



山东高等技术研究院

SHANDONG INSTITUTE
OF ADVANCED TECHNOLOGY

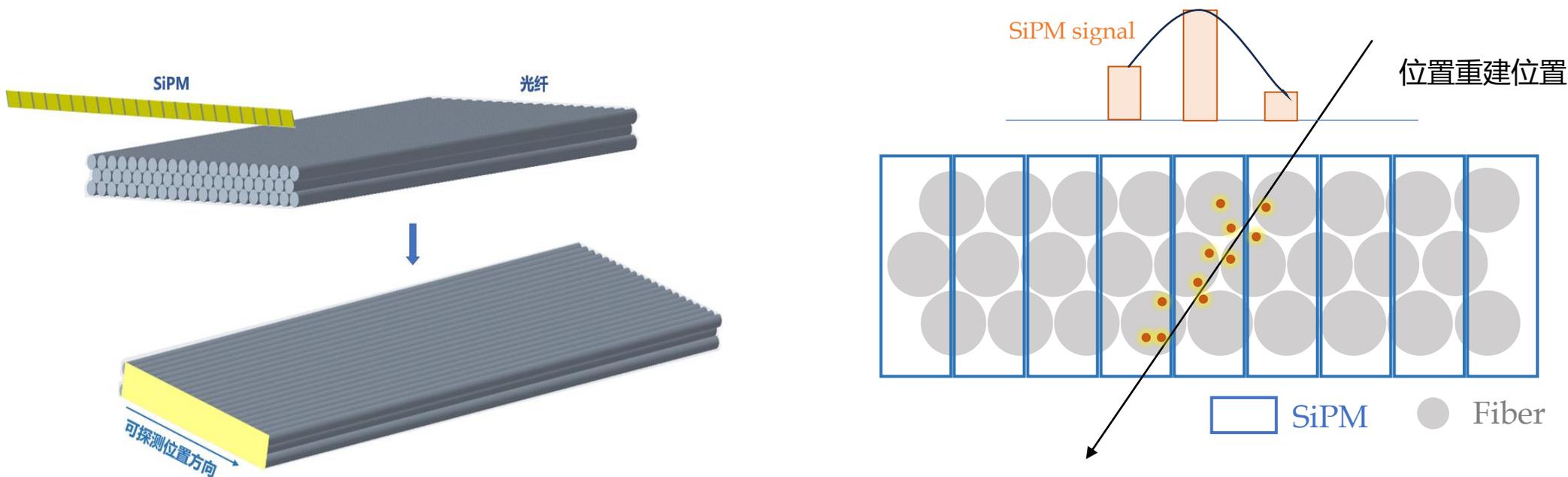
位置灵敏的塑料闪烁光纤探测器研制

李慧玲

2024年07月16日

第二十二届全国核电子学与核探测技术学术年会暨第十二届
全国先进气体探测器研讨会，青岛

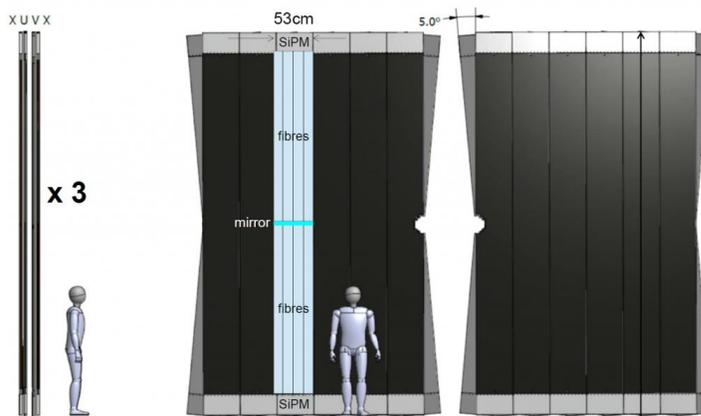
塑闪光纤探测器



- 塑料闪烁光纤探测器：光纤探测主体和1维SiPM光电转换器件
- 光纤交叠紧密排布，可实现多种尺寸和形状的制作
- 可实现与传统硅微条探测器相当的位置分辨能力，但设计制造上的成本和复杂度低
- 国内有相关塑料闪烁光纤和SiPM器件产品，未来可实现国产化

应用：粒子物理实验

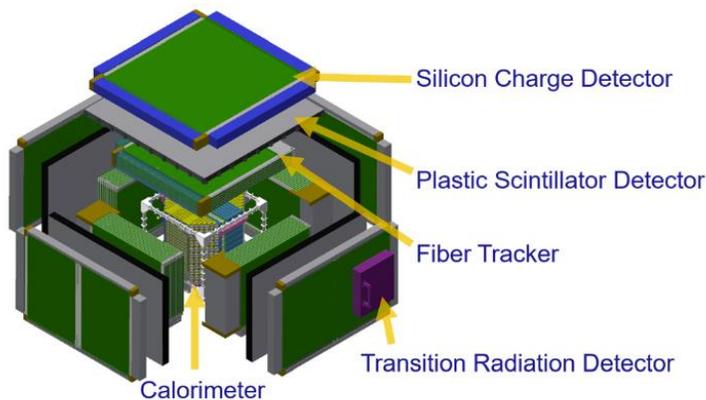
LHCb SciFi Tracker



LHCb tracker upgrade TDR

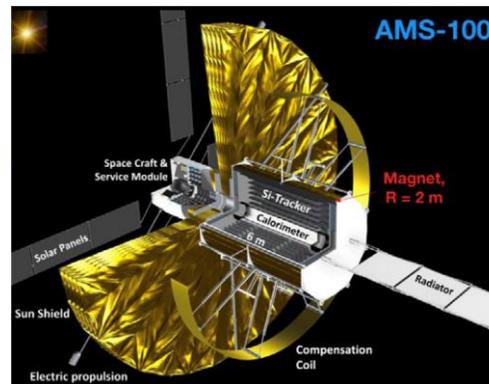
采用 $\varnothing 250\mu\text{m}$ 光纤
单侧读出模块长度 2.5m
位置分辨率 $<100\mu\text{m}$

HERD



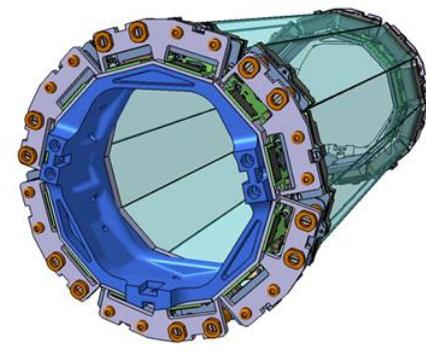
$<100\mu\text{m}$ 高位置分辨
面向不同电荷的宇宙线粒子,
更大动态响应范围

