

双读出量能器的模拟与样机研制

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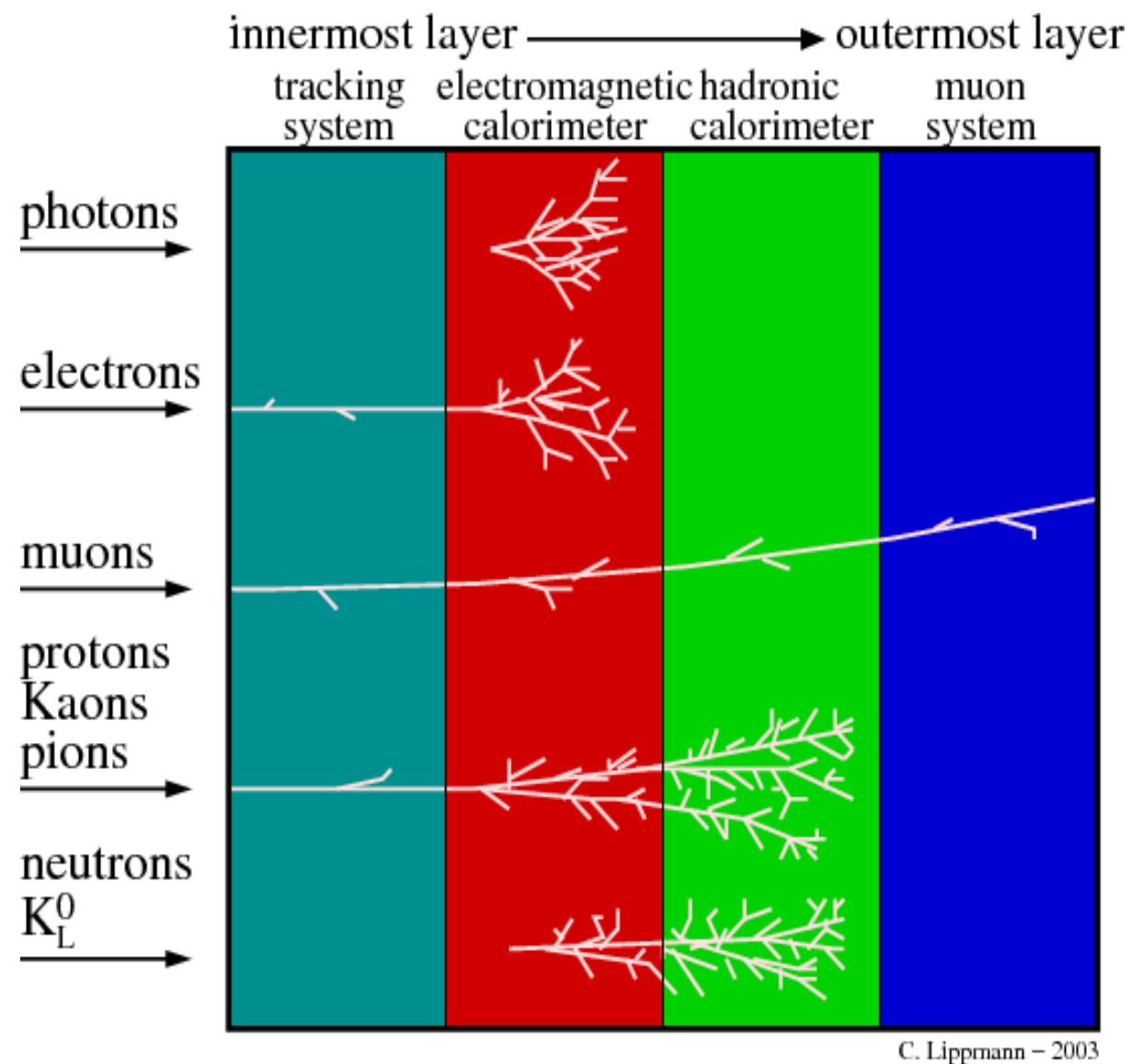
目录

 1 双读出量能器性能分析

 2 单元模块模拟

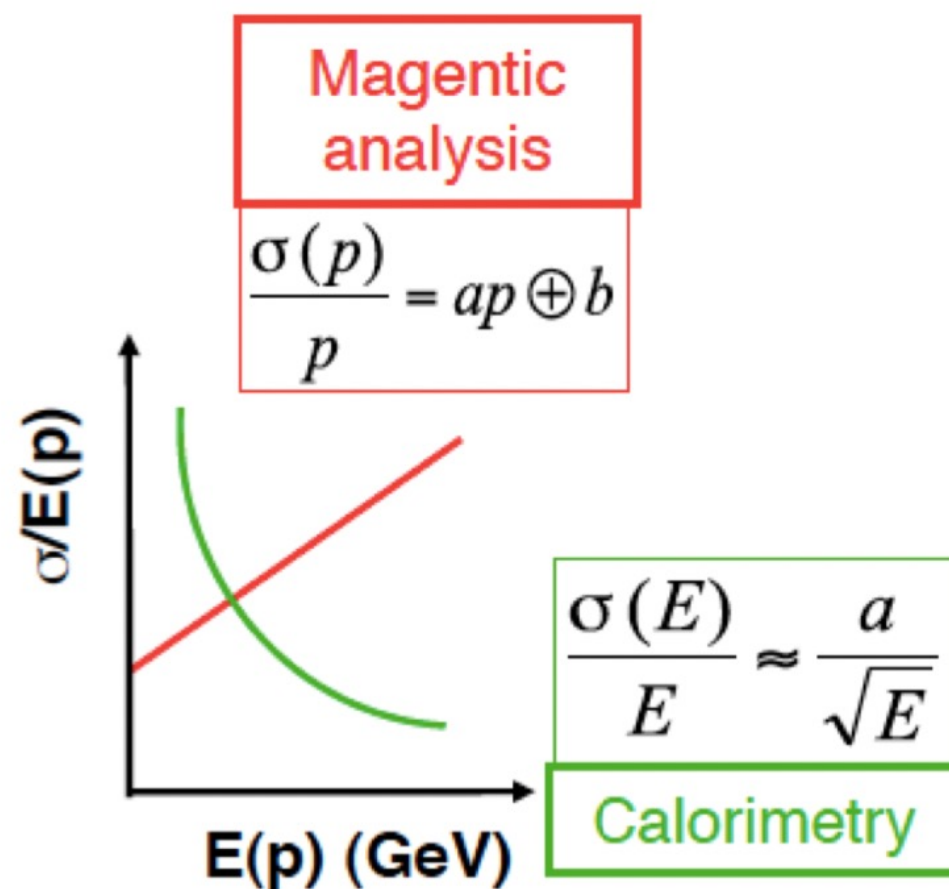
 3 模块研制与测试

量能器在谱仪探测器中的应用

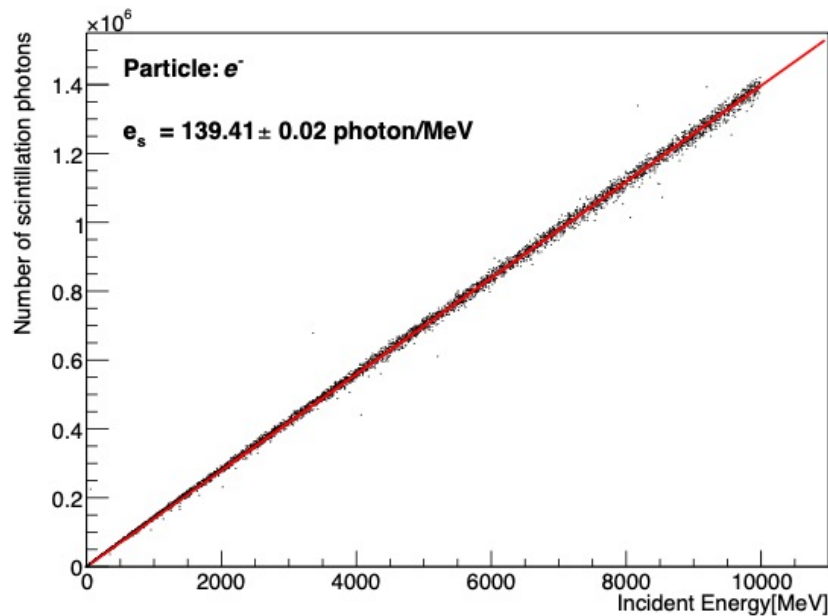


电磁量能器: $e^\pm, \gamma$

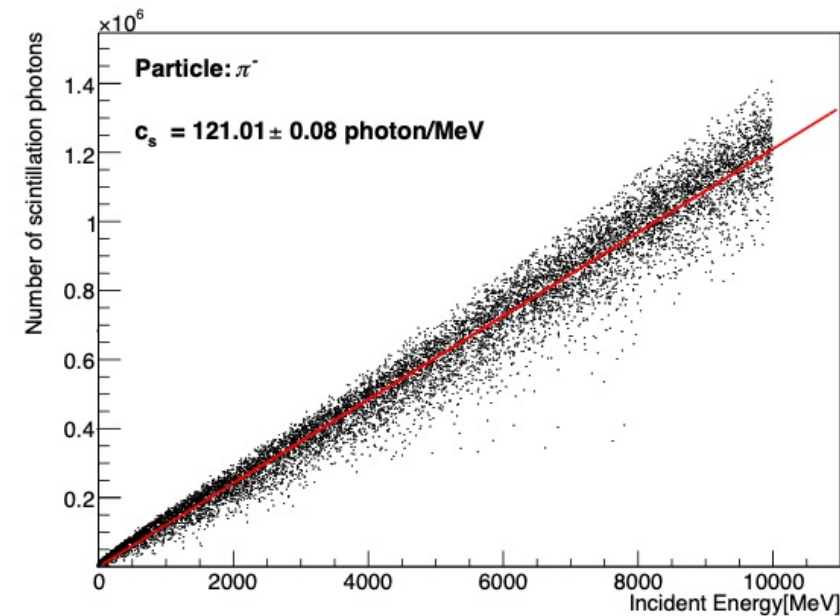
强子量能器: $\pi^\pm, p^\pm, K^\pm, K_L^0, n$



电磁信号与强子信号能量分辨率比较



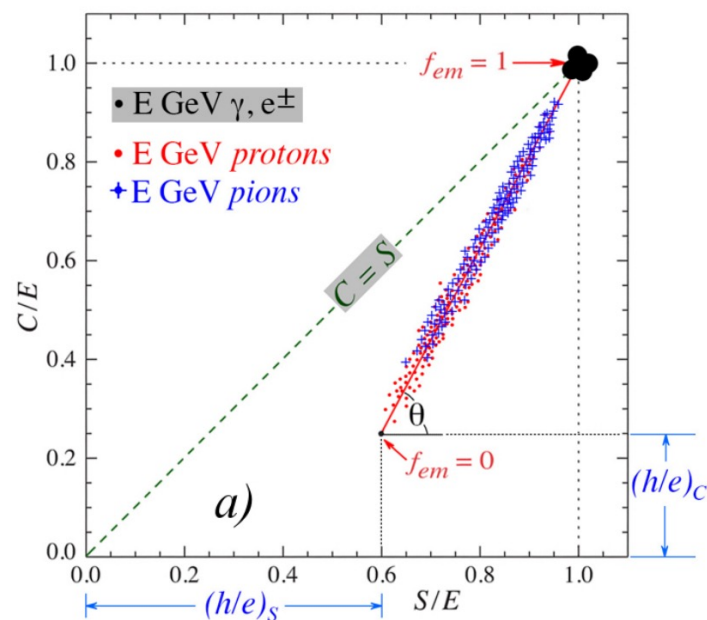
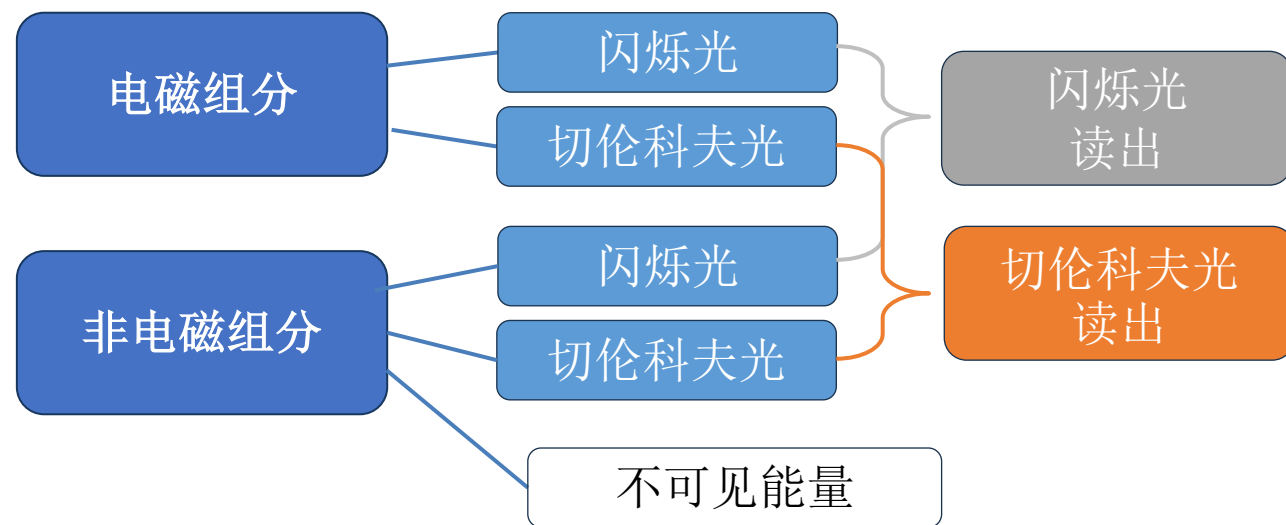
(a)



(b)

Figure 2. Response coefficients between the incident particle energy E_{in} from 0 to 10000 MeV and the number of produced photons in the homogeneous calorimeter. Plot (a) shows the response coefficient obtained from incident e^- , and Plot (b) shows the response coefficient obtained from incident π^- . The red line is linear fit.

双读出量能器优点

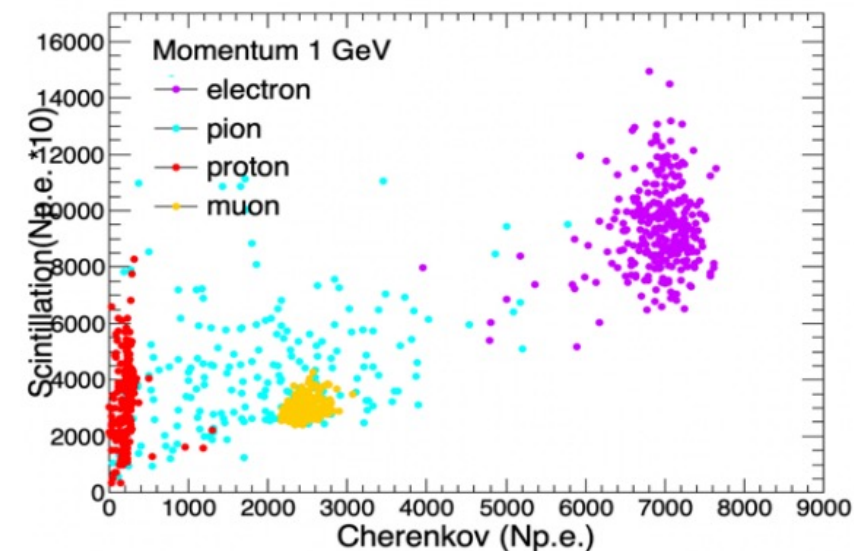


$$\cot \theta = \frac{1 - (h/e)_s}{1 - (h/e)_c}$$

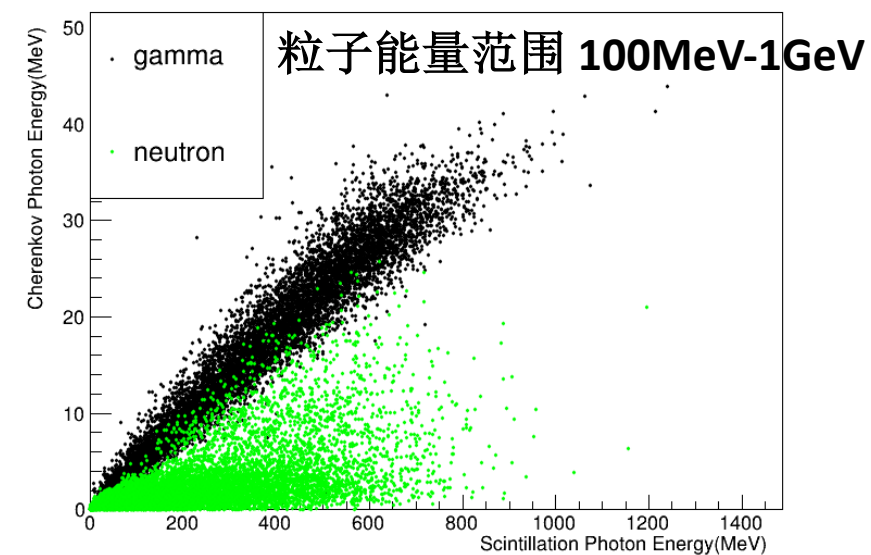
$$E = \frac{S - \cot \theta C}{1 - \cot \theta}$$

在强子探测中，双读出算法可以对能量进行修正。

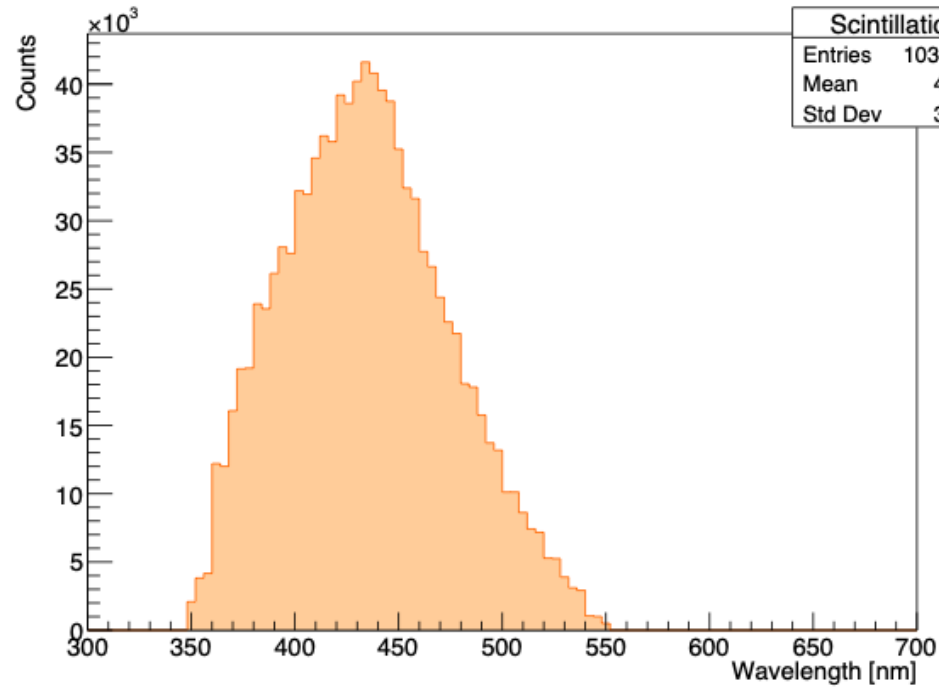
PID 能力



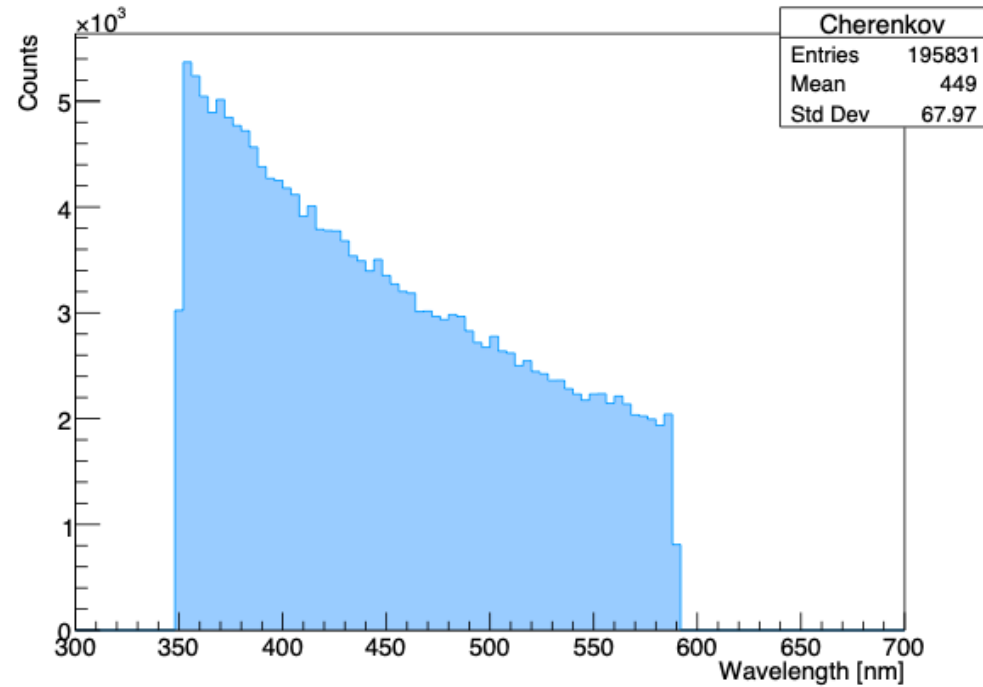
Particles Scintillation-Cherenkov



闪烁光谱与切伦科夫光谱



(a)



(b)

Figure 1. Photon energy spectra within the assumed acceptance of a photodetector for 10 GeV π^- mesons incident on the calorimeter: (a) scintillation photon emission spectrum, (b) Cherenkov photon emission spectrum.

Table 1. Summary of energy resolutions for the homogeneous PbWO₄ calorimeter using different signal-channel configurations and reconstruction methods.

Input configuration / Method	Energy resolution / $\sqrt{E}/GeV$
Machine-learning-based reconstruction	
ML1	$(12.5 \pm 1.6)\%$
ML2	$(22.0 \pm 0.8)\%$
ML3	$(30.2 \pm 0.9)\%$
ML12	$(10.8 \pm 0.3)\%$
ML13	$(12.8 \pm 0.4)\%$
ML23	$(19.3 \pm 0.7)\%$
ML123	$(11.2 \pm 0.4)\%$
Conventional reconstruction (photon counting)	
Scint	$(17.2 \pm 2.4)\%$
Dual	$(16.5 \pm 0.2)\%$

取样量能器的能量分辨率分析

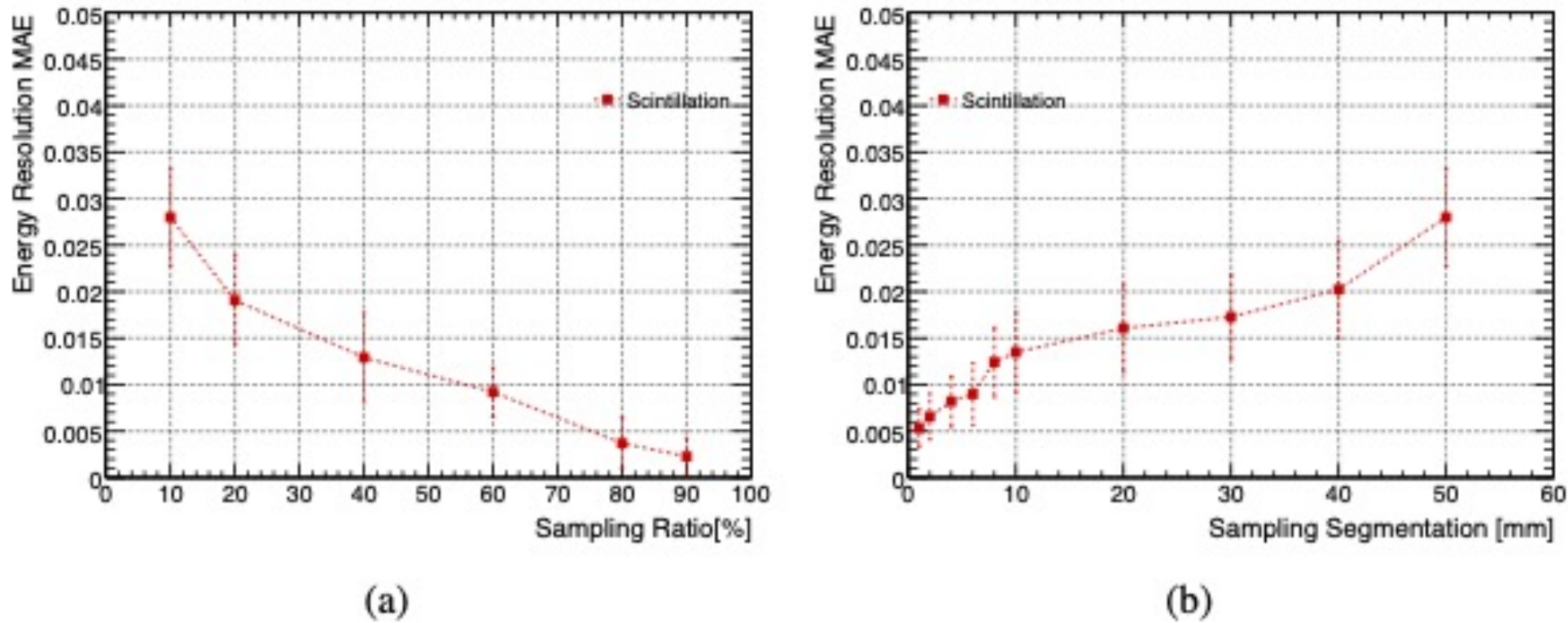
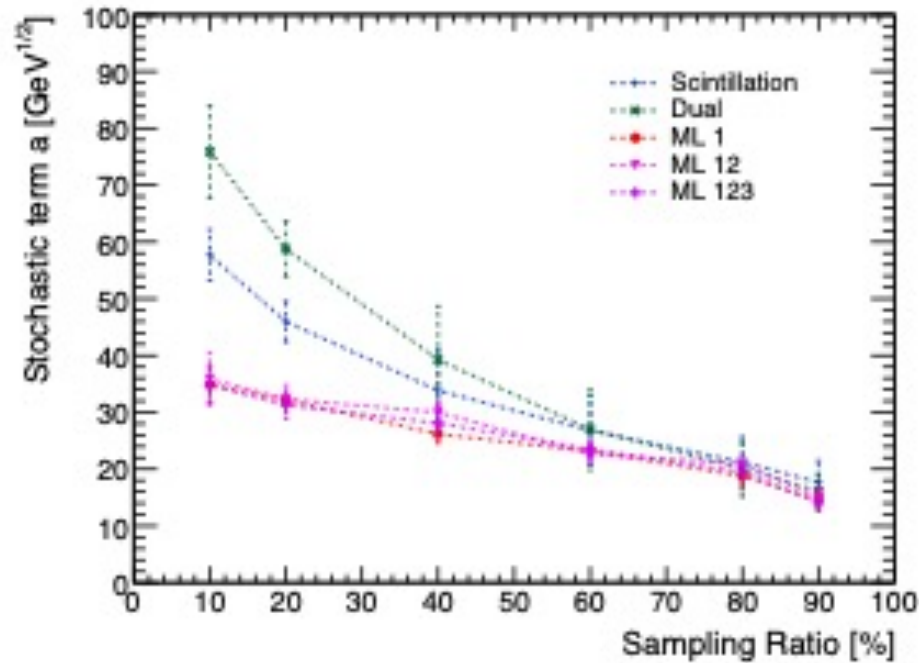
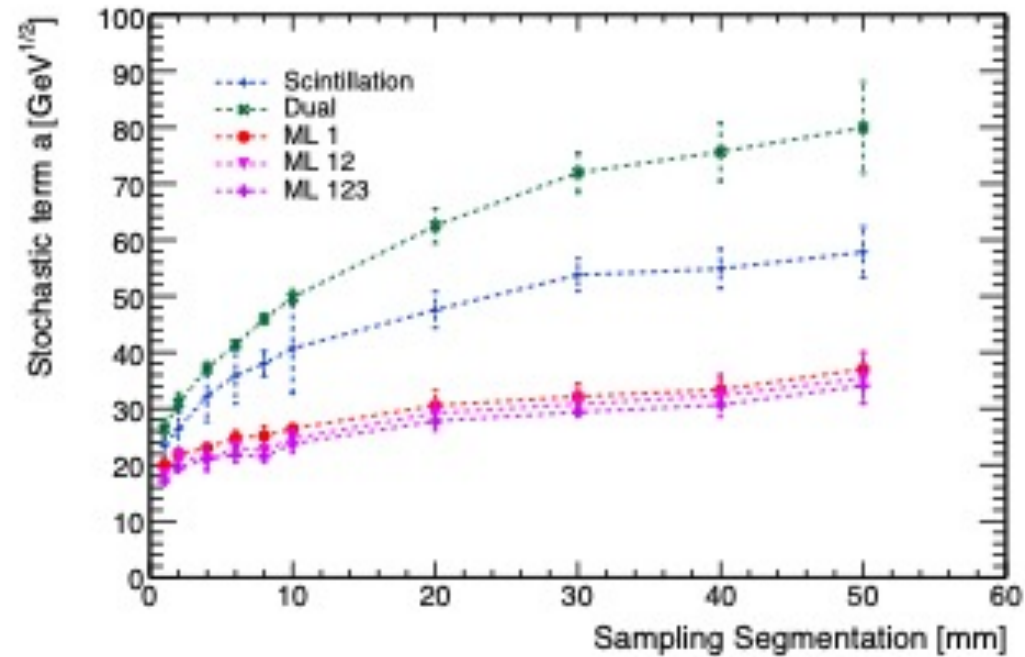


Figure 19. Variation of the energy-resolution MAE of the sampling calorimeter in the 3.25–5.75 GeV range. (a) MAE as a function of the sampling ratio (with a fixed sampling segmentation of 50 mm); (b) MAE as a function of the sampling segmentation (with a fixed sampling ratio of 10%)

取样型量能器的能量分辨率分析



(a)



(b)

Figure 20. Trends of the energy resolutions obtained from the Scint, Dual, and ML methods. Plot (a) shows the energy resolution as a function of sampling ratio (with a fixed sampling segmentation of 50 mm), and Plot (b) shows the energy resolution as a function of sampling segmentation (with a fixed sampling ratio of 10%).

