Modification of HCAL-TDR

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On behalf of HCAL Group

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Determination of glass scintillator

V.20250414

Table 1.4: R&D targets of key performance parameters for the glass scintillator (GFO and GFO+), compared with the Bismuth Germanate (BGO) and DSB glass.

Key parameters	GFO	GFO+	BGO[21]	DSB Glass [20]
Density (g/cm^3)	6.0	6.0	7.13	4.2
Melting point (℃)	1250	1150	1050	1550
Radiation Length (cm)	1.59	1.64	1.12	2.62
Molière radius (cm)	2.49	2.50	2.23	3.33
Nuclear interaction length (cm)	24.2	24.1	22.7	31.8
Z_{eff}	56.6	56.9	71.5	49.7
dE/dX (MeV/cm)	8.0	8.0	8.99	5.9
Emission peak (nm)	400	390	480	430
Refractive index	1.74	1.76	2.15	
Light yield (ph/MeV)	985	2445	7500	2500
Energy resolution (% @662keV)	30.3	25.8	9.5	
Scintillation decay time (ns)	36, 105	101, 1456	60, 300	90, 400

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dE/dX (MeV/cm)	8.0	8.99	5.9
Emission peak (nm)	400	480	430
Refractive index	1.74	2.15	
Light yield (ph/MeV)	≈1500	7500	2500
Energy resolution (% @662keV)	≈23	9.5	
Scintillation decay time (ns)	≈60 and 500	60, 300	90, 400

- To achieve a balance between light yield and decay time, the GFO glass system has been selected for the HCAL, delivering a stable light yield exceeding **1500 ph/MeV** with a scintillation decay time of approximately 500 ns.
- Large-size GFO glass (40*40*10 mm^3) can now be stably manufactured in batches with consistent quality.

Light attenuation length

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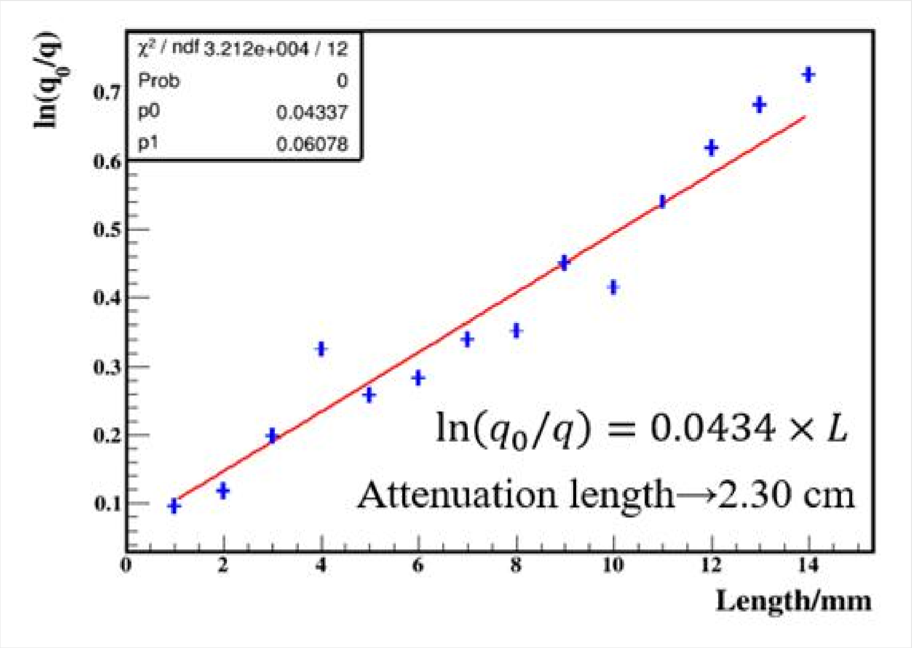