AMS-100



拟采用 $\varnothing 125\mu\text{m}$ 光纤,
更高的位置分辨率

Mu3e

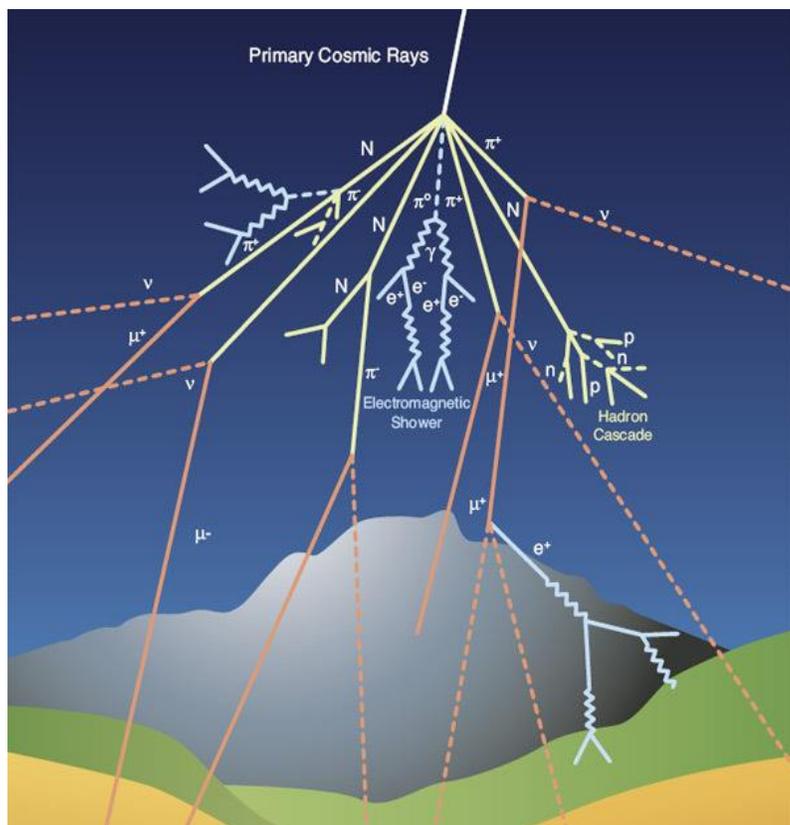


NIMA1058 (2024) 168766

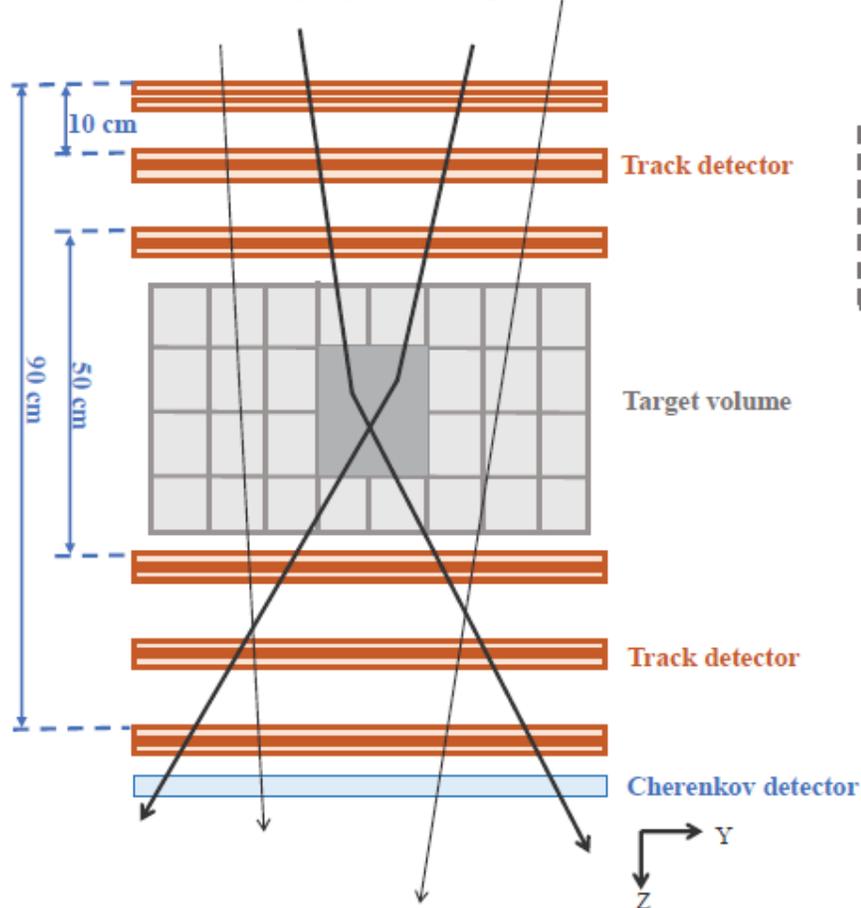
同时测量时间和位置
250ps时间分辨
100 μm 位置分辨率

应用：缪子散射成像

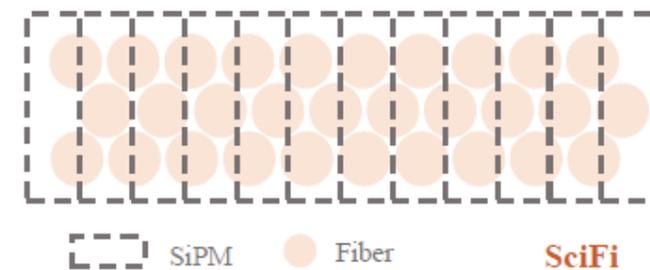
宇宙线缪子



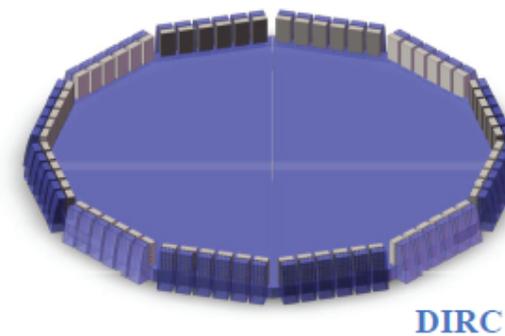
缪子散射成像系统



塑料闪烁光纤探测器



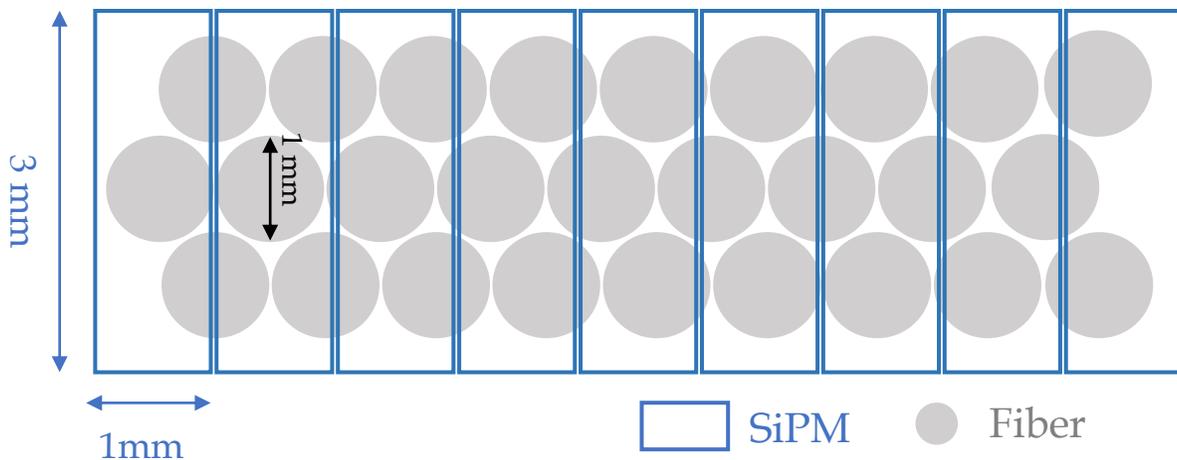
内反射切伦科夫探测器



研制目标

光纤模块: 10cm × 1m area

- 三层 $\varnothing 1\text{mm}$ 塑闪光纤交叠排布, 单端 1D SiPM阵列读出
- SiPM前端电子学对单光子灵敏, 动态范围覆盖 $\sim 200\text{pe}$
- 模块对宇宙线缪子的探测效率 $>99\%$
- 位置分辨能力 $\sim 300\mu\text{m}$