取样型量能器的能量分辨率分析

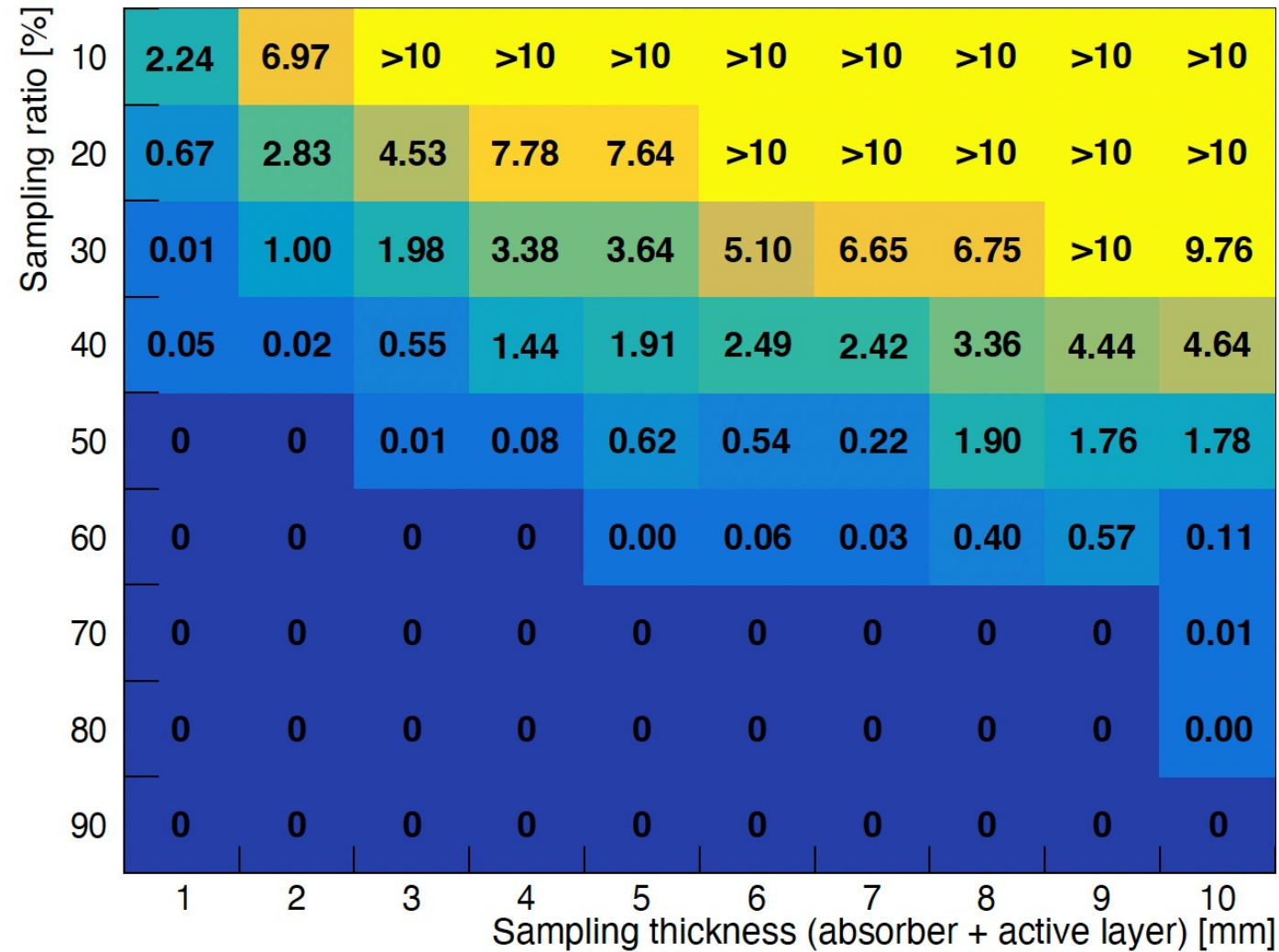


Figure 8. Distribution of the energies at which the dual-readout and scintillation-channel resolutions are equal under different parameter settings. Energy unit: [GeV].

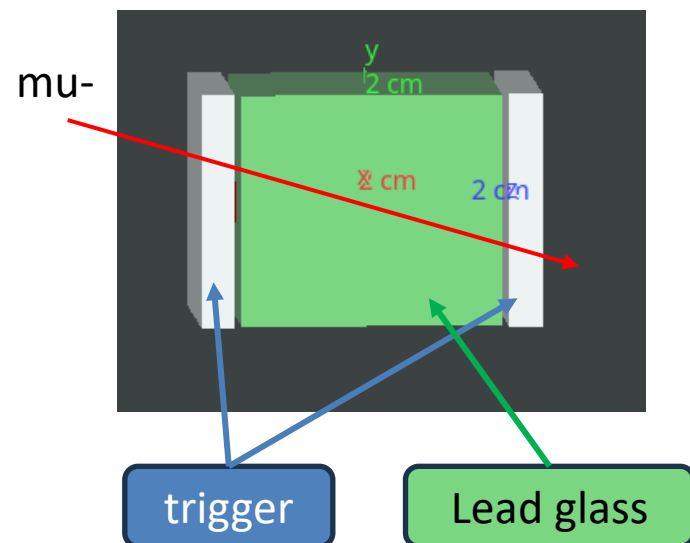
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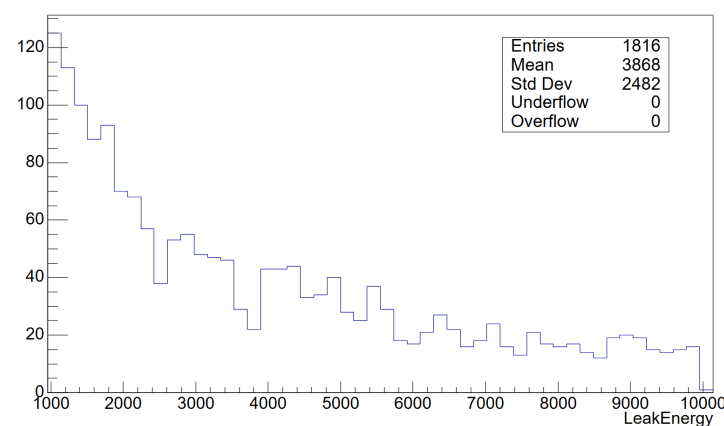
模拟结果



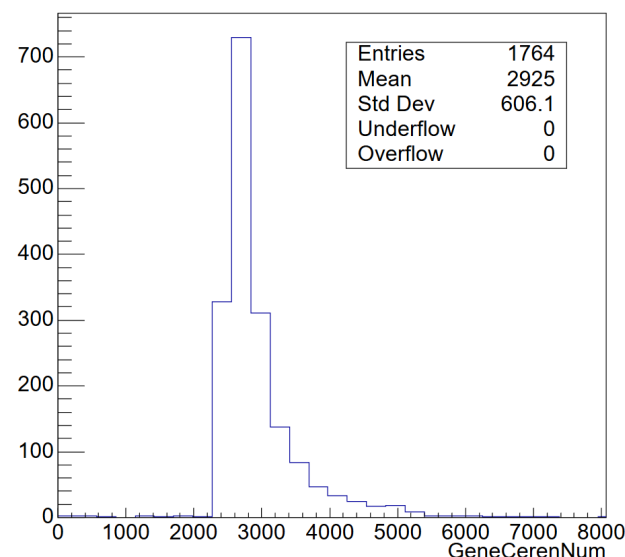
触发器材料为塑闪

将单个 SiPM 置于铅玻璃的中心位置，以进行信号收集。

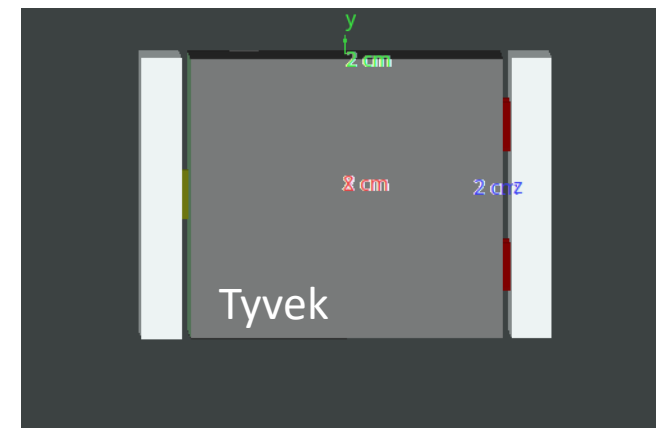
当两个触发器均产生信号时，SiPM 探测到的光子将被记录。



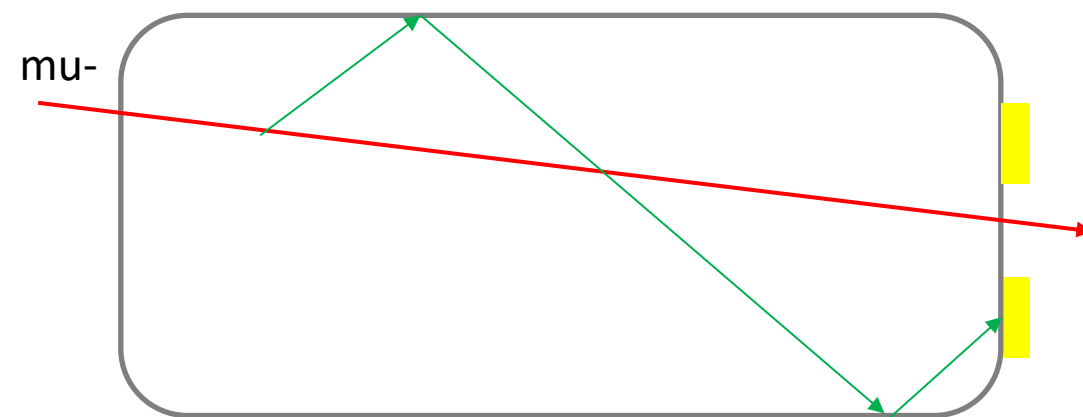
宇宙射能量为 1 GeV 到 10 GeV 范围内进行的对数均匀采样。



由宇宙线产生的切伦科夫光子

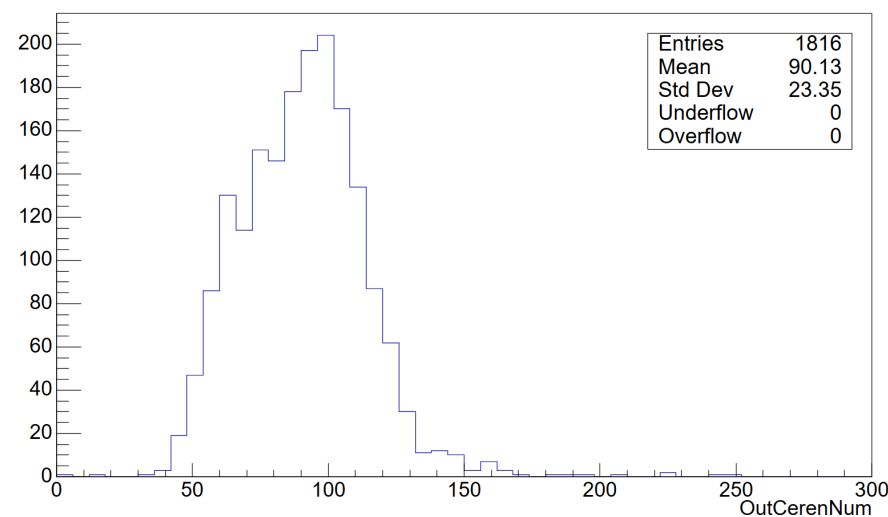
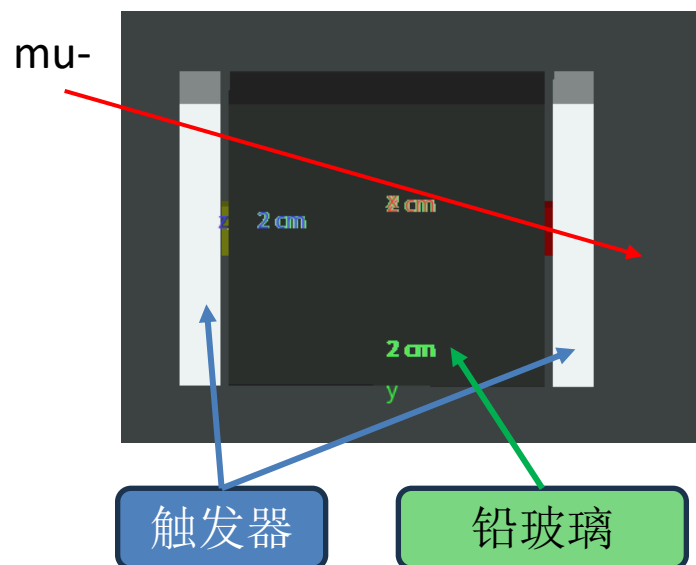


使用反射率为 96% 的 Tyvek 材料作为反射层。

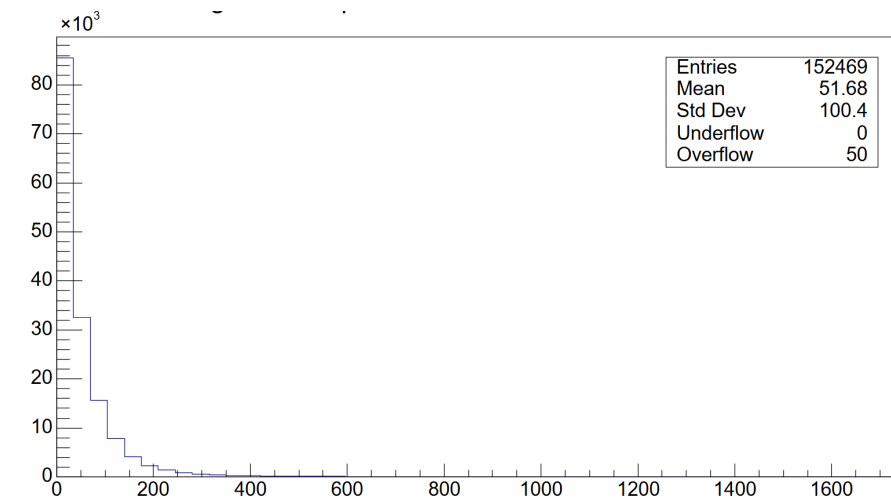


记录 SiPM 收集到的光子数量。并且记录这些光子的反射次数。

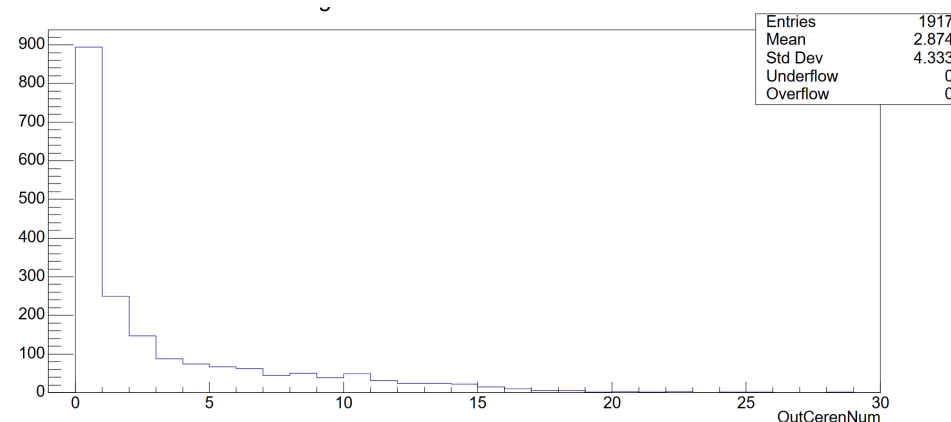
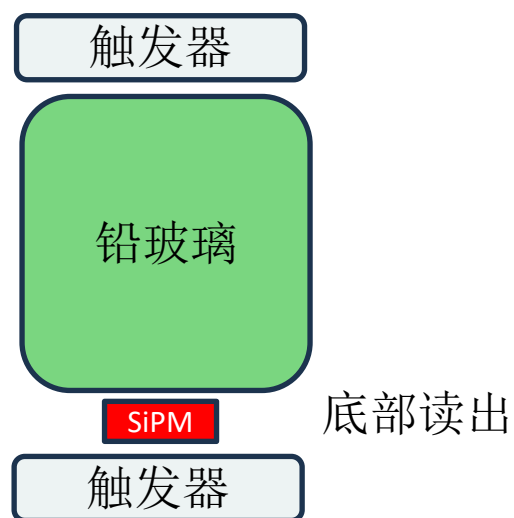
模拟结果



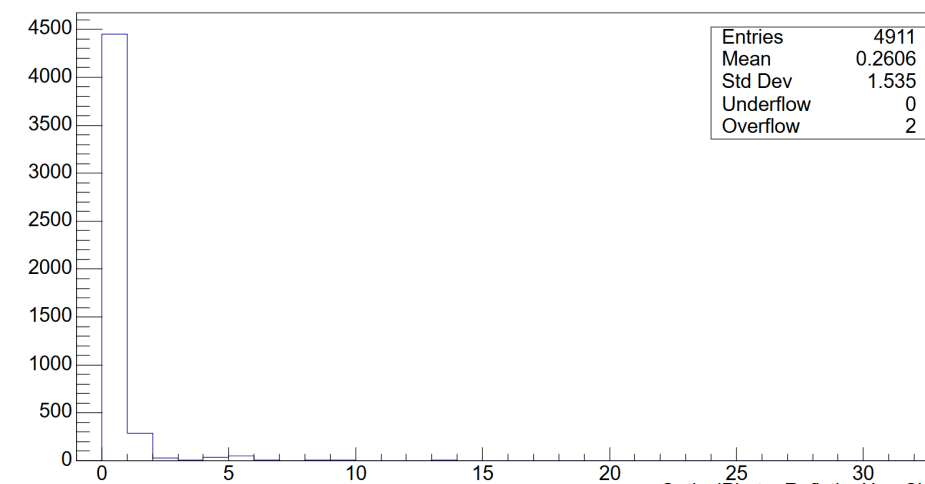
平均探测光子数 90



探测光子平均反射次数 51



平均探测光子数 2.6



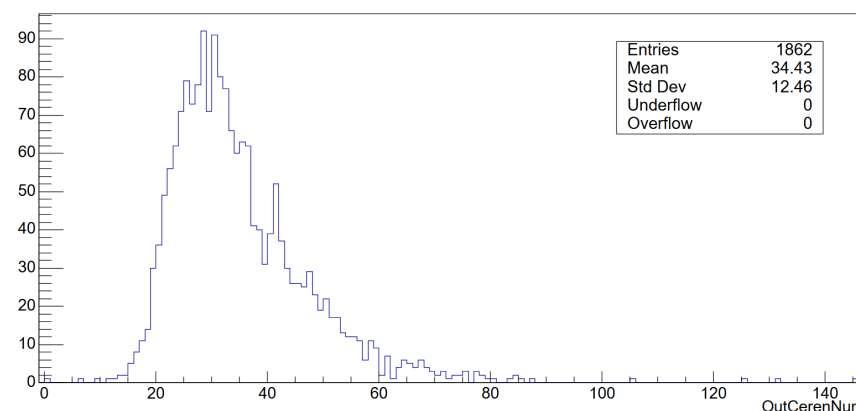
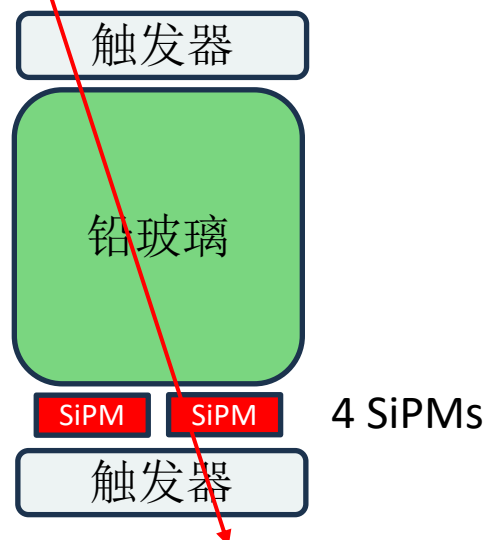
探测光子平均反射次数 0.2

在铅玻璃和塑闪之间增加 0.05mm 空气间隔

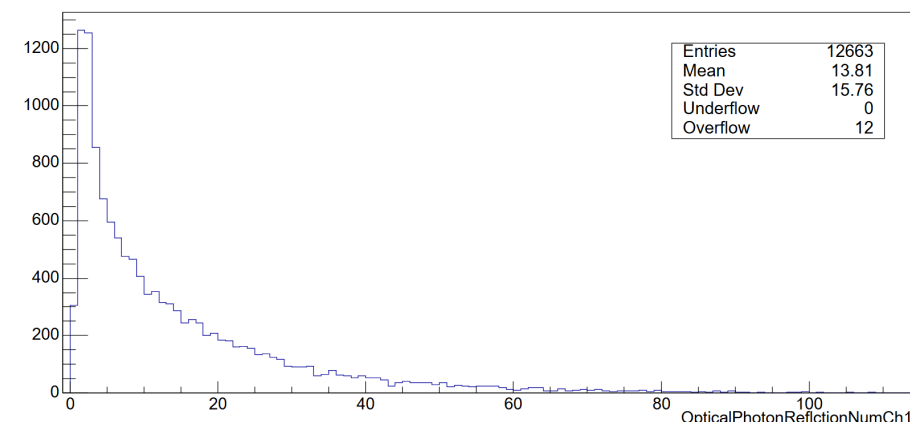
模拟结果

4 侧面粗糙

mu-



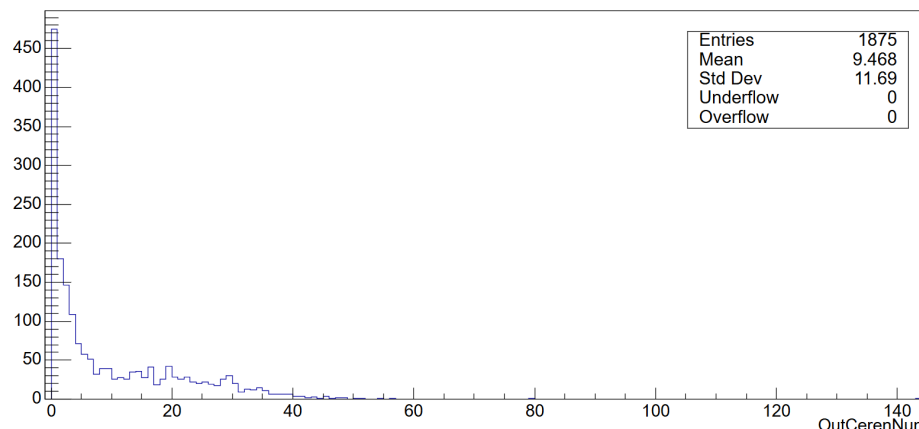
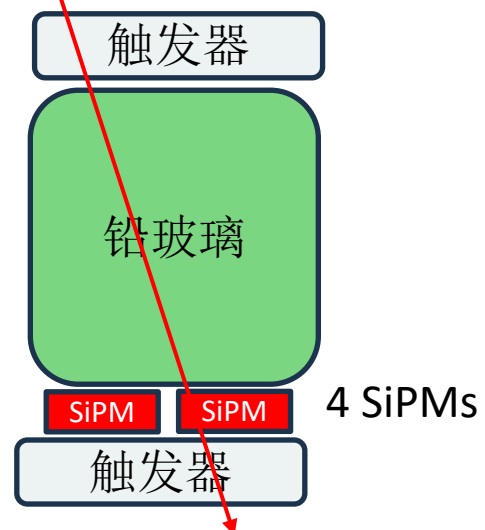
平均探测光子数 : 34.3



