

新型量能器的研究

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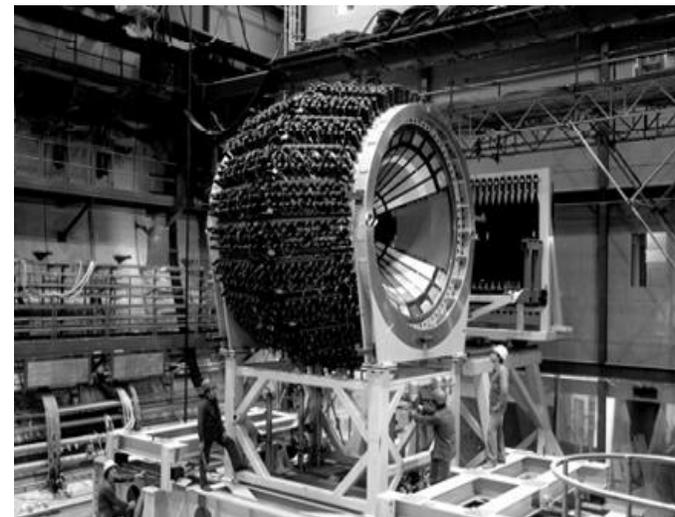
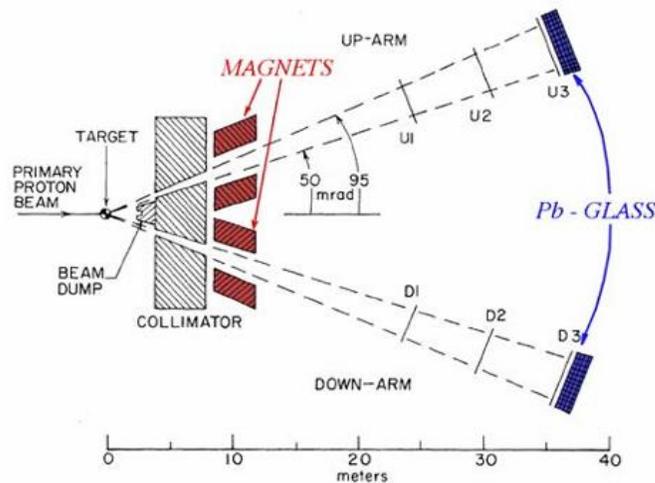
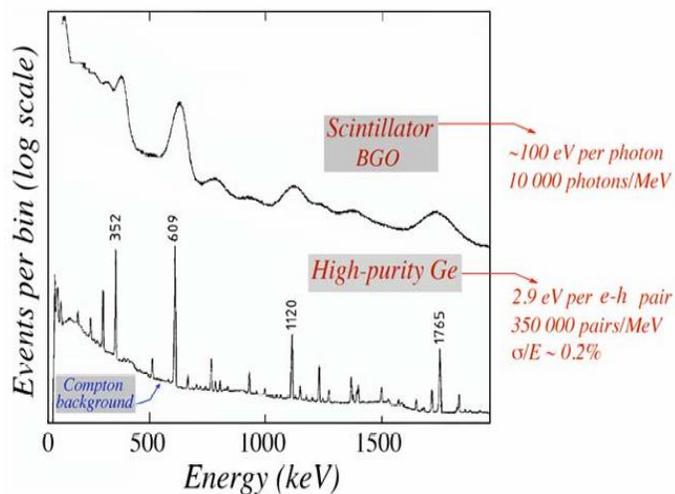
报告提纲

- 量能器技术前沿
- 高颗粒度量能器
- 新型晶体型量能器
- 总结



量能器的历史

- 1950s, 闪烁晶体在核物理实验中用于伽马能谱测量
- ~1970, 量能器开始应用于粒子物理实验, 用于测量中性粒子, 作为shower counter
- 1980, 量能器在对撞实验谱仪中扮演了重要的功能, 分成电磁量能器和强子量能器



Fermilab E-70实验

CERN UA2实验

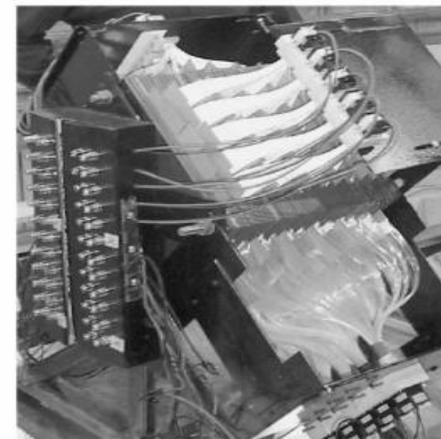
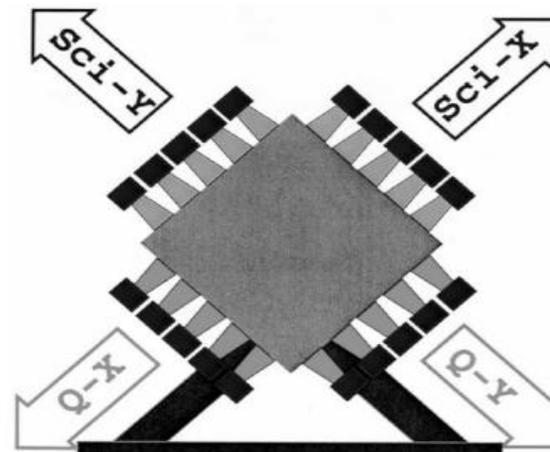


量能器的历史

- 提高量能器对强子响应的能量分辨
- 补偿型
 - 优化量能器对高能粒子簇射过程中的电磁成分和强子成分响应，使得 $e/h=1$
- 荧光-切伦科夫光双读出
 - 利用切伦科夫光的信号，修正电磁成分的涨落