研究内容

光纤及探测器模拟

SiPM及光纤性能测试

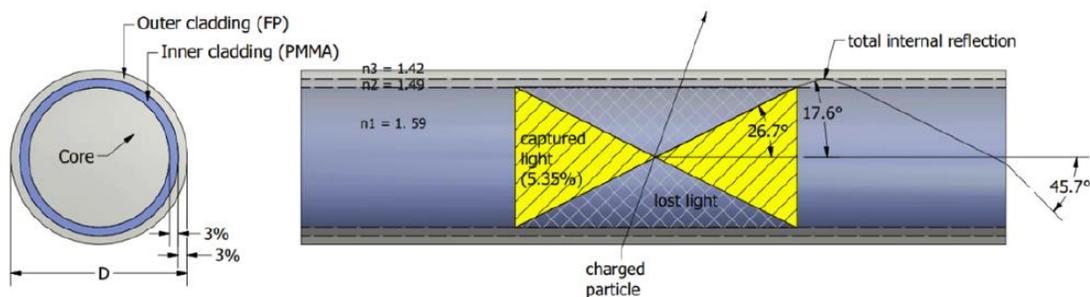
多通道前端电子学

光纤模块制备

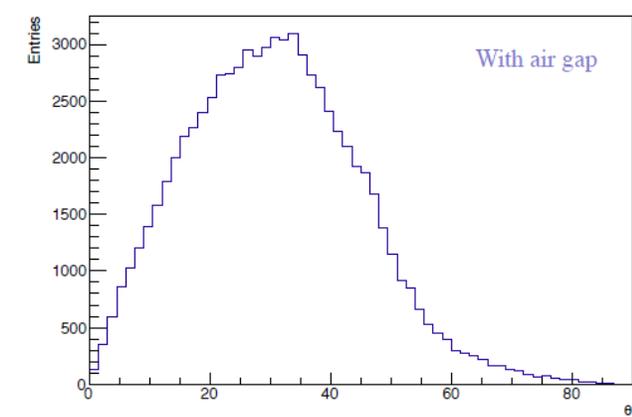
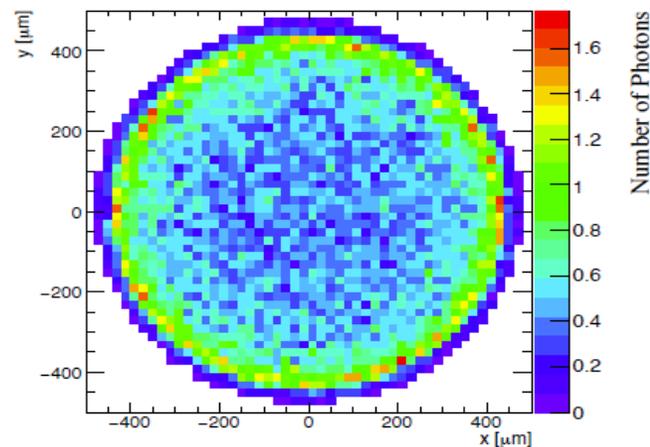
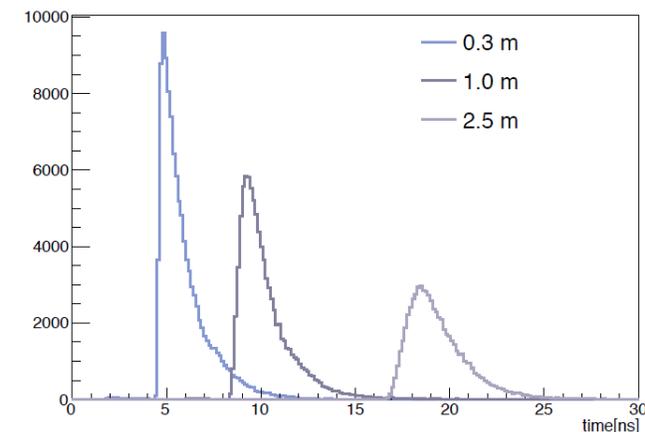
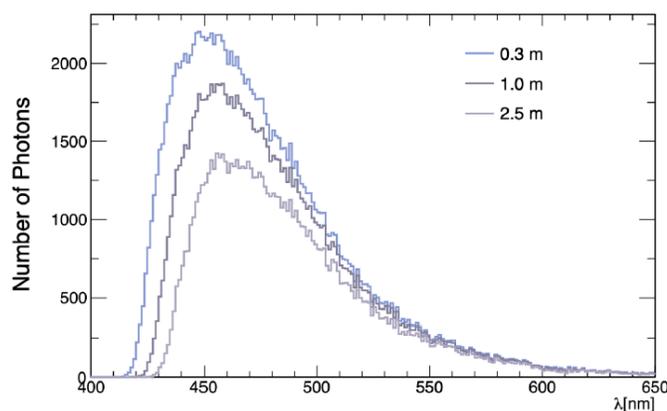
塑料闪烁光纤

通过模拟塑闪光纤的闪烁发光、波长位移、光收集和光衰减等过程，得到光纤端面光子的空间和时间分布特征等信息

Kuraray SCSF 78M

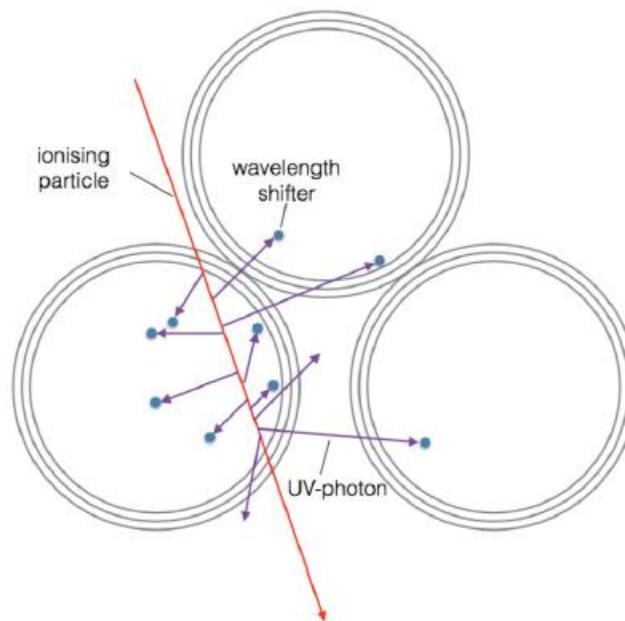


- 带电粒子探测: 光产生和光导
- 光产额~8000 ph/MeV
- 衰减长度>4 m,
- 快衰减时间~2.8 ns
- 光纤束缚效率~5.4%

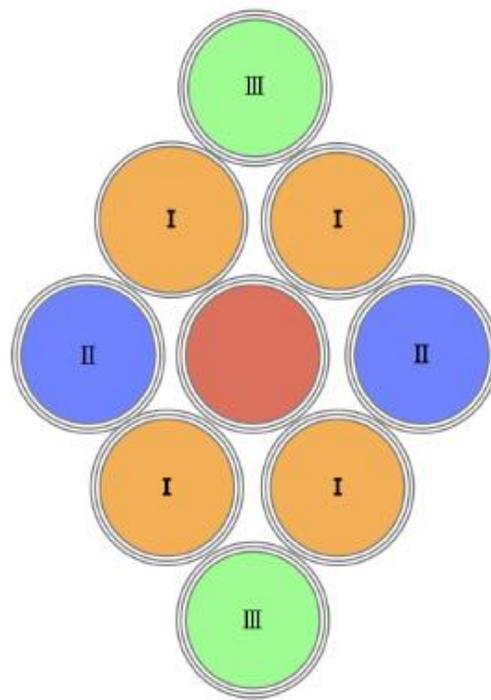


光纤间的串扰

串扰由发生WLS过程前的紫外光子激发临近光纤导致



通过模拟单根光纤中的紫外光，研究不同距离的临近光纤的串扰几率。



光纤串扰概率

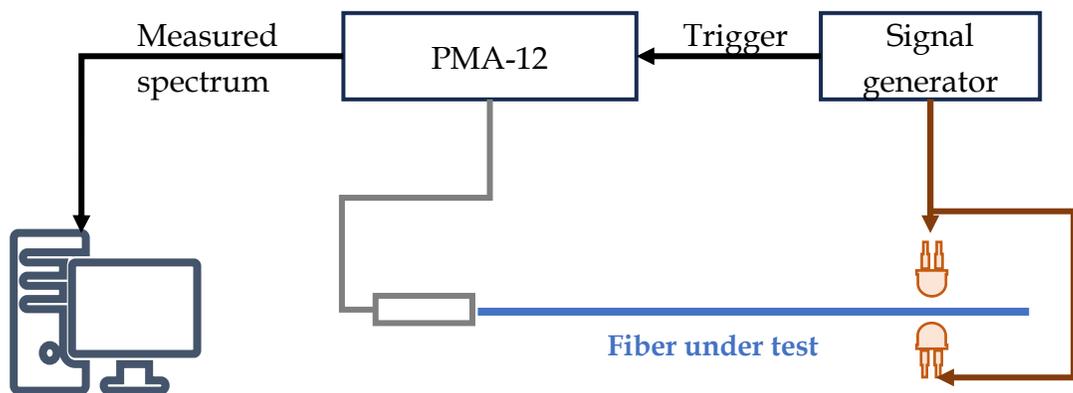
Diameter	Center fiber	Class I	Class II	Class III	X-talk
0.25 mm	0.8257	0.1136	0.0510	0.0096	~17%
1.00 mm	0.9543	0.0363	0.0175	0.0013	~5%