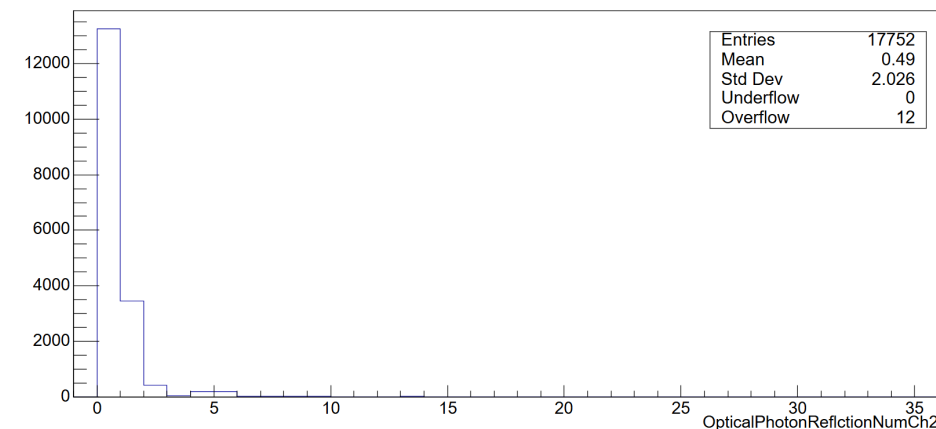
探测光子平均反射次数 : 13.81

6 表面光滑

mu-



平均探测光子数 9.4



探测光子平均反射次数 0.49

模拟结果

切伦科夫光子数

量能器结构	产生光子	量能器吸收	反射层吸收	SiPM(顶部)接收	SiPM(顶部)探测	SiPM(底部)接收	SiPM(底部)探测
没有空气层	2904	1391	713	390	85	410	90
(%)	100%	47.8%	24.5%	13.4%	2.92%	14.1%	3.09%
包含空气层	2942	2207	722	1.78	0.45	11.35	2.87
(%)	100%	75.0%	24.5%	0.06%	0.02%	0.38%	0.09%

加入空气间隔后，被吸收的光子数量明显增加。

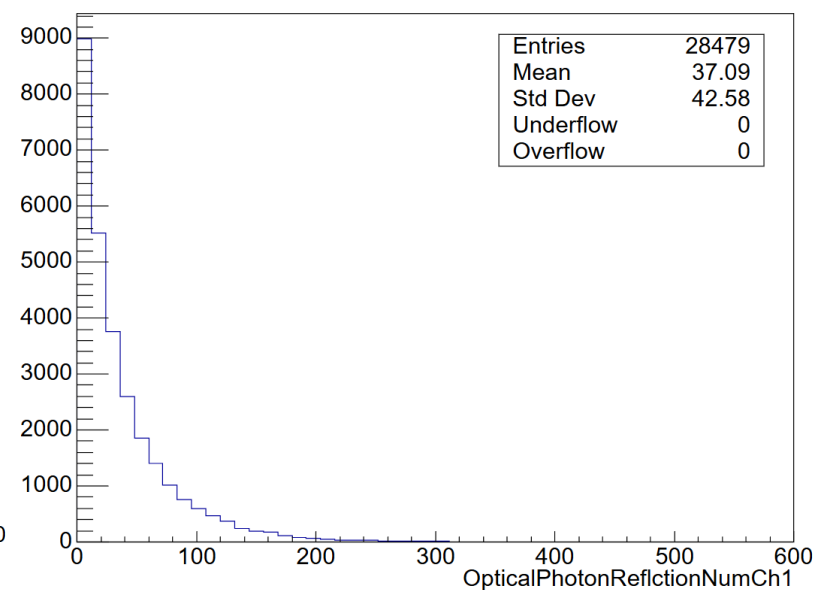
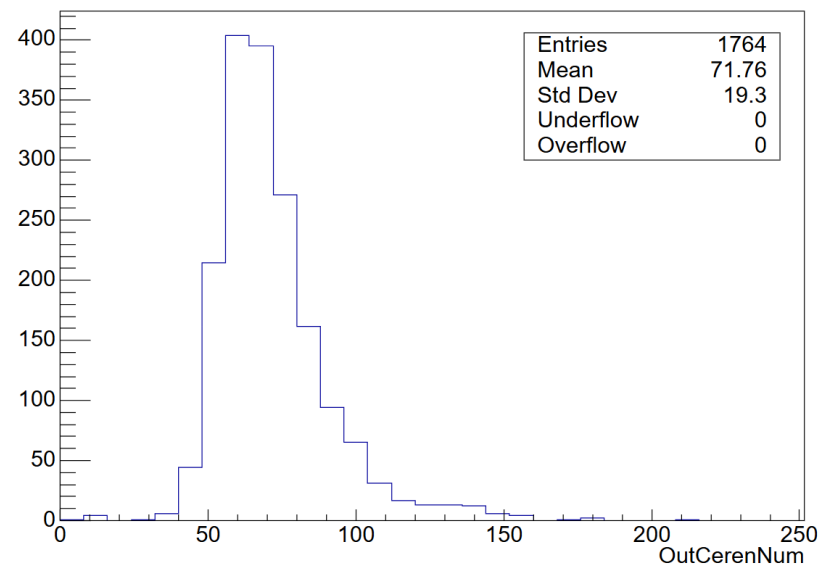
量能器结构	产生光子	量能器吸收	反射层吸收	SiPM(顶部)接收	SiPM(顶部)探测	SiPM(底部)接收	SiPM(底部)探测
粗糙表面	2964	945.6	1858	26.56	6.8	134.2	34.43
(%)	100%	31.90%	62.69%	0.90%	0.23%	4.53%	1.16%
没有粗糙表面	2954	2210	706	1.54	0.38	36.81	9.46
(%)	100%	74.81%	23.90%	0.05%	0.01%	1.25%	0.32%

增大铅玻璃表面粗糙度后，反射损失增加而吸收损失减少，这说明确实有更多的光子逃逸了。

模拟结果

4侧面粗糙铅玻璃

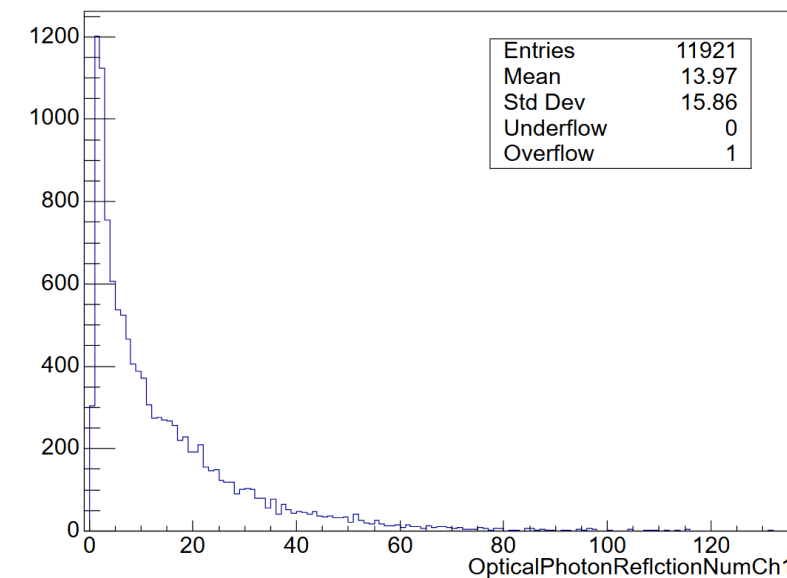
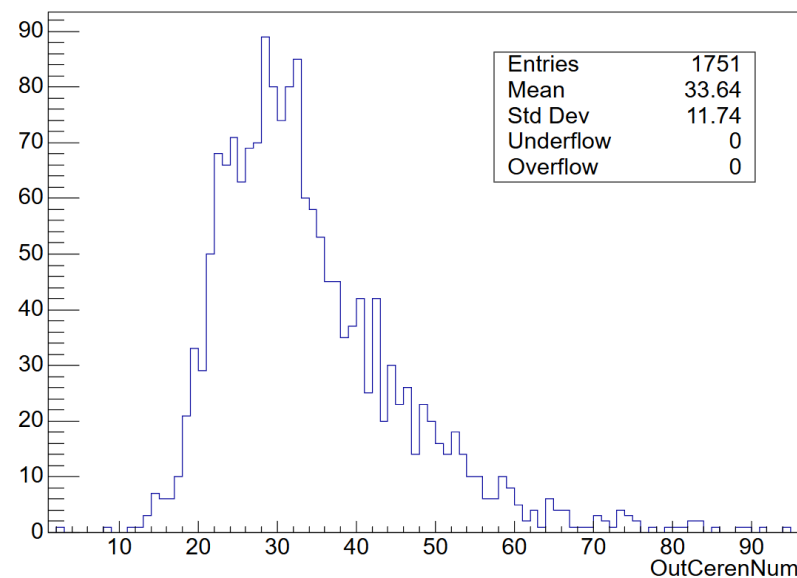
Tyvek 全包裹



平均探测光子数 : 71.76

探测光子平均反射次数 : 37.09

4侧面包裹



平均探测光子数 : 33.64

探测光子平均反射次数 : 13.97

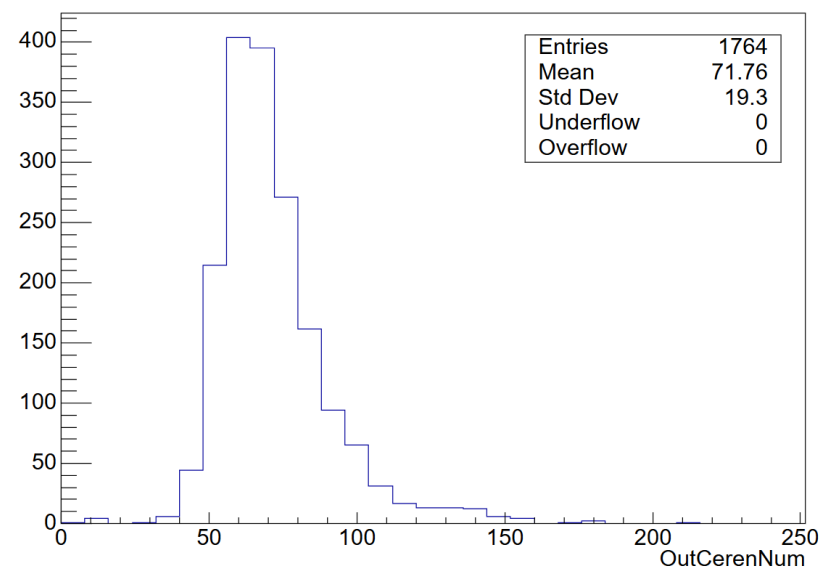
模拟结果

Tyvek 全包裹



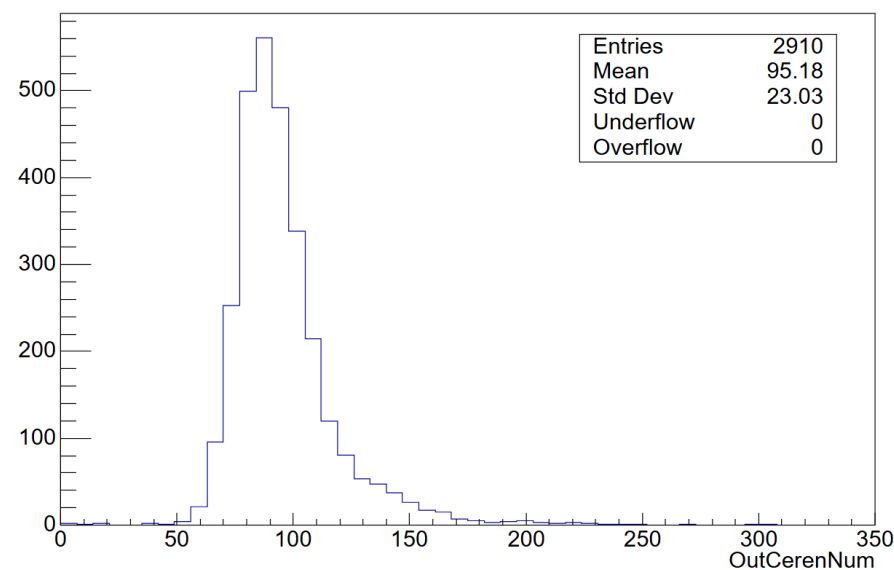
由于铅玻璃的粗糙表面会导致更多光子逃逸，因此进行了额外模拟研究，以统计不同粗糙度表面下的探测光子数量。

4侧面粗糙



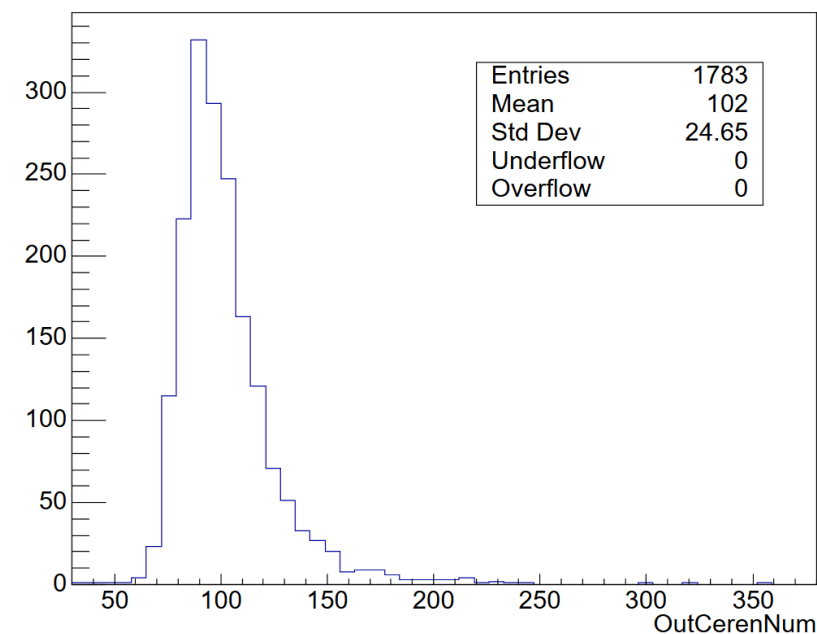
平均探测光子数 : 71.76

全表面粗糙



平均探测光子数 : 95.18

仅SiPM读出窗口粗糙



平均探测光子数 : 102

模拟结果

切伦科夫光子数

量能器结构	产生光子	量能器吸收	反射层吸收	SiPM(顶部)接收	SiPM(顶部)探测	SiPM(底部)接收	SiPM(底部)探测
4侧面粗糙	2946	1369	1195	68.79	16.14	303.2	71.67
(%)	100%	46.47%	40.56%	2.34%	0.55%	10.29%	2.43%
全表面粗糙	2945	1479	883.4	108.5	24.22	454.2	102
(%)	100%	50.22%	30.00%	3.68%	0.82%	15.42%	3.46%
SiPM读出窗口粗糙	2927	1342	1073	102.4	24.2	403.2	95.18
(%)	100%	45.85%	36.66%	3.50%	0.83%	13.78%	3.25%

如果铅玻璃表面的粗糙区域较少，会有更多的光子被吸收，而因反射损失的光子则会更少。

当仅对 SiPM 的窗口进行粗糙处理时，SiPM 探测到的光子数量最多。

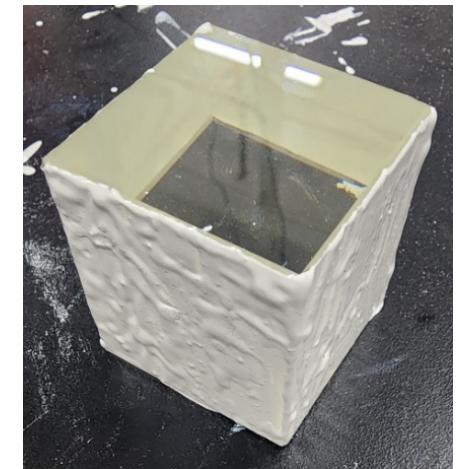
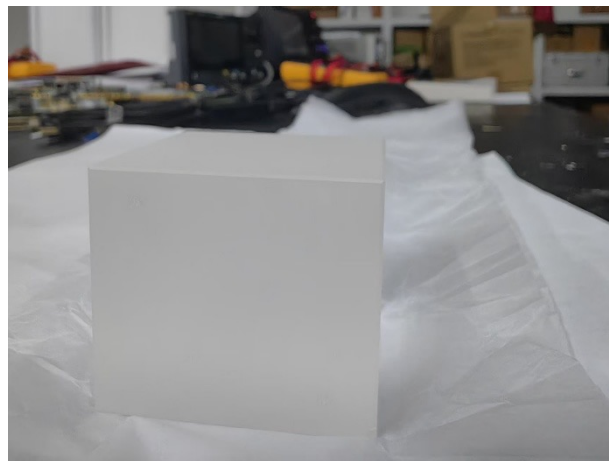
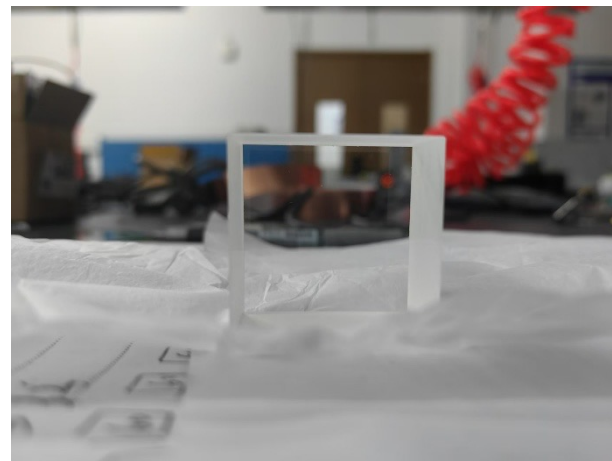
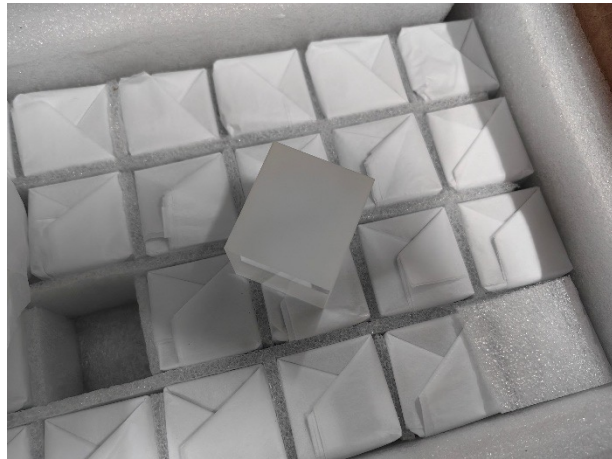
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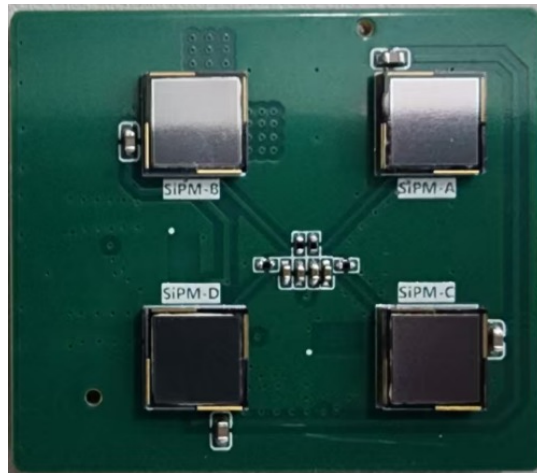
铅玻璃



其尺寸为 $3.5 \times 3.5 \times 3.9 \text{ cm}^3$ ，读出端面进行抛光处理。

用 TiO_2 反射层对铅玻璃的四个侧面进行涂层

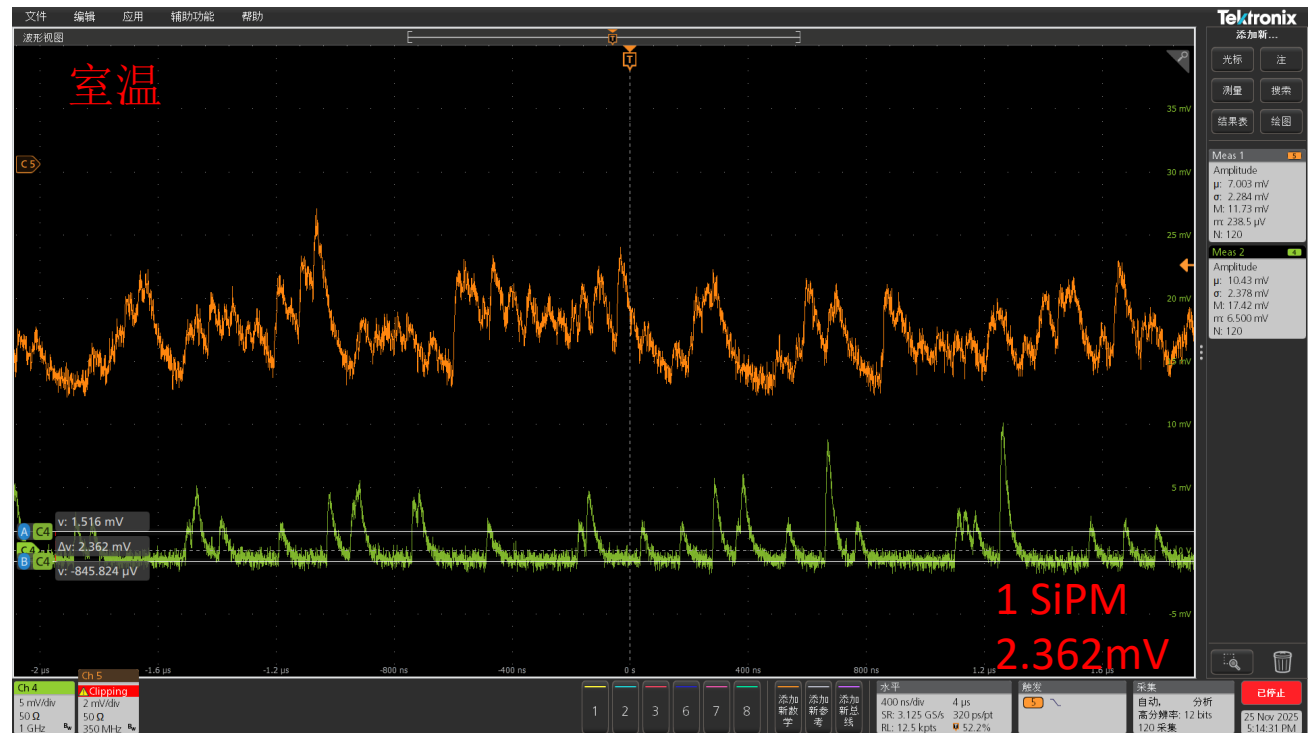
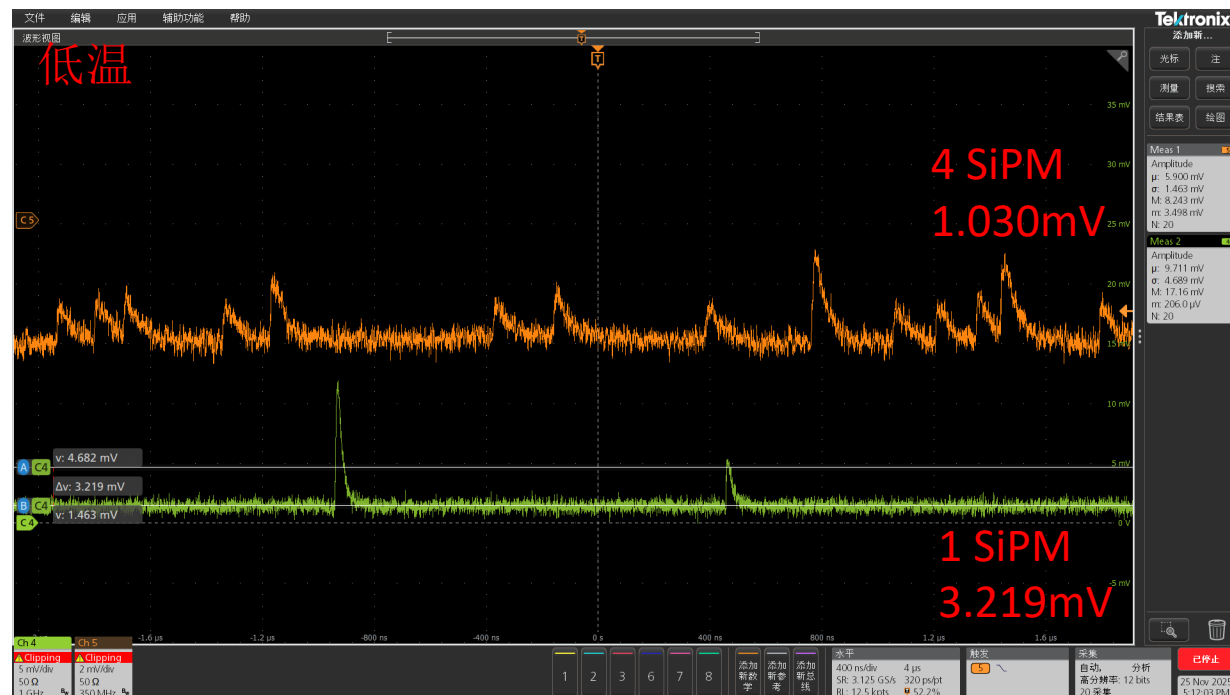
宇宙线测试