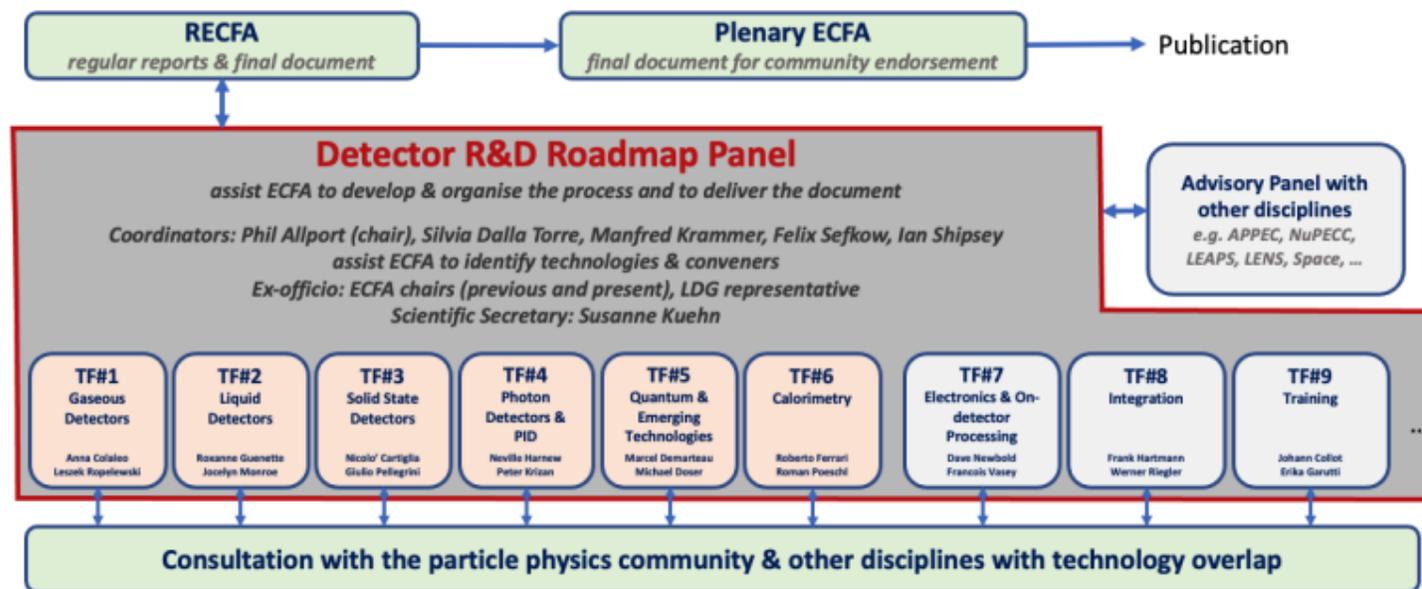


补偿型 (~1990), SPACAL in CERN



双读出 (~2000), ACCESS in NASA

量能器技术前沿



先进量能器技术

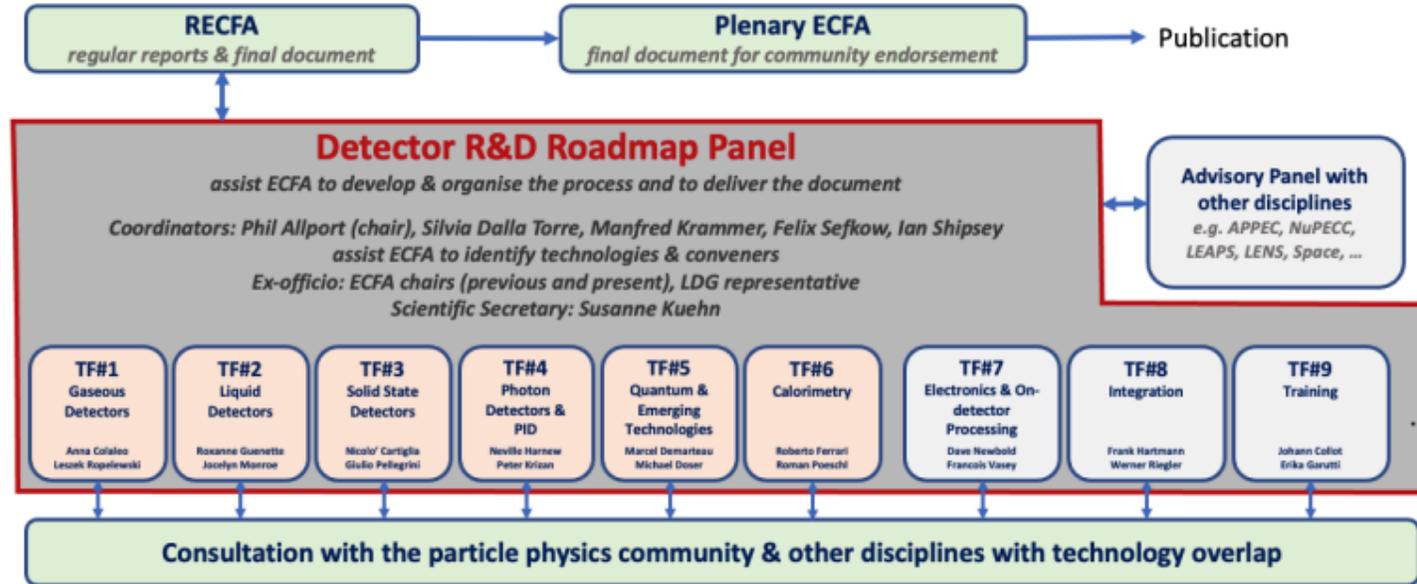
方向1:
读出电子学全嵌入式
“三明治”结构量能器

方向2:
液化惰性气体量能器

方向3:
闪烁体量能器



量能器技术前沿



先进量能器技术

方向1:
读出电子学全嵌入式
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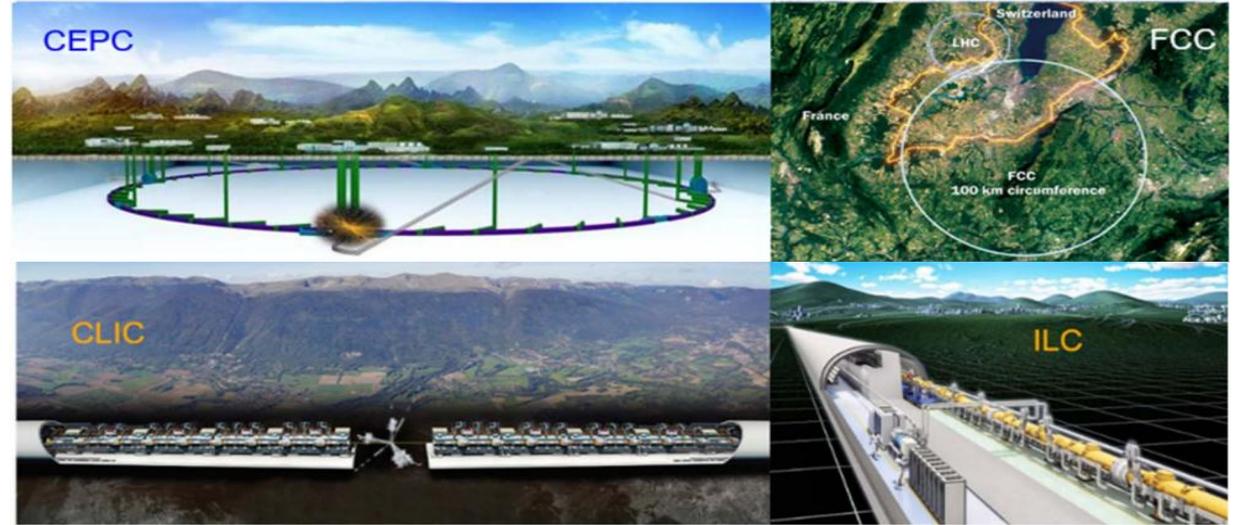
方向2:
液化惰性气体量能器

方向3:
闪烁体量能器

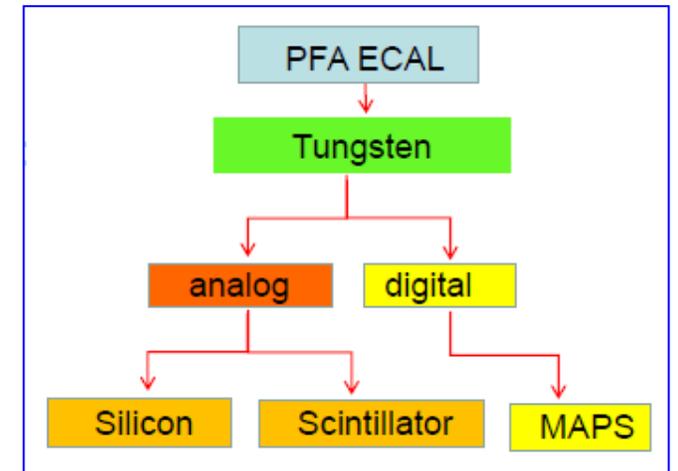
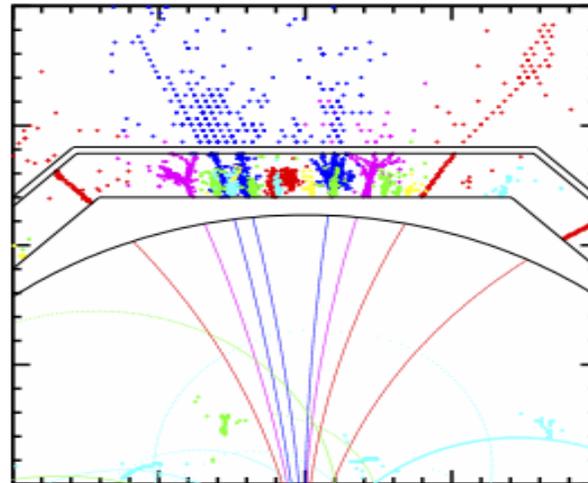
高能量前沿对量能器的需求

Challenges:

- Momentum: $\sigma_{1/p} < 5 \times 10^{-5} \text{ GeV}^{-1}$
- Impact parameter: $\sigma_{r\phi} = 5 \oplus 10 / (p \cdot \sin^2 \theta) \mu\text{m}$
- Jet energy: $\frac{\sigma_E}{E} \approx 3 - 4\%$

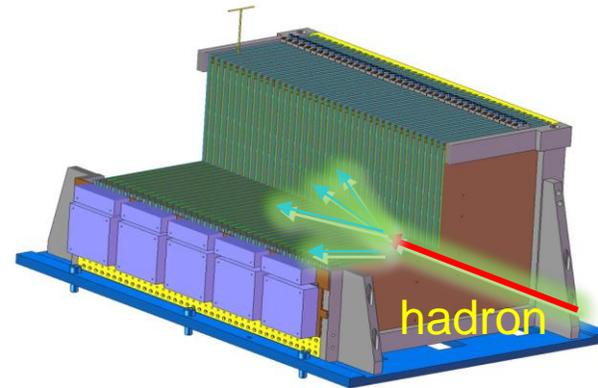
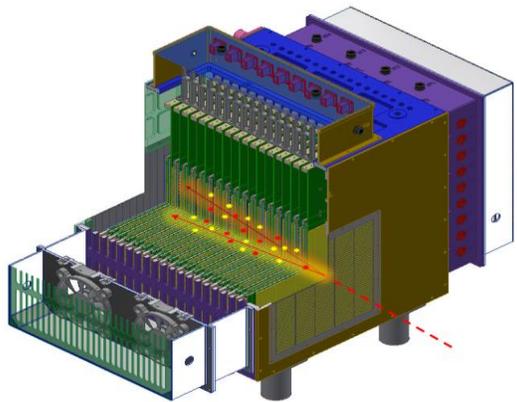


- The Particle Flow Algorithm (PFA) calorimeter concept was proposed
 - High granularity
 - Good track finding
 - Good energy resolution



高颗粒度量能器样机

Calo	Sampling No.	Sensitive detector	Absorber	Granularity	Electronics	Absorb length	Energy Resolution	weight
Sci-W ECAL	32	PSD+SiPM	W-Cu	5mm×5mm	SP-2E	22 X_0	16%@ 1 GeV	0.3 T
AHCAL	40	PSD+SiPM	Fe	40mm×40mm	SP-2E	4.7 NIL	60%@ 1 GeV	5.0 T

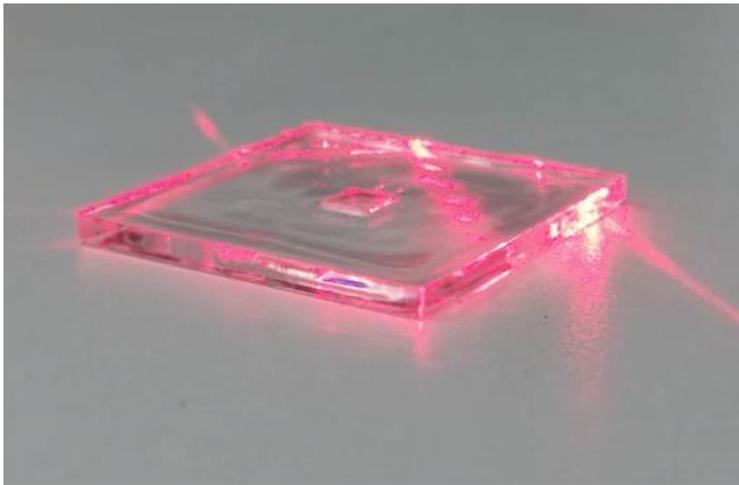


电磁量能器

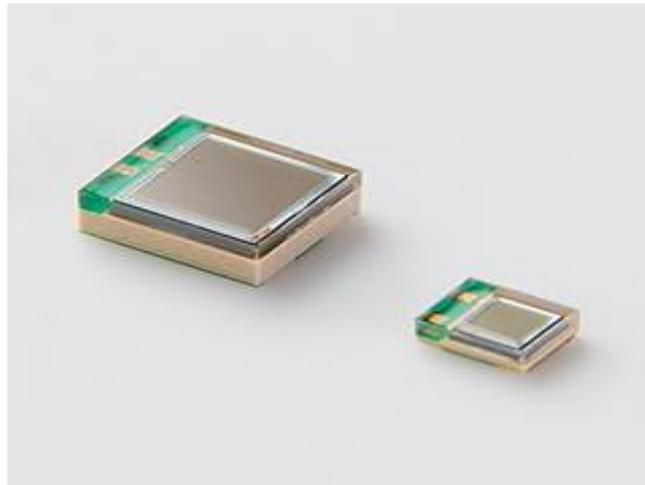
强子量能器

强子量能器单元

- 基于MC模拟优化探测器单元尺寸、确定读出动态范围等
 - 塑料闪烁体尺寸: 40 mm × 40 mm × 3 mm
 - SiPM: 像素尺寸为15 μm, 共~7300像素
 - 电子学芯片: SPIROC, 36 channels/chip, 30fC - 300 pC