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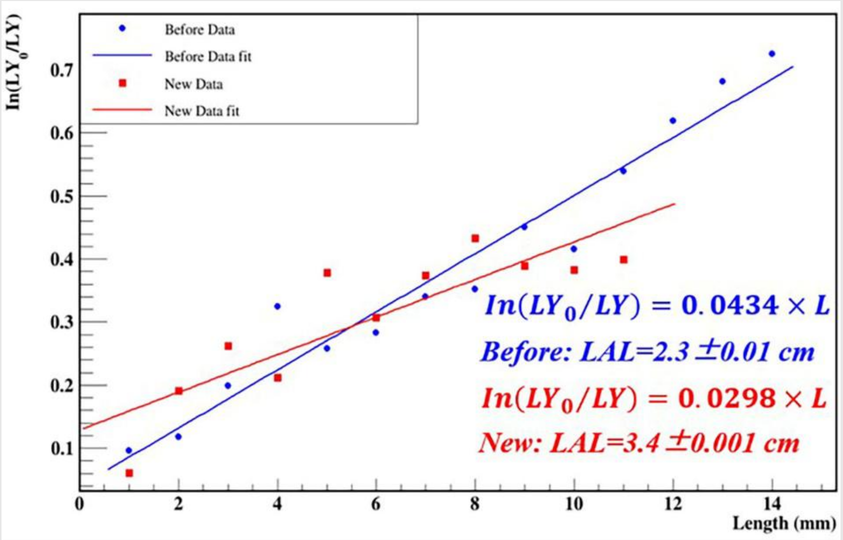

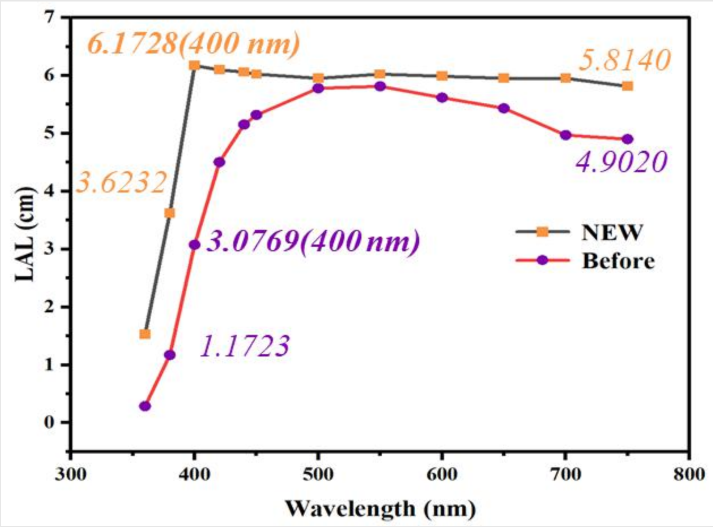

- GS of 1000 ph/MeV grade： **LAL→2.30 cm**
- GS of 1500 ph/MeV grade： **LAL→3.40 cm**

- Through optimization in process and composition, the LAL of the glass at **400 nm** (around the emission peak) was increased from **3.08 cm** to **6.17 cm**.

GS coupled with SiPM

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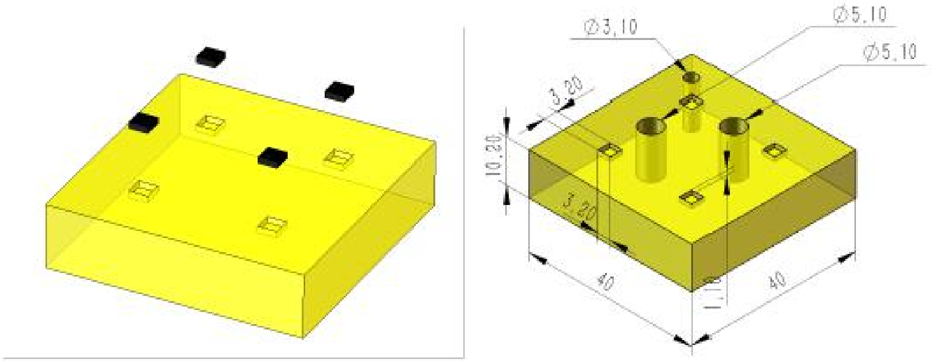

Figure 1.67: Structure of one cell (left is normal cell, right is corner cell)

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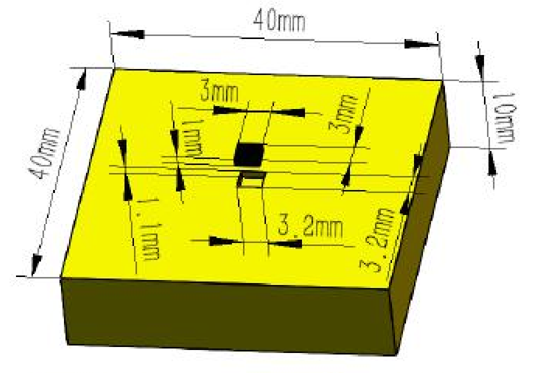

Figure 1.4: Structure of one cell (length unit is mm).