SiPM 四通道的暗计数率过高，导致难以探测单光子。因此，实验首先在低温环境下进行。

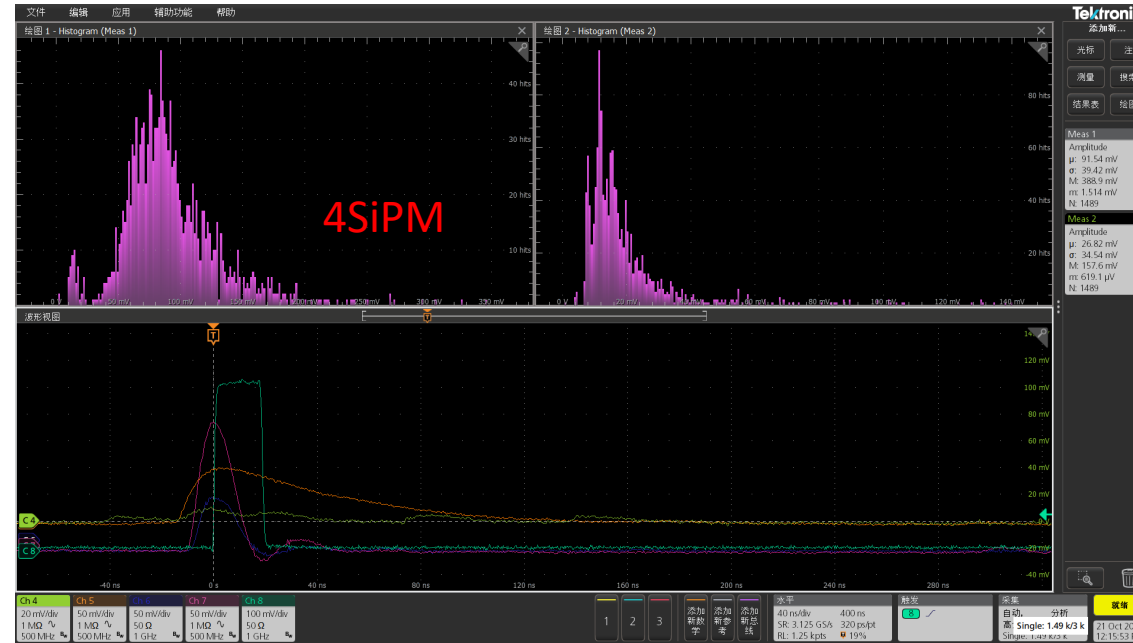
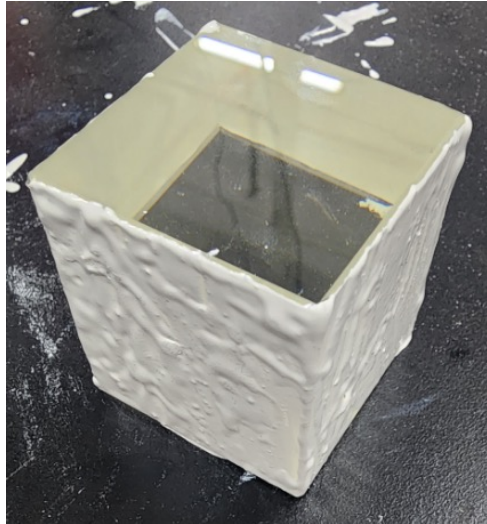
低温下，单光子电压值也会随之变大。

利用低温下的单光子电压值，估算该结构在室温下的单光子电压值。

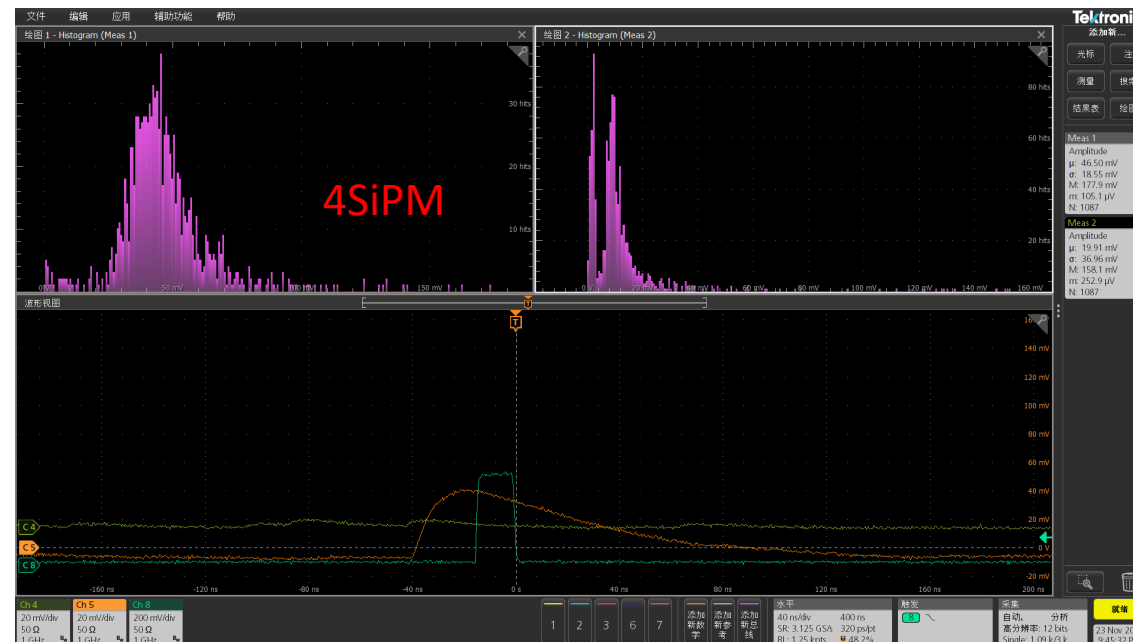


测试结果

侧面涂层结构

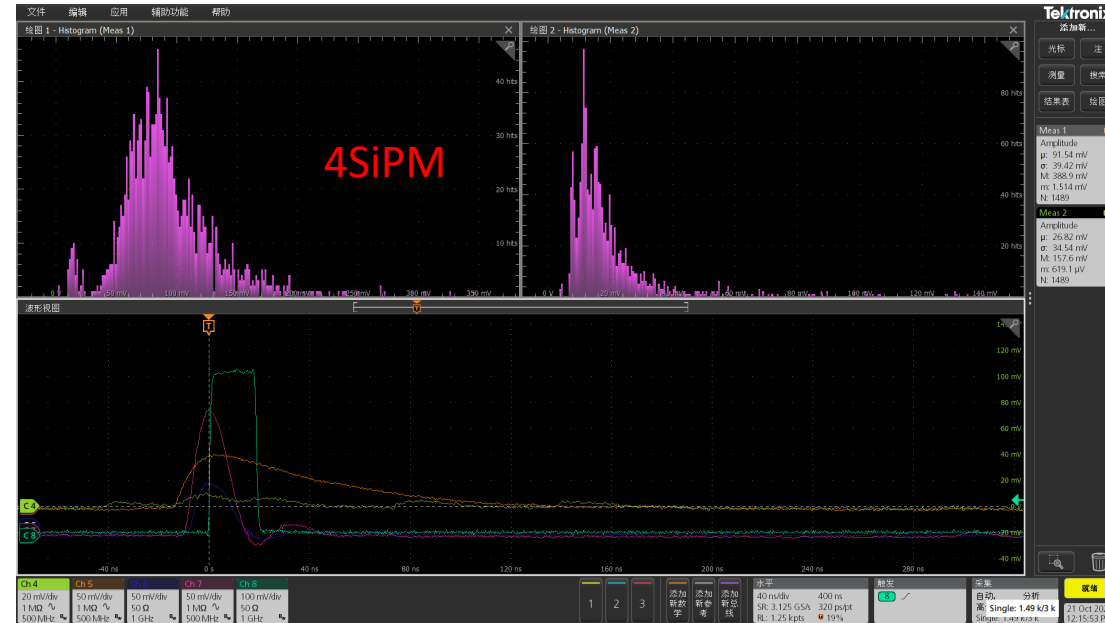
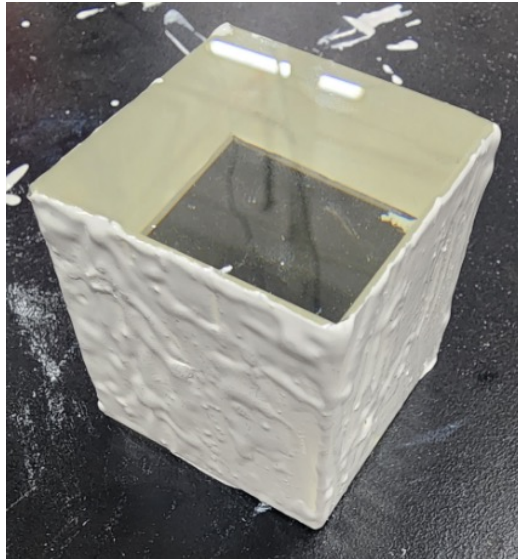


抛光表面
4 SiPM
平均光子数: 56.68

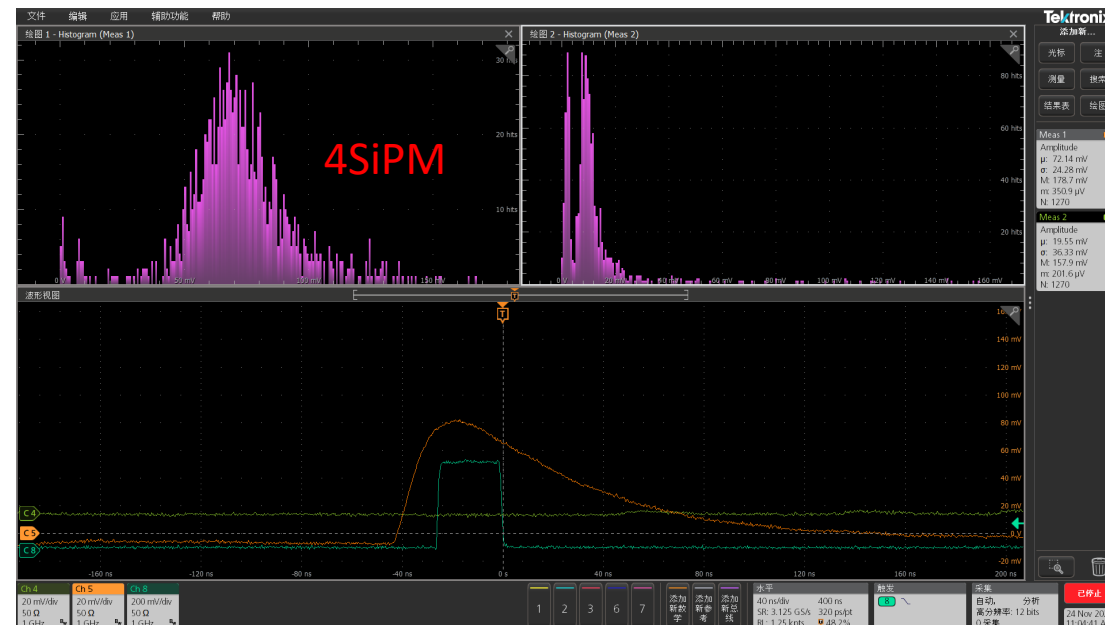
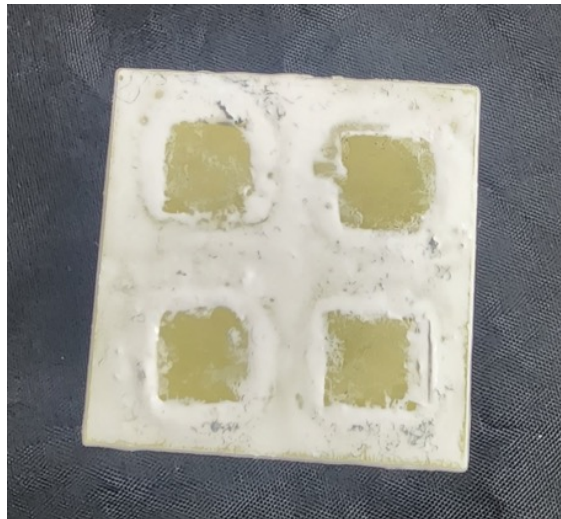


粗糙表面
4 SiPM
平均光子数: 57.58

测试结果



抛光表面
4 SiPM
平均光子数: 56.68

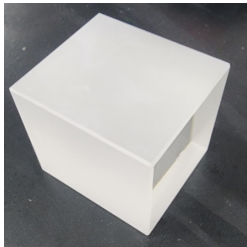
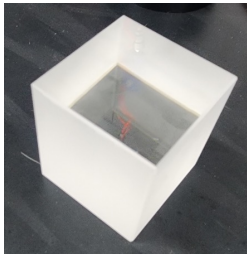


粗糙表面
4 SiPM
平均光子数: 89.83

测试与模拟结果对比

切伦科夫光子数

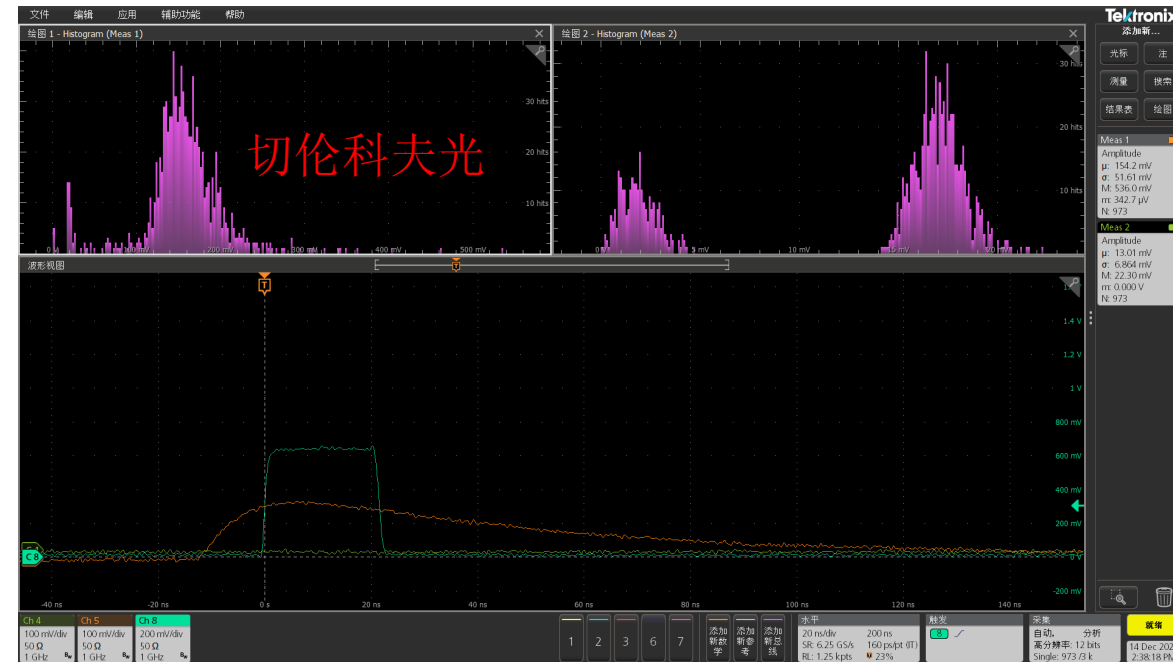
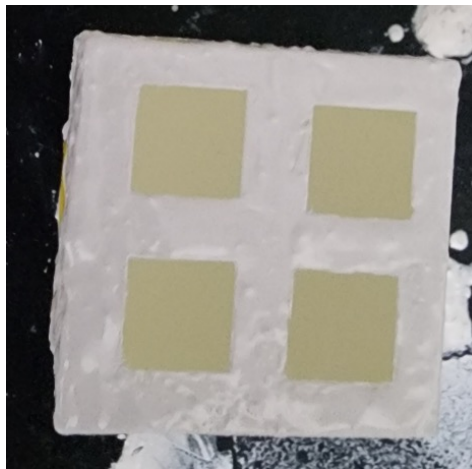
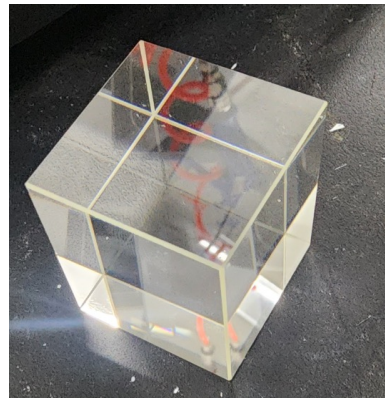
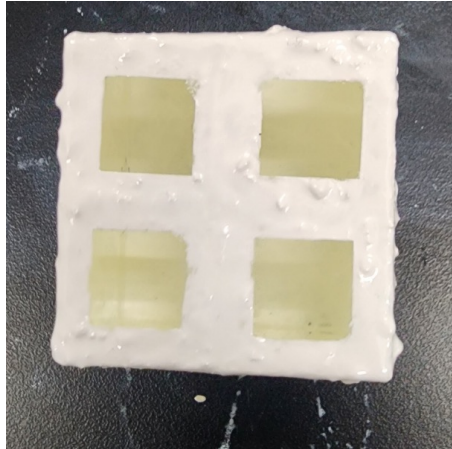
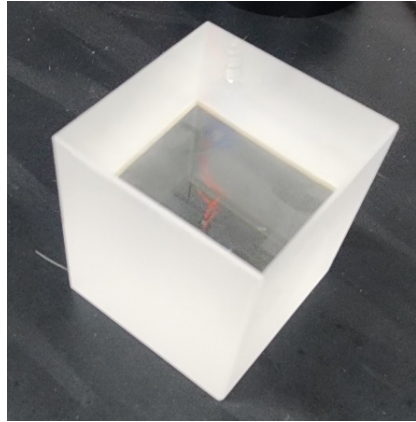
4 SiPM 用于获取光子



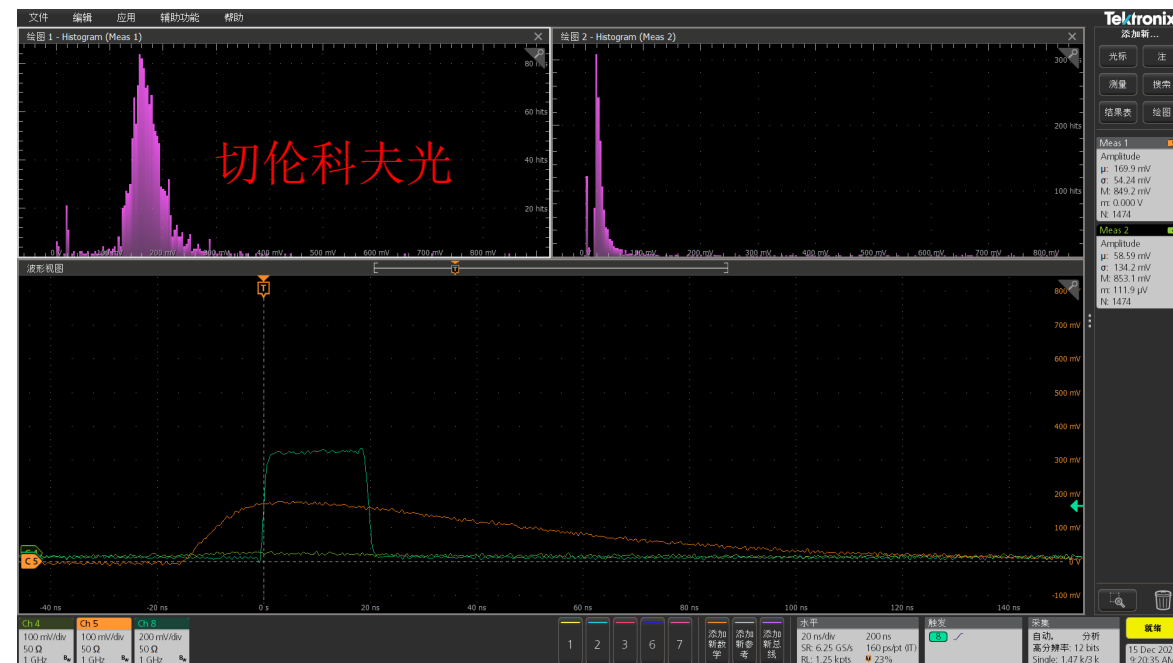
表面	涂层	无涂层	4侧面涂层	5表面涂层	除 SiPM 窗口外 全涂层
抛光	宇宙线测试	33.72	56.68	85.11	95.42
	模拟	14.88	34.3	52.02	71.76
粗糙	宇宙线测试	40.2	57.58	79.70	
	模拟	18.56	33.79	54.95	

模拟结果略低于实际测试测量值，但两者仍处于大致相同的量级范围内。
这主要是因为实际实验中的空气间隔比模拟中的设定值更小。

测试结果



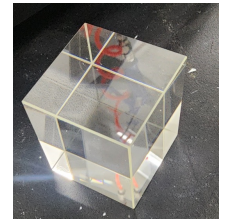
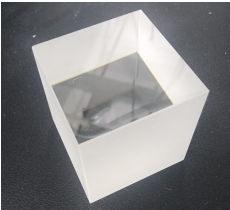
4 侧面粗糙
光滑表面读出
使用硅油
4 SiPMs
平均光子数: 203.96



全表面光滑
光滑表面读出
使用硅油
4 SiPMs
平均光子数: 224.73

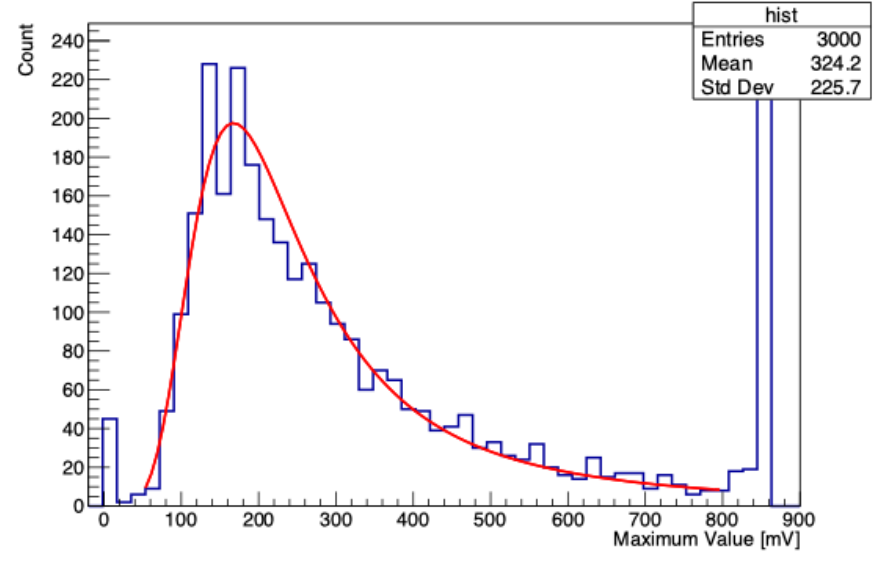
铅玻璃与塑闪测试结果

对于单块（3.5 cm × 3.5 cm × 3.9 cm）铅玻璃，其粒子入射厚度为 3.9 cm，且除了 SiPM 窗口外，其余 6 个表面均涂有反射涂层。



铅玻璃表面结构	读出面	硅油耦合	平均光子数
4个侧面粗糙	光滑	否	139.02
		是	203.96
1个顶面粗糙	光滑	否	126.03
		是	207.73
	粗糙	否	127.67
		是	221.69
无粗糙表面	光滑	否	149.47
		是	224.73