塑料闪烁体单元



SiPM (1.3mm×1.3mm)



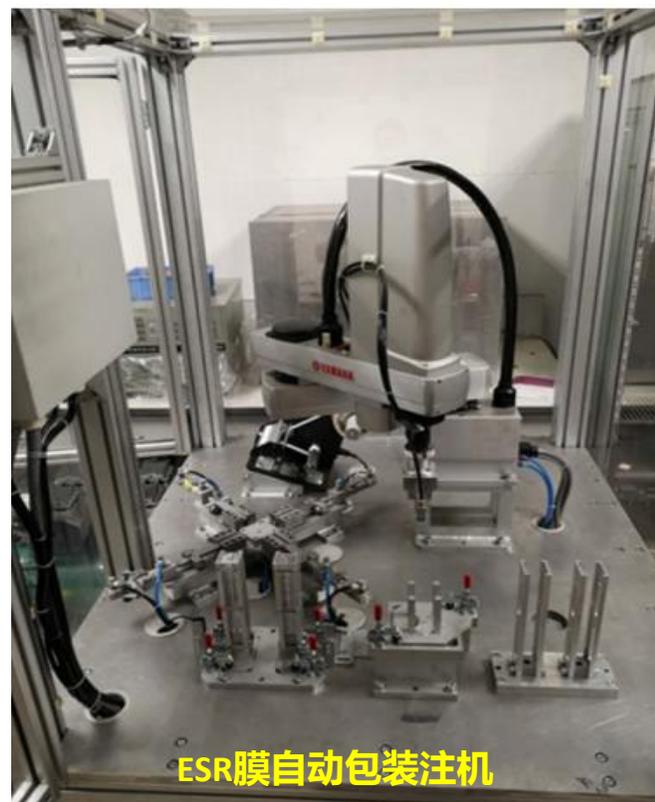
SPIROC chip



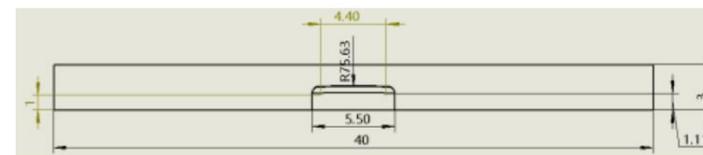
塑料闪烁体单元

闪烁体制作

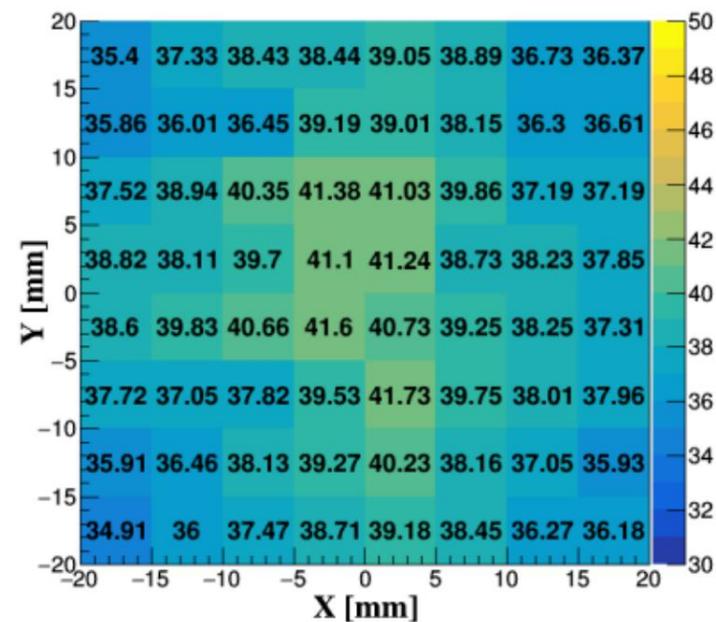
- 注塑工艺生产
- ESR反射膜由机器自动包装



闪烁体单元的光输出均匀性~4%



(a)

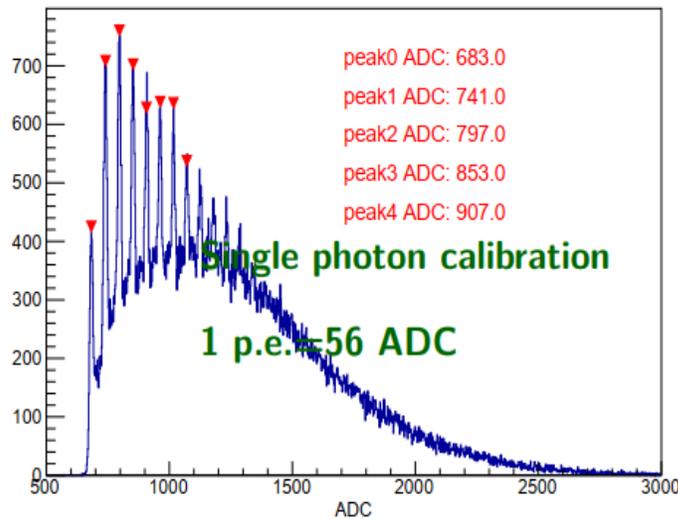


闪烁体单元性能批量测试

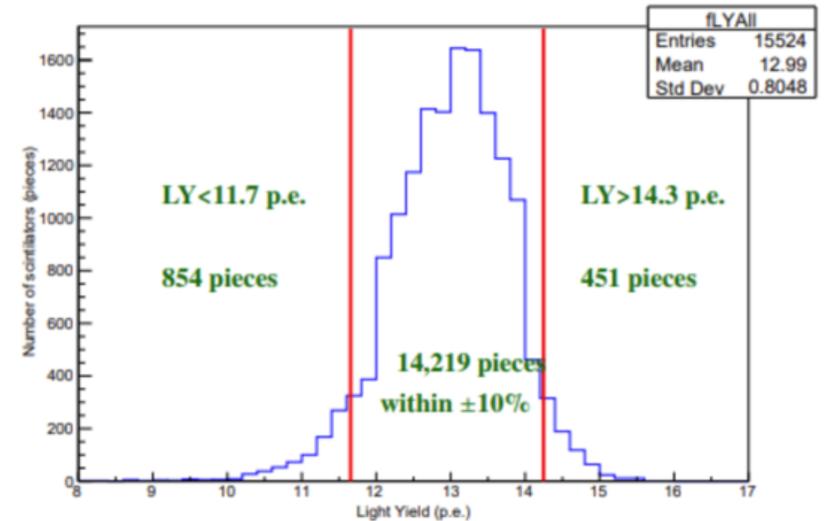
- ◆ All packaged scintillator tiles were tested for quality control. A batch test system was developed for this purpose.
- ◆ The average light yield was about 13 pe/MIPs. Only tiles with light yield within an acceptance region were used for the prototype: acceptance ratio ~ 92%



闪烁体光产额批量测试系统



单个闪烁体单元MIP谱



闪烁体单元光产额分布



SiPM选型

◆ Two types of SiPMs were selected for this prototype

◆ NDL for 2 layers

◆ HAMAMATSU for 38 layers

Company	NDL	HPK
Type	22-15	S14160-1315PS
Sensitive area (mm ²)	1.6*4	1.69
PDE (%)	40	32
Gain (*10 ⁵)	2.4	3.6
Pixel No.	7400*4	7284
Breakdown Voltage (V)	19	38
OverVoltage (V)	4	4
Dark Count (kHz)	330*4	120
Cross Talk (%)	8.5	1.0

HPK S14160-1315PS

- 光产额适中
- 像素数足够
- 串扰率极低
- 应用于AHCAL样机前38层

EQR15-22-1313D-S

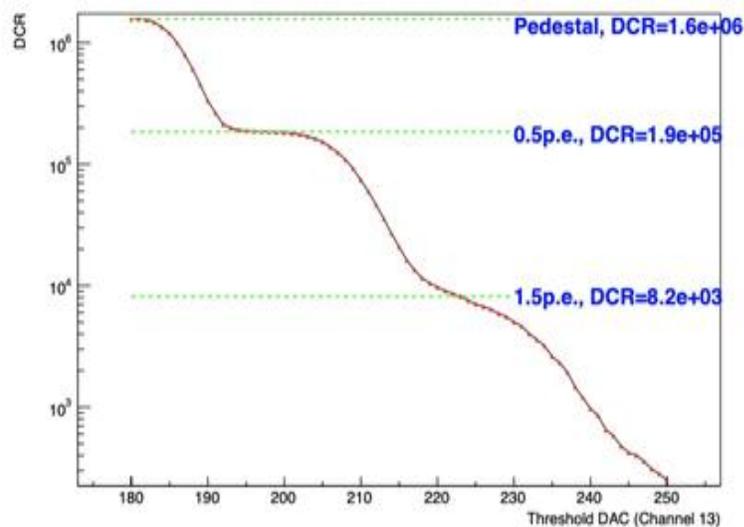
- 光产额高
- 像素数足够
- 串扰率偏高
- 应用于AHCAL样机最后2层
- 探索SiPM器件国产化可行性

