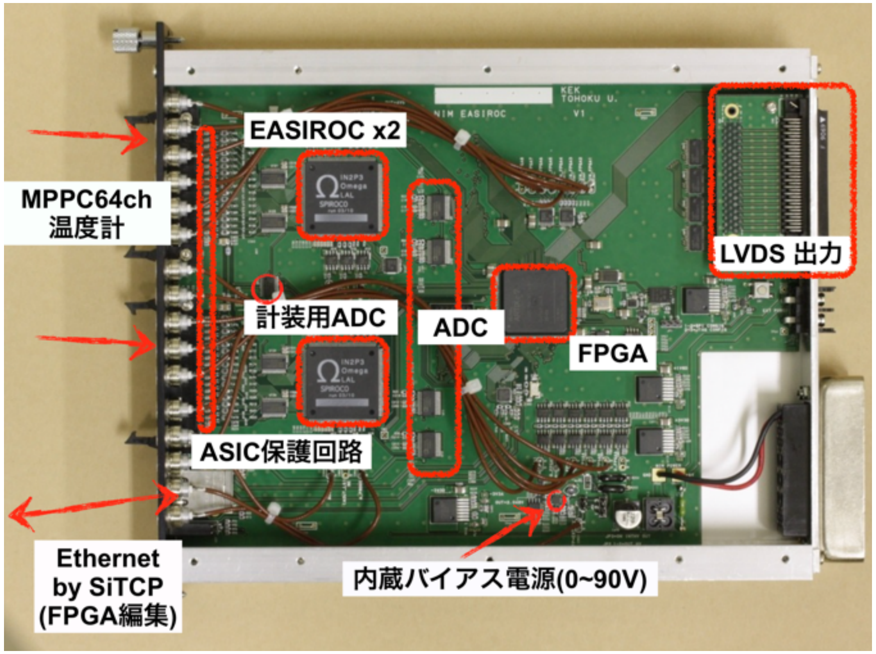
- Developed by Osaka Univ., Tohoku Univ., and KEK
- Readout ASIC using EASIROC chip

  Operate 64ch SiPM simultaneously
- Include bias voltage supply (~90 V), preamplifier, shaper, and discriminator