塑闪测试结果



平均幅值 324.2 mV

单光子幅值 1.963 mV

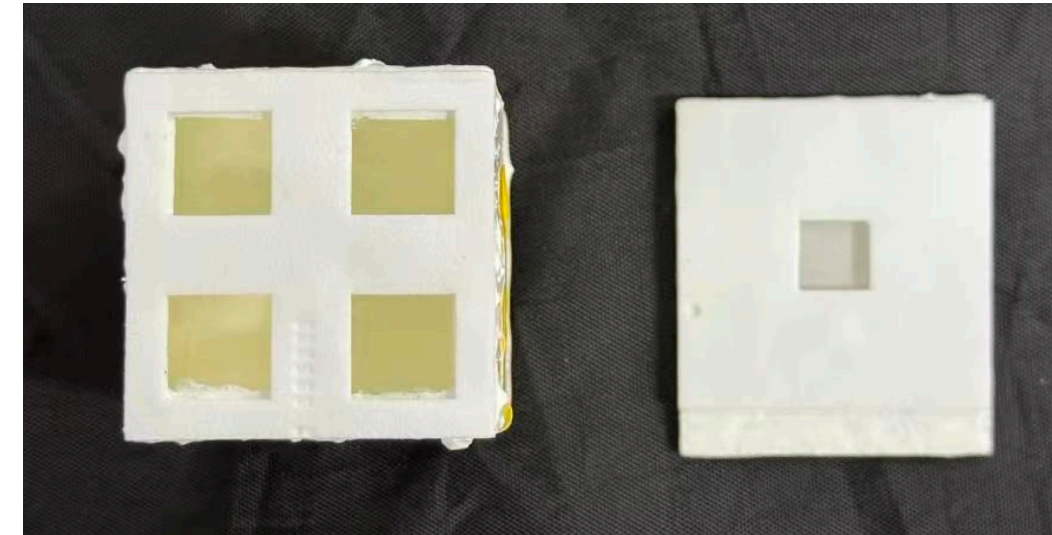
平均光子数 165.15

柔性 PCB

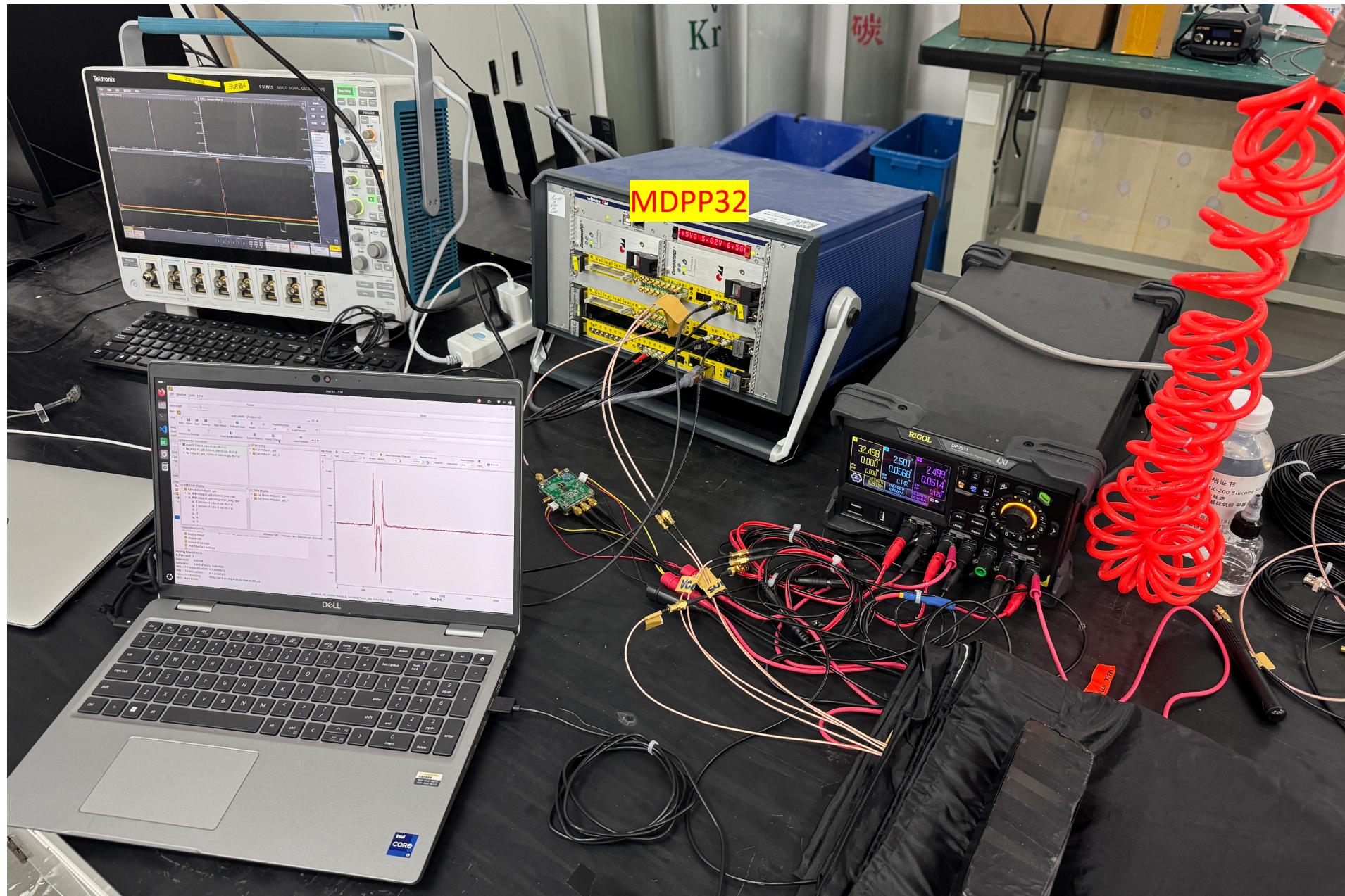
柔性 PCB



铅玻璃: 抛光 塑闪: 2mm

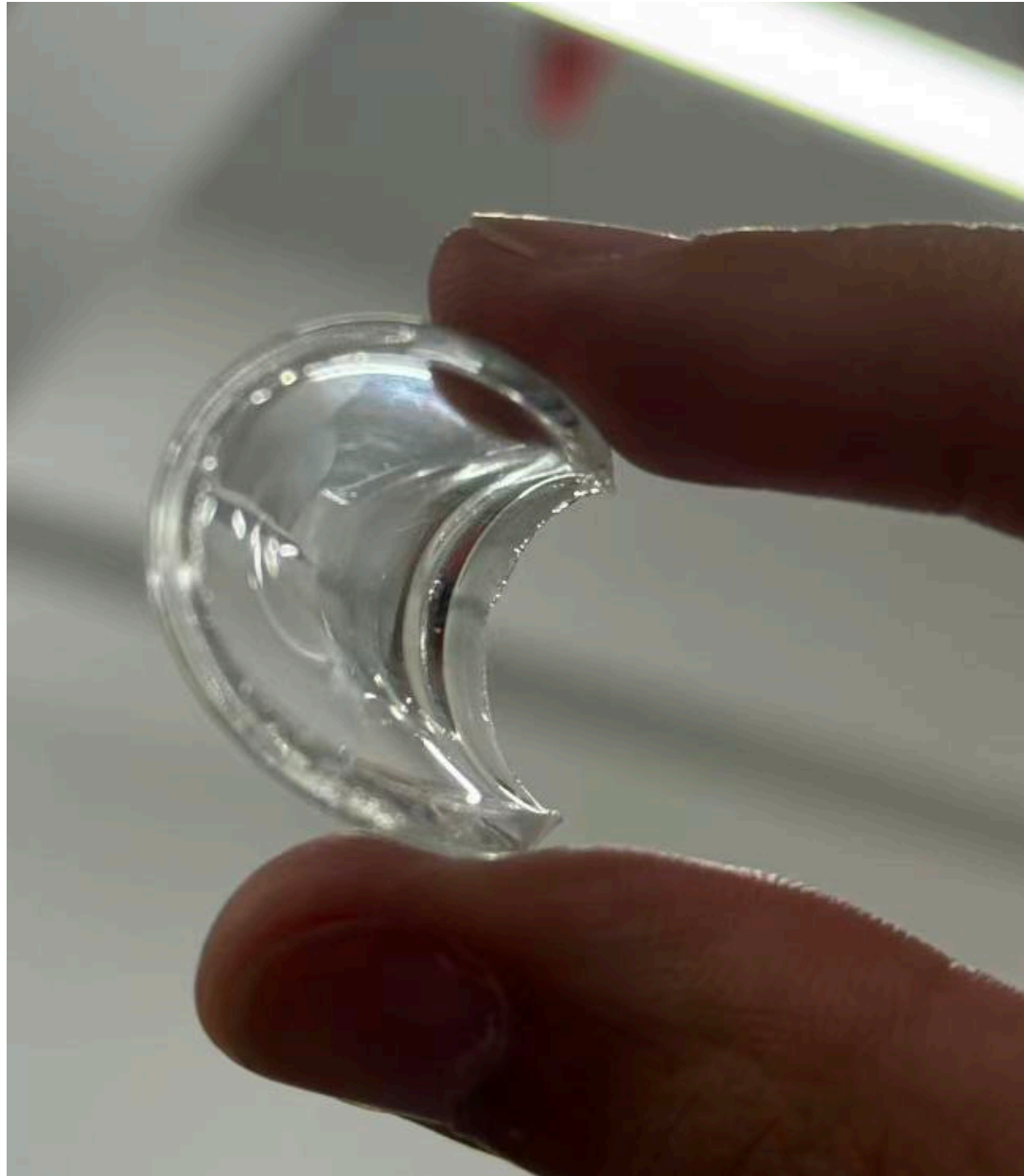


MDPP32 读出



PDMS

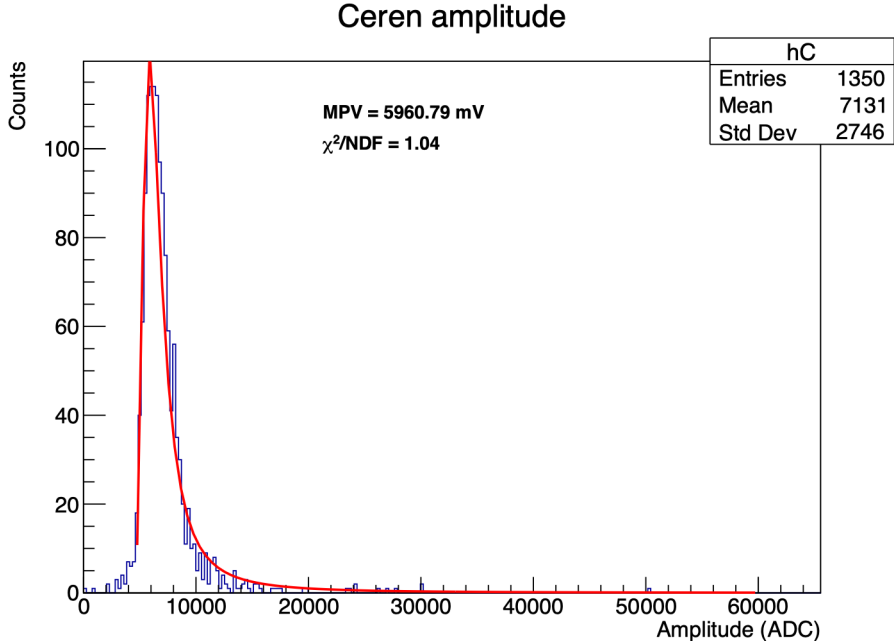
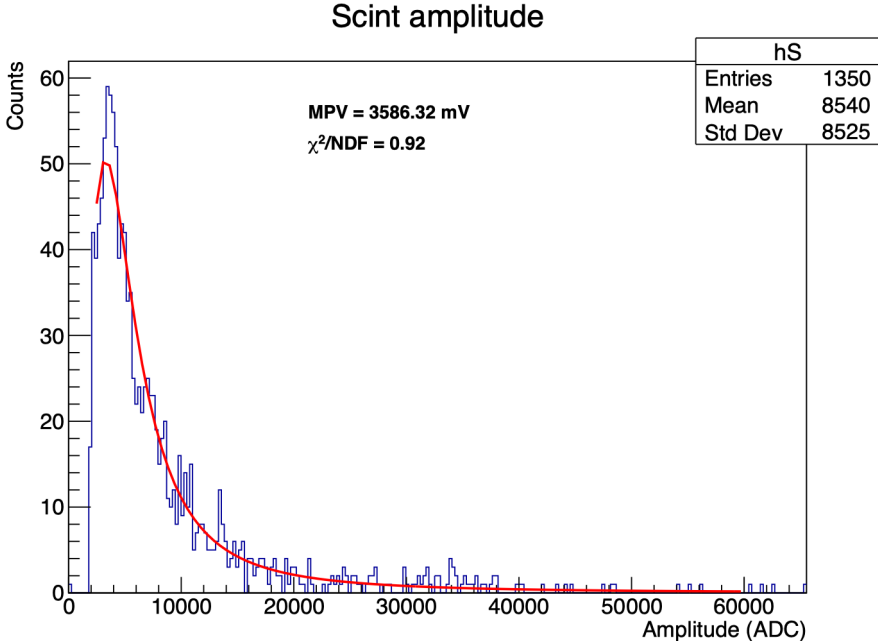
SYLGARD DC184 Silicone Elastomer(PDMS)



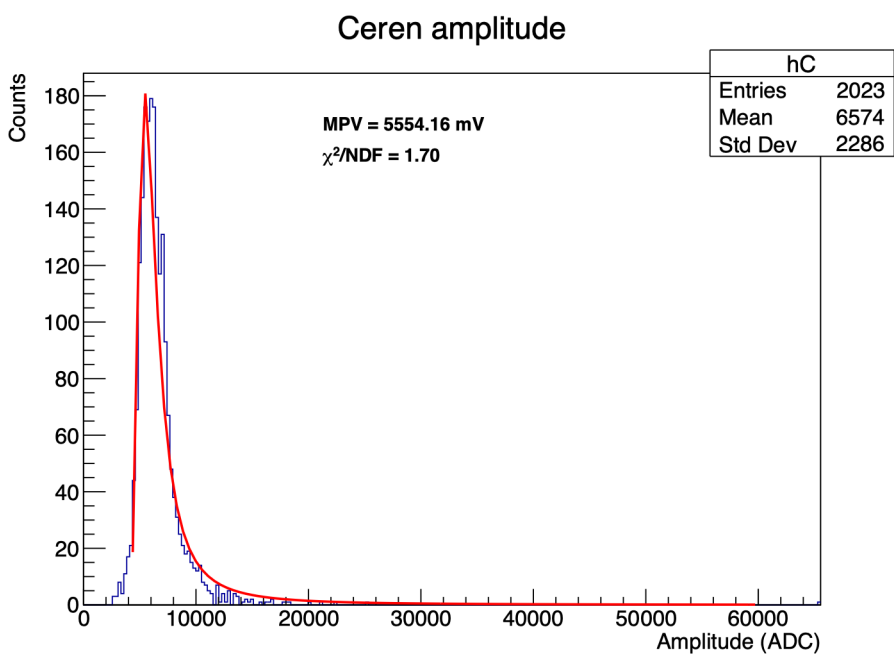
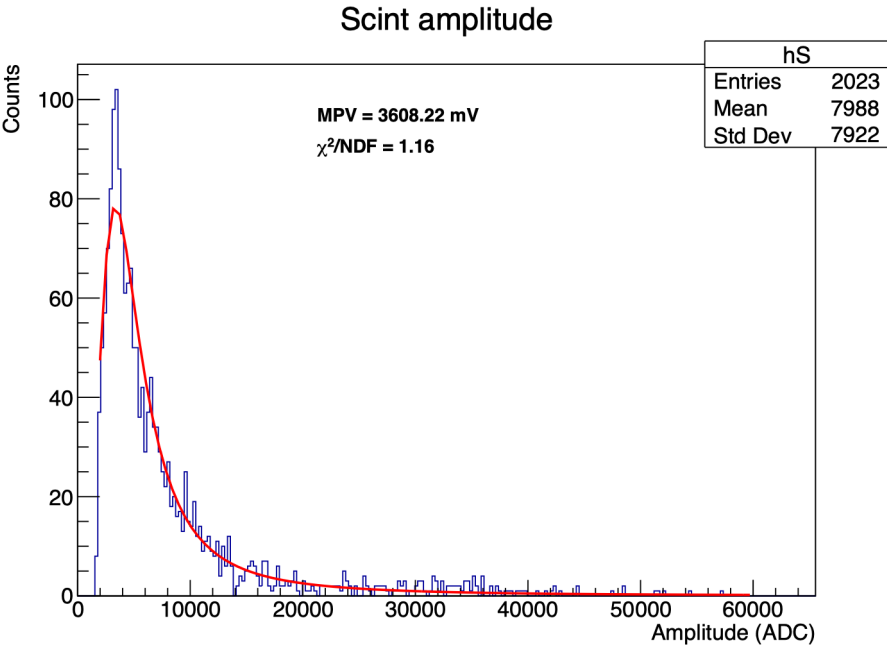
测试结果

MDPP32_QDC

硅油

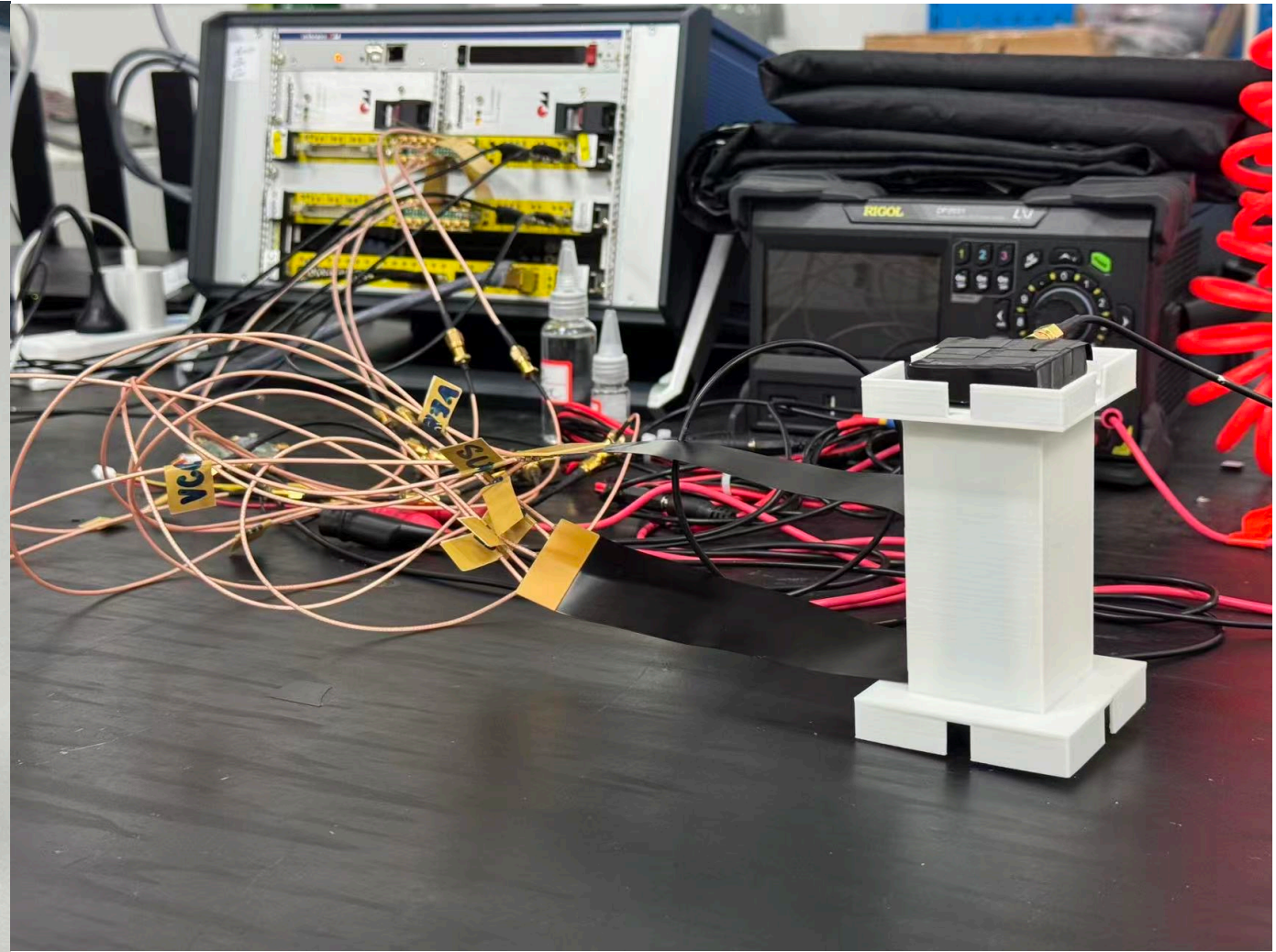
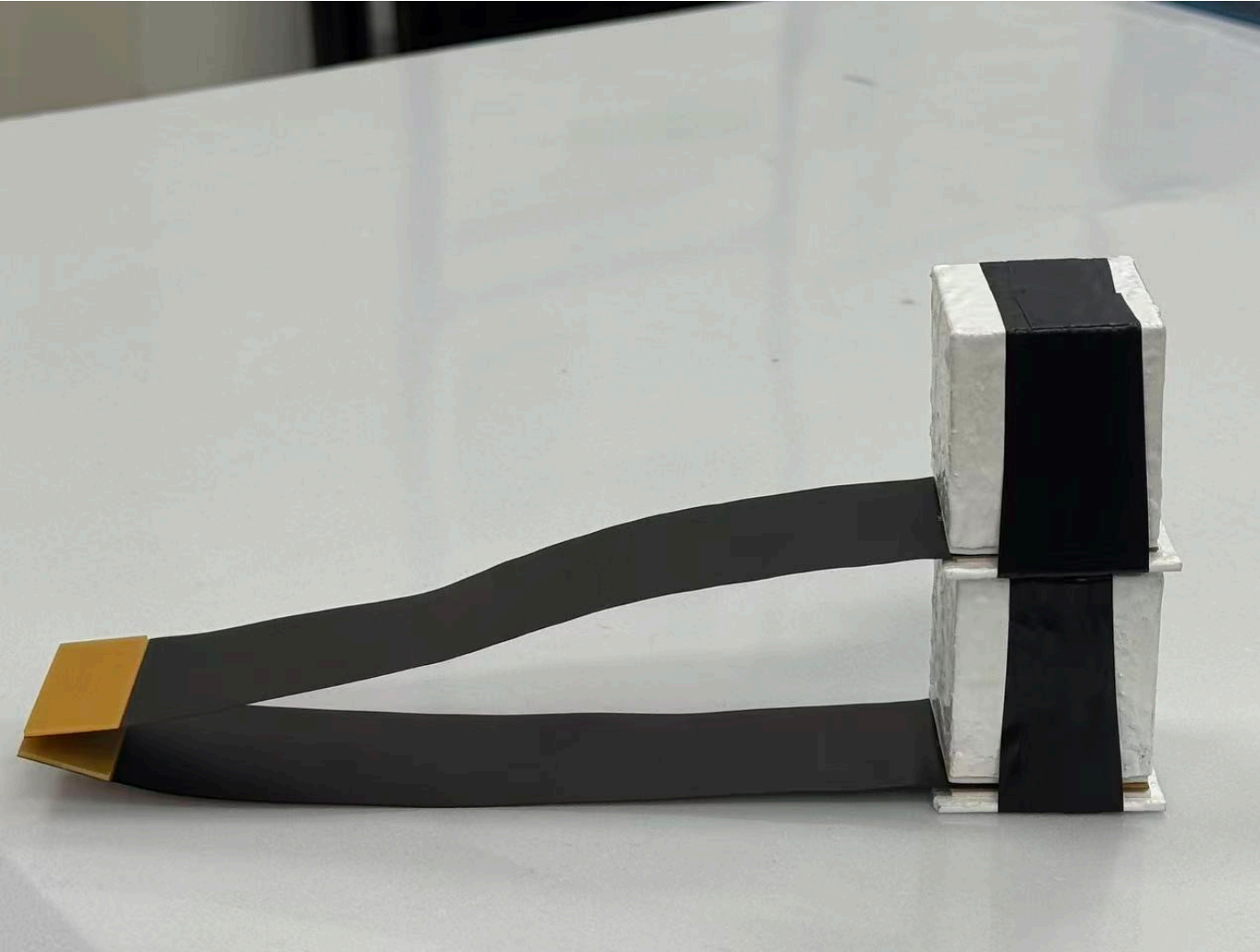