SiPM性能测试

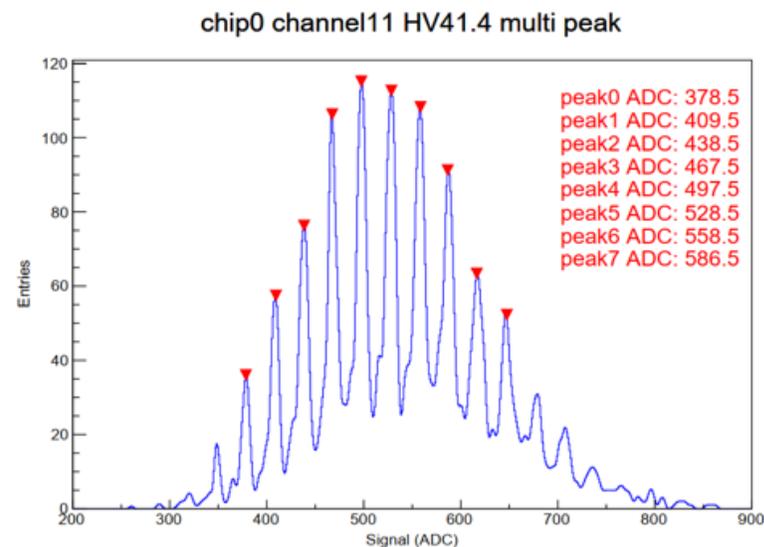
- Two SiPM batch test devices were developed for NDL SiPM and HPK SiPM
- A random sample of SiPMs was tested and found to be to specifications



测试装置



暗计数率

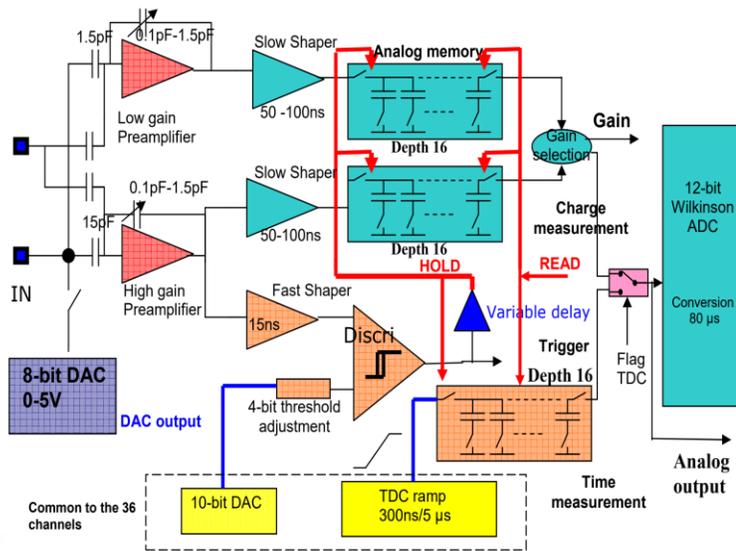


光电子谱



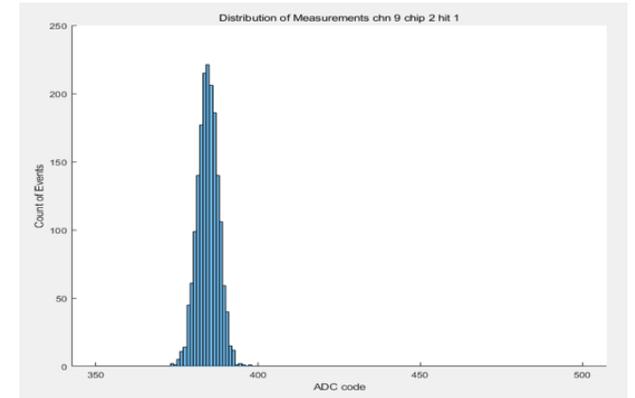
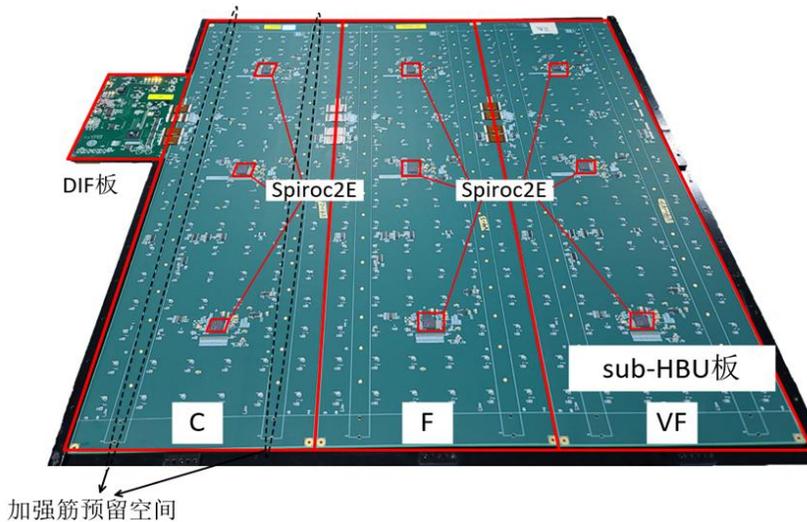
• SPIROC芯片

- 36 模拟回路+1 ADC
- 高低双增益
- 功耗: 6 mW/channel
- 时间窗: 4 μ s



• HCAL Board Unit(HBU)

- 信号读出
 - 9 SPIROC + 324 灵敏单元
- 监测刻度
 - 324 LED + 48 温度芯片



台基噪声分布

闪烁体组装

◆ Developed a procedure dedicated to fitting scintillator tiles onto the HBU boards

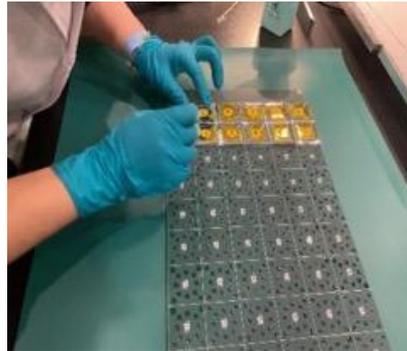
inspection



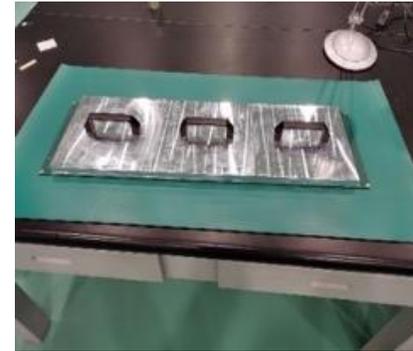
gluing



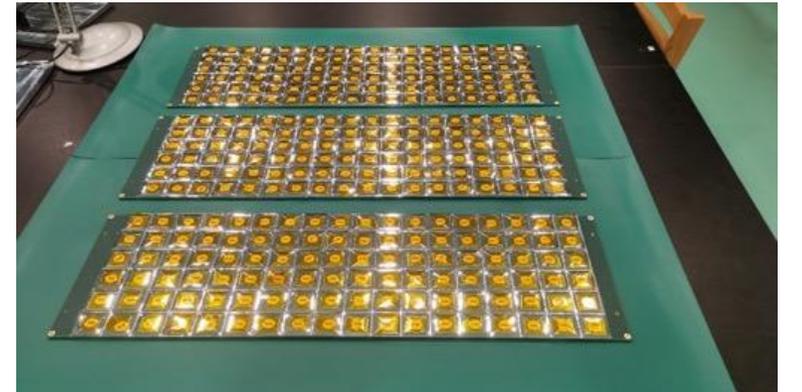
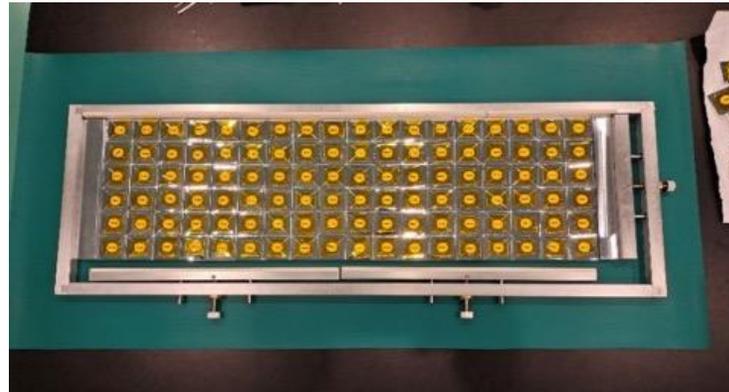
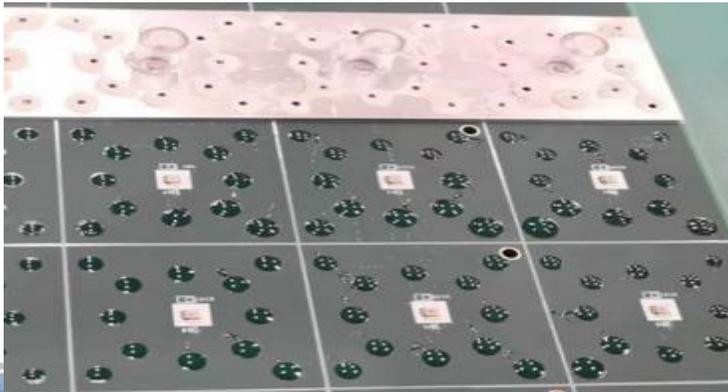
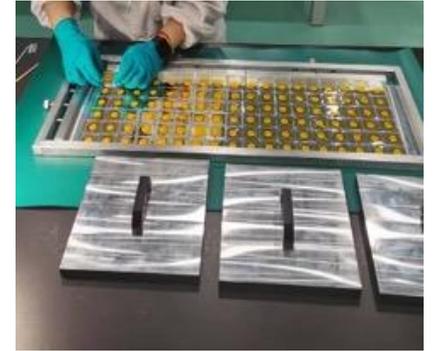
mounting