  Bias voltage of each channel can be tuned: [-4.5 , 0] V



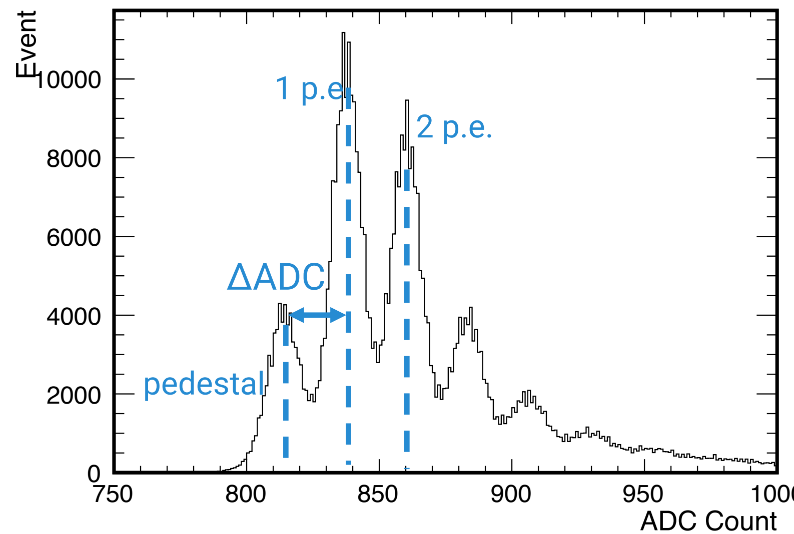
Omega group, EASIROC DATA SHEET, 2011

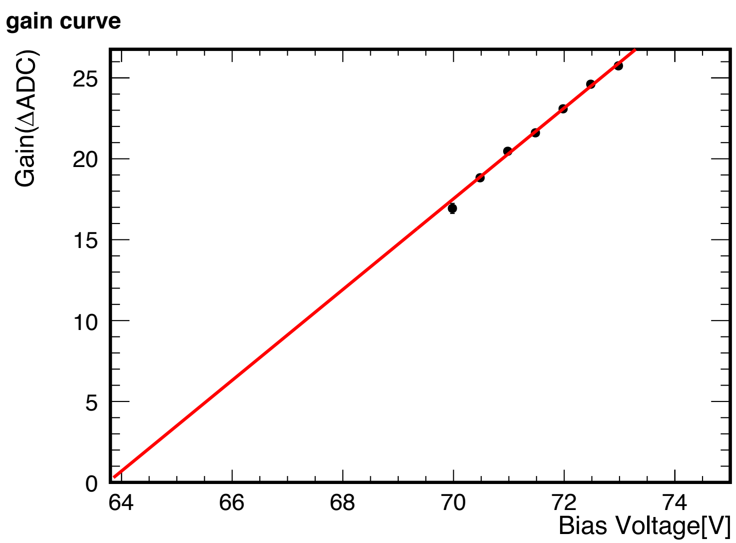


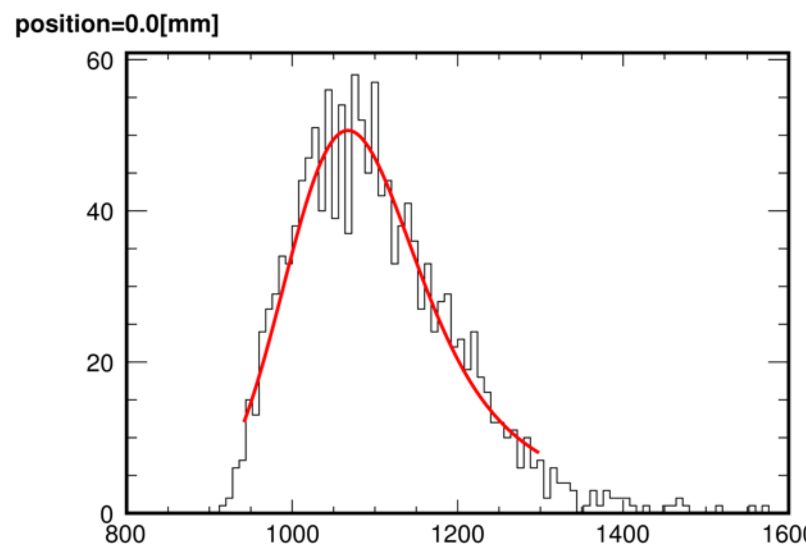
Naoki ISHIZHIMA, Yuki NAKAI, EASIROC MODULE user Guide, 2014

SiPM Calibration

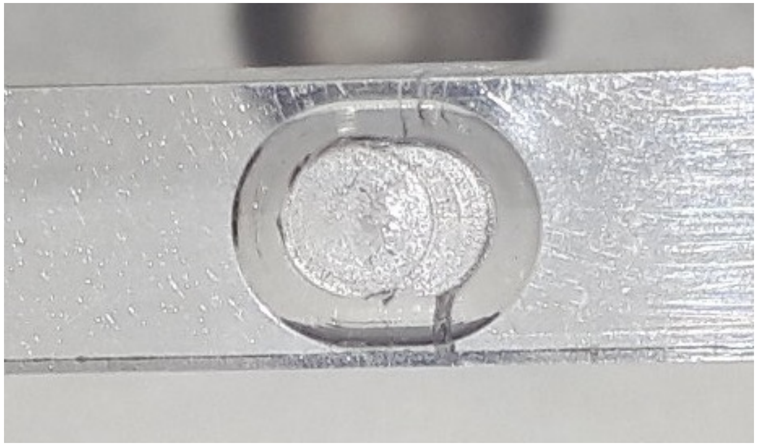
- EASIROC + SiPM
  1 p.e. = 11.5 ADC count @dV = 4 V
  pedestal = 818 ADC count
- Fit by convolution function of Landau dist. and Gaussian, and convert to ligh yield
  light yield = (Landau mean - 818)/11.5