- Due to the improved light yield **(1000→1500 ph/MeV)** and attenuation length **(3.08 cm to 6.17 cm)**, a single 3×3 mm² SiPM coupled with GFO glass can detect a sufficient number of photons.
- Both radioactive source tests and cosmic ray experiments are being conducted simultaneously to verify the light output and MIP (Minimum Ionizing Particle) response characteristics, as well as their correlation.

SiPM + GS

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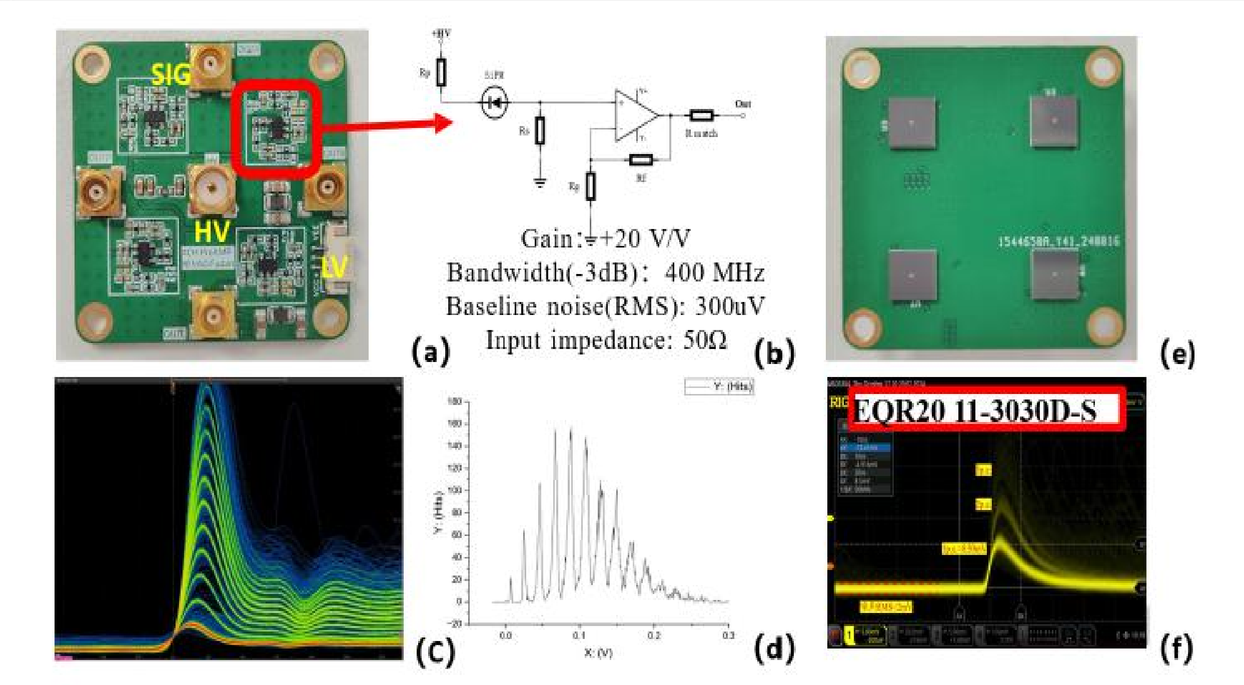