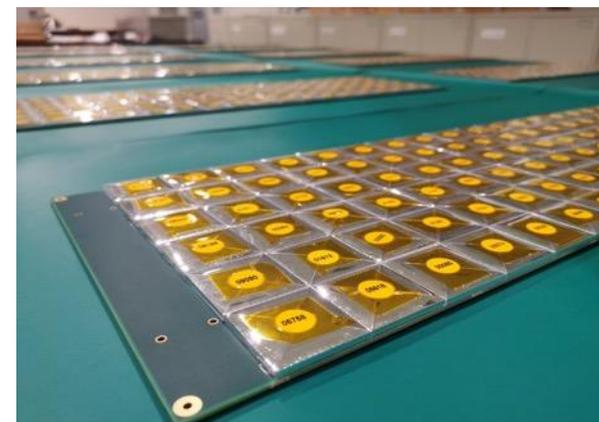
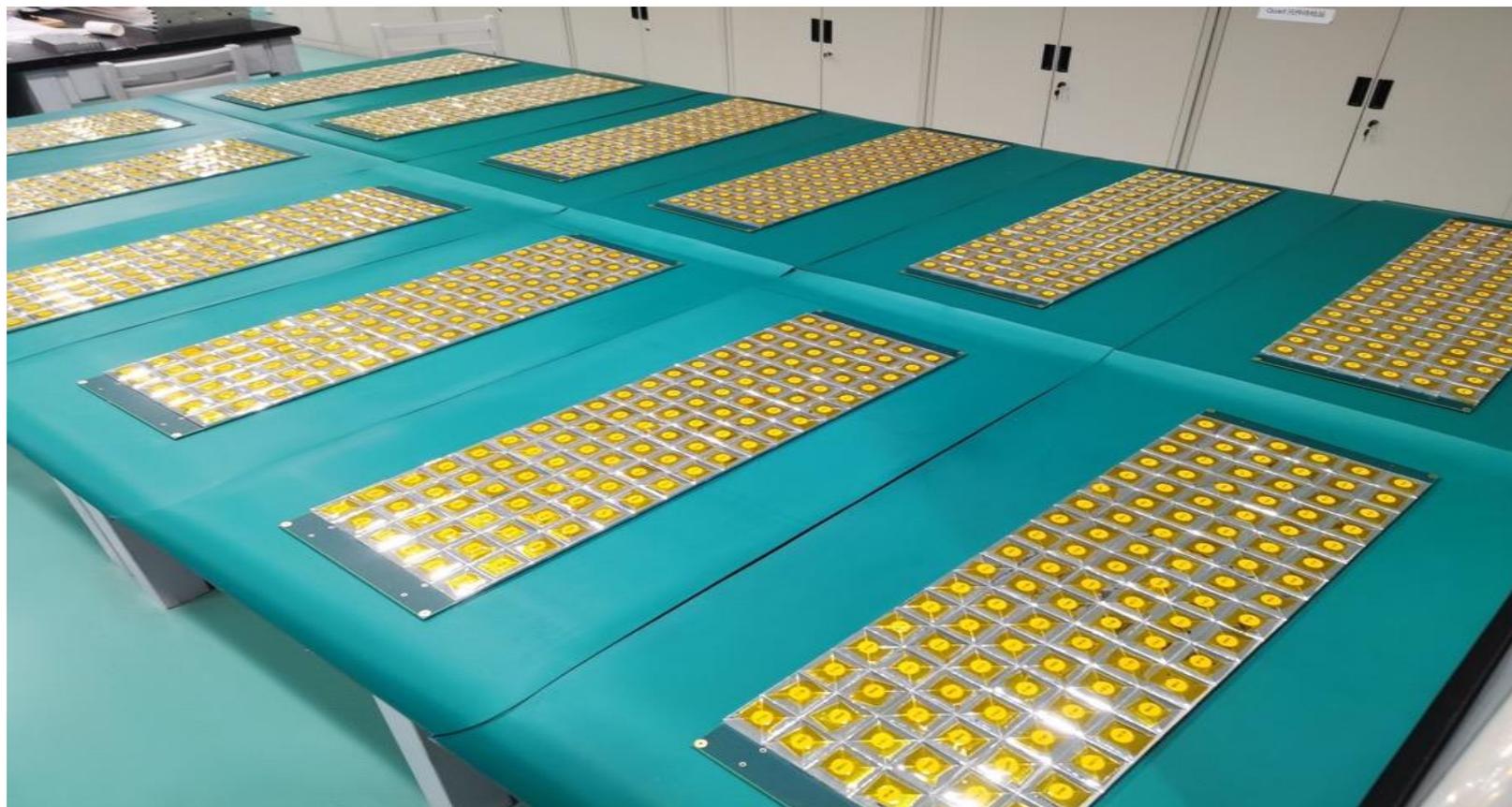
curing



inspection



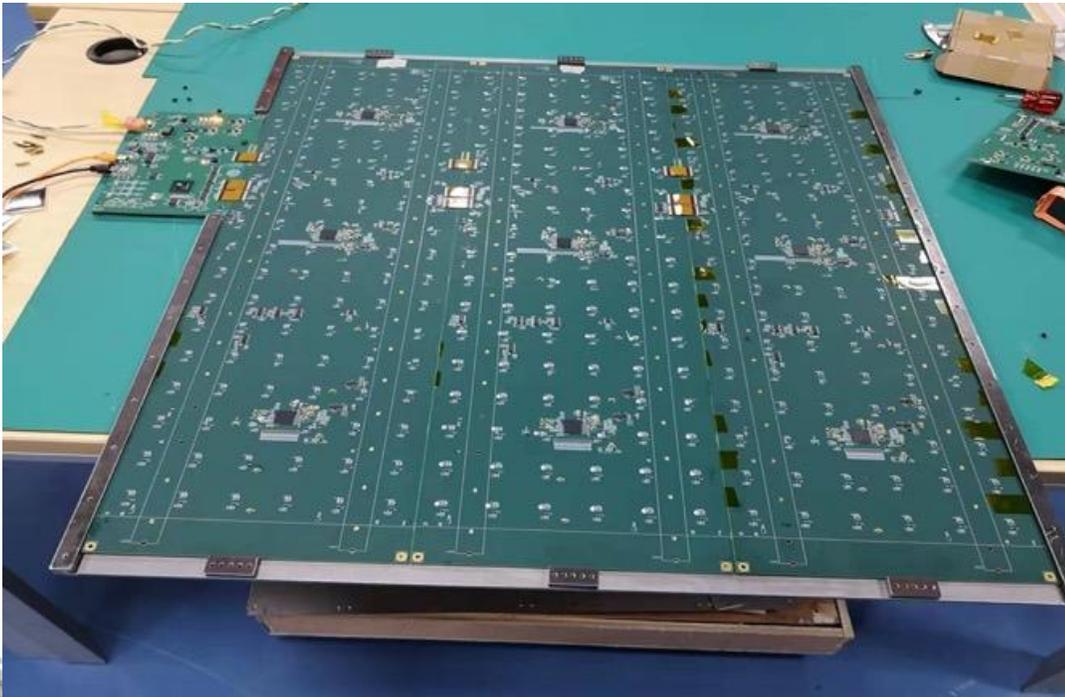
闪烁体组装



灵敏层组装

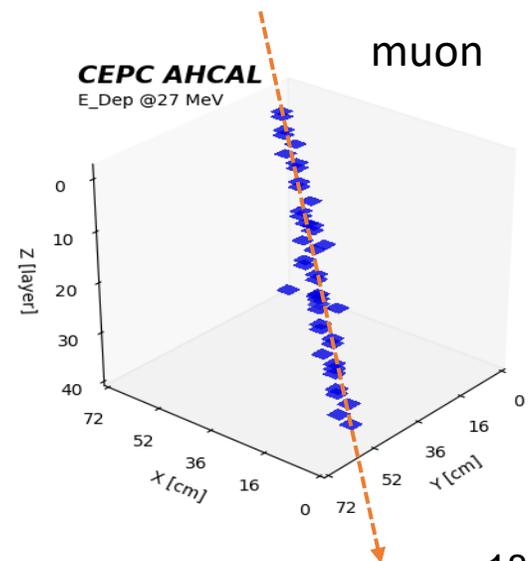
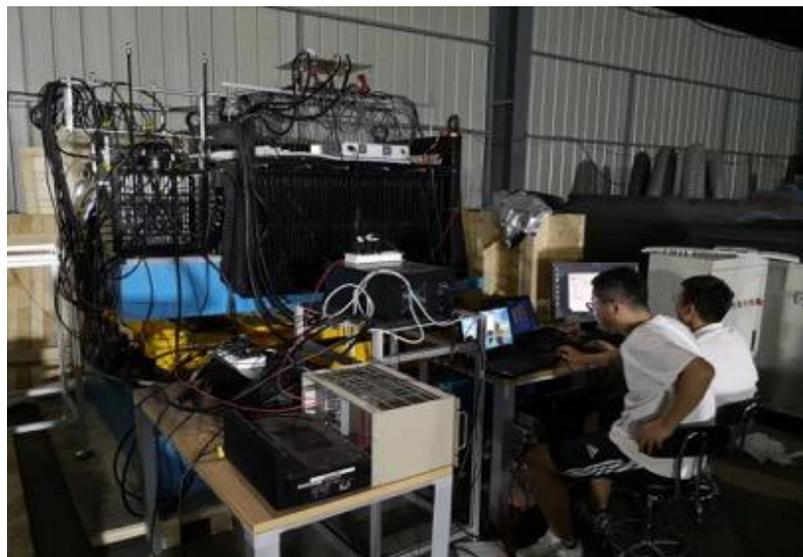
◆ Fitting a HBU into a cassette