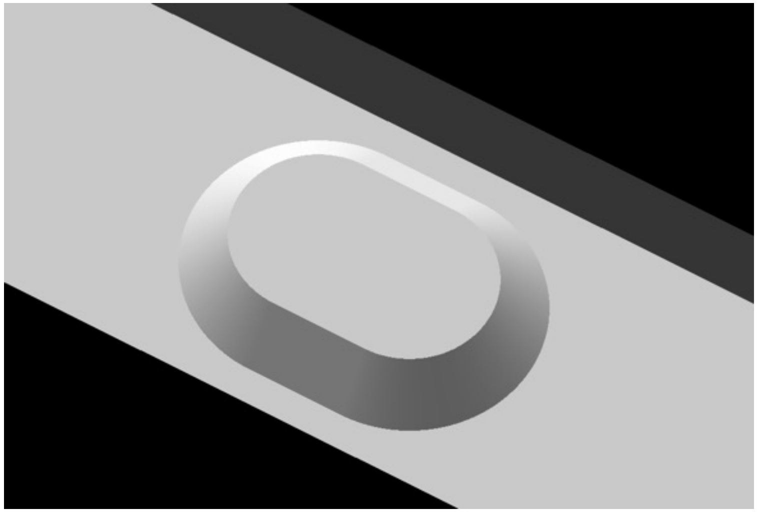




Dimple Shape

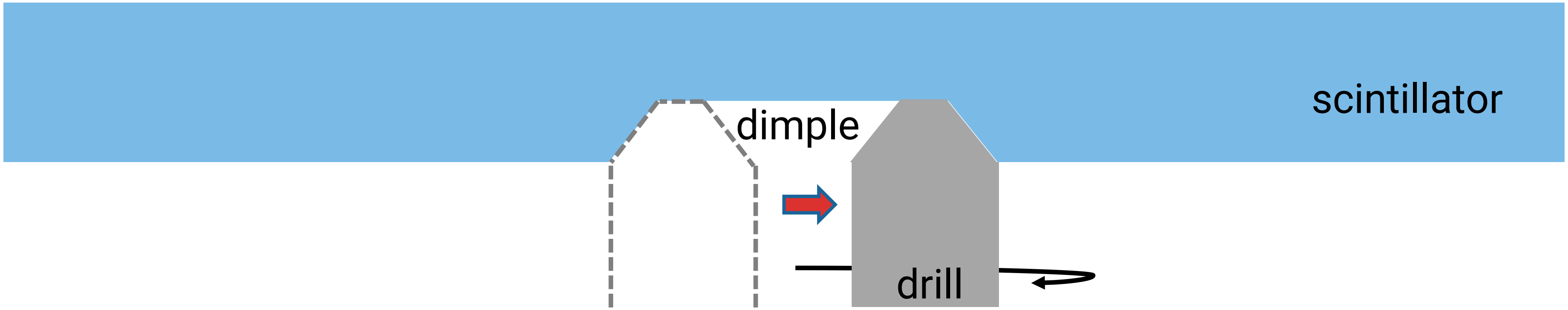


Scintillator shape using measurement



Scintillator shape implemented in Geant4

Making method: cut by drill



Reflection at Surface of Material

- Surface of reflector

Reflection based on reflectivity P_{ref}, or absorption based on $(1 - P_{ref})$

- Surface of scintillator

Get normal vector based on roughness of surface

→Calculate probability of reflection using incident angle

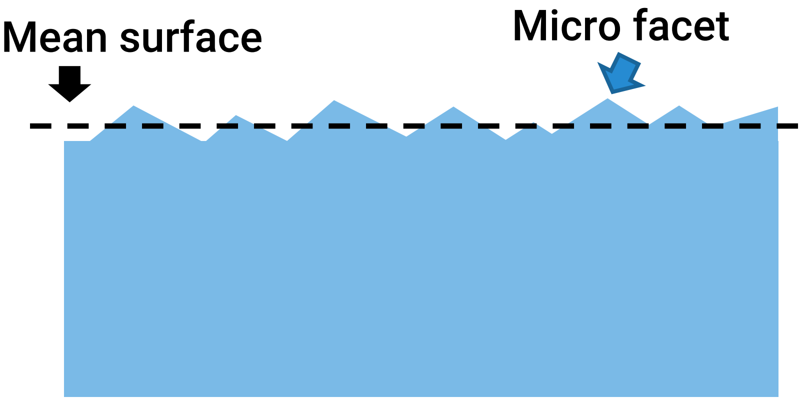
→Determine reflection or refraction

There are 4 kinds of reflections

  - Fresnel reflection (at mean surface)
  - Fresnel reflection (at micro facet)
  - Back scatter
  - Diffusion