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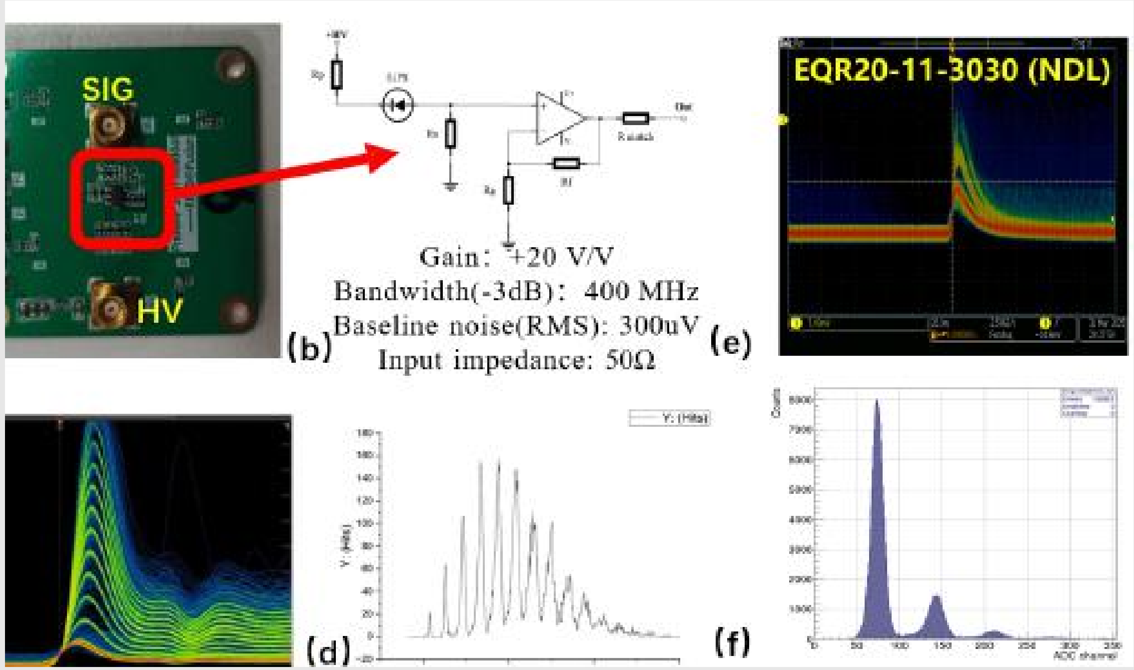

- Test the signal of one 3×3 mm2 SiPM (EQR20 11-3030D-S) coupling with a readout PCB and ADC distribution of dark noise of a 3×3 mm2 NDL SiPM.

The Cell Simulation

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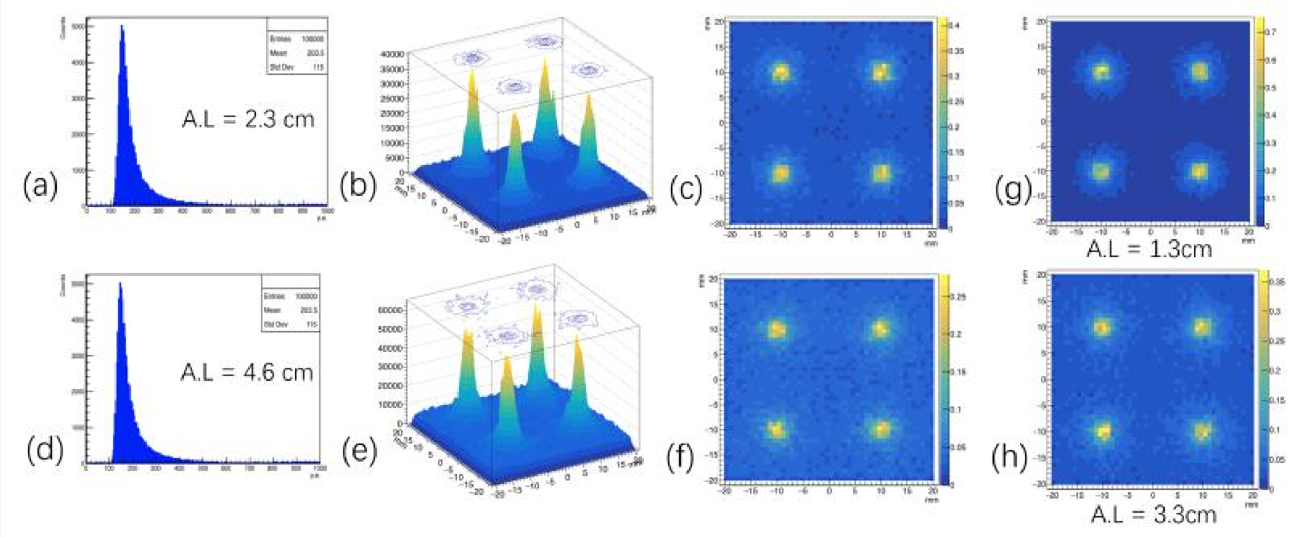