- ◆ Scintillation tiles facing down and electronic components facing up
- ◆ Rubber strips were used to support the two large plates of the cassette to prevent the plates from contacting the readout chips

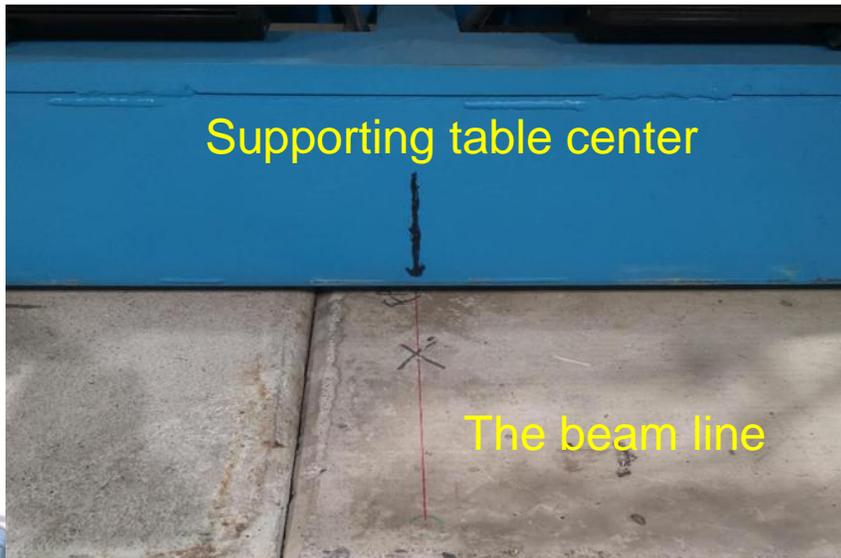
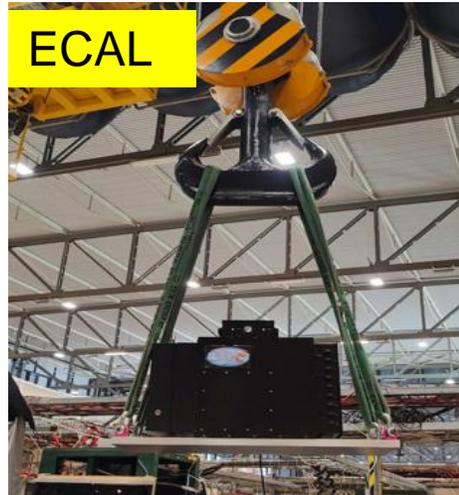


量能器组装

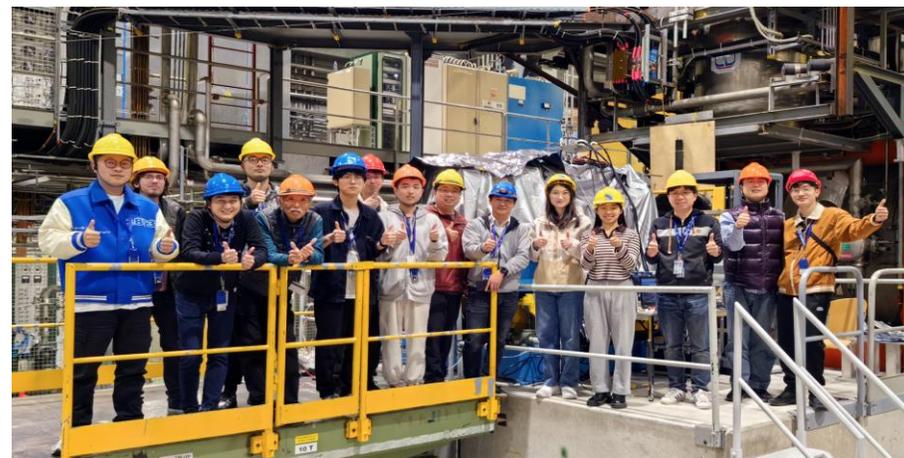
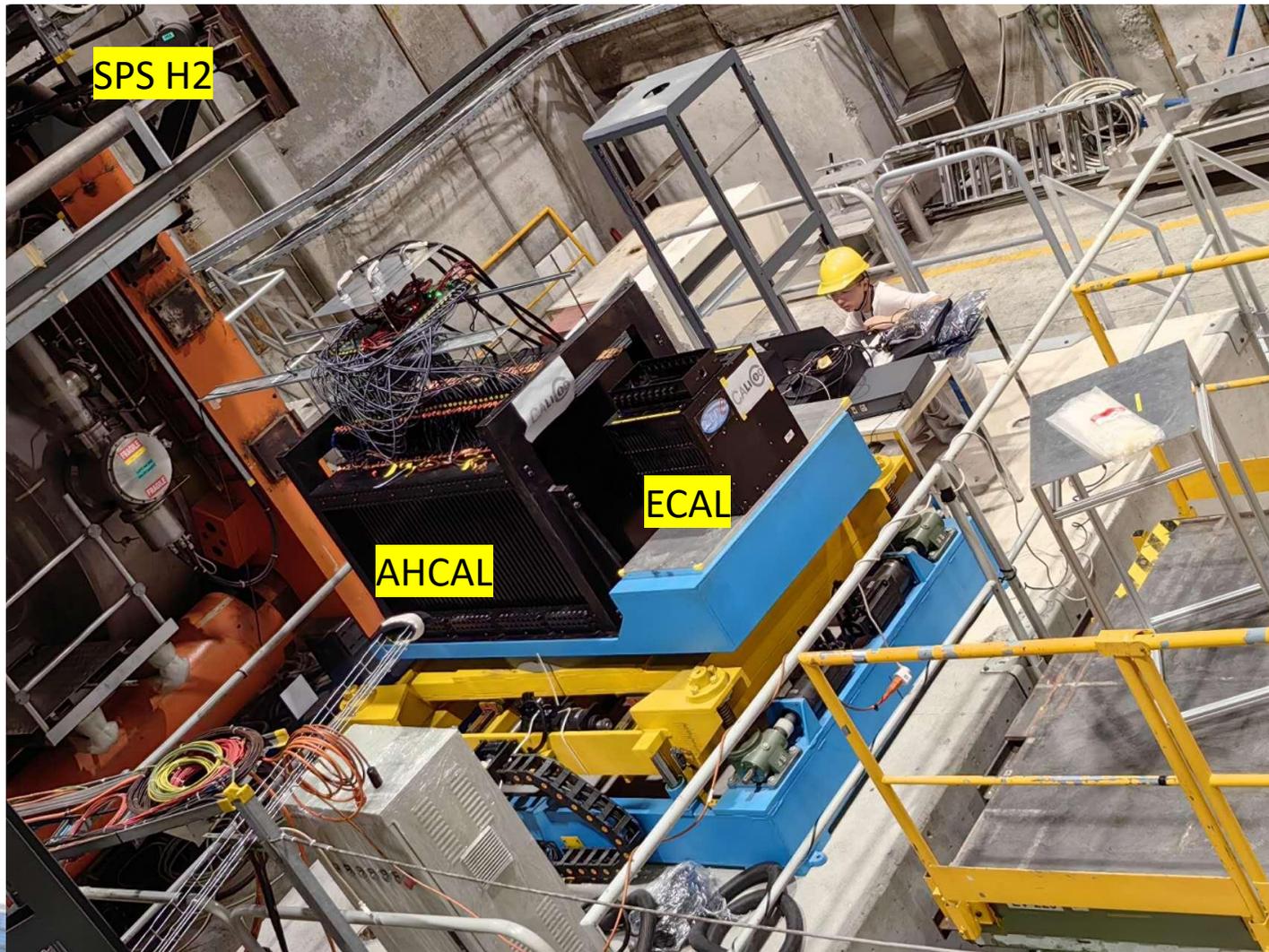
- 量能器包含40层Fe吸收体，每层16 mm厚度
- 把40层灵敏层等间隔组装到量能器结构中