光纤串扰概率随着光纤直径增加而降低
制备时可通过在光纤间的胶水中添加TiO₂来降低串扰

THESIS-Stephan Escher-2017-331

塑闪光纤性能测试

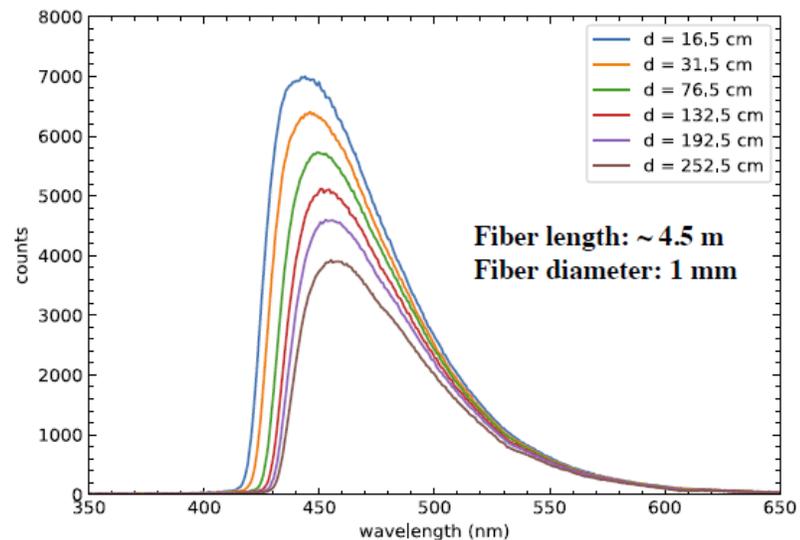
光纤测试平台



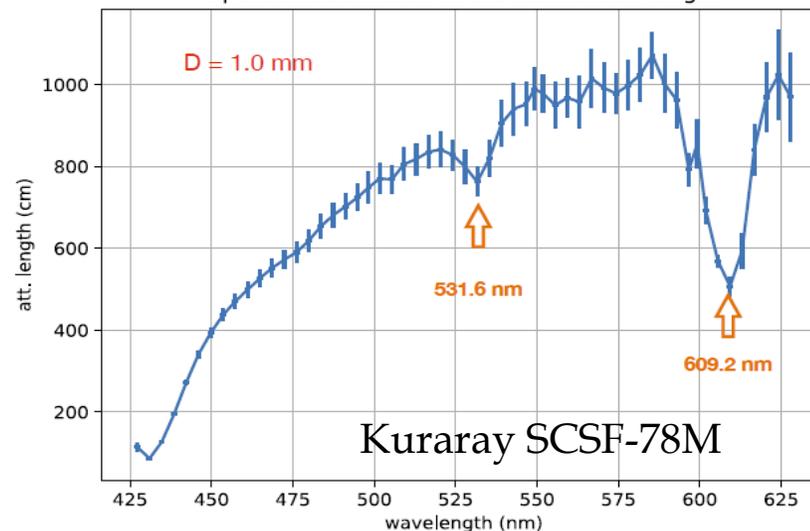
370 nm UV LED



测试不同波段光衰减长度表现

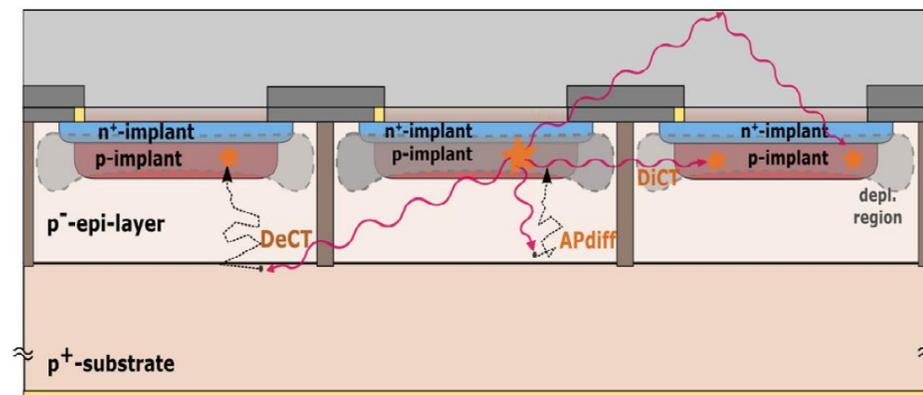
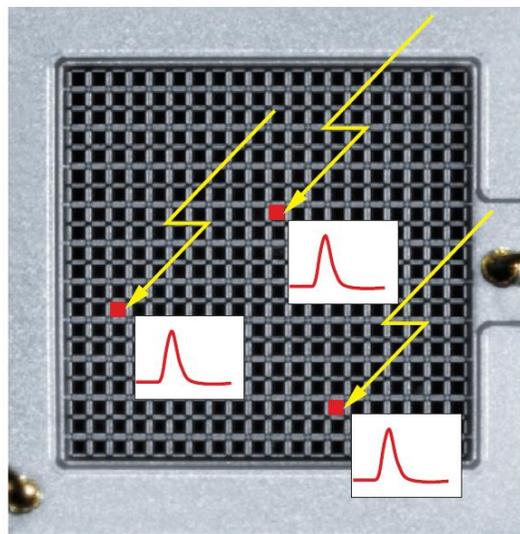
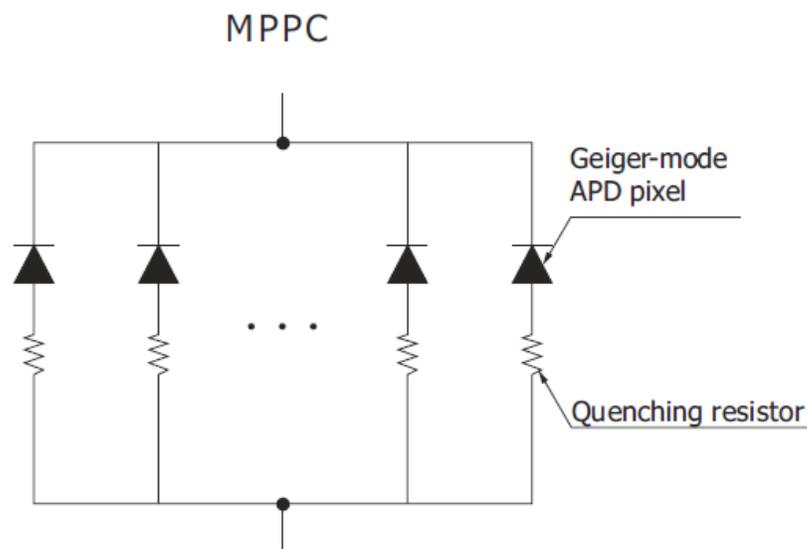


Spectral distribution of the attenuation length



主要由分子振动吸收导致

硅光倍增器SiPM



NIM A926 (2019) 16-35

优点:

结构紧凑, 不同通道尺寸易加工

像素工作在在Geiger模式下

所需偏压低, 增益约 10^6 量级, 探测效率高

缺点: 噪声大, 且受温度影响

噪声主要包括:

- 主噪声: 热激发的或隧穿效应产生的载流子引发的雪崩脉冲
- 关联噪声: 光串扰和后脉冲

SiPM性能测试

SiPM测试平台:

- 击穿电压、增益：温度补偿系数
- 暗噪声、串扰、后脉冲
- 探测效率PDE
- 波形时间特征
- ...

评估不同型号器件，挑选合适的SiPM性能指标

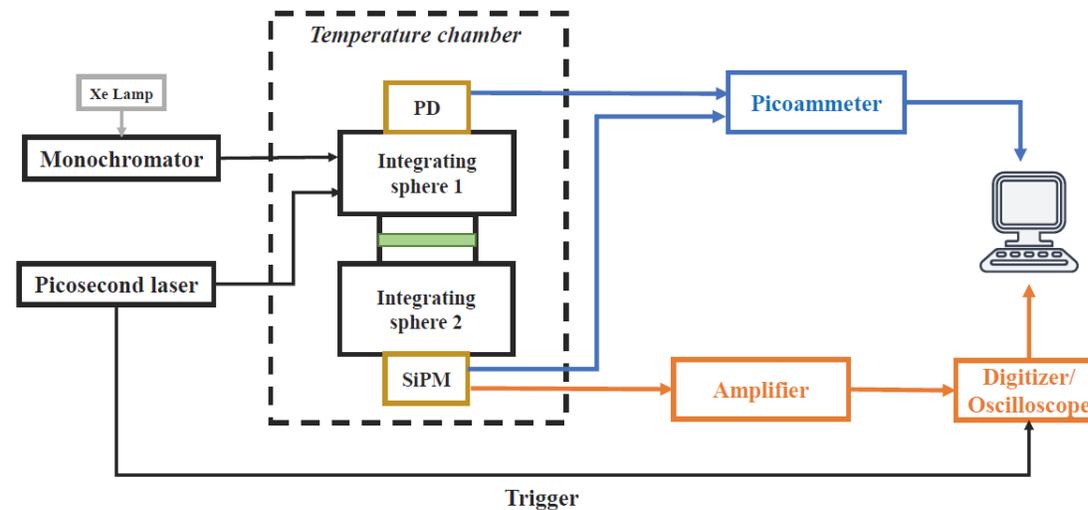
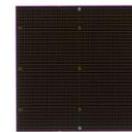
NDL EQR15 11-3030D-S