PDMS



宇宙线测试结构

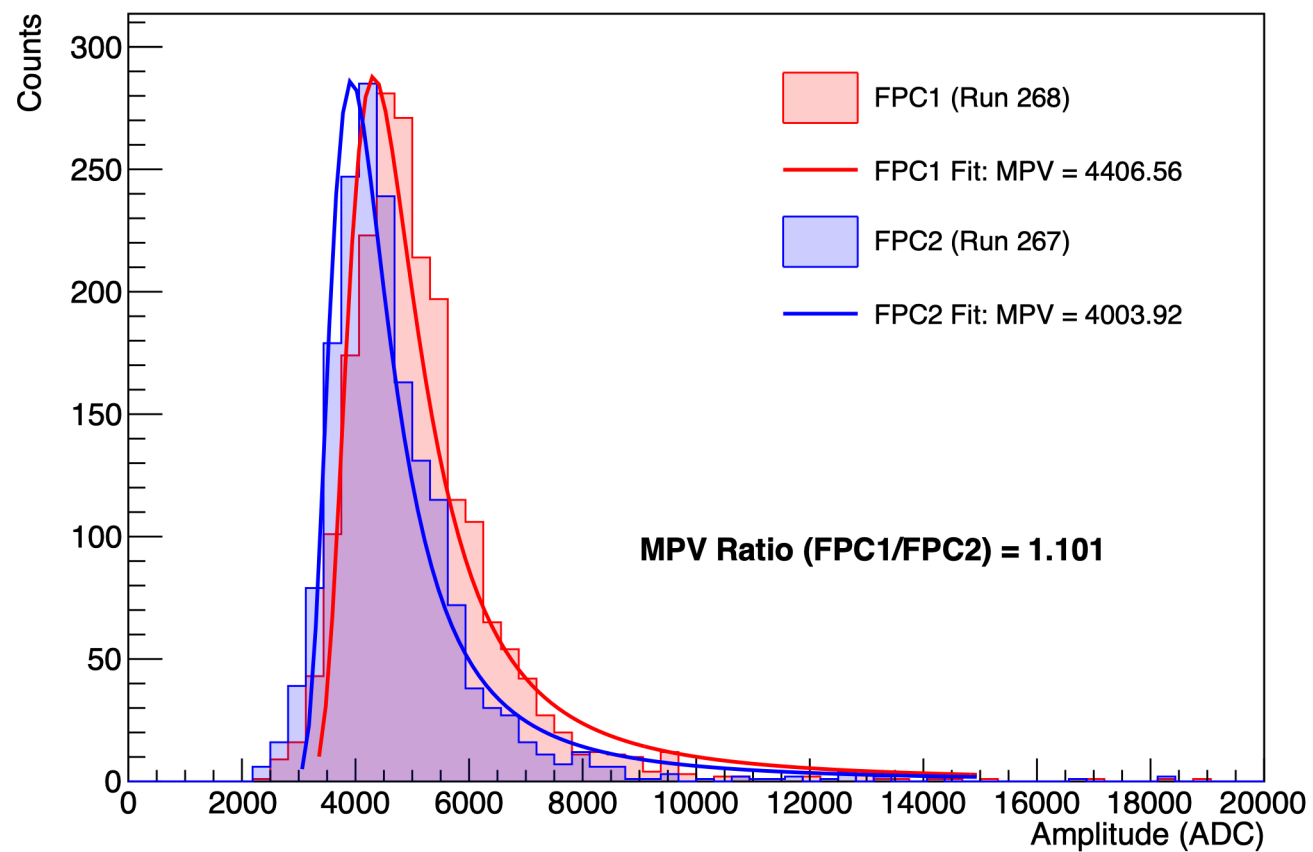
两个模块使用了相同的配置



测试结果

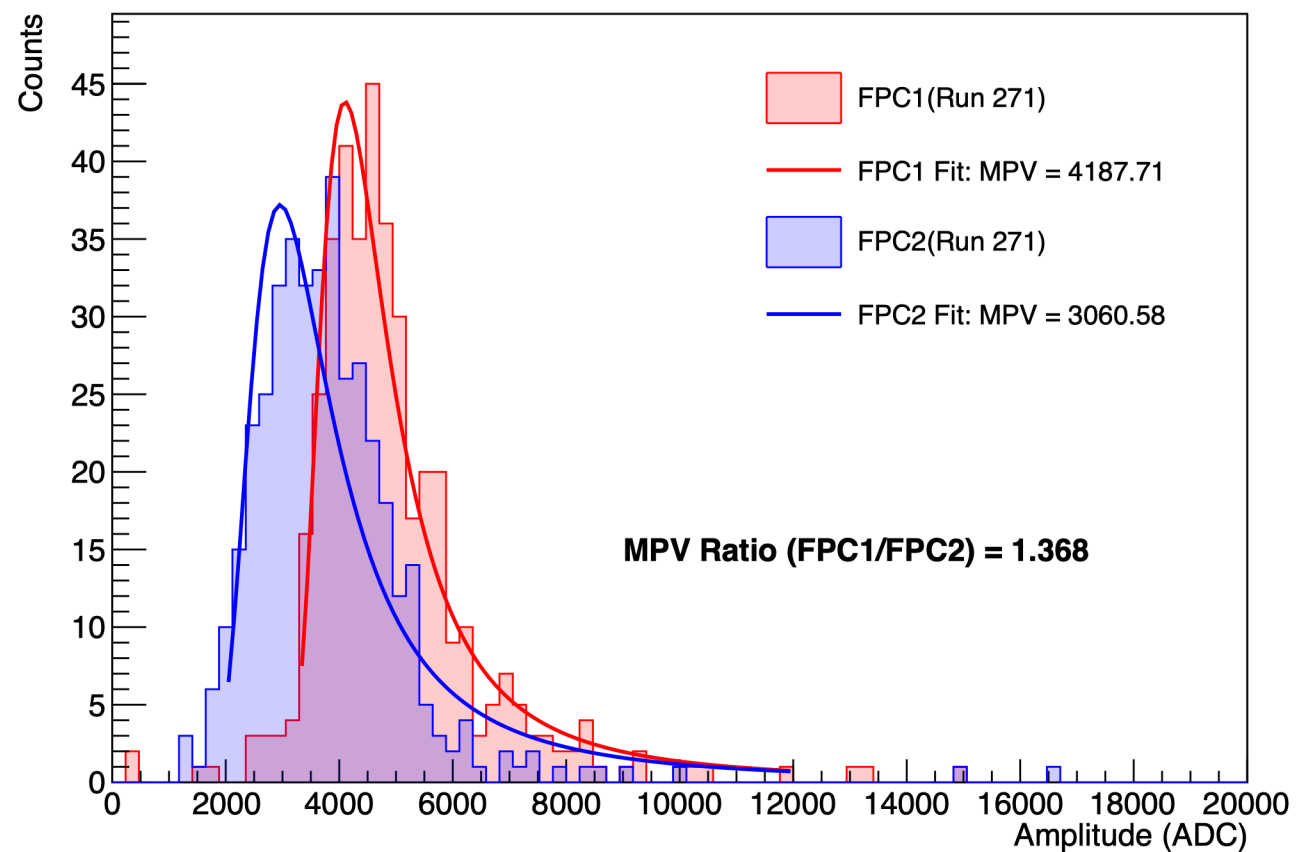
单独测试

Cerenkov Amplitude



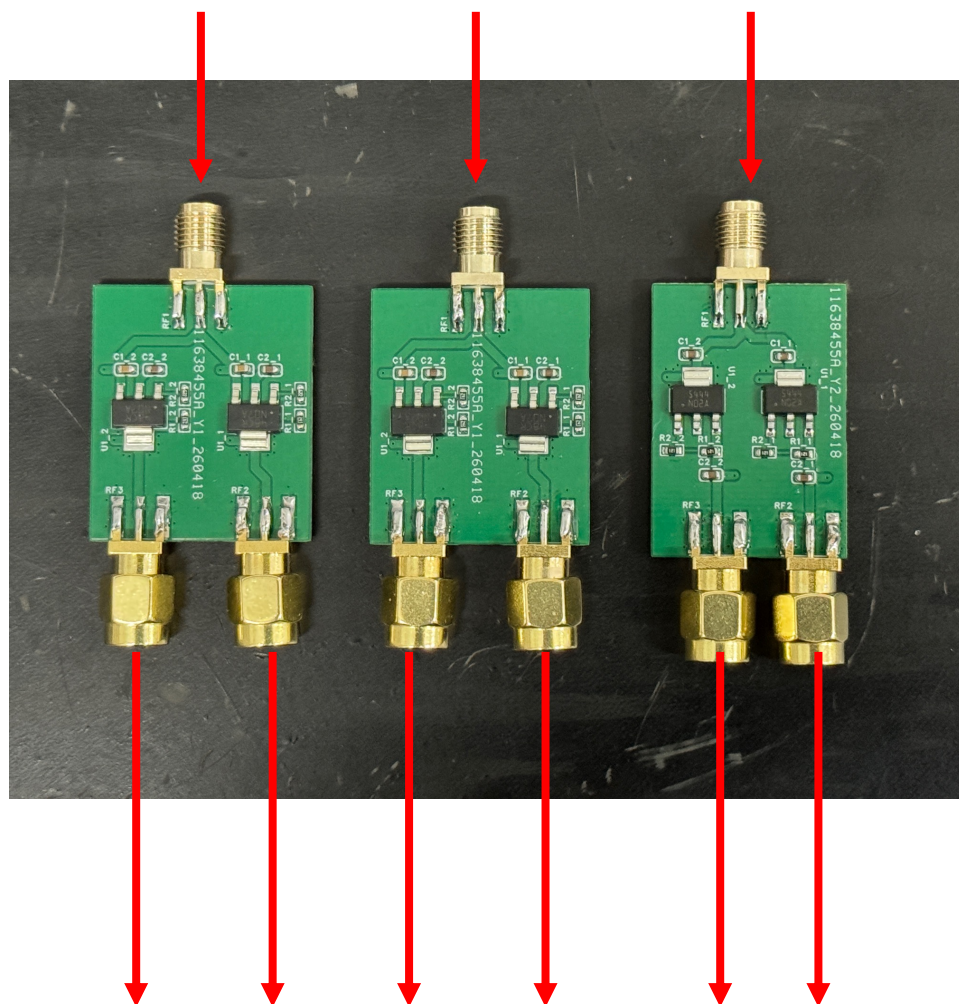
使用同一电源进行并联测试

Cerenkov Amplitude



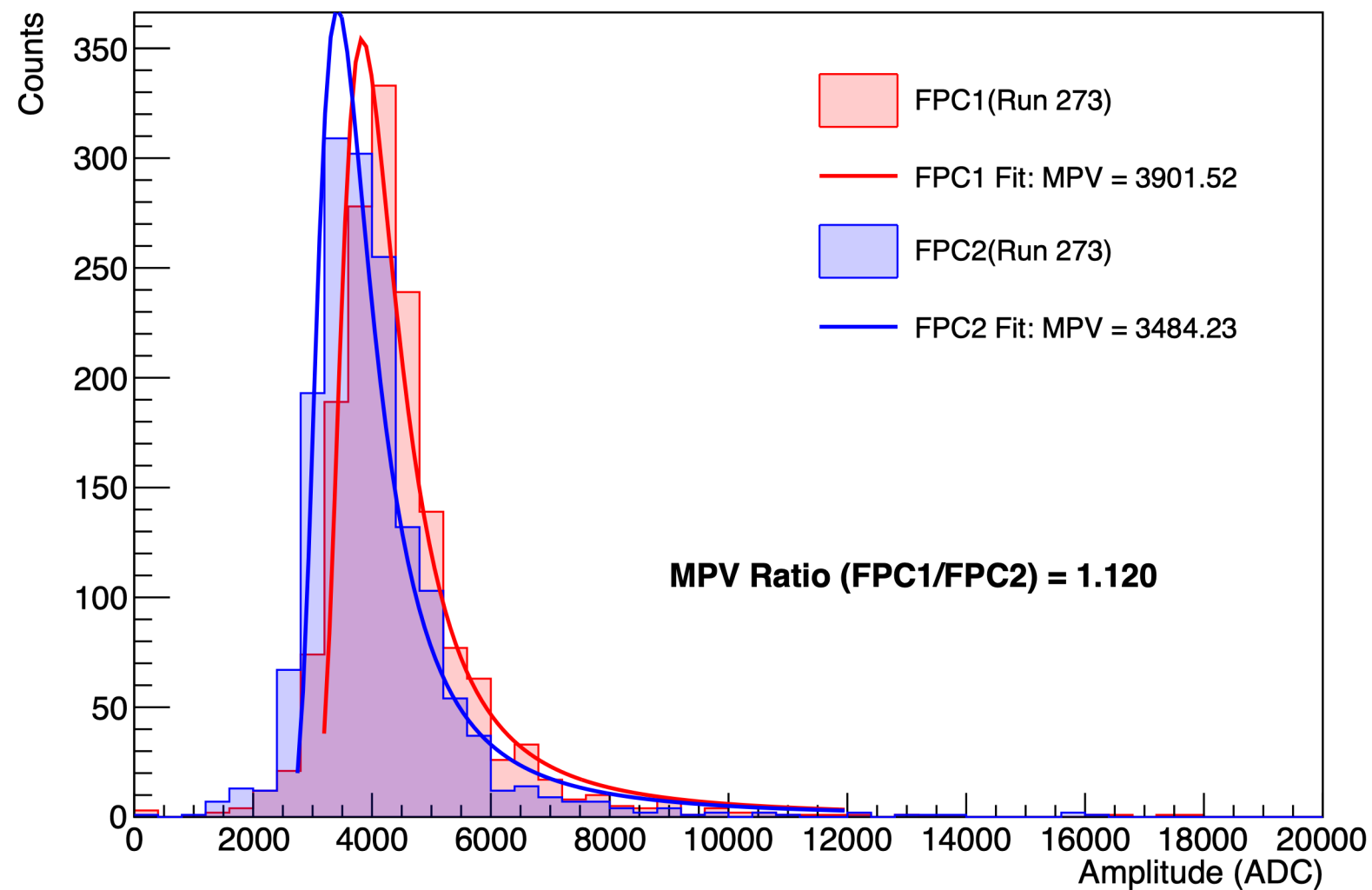
稳压器

DC 输出信号

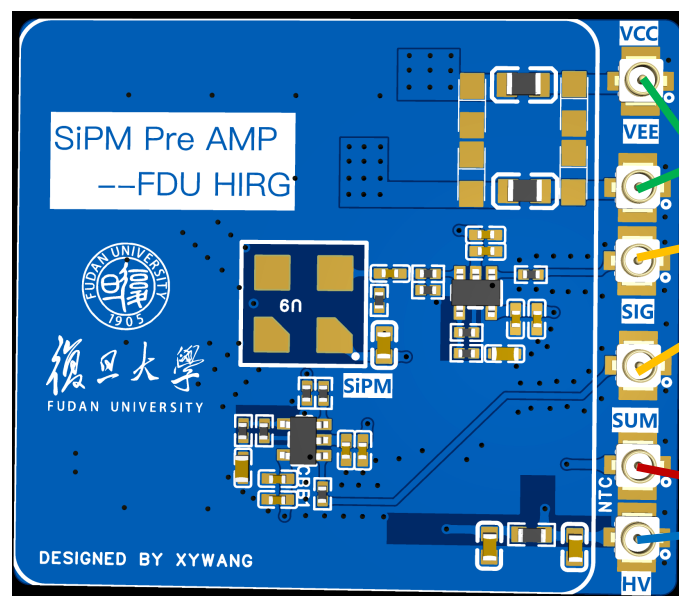


线性稳压输出

Cerenkov Amplitude



SiPM 温度补偿测试板



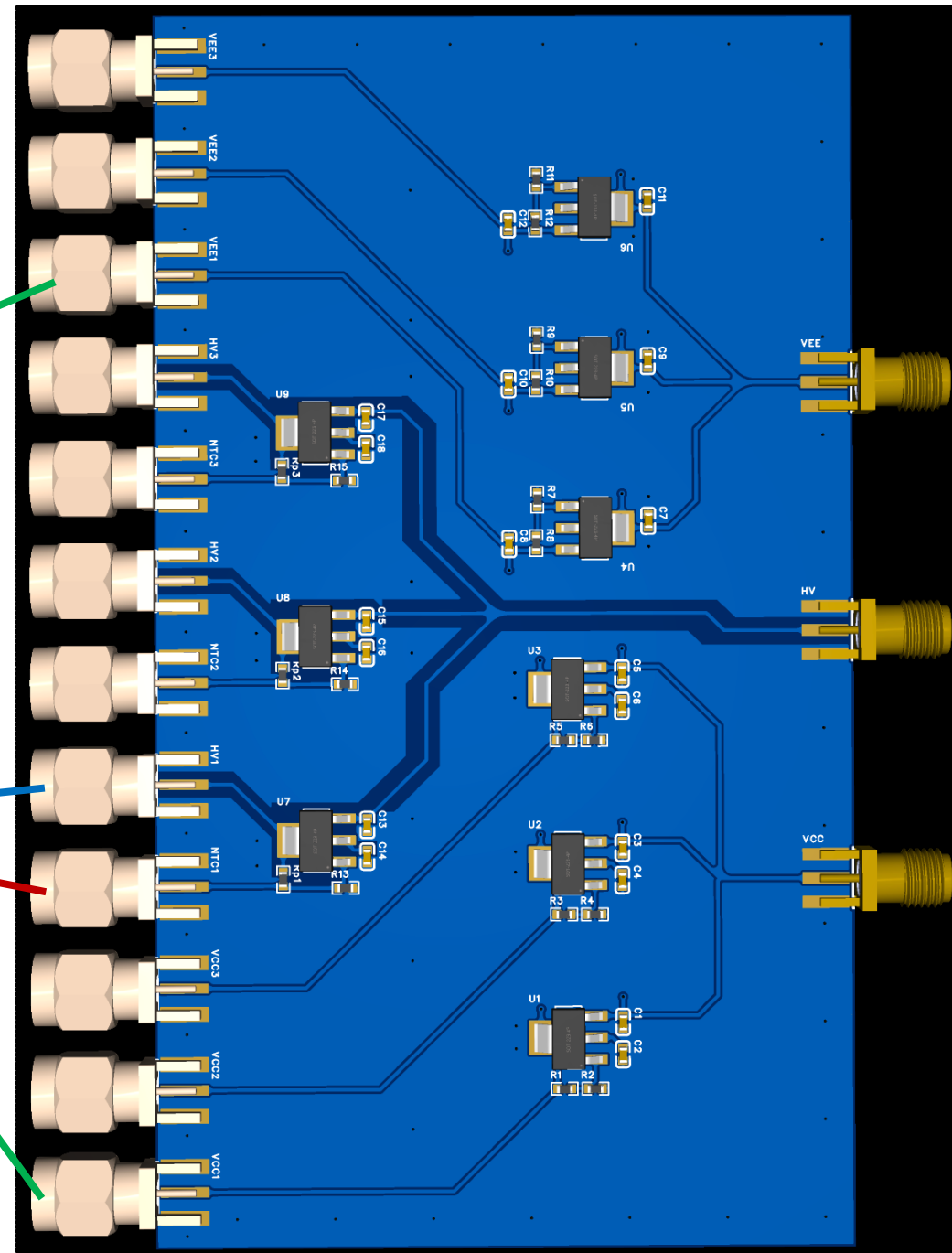
VEE

OUT

HV

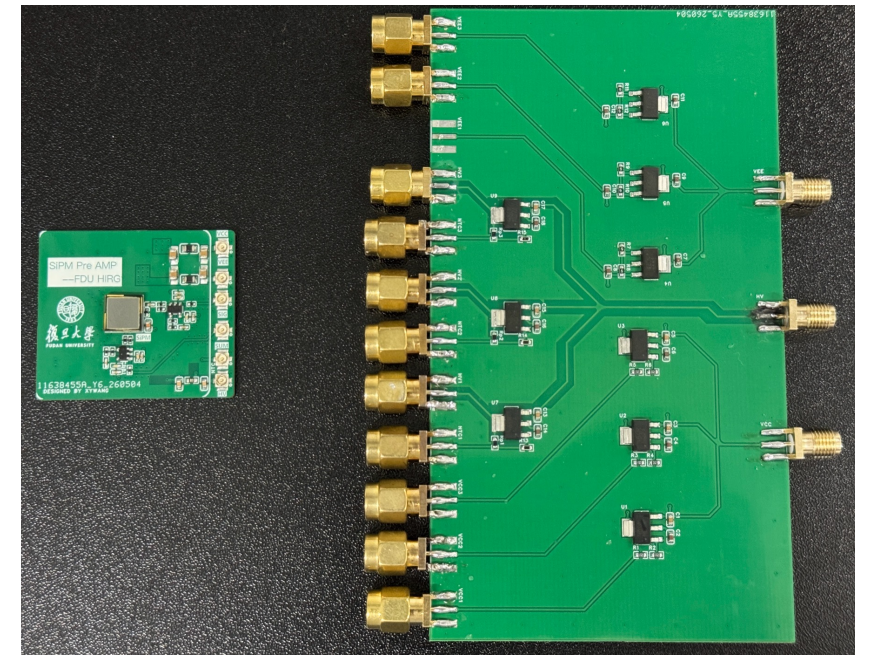
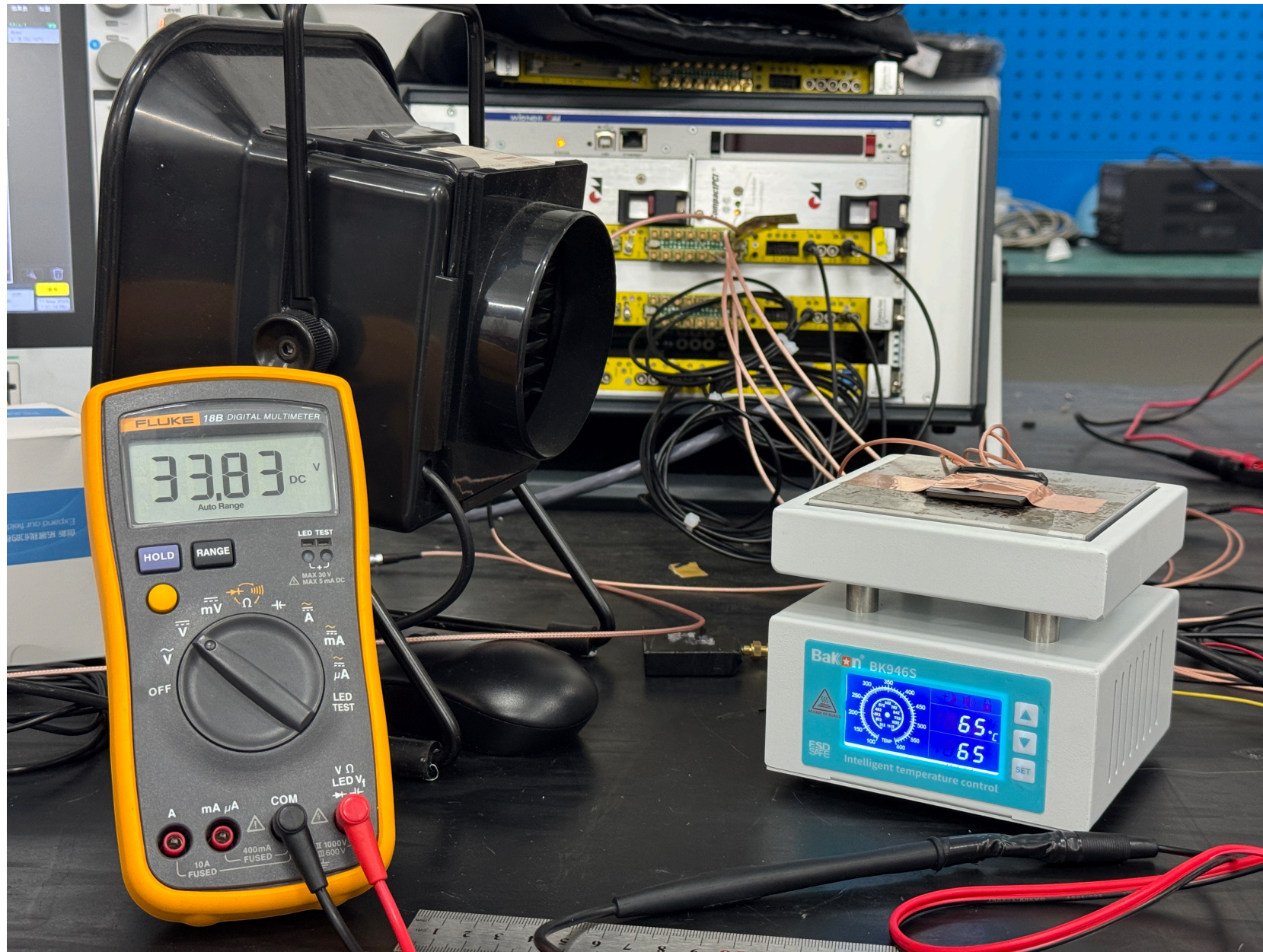
NTC 反馈

VCC

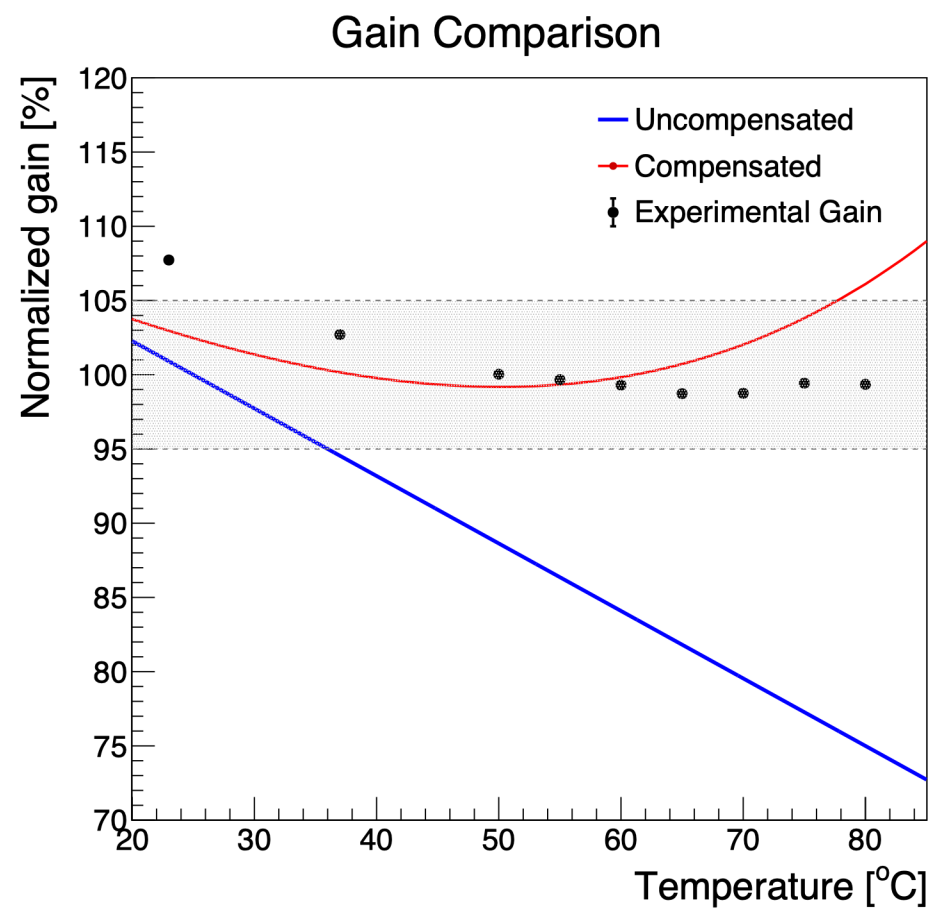
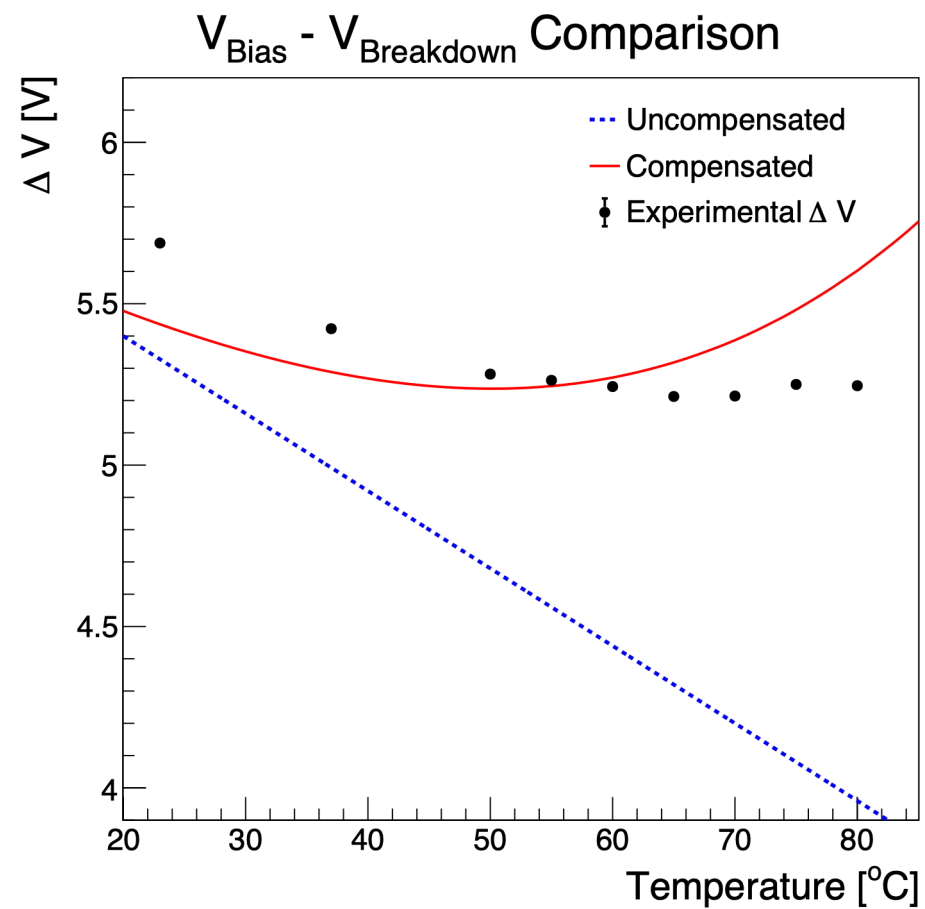
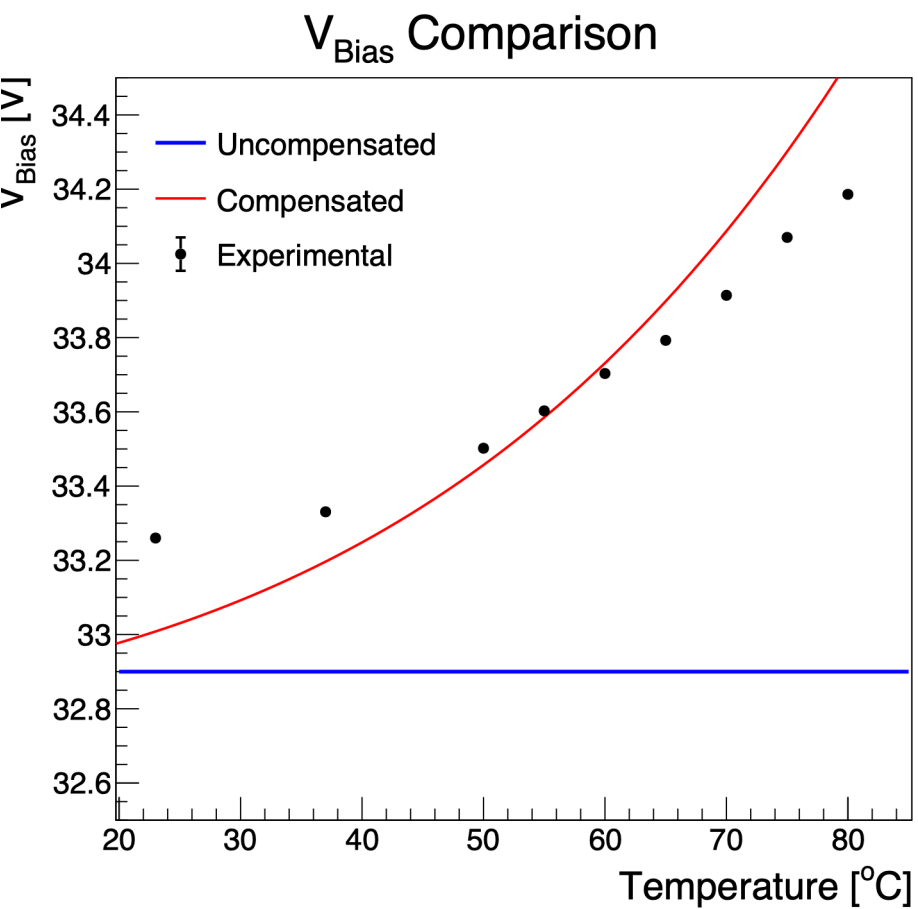