束流测试



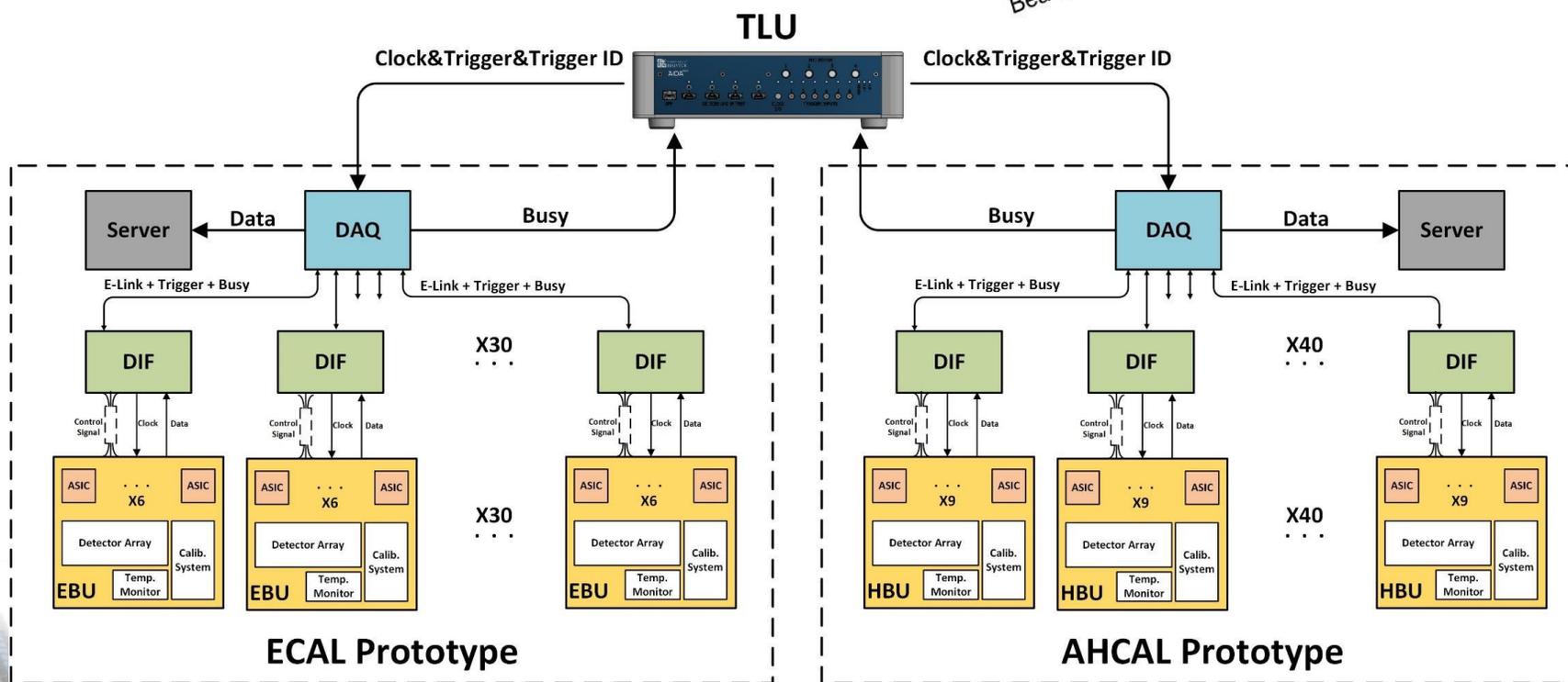
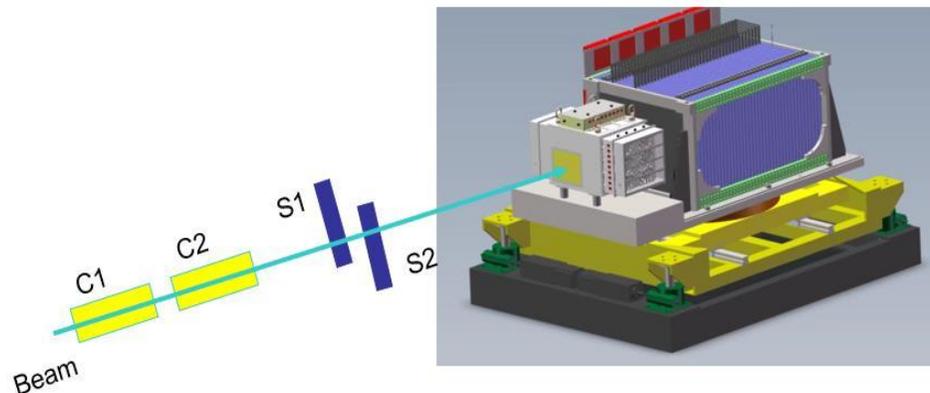
束流测试



束流测试

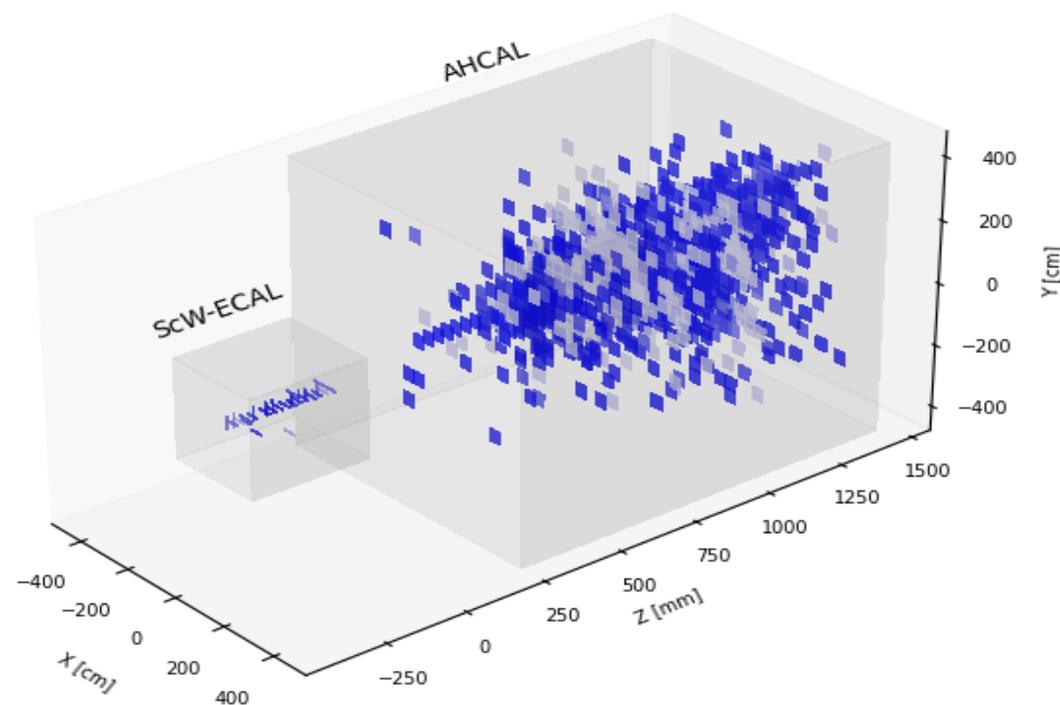
- DAQ system for ECAL and AHCAL Prototypes

- ECAL has 32 DIFs, AHCAL has 40 DIFs
- Using TLU to synchronize two systems



束流测试

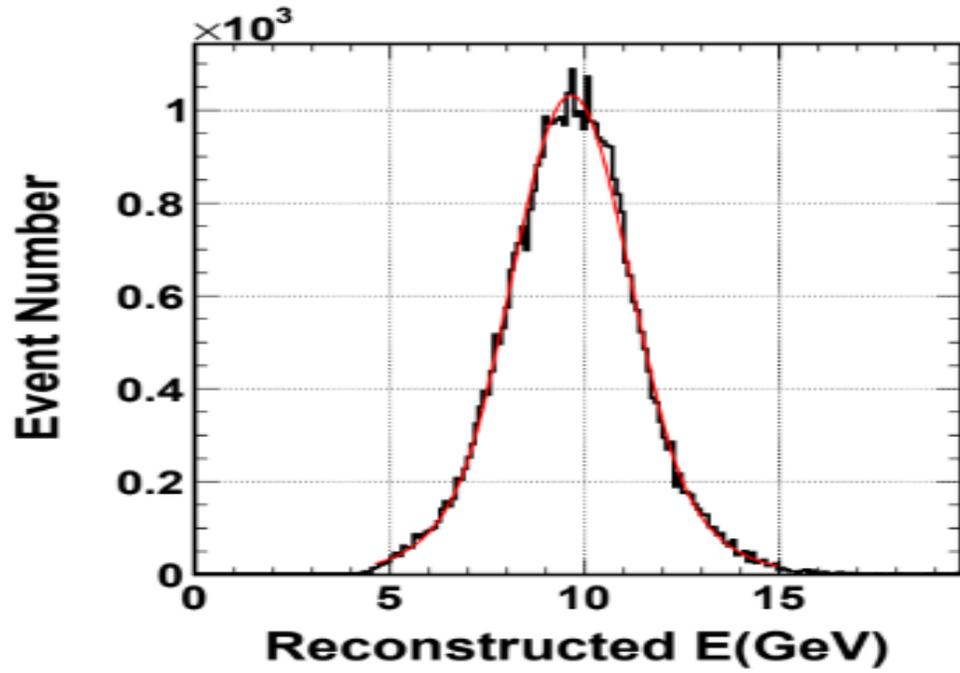
- Muon Test
 - Momentum: 100 GeV/c, 10 GeV/c
 - 11 million
- Pion- test
 - 1 – 120 GeV/c, 350 GeV/c
 - 50 million
- Electron Test
 - 1 – 250 GeV/c
 - 10 million
- Proton, 350 GeV/c
 - 1 million