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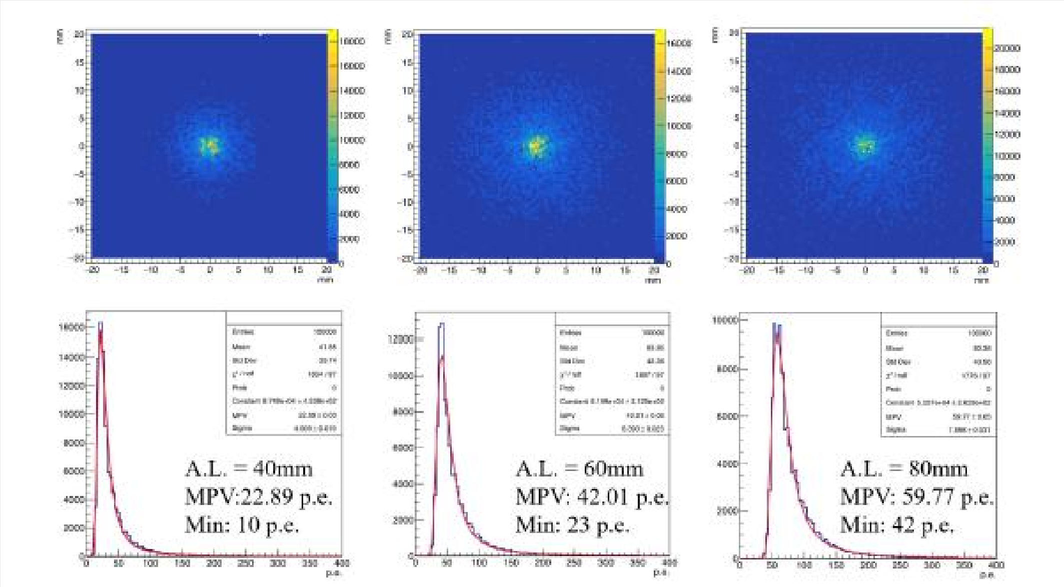

- The average effective light yield nearly doubles when the attenuation length increases by 20 mm.
- Longer attenuation lengths yield higher collection efficiency and better uniformity across the SiPM surface.

ADC spectrum of GS cell with a SiPM

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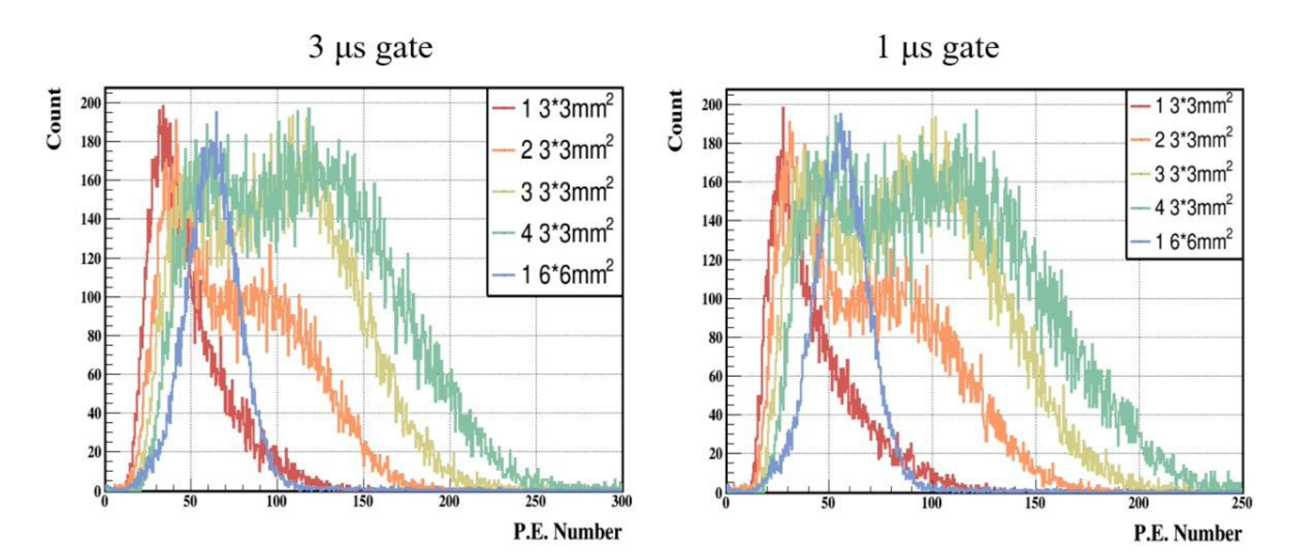