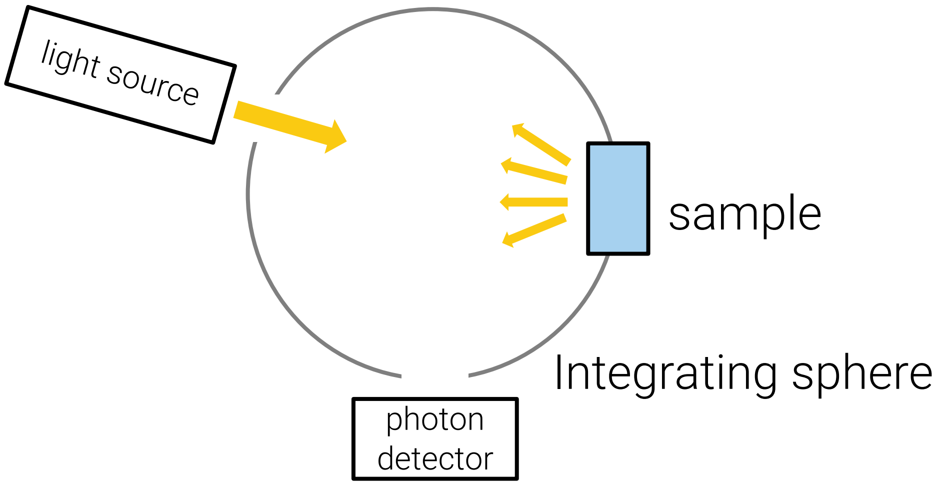
Sum of these reflection rates equals 1

Set standard deviation of Gaussian as grade of Micro facet

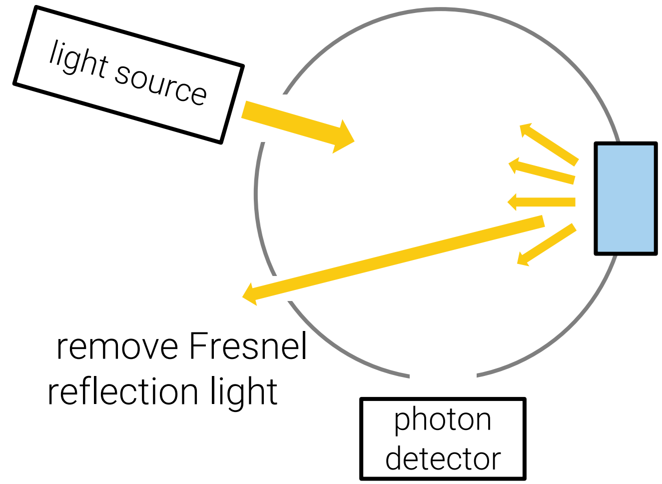


Measurement of Optical Properties

- Operation principle of spectrophotometer



measurement method of total reflectivity

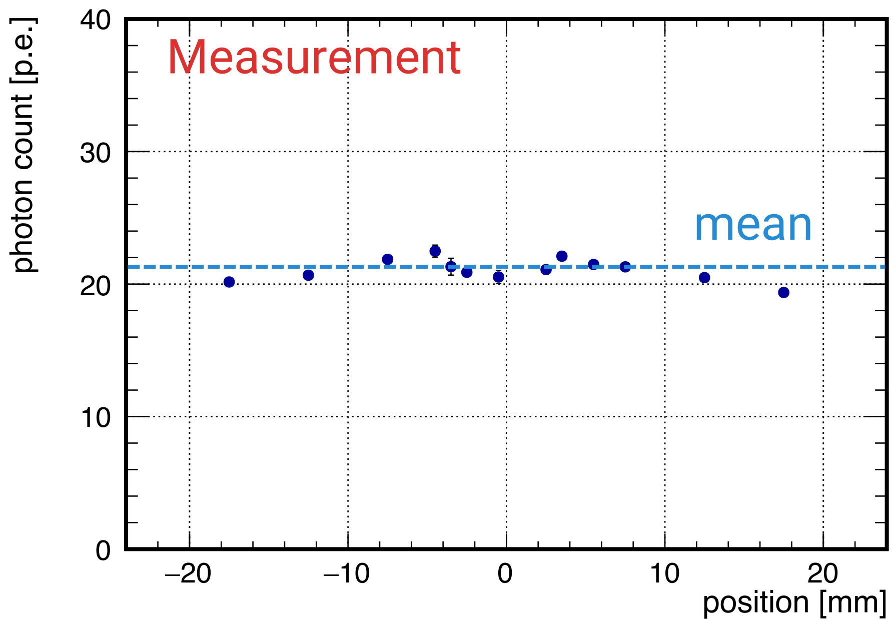


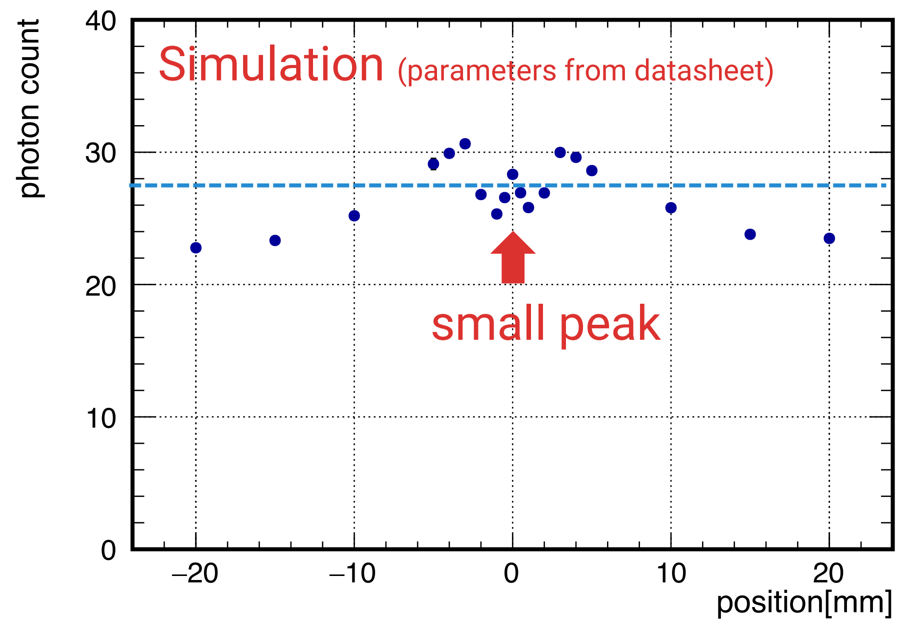
measurement method of diffuse reflectivity

Comparison with Measurement

- Result of simulation with parameters referred from datasheet
  - Mean light yield of simulation is higher than result of measurement
  - In simulation result, there is a small peak around the center
- Input parameters such as reflectivity or absorption length would be smaller than standard parameters
- Intervals of measurement points must be shortened to see the peak