DC 电流输入

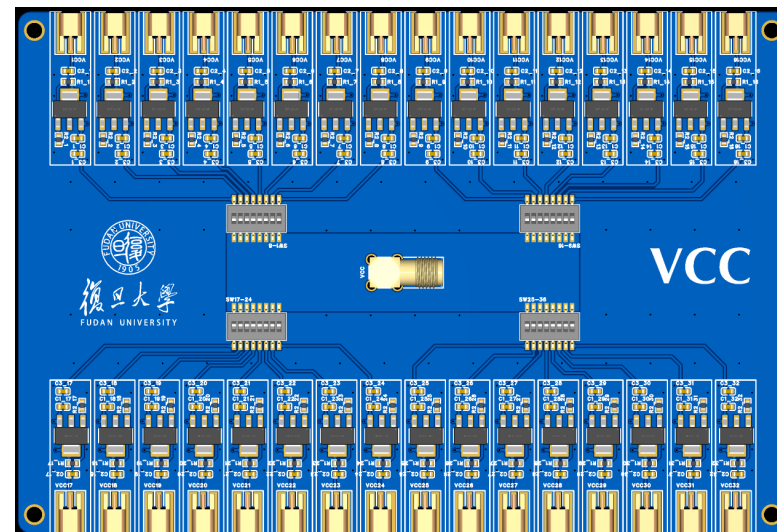
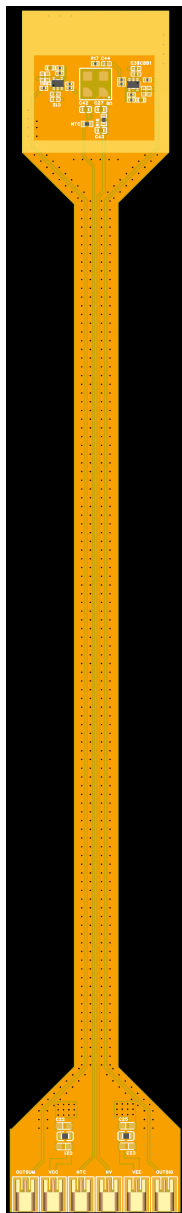
NTC 测试结构



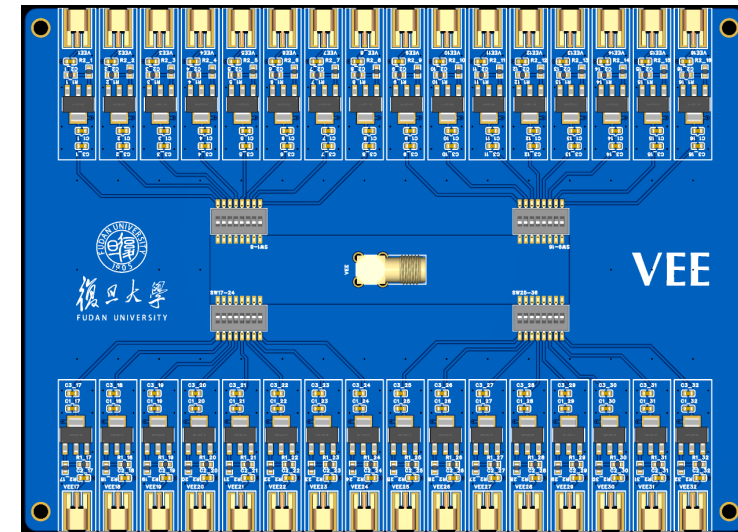
测试结果



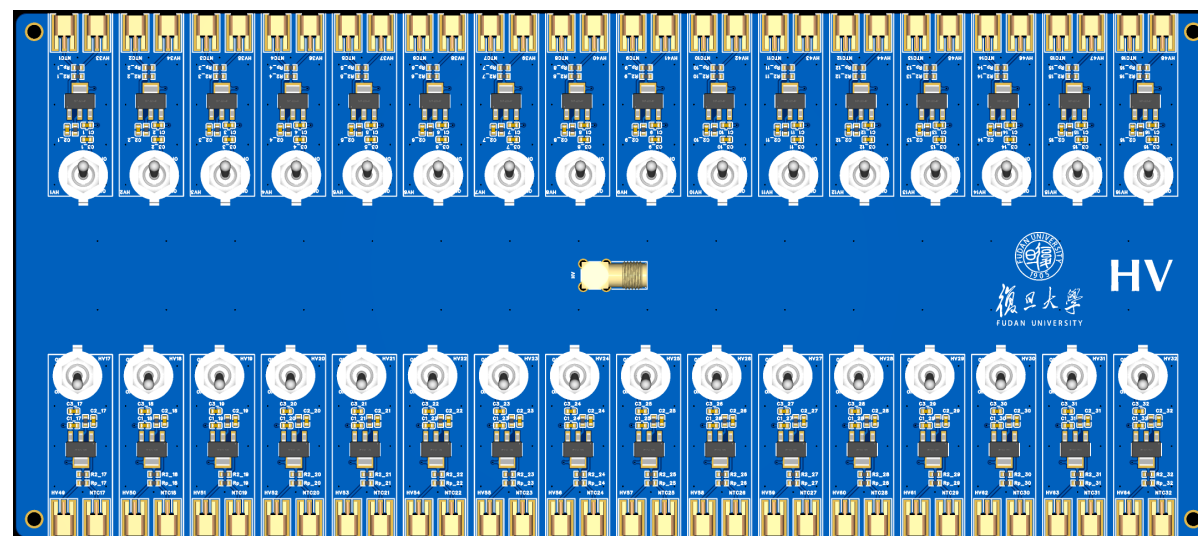
电路板设计



VCC(32Ch) ×11



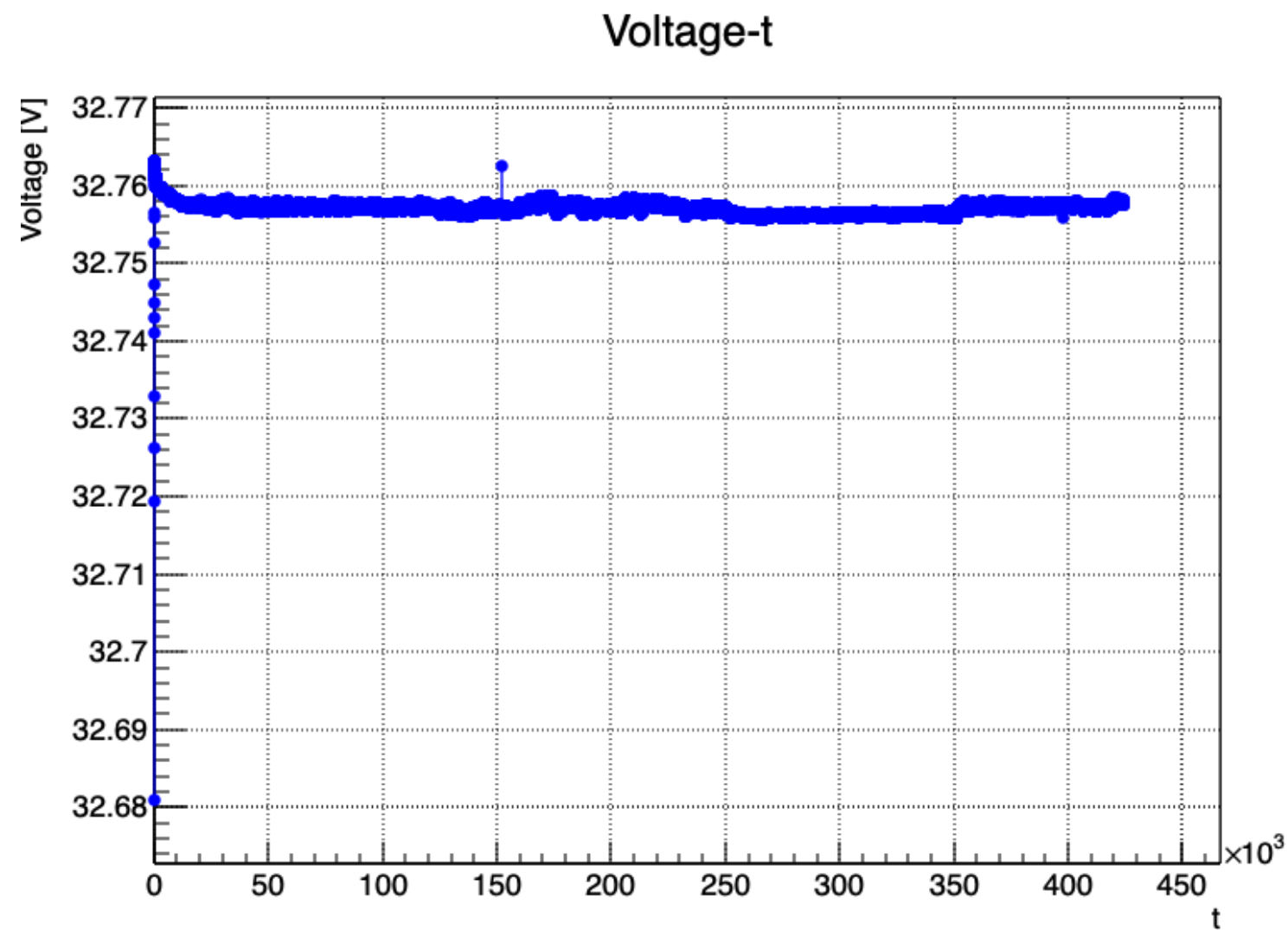
VEE(32Ch) ×11



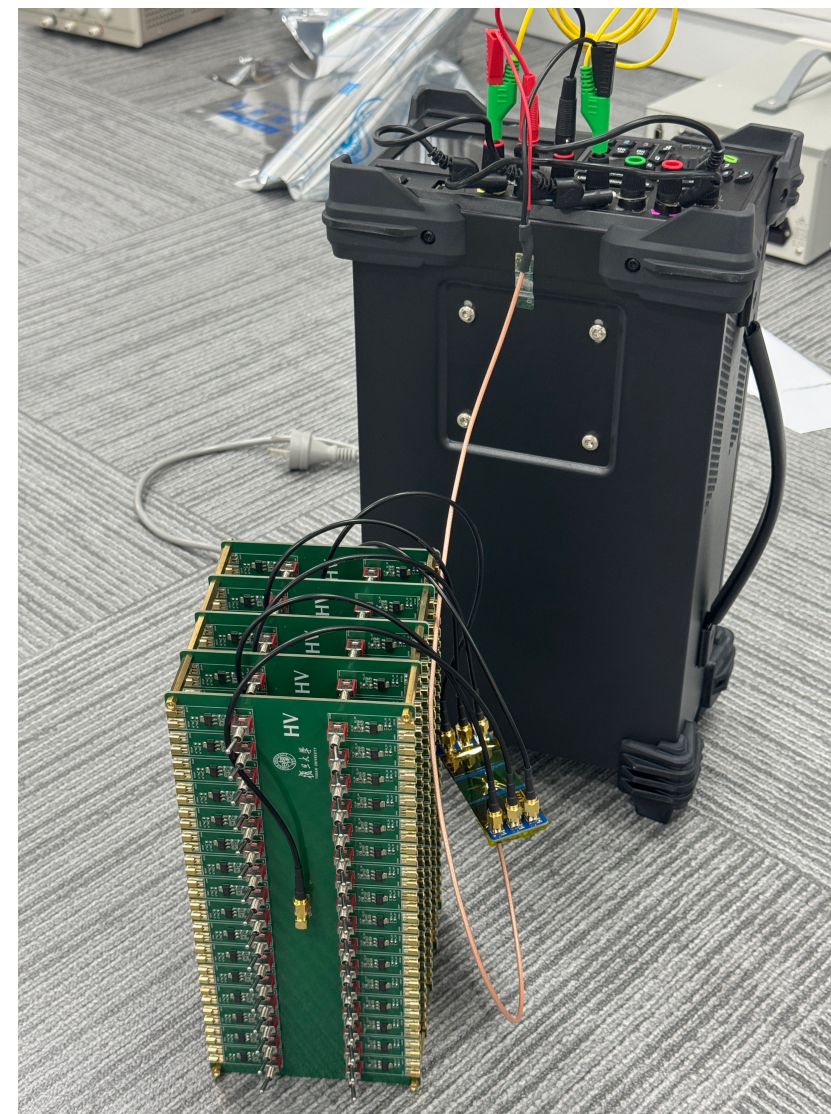
HV + 温度补偿(32Ch) ×11

包含温度补偿的SiPM读出板 ×350

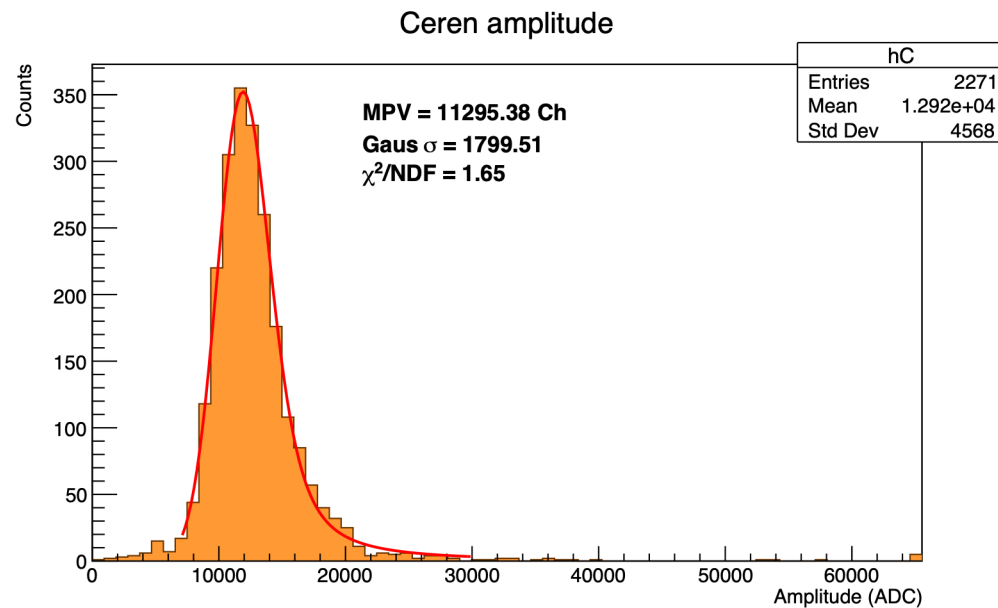
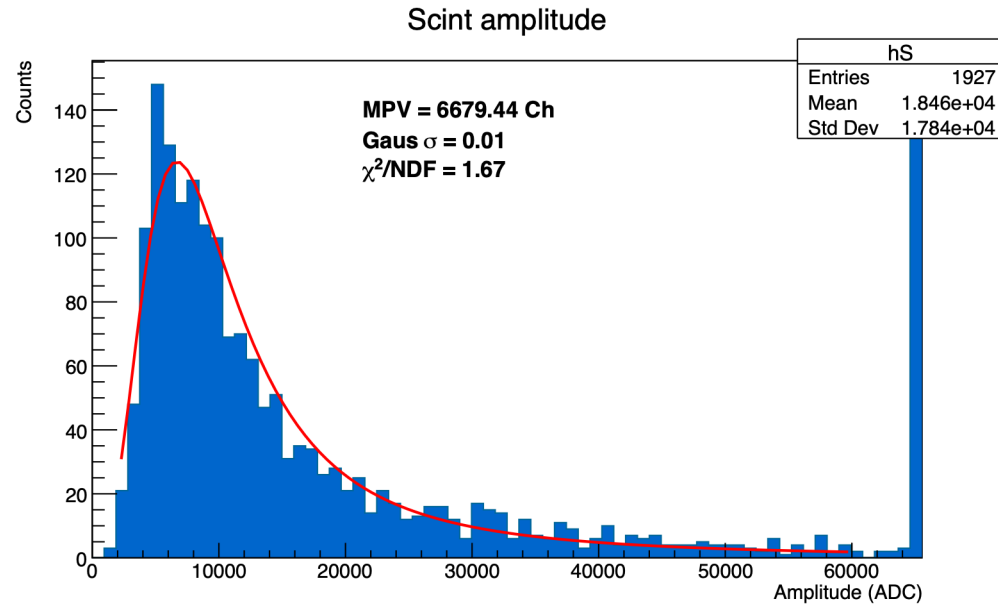
电源稳定性测试



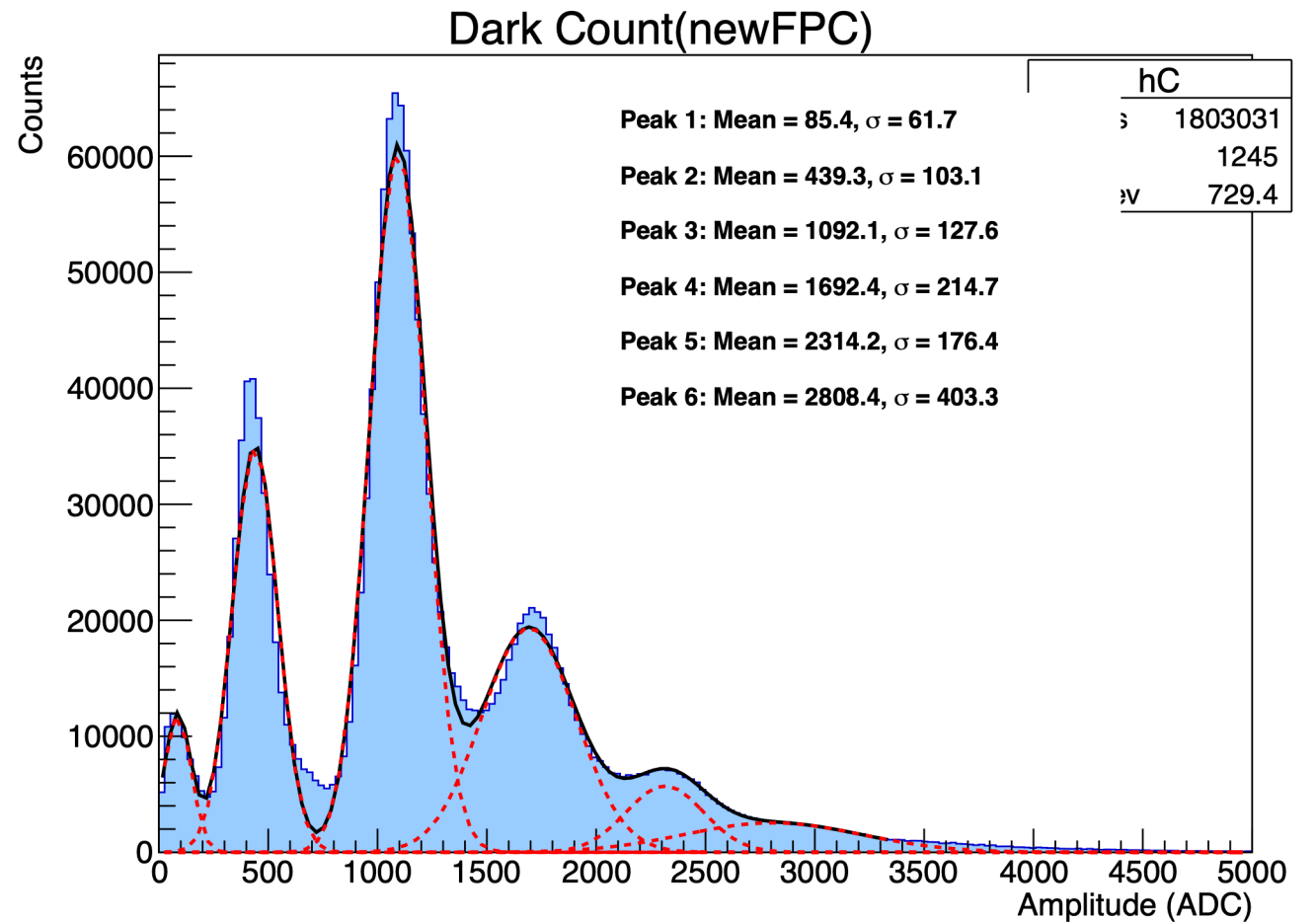
测试约每2.5s采集一个数据点



新柔性PCB测试

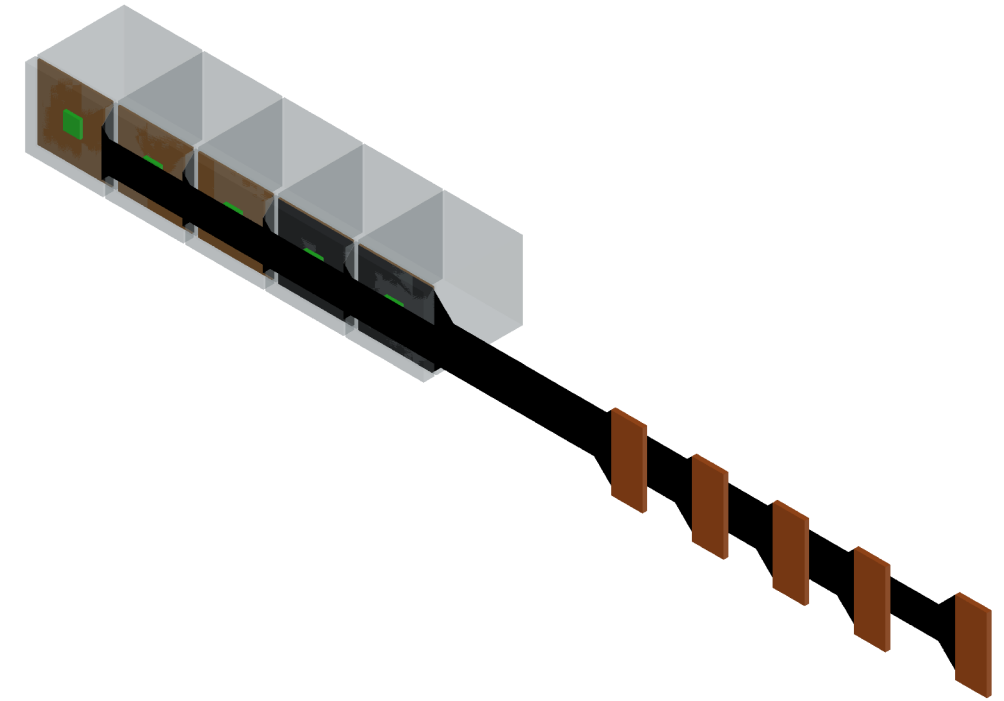
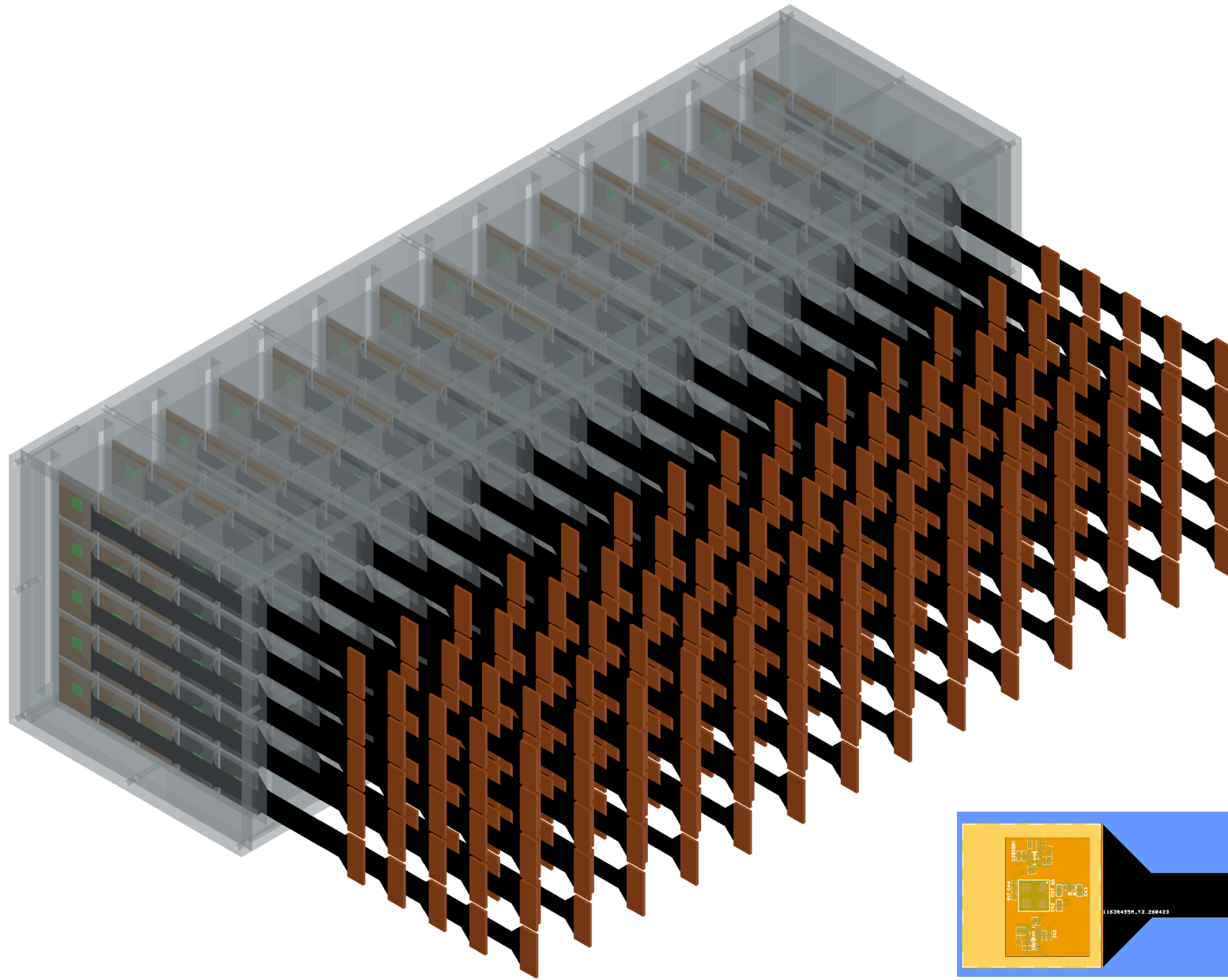