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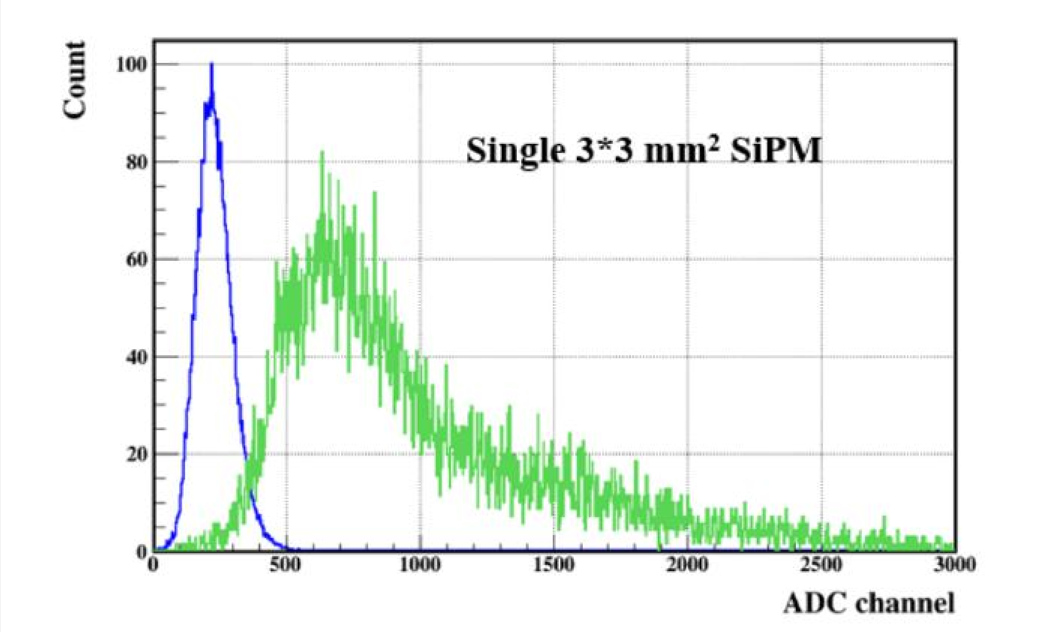

Dark count rate

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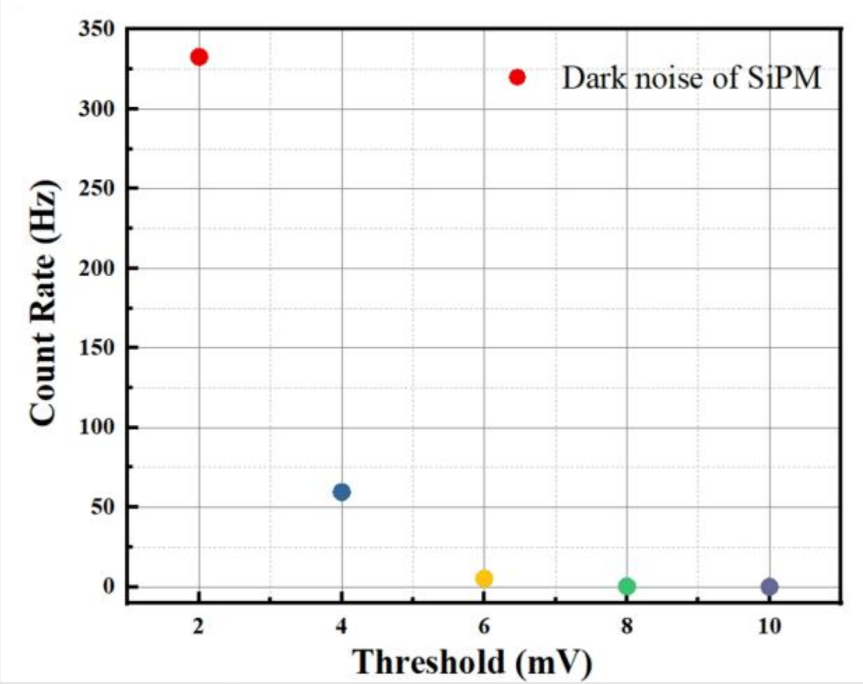