HPK S13363-3050NE-16

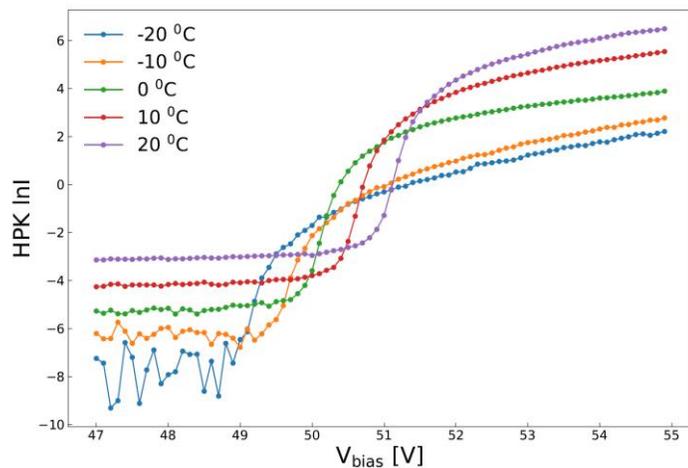


SensL MicroFJ-30035-TSV

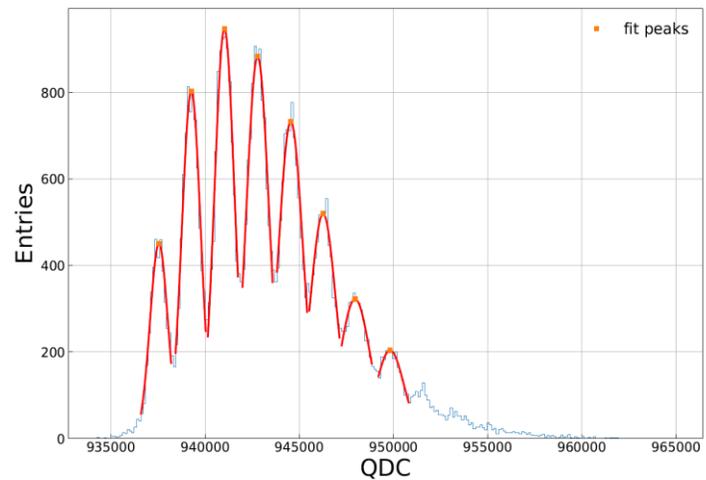


SiPM性能测试

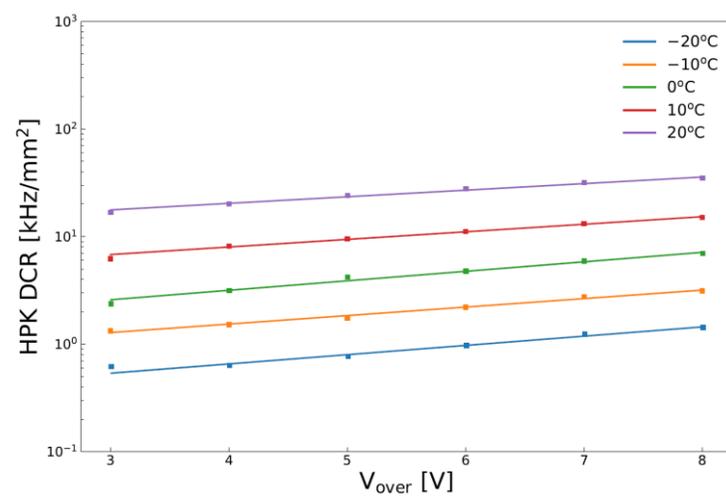
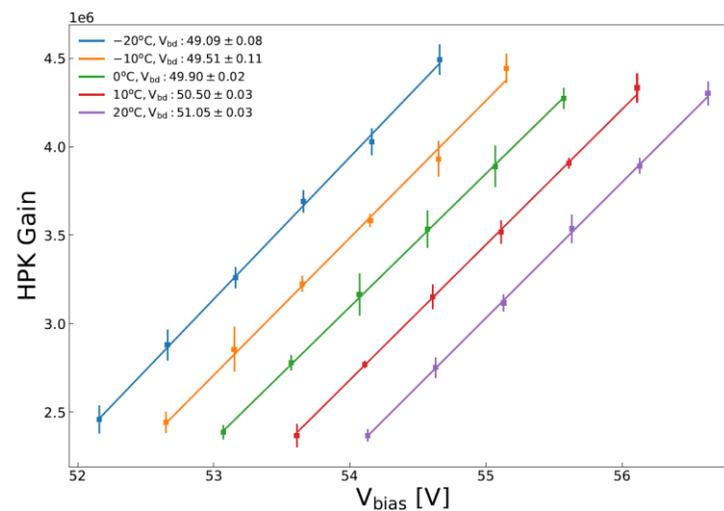
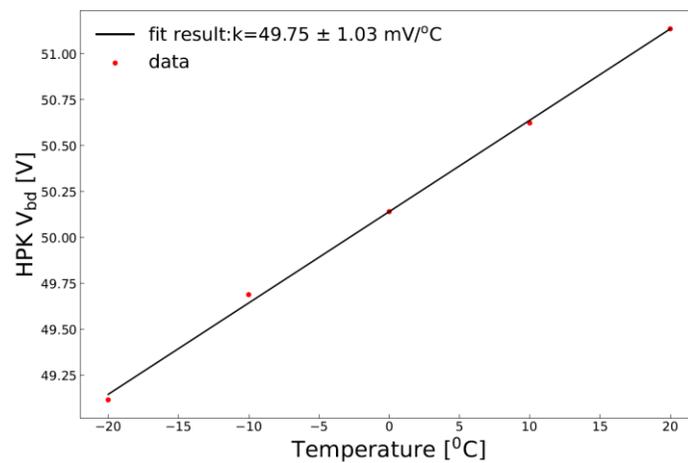
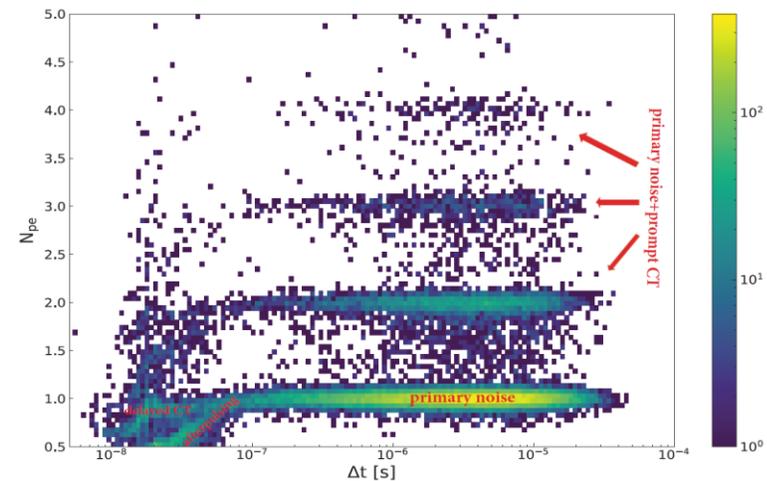
击穿电压