宇宙线测试



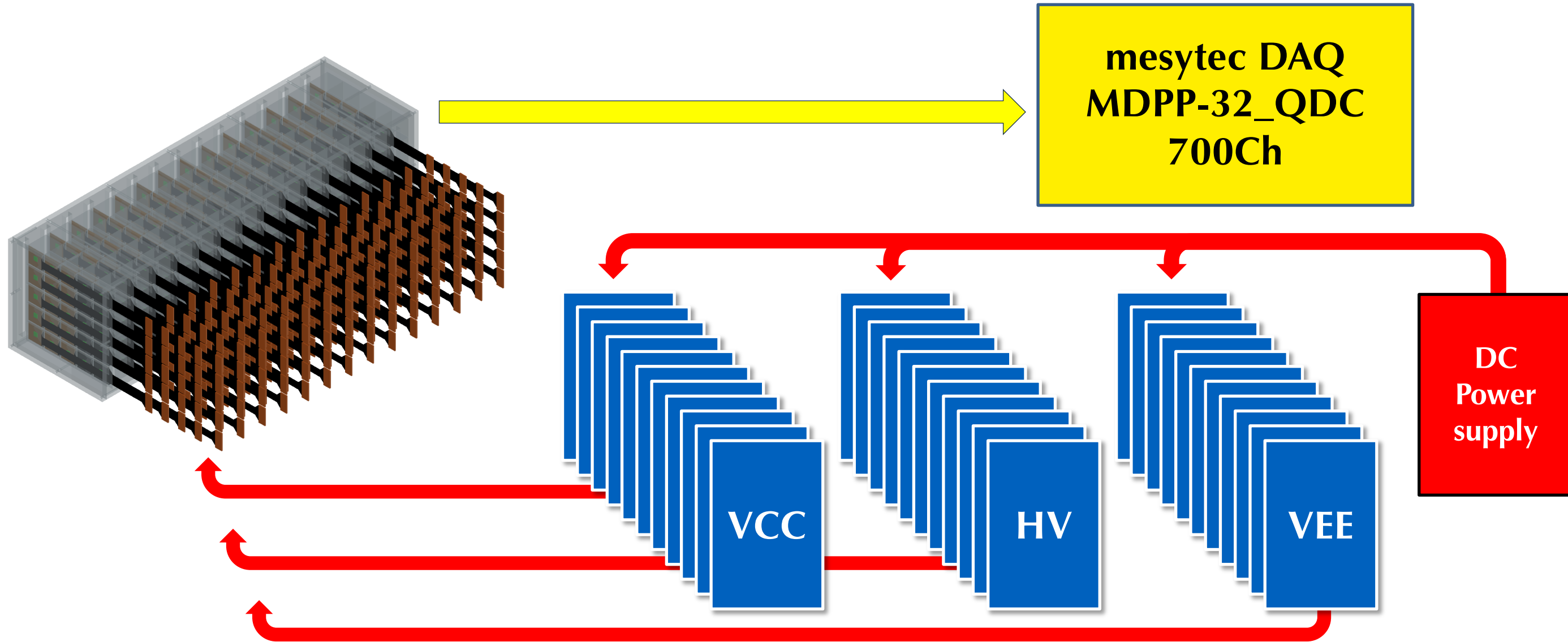
SiPM暗计数测试

样机整体设计



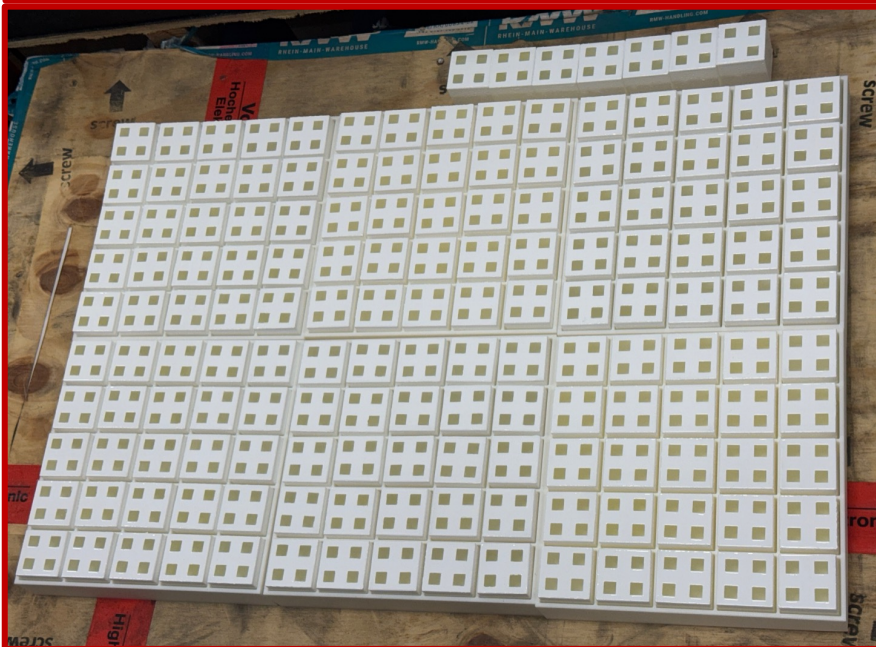
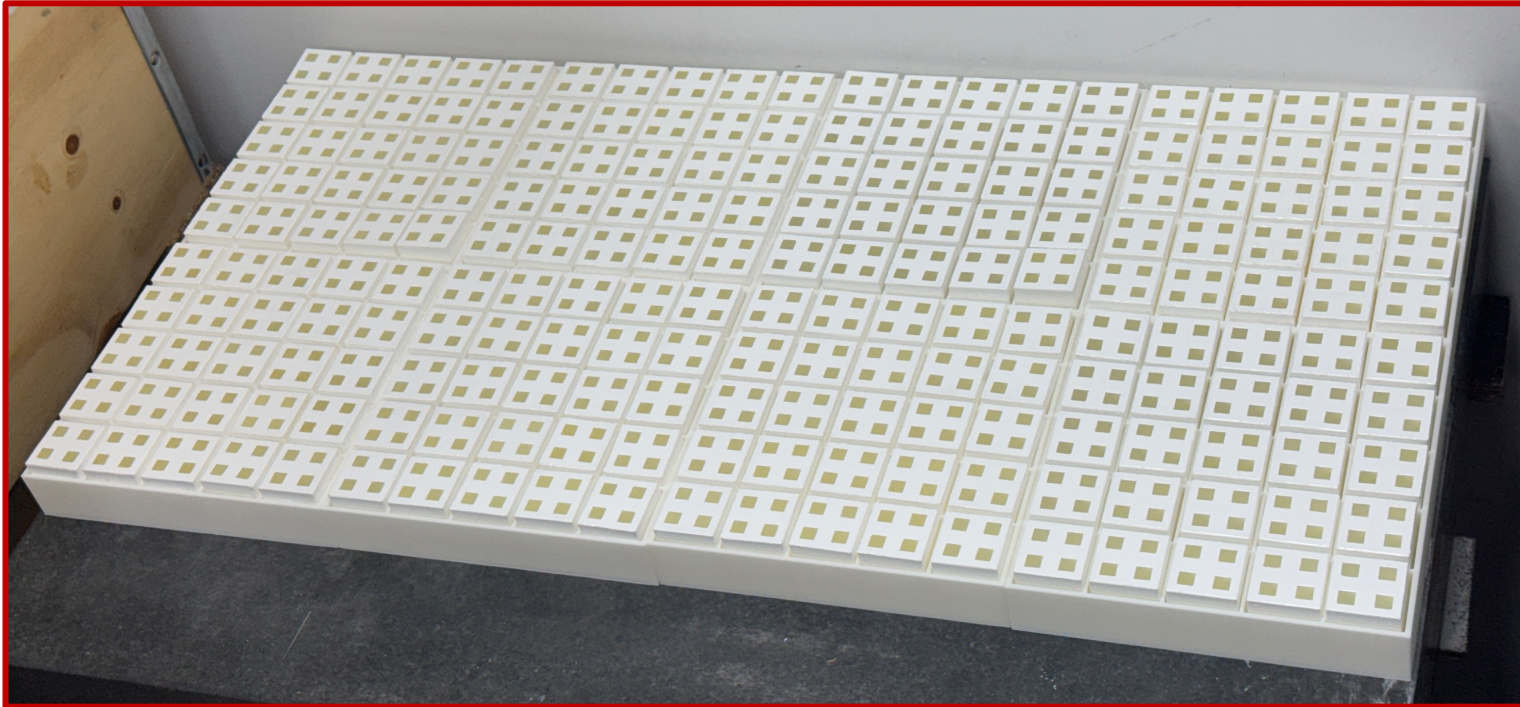
FPC 读出板





VCC(32Ch) ×11 HV (32Ch) ×11 VEE(32Ch) ×11

单元块制作



铅玻璃模块
39*35*35mm

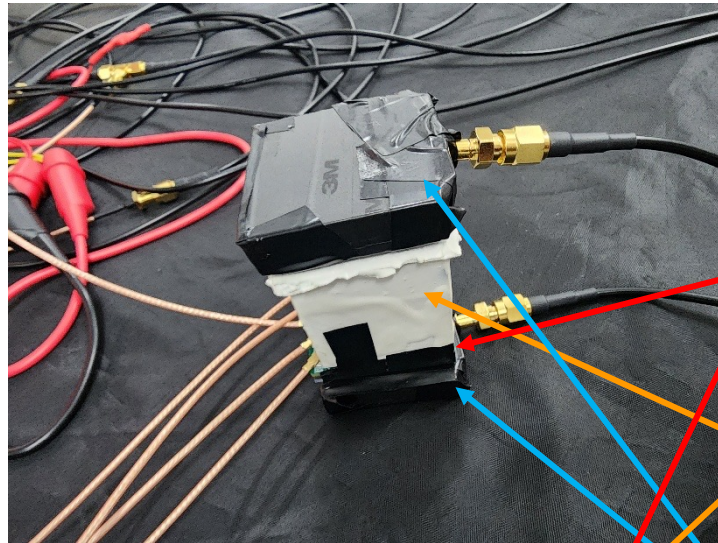
塑料闪烁体模块
1.5*35*35mm



1. 完成了双读出量能器的原理模拟与性能分析
2. 完成了单元块的结构设计与性能模拟
3. 完成了单元块及读出电子学的宇宙线测试
4. 正在进行样机组装

THANKS

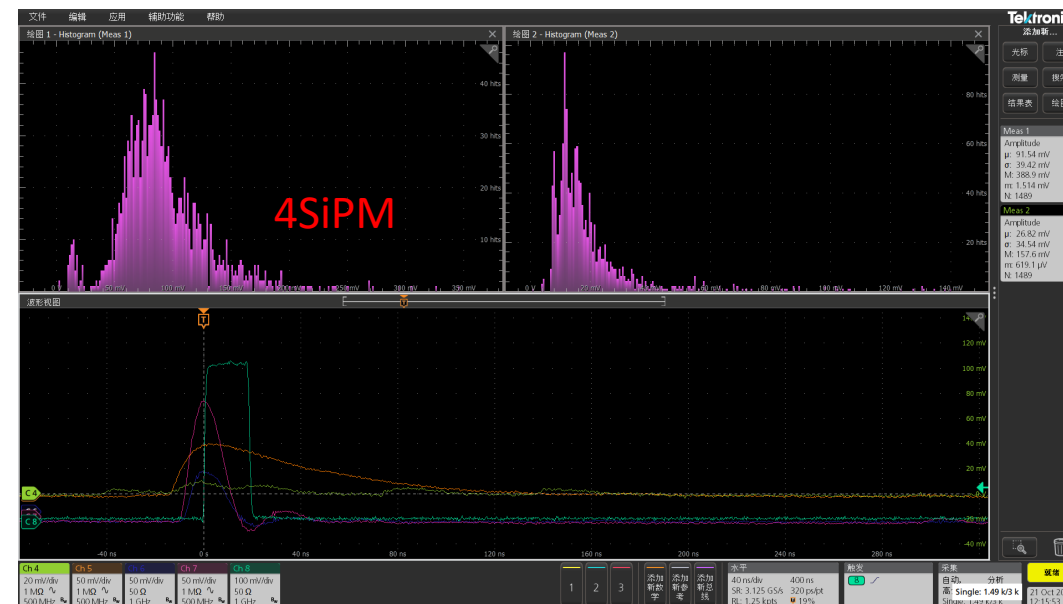
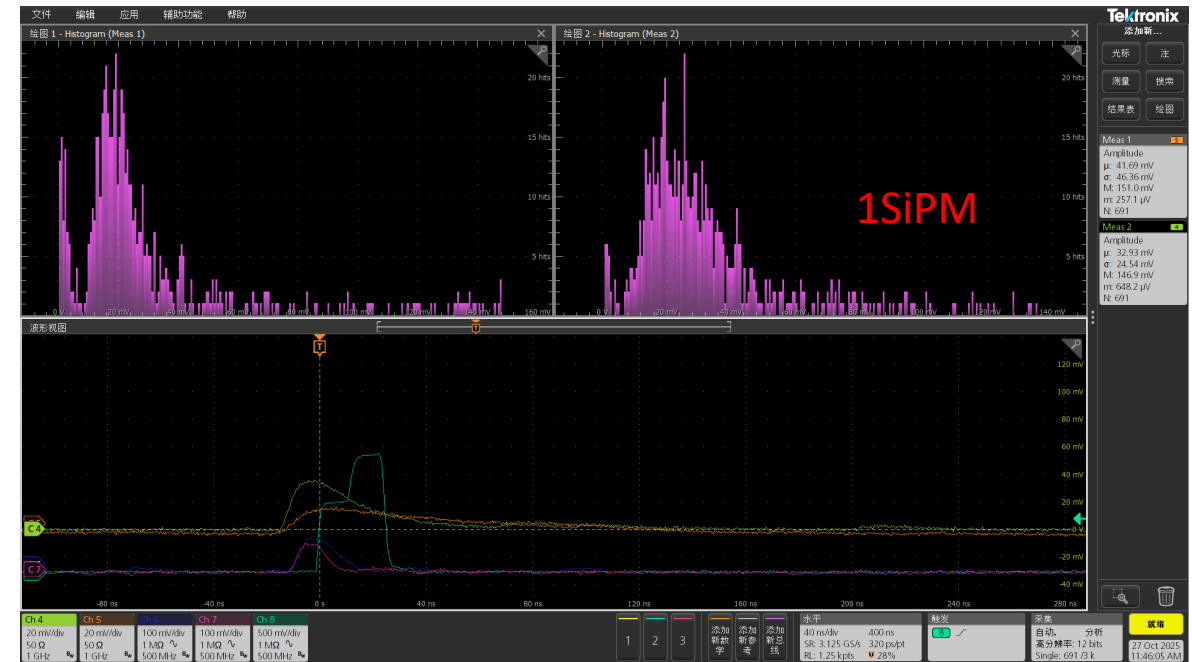
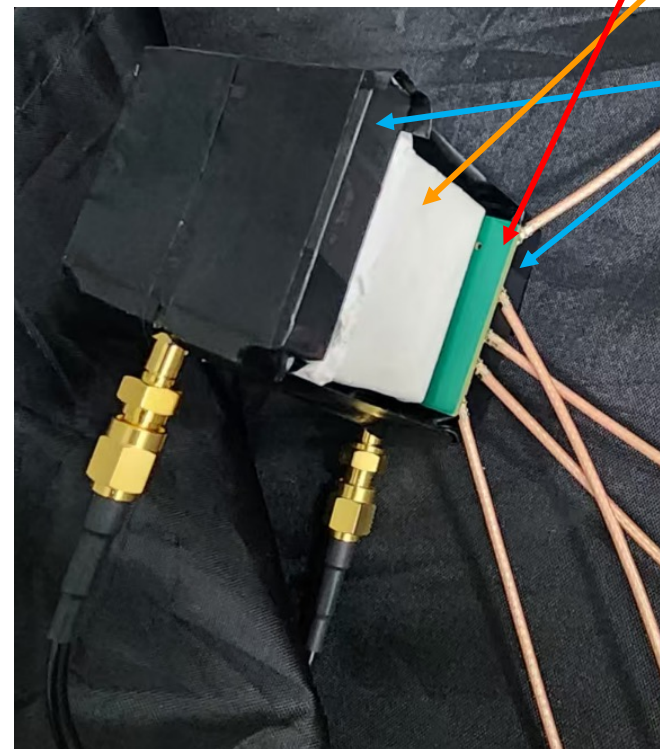
Backup 测试结果



SiPM 读出

铅玻璃

触发器



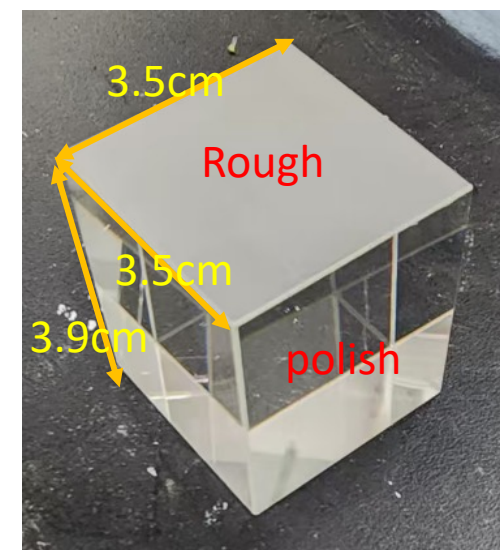
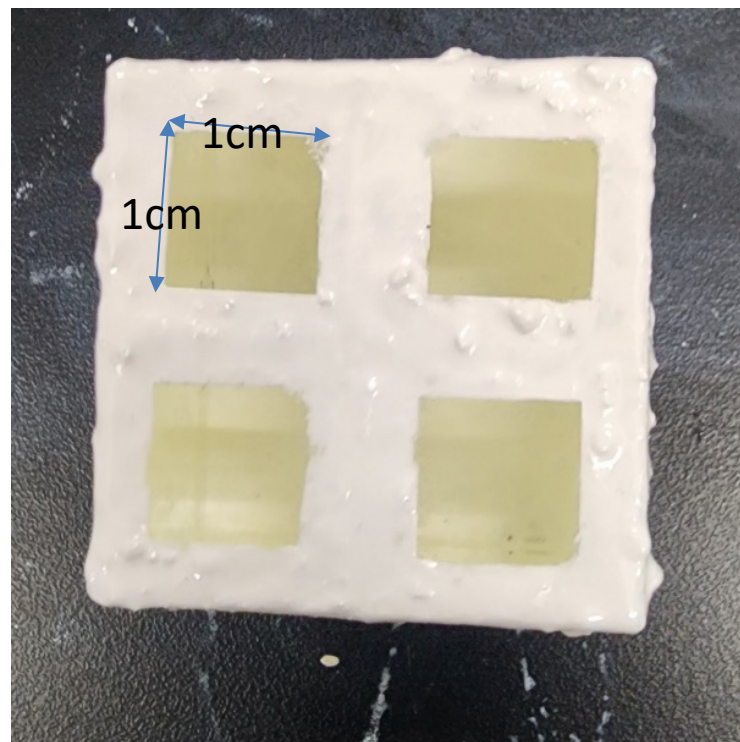
切伦科夫光子 1 SiPM
单光子电压值 2.362mV
平均光子数 : 15.23

切伦科夫光子 4 SiPM
单光子电压值 0.756mV
平均光子数 : 121.08

涂层方式

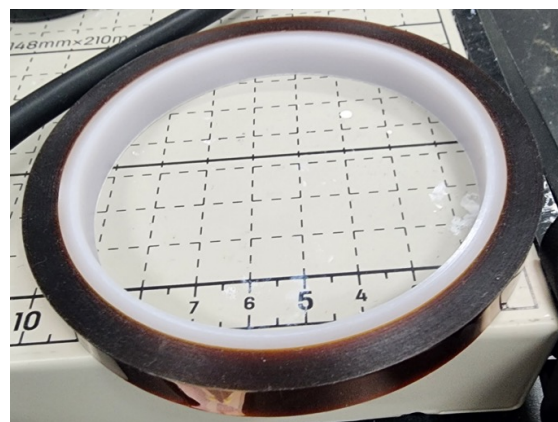
新的涂层方法

采购了两批新型铅玻璃块，每种类型各 20 块，以用于后续测试。



$3.5 \times 3.5 \times 3.9 \text{ cm}^3$

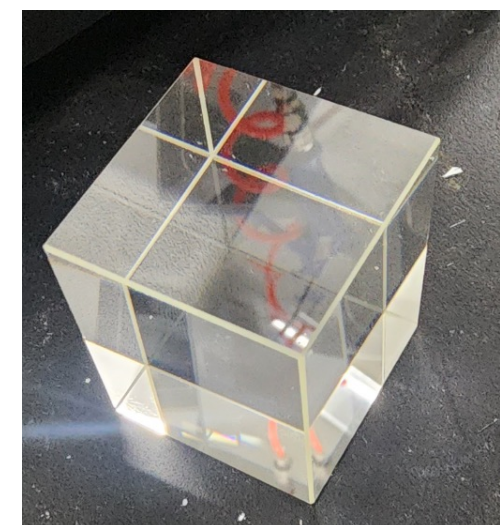
单个 $3.5 \times 3.5 \text{ cm}^2$
粗糙表面



将胶带切割成 $1 \text{ cm} \times 1 \text{ cm}$ 的正方形。

涂反射涂层。

在涂层基本固化后，撕掉胶带。

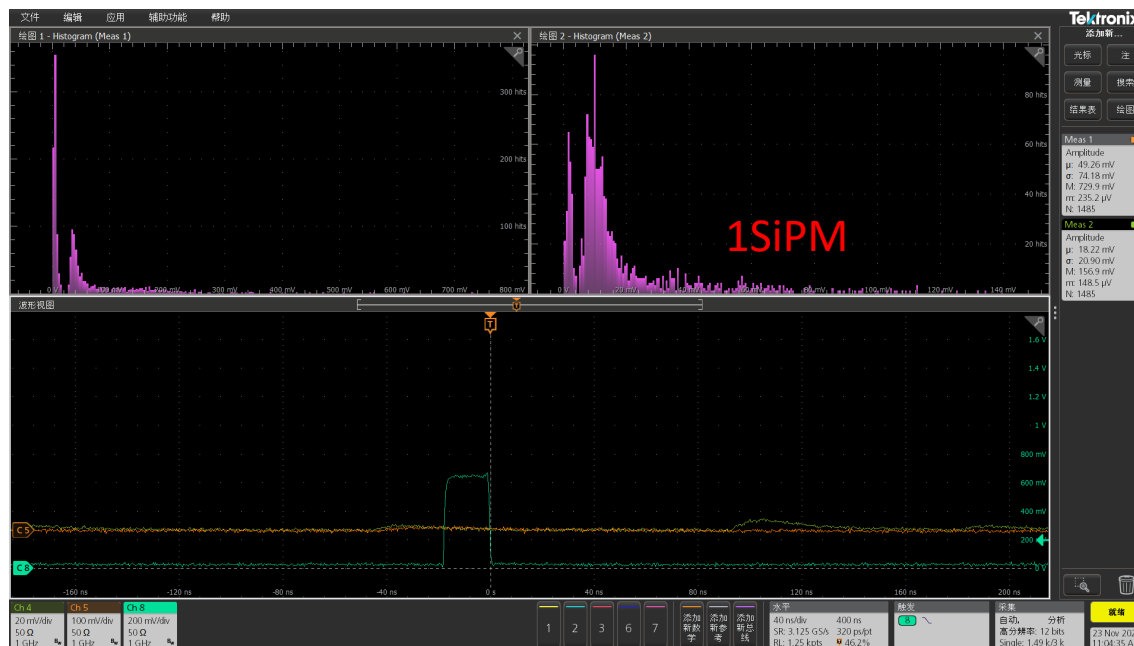
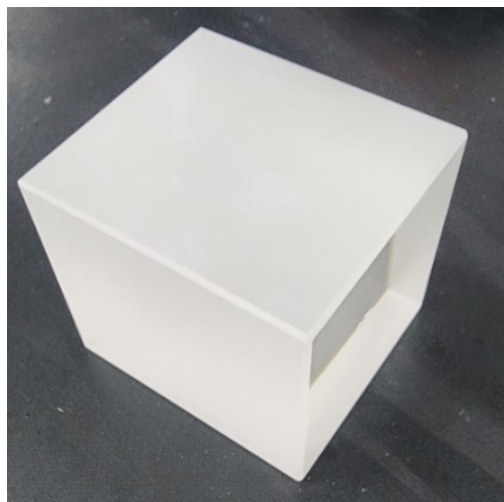
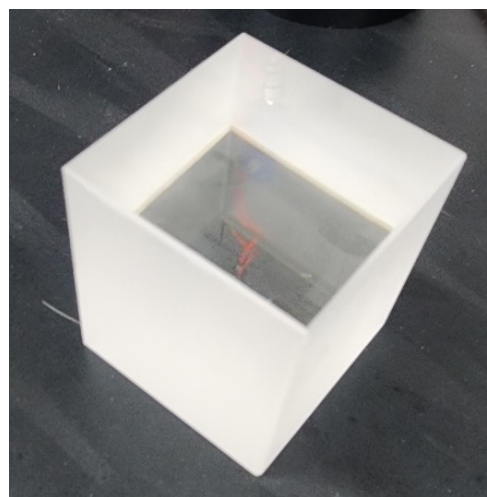


$3.5 \times 3.5 \times 3.9 \text{ cm}^3$

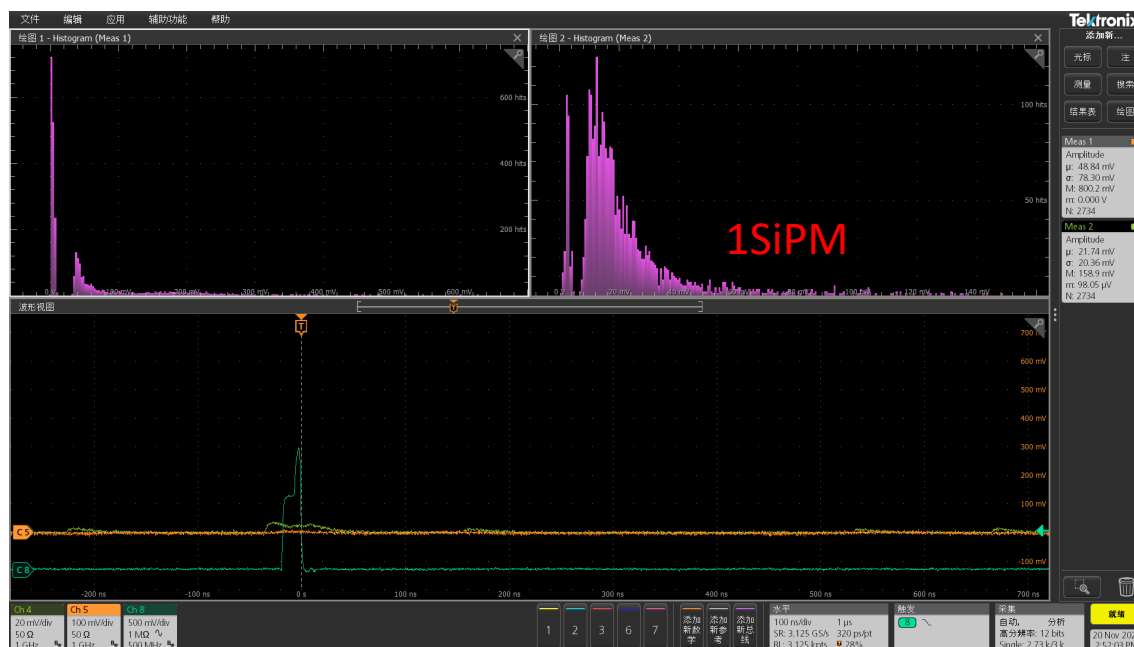
全表面光滑

测试结果

我们测试了铅玻璃的粗糙表面与抛光表面对光子数量的影响。实验中未添加任何反射涂层。



抛光表面
1 SiPM
平均光子数: 8.43



粗糙表面
1 SiPM
平均光子数: 10.05

我们所使用的铅玻璃尺寸为 $3\text{ cm} \times 3\text{ cm} \times 3.9\text{ cm}$ ，其中 $3\text{ cm} \times 3\text{ cm}$ 的表面经过了抛光处理。

若采用粗糙表面，块体的厚度将由 3.9 cm 变为 3 cm ，这将导致切伦科夫光子的数量减少。