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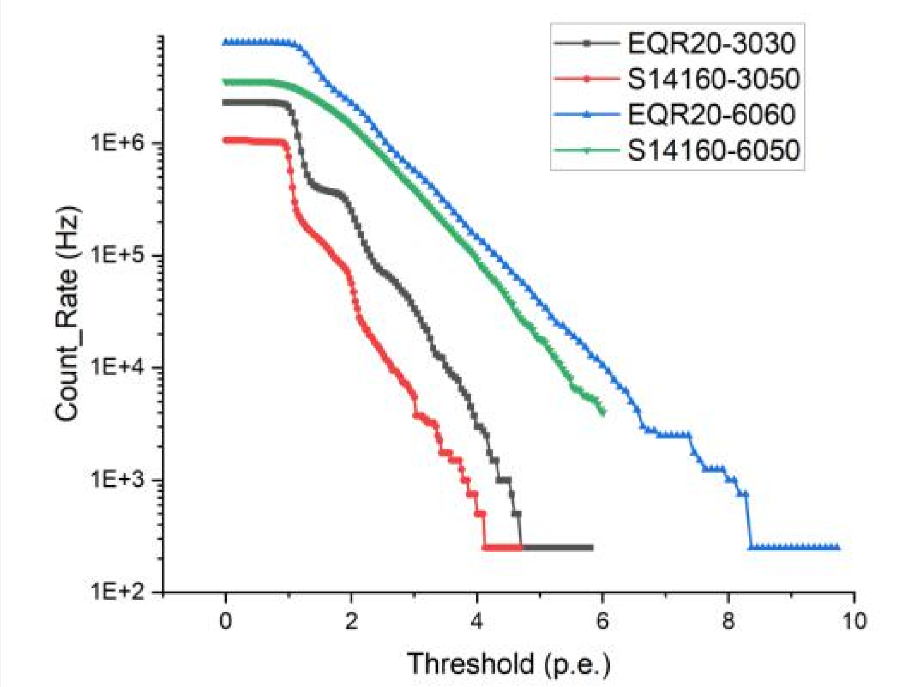

- A baseline DCR of 255 kHz/mm² at 0 p.e. threshold for the NDL EQR20 SiPM, compared to 112 kHz/mm2 for the Hamamatsu S14160-3050 SiPM.
- significant DCR suppression at higher thresholds: at 5 p.e., the DCR reduces to approximately 28 Hz/mm2 and 12 Hz/mm2 for the NDL and Hamamatsu devices, respectively.

Calibration

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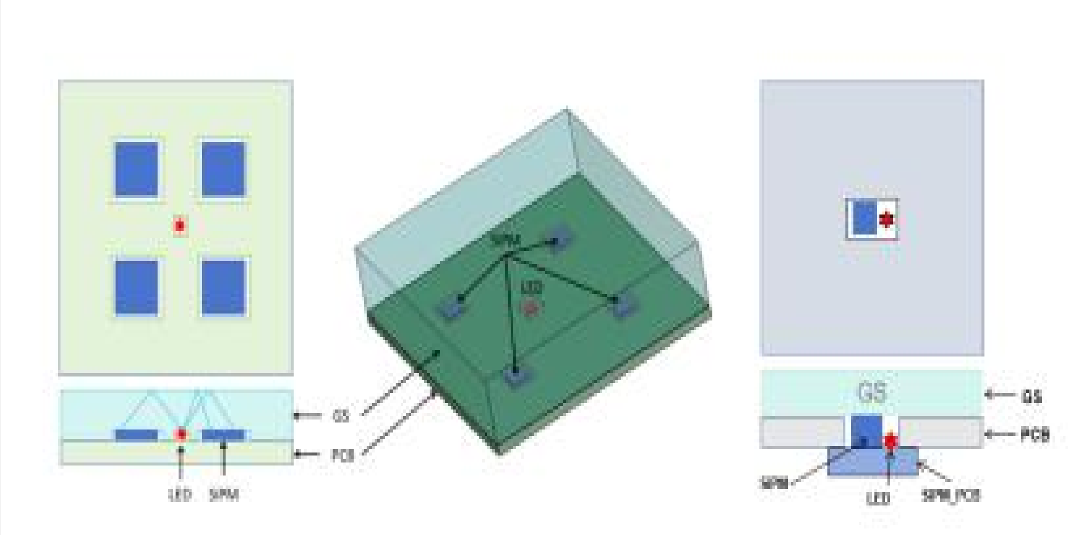

Delete the P.E./MeV

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Table 1.14: Measured photon electron of five types of GS+SiPM settings with different integral time.