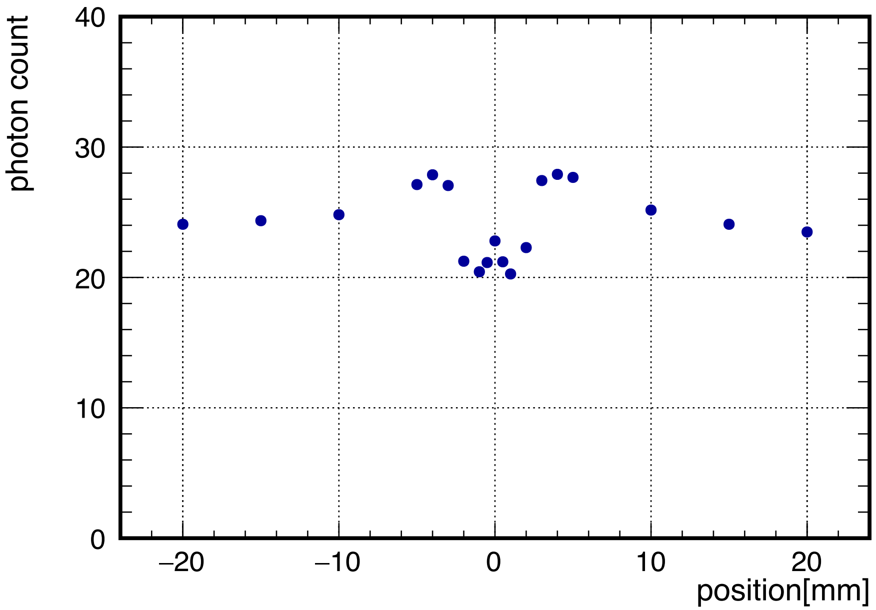
dimple readout

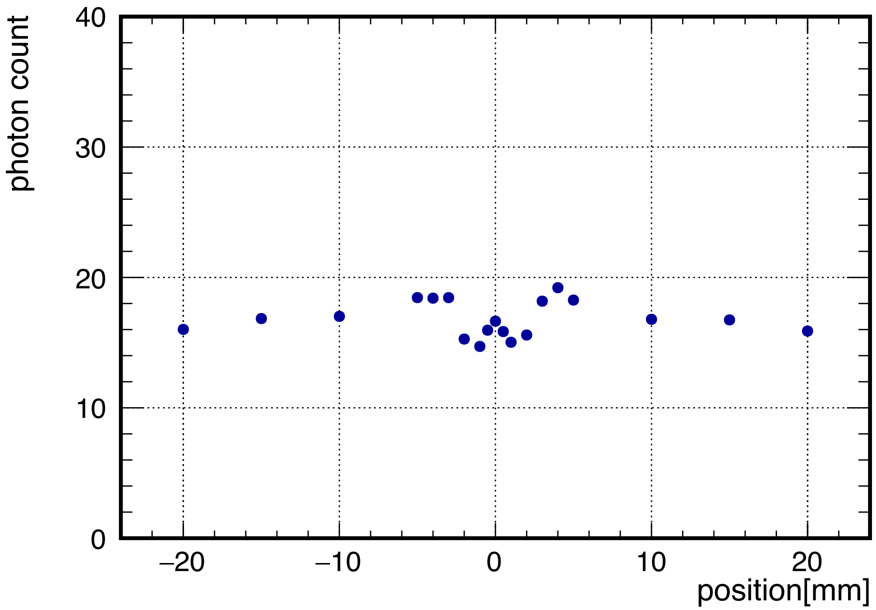


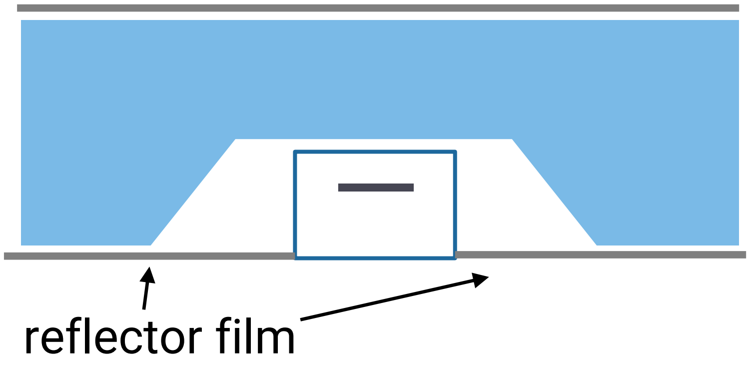


Toward Optimization of Scintillator Shape

Shape of reflector film