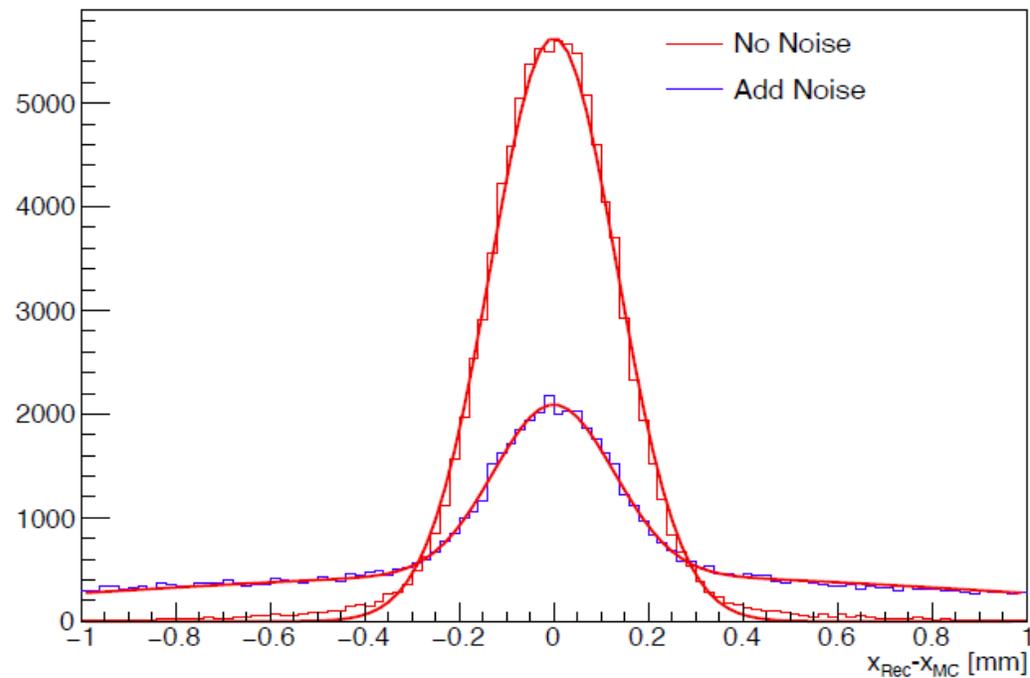
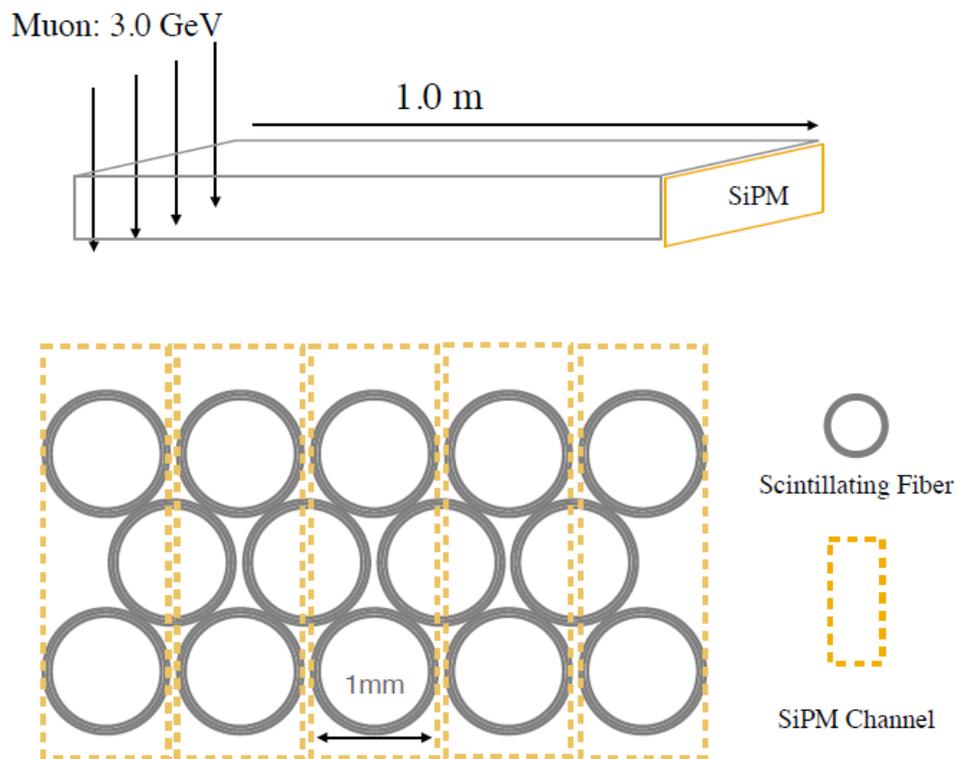
增益