Settings	3μs gate	1μs gate	ratio
	P.E./MeV		1μs/3μs
1 pcs 3×3 mm^2 (NDL)	35	26	0.743
2 pcs 3×3 mm^2 (NDL)	**114**	**100**	**0.877**
3 pcs 3×3 mm^2 (NDL)	146	130	0.89
4 pcs 3×3 mm^2 (NDL)	163	146	0.896
1 pcs 6×6 mm^2 (HPK)	88	77	0.877

MIP response is 397.5 P.E./MIP after subtracting the pedestal. To verify the accuracy of the test results, Gamma energy spectrum was measured with the same experimental setup, as shown in Figure 1.118(b). Under ^{137}Cs, the light output of the glass is 64.4 P.E./MeV. According to previous simulation result, 1 MIP is about 7 MeV/cm, and the measured value of MIP response is relatively small. Compared to previous results, the poor MIP response may be due to the low light yield, low photon collection efficiency and poor light attenuation length.

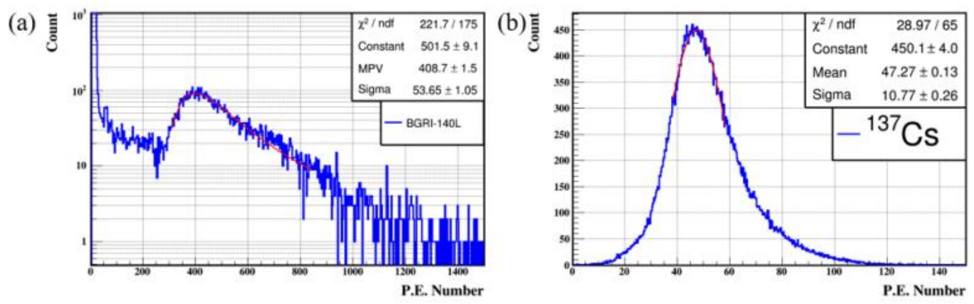

Figure 1.118: Energy spectrum of the glass under (a) cosmic ray and (b) Gamma ray.

Table 1.13: Light yield comparison of three types of GS+SiPM settings

Settings	Light yield ratio	
	Measured	Simulation
1 pcs 6×6 mm^2	1.0	1.0
2 pcs 3×3 mm^2	0.81	0.74
4 pcs 3×3 mm^2	**1.84**	**1.2**

Comments

1. Scintillating glasses represent new territory for hadronic calorimetry. The material properties, such as radiation length and hadronic interaction length, are not yet fully characterized.

Although the decision to adopt this technology is well justified, it carries significant risk. Therefore, extensive prototyping and simulation studies are mandatory to validate the concept.

A deep understanding of the response to hadrons is essential, including clarification of the constant term origin, study of the e/h ratio (software compensation), validation of GEANT4 physics lists, and accurate characterization of material properties such as quenching (Birks' law).

2. The introduction of the TDR currently lacks references to important developments such as the CALICE AHCAL, built by German, Czech, and Japanese groups, which served as a foundation for the scintillator section of the CMS HGCAL.
3. The process of down-selecting technology options should be better explained in the text. Statements such as "excessive power consumption" should be supported with quantitative arguments for clarity and transparency.

Recommendations

4. Develop a detailed plan to validate the choice of GS-HCAL technology in a timely manner. This plan should include the development of glass samples with reproducible and controlled quality, along with a detailed understanding of single-particle and jet energy resolution.
5. Prioritize the construction of a full-scale prototype. This prototype should incorporate the preliminary selection of glass tiles and ideally include a first version of both the readout ASIC and the PCB.
6. Decide early on the final configuration regarding the number of SiPMs per tile and implement this choice in the prototype.
7. Organize the group's work such that the prototype is simultaneously implemented into the simulation framework, including a complete digitization chain, to enable rapid feedback from test beam campaigns.