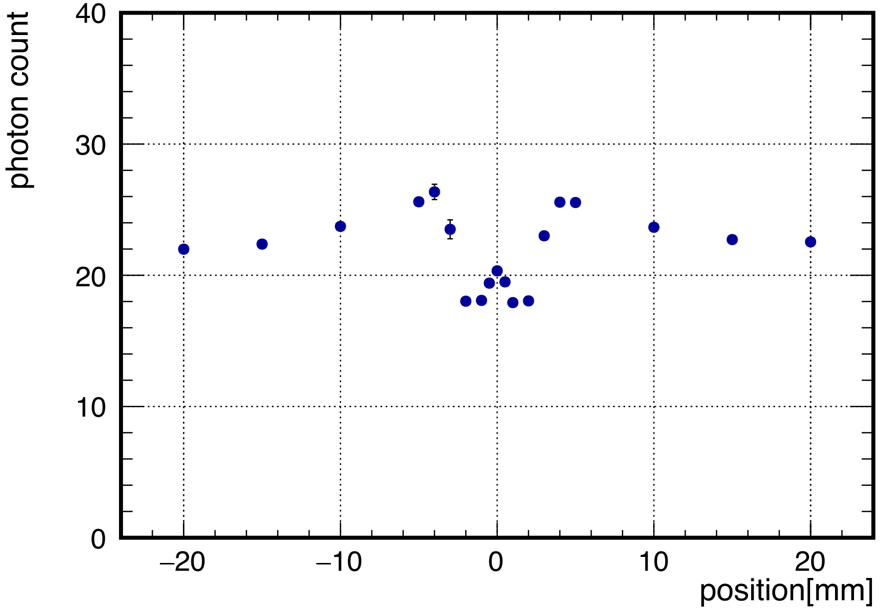


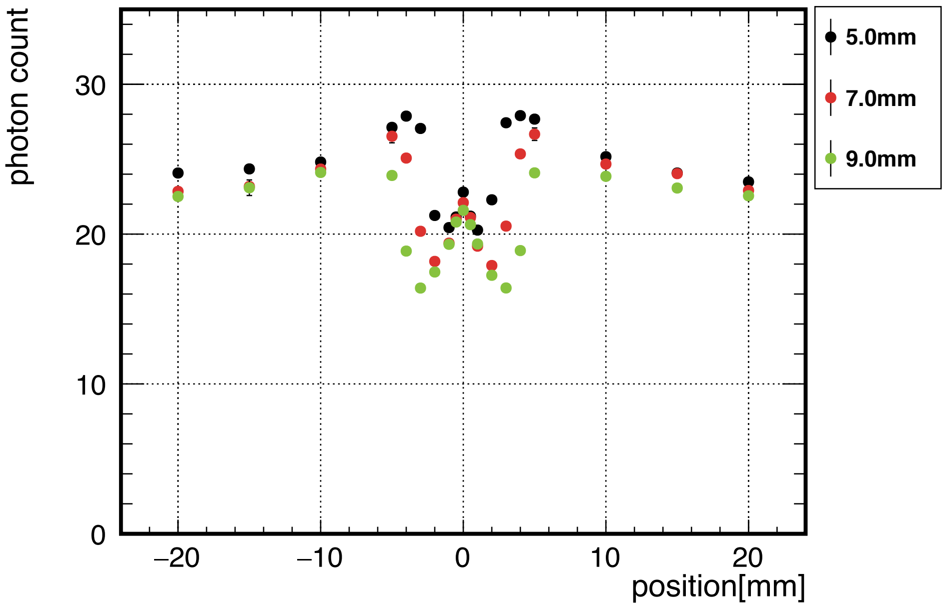


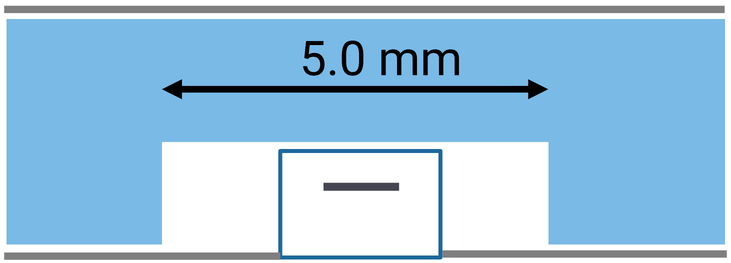


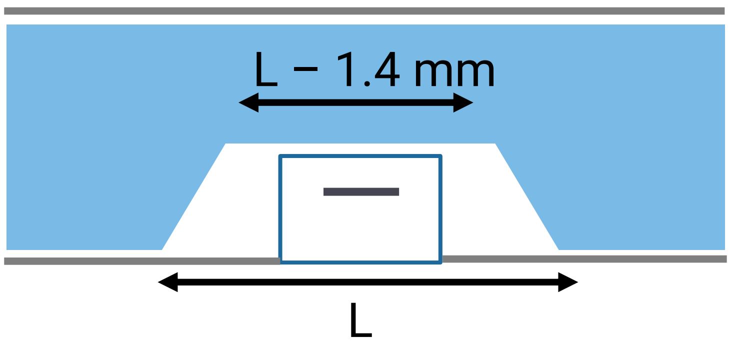
Toward Optimization of Scintillator Shape