暗噪声



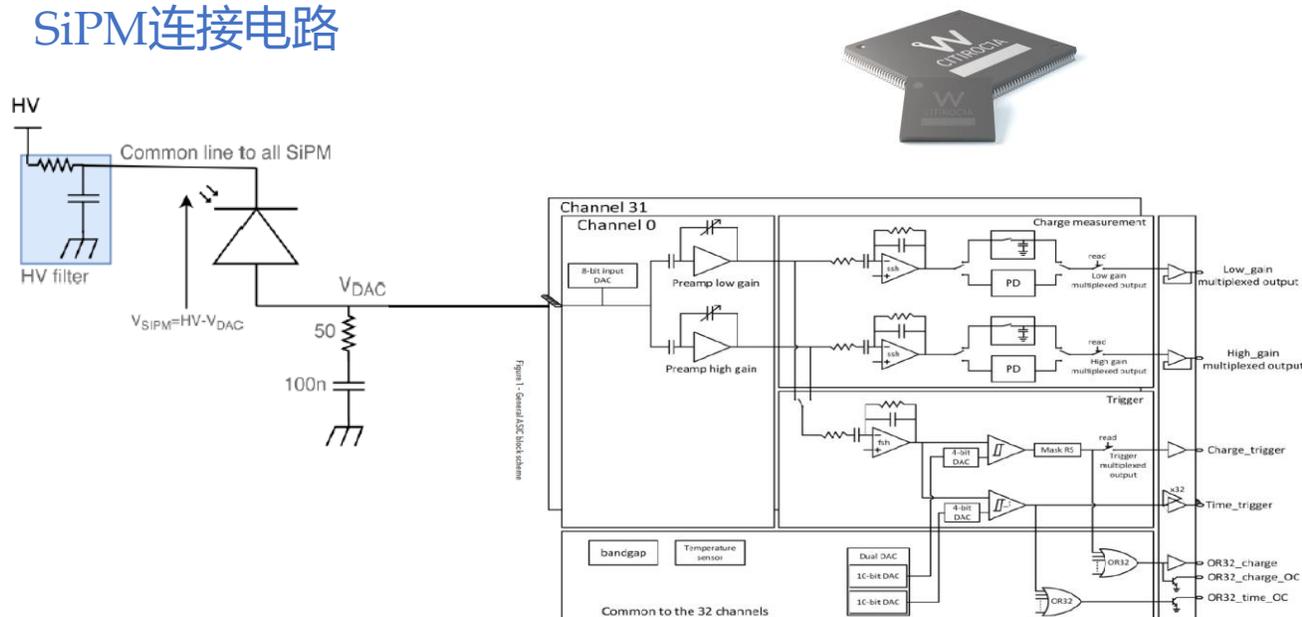
探测器模拟



利用 \varnothing 1mm fibers和典型的HPK SiPM参数值, 模拟得到位置分辨率 $<300\mu\text{m}$

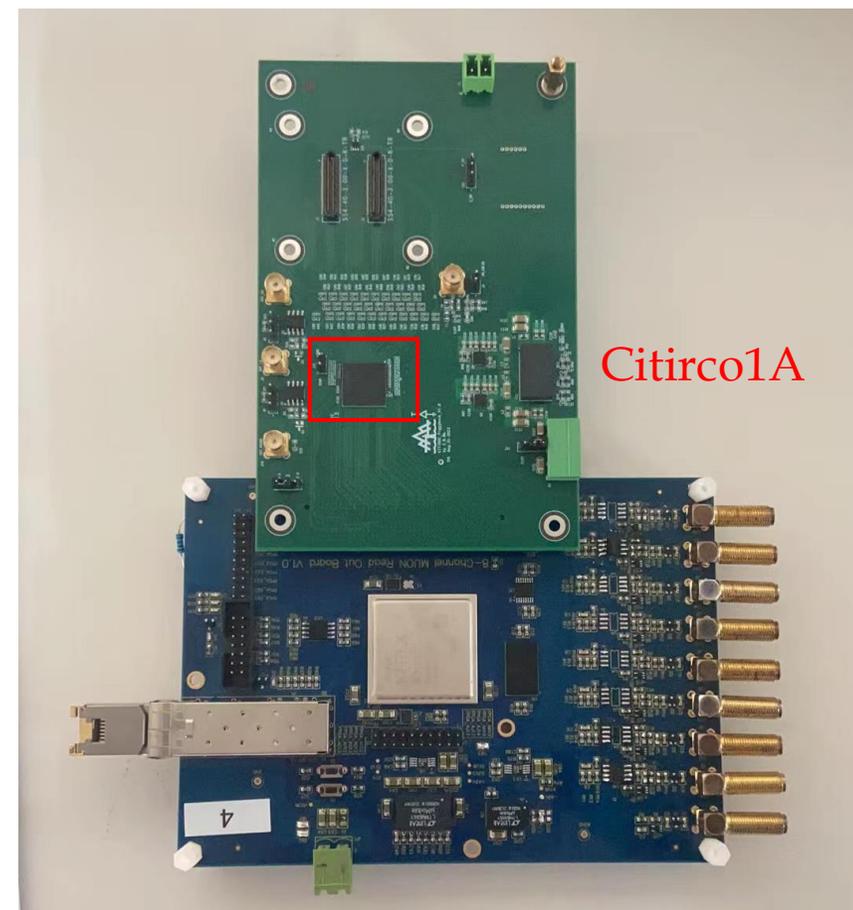
前端电子学

SiPM连接电路

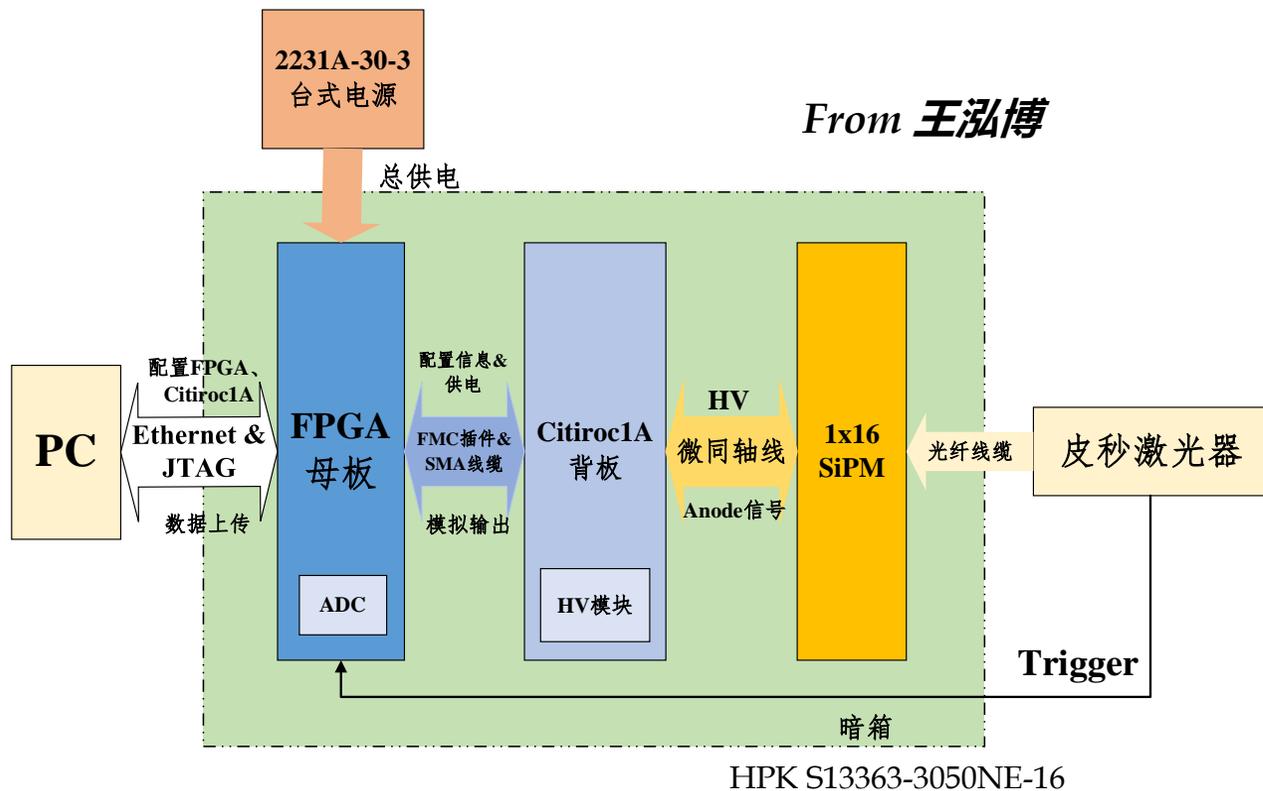


Citiroc1A

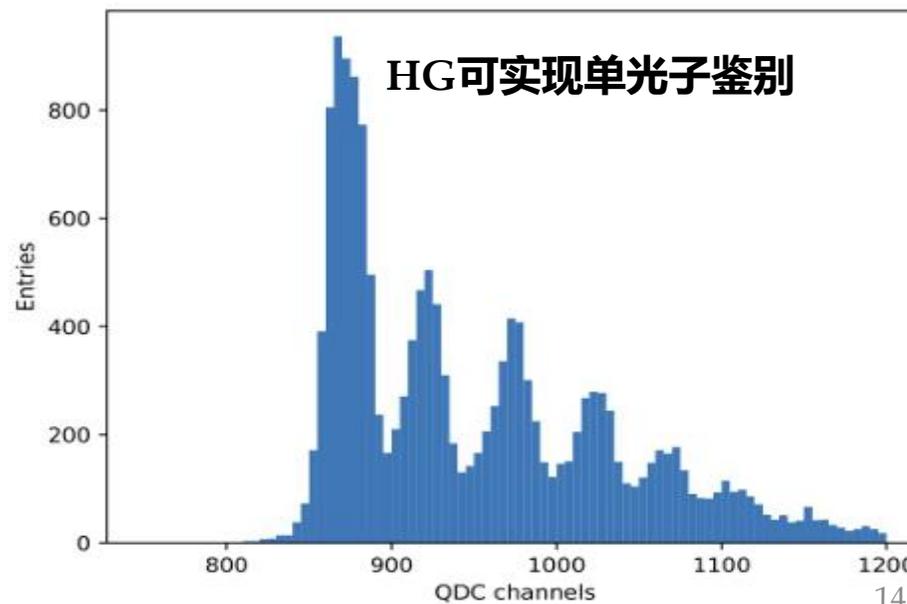
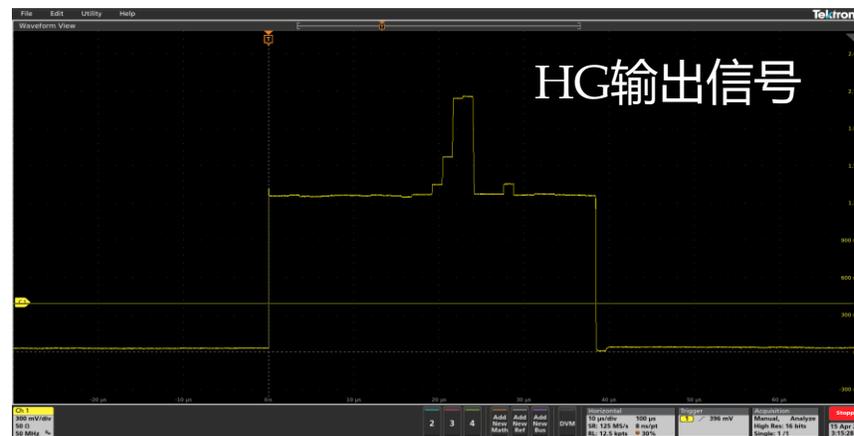
- 32 channels with HV adjustment for SiPM
- CR-RC² slow shaper with 12.5-87.5ns peaking time
- 2 multiplexed analogue charge output of HG and LG
- Dynamic range:0-400 pC, up to 2500 pe @ 10⁶ SiPM gain



前端电子学

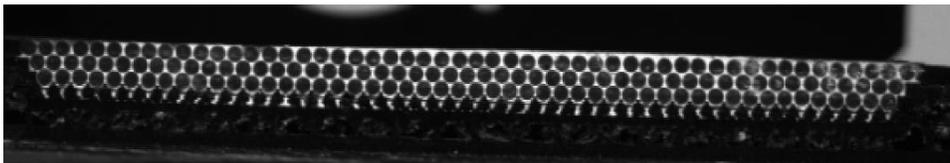


测试方案

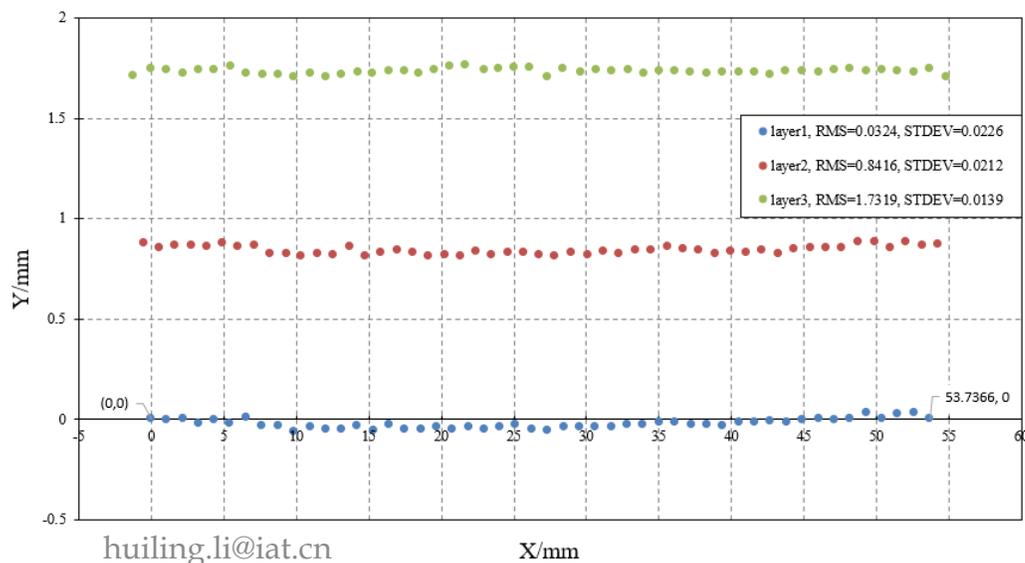


光纤模块制备

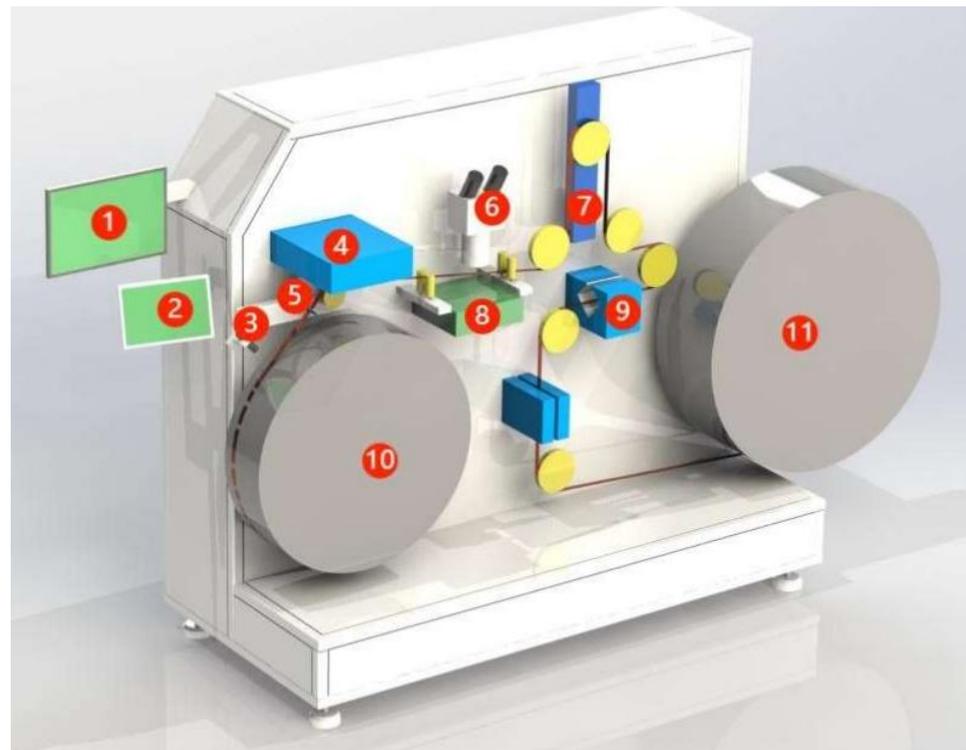
针对直径 $\geq 1\text{mm}$ 塑闪光纤，发展大尺寸光纤模块手动排布工艺（含模具、排纤、掺胶、端面切割及打磨等）



模块端面光纤位置分布



针对直径 $< 1\text{mm}$ 塑闪光纤，研制绕线机光纤排布工艺。绕线机含张力控制、线径监测以及排线监控等
目前正在组装测试

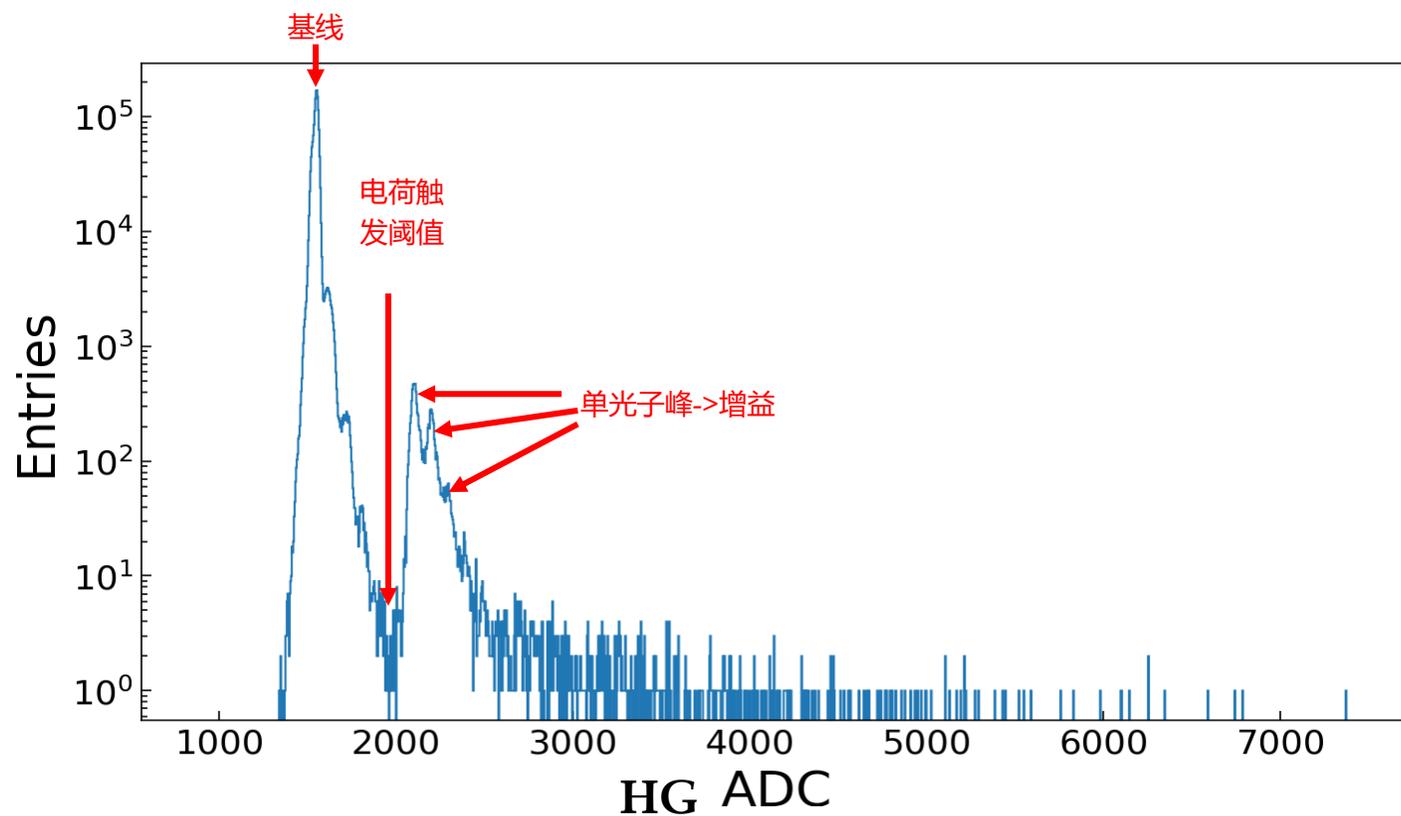


模块测试

采用Citiroc1A电荷触发开展多层模块测试，初步得到合理信号



HPK S13363-3050NE-16



总结与展望

- 塑料闪烁光纤探测器在设计制造上的成本和复杂度降低，可实现多种尺寸和形状的制备和高位置分辨性能，在空间和地面的粒子物理实验中具有广泛的应用前景
- 从单根光纤的发光和光传播过程出发，构建了塑闪光纤探测器模拟软件
- 搭建了光纤和SiPM性能测试平台，对Kuraray光纤以及多个SiPM性能开展了评估，可满足研制需求
- 初步实现了前端电子学设计以及光纤模块手排工艺
- 继续开展宇宙线测试，评估探测器模块性能，不断优化设计和工艺

谢谢大家!