- Dimple shape



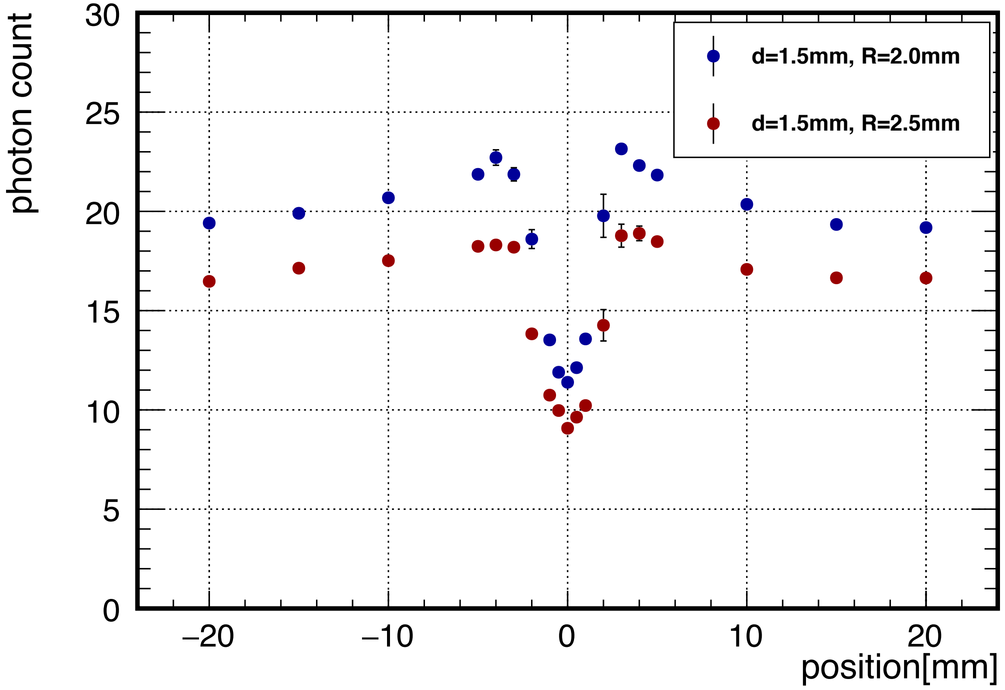


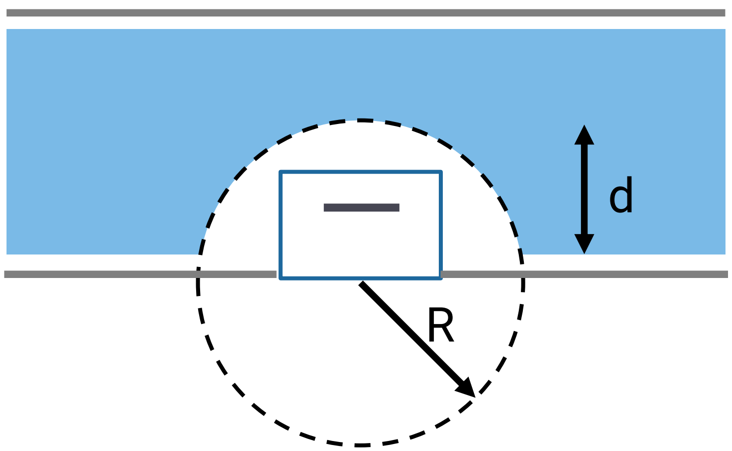


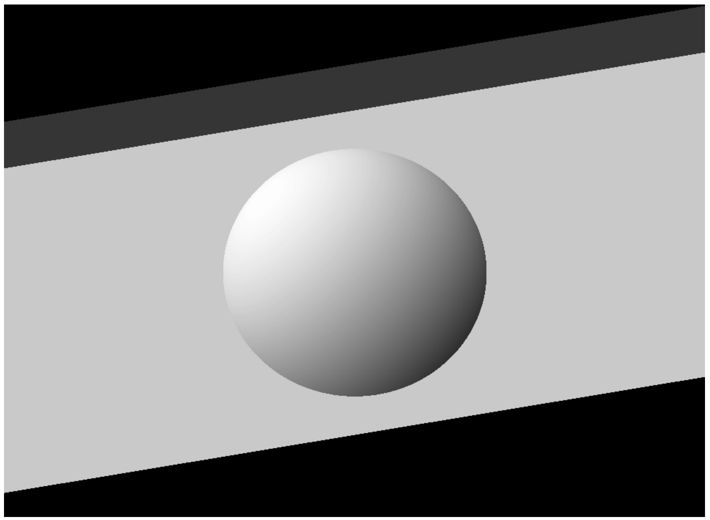


Toward Optimization of Scintillator Shape

- Spherical dimple







Double Side Readout [90 mm strip]