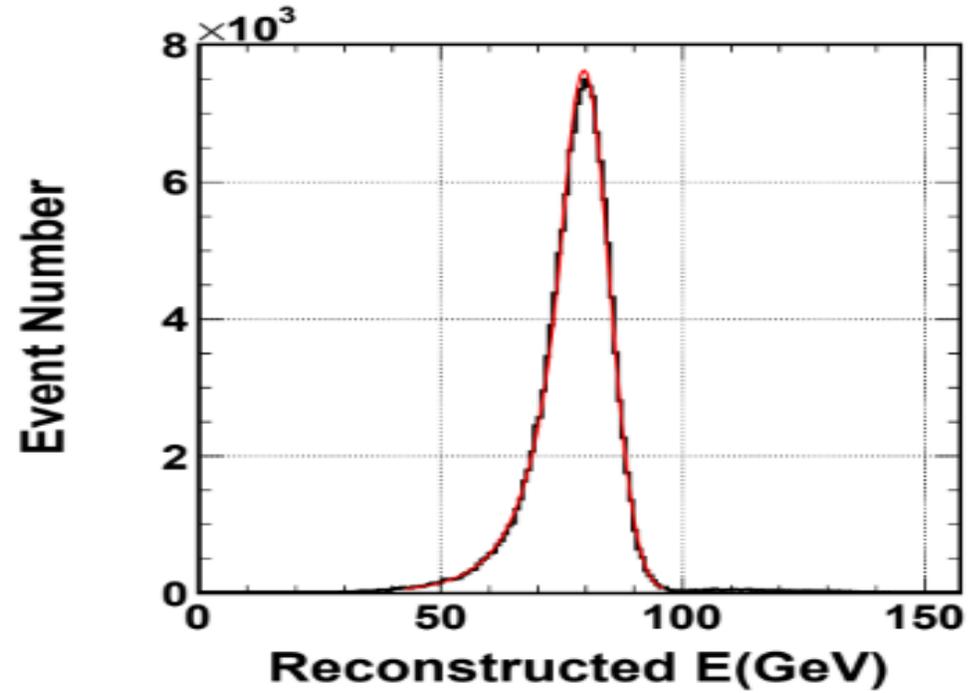
束流事例显示



AHCAL对强子的能量响应



10 GeV pion

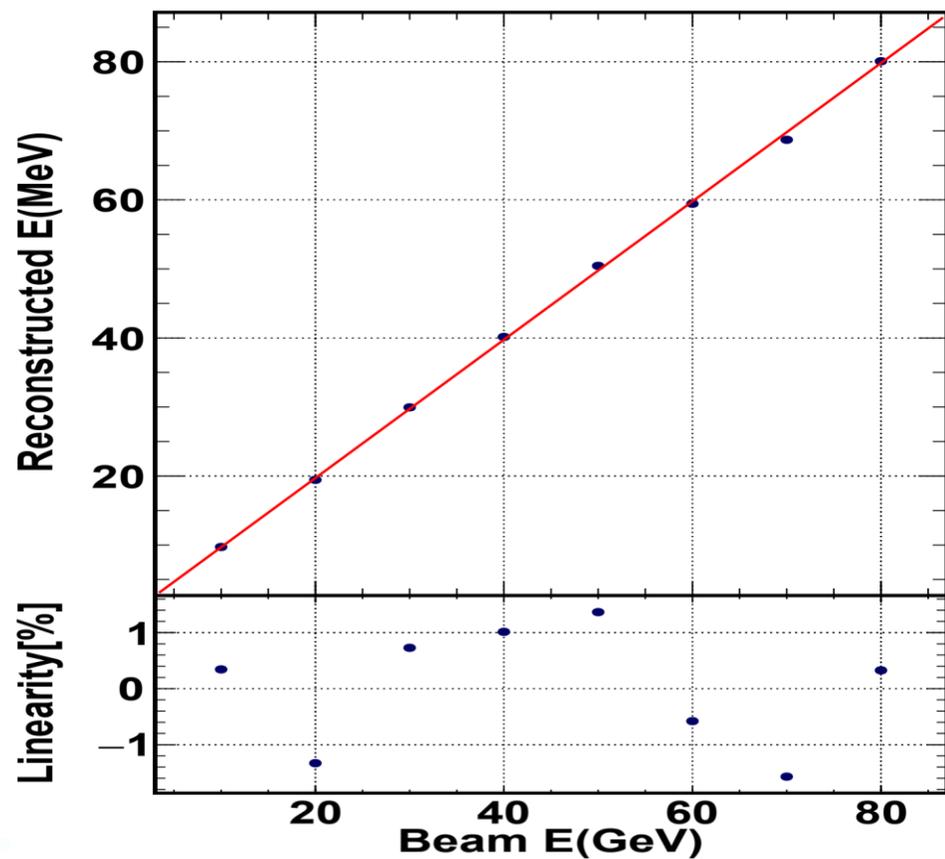


80 GeV pion

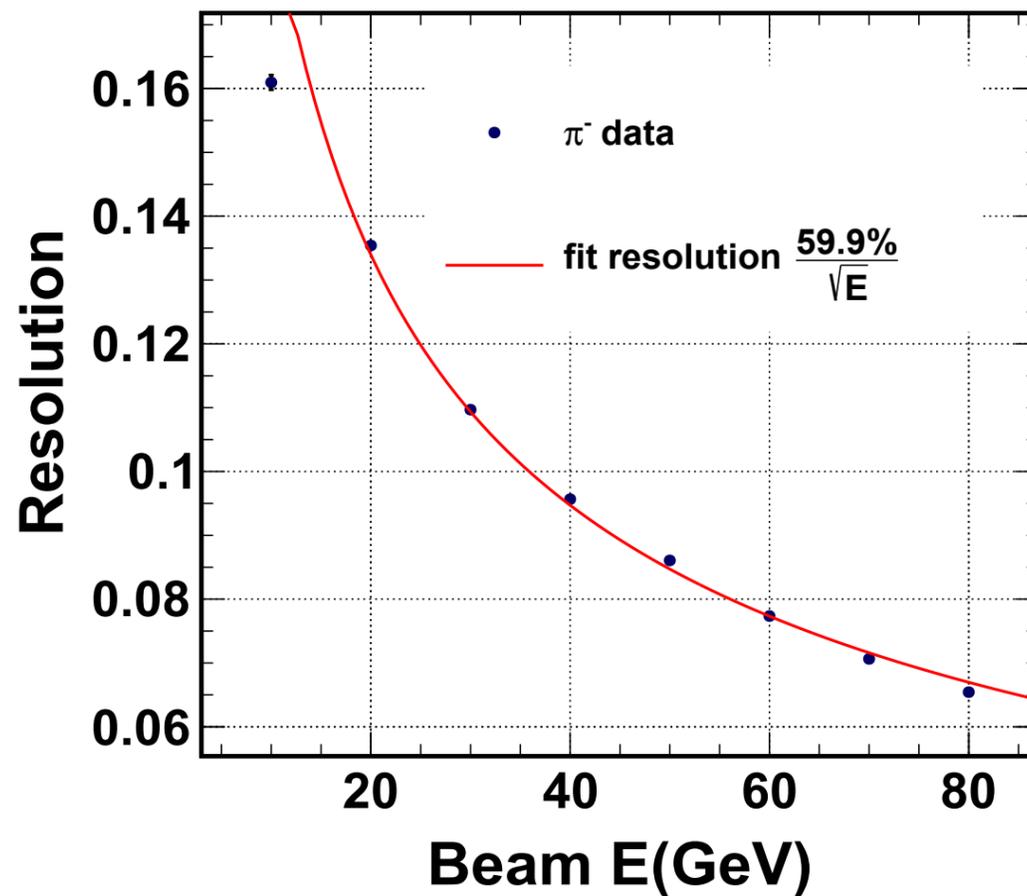


AHCAL对强子的能量响应

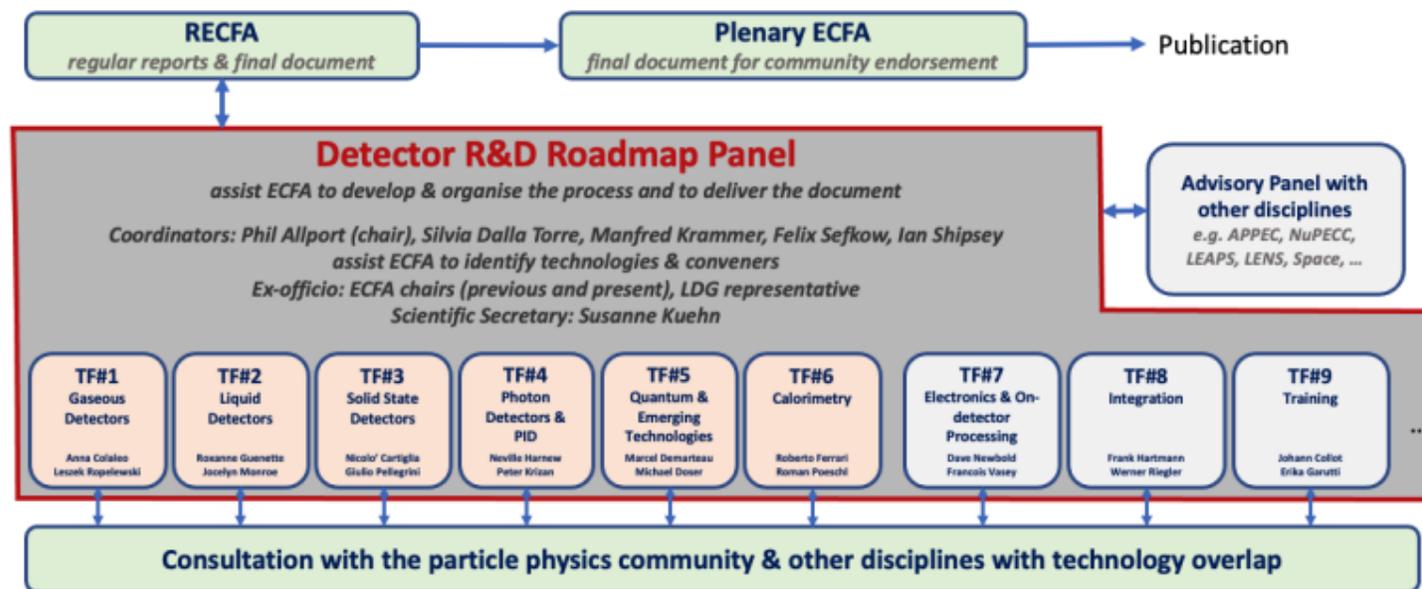
能量线性



能量分辨



量能器技术前沿



先进量能器技术

方向1:
读出电子学全嵌入式
“三明治”结构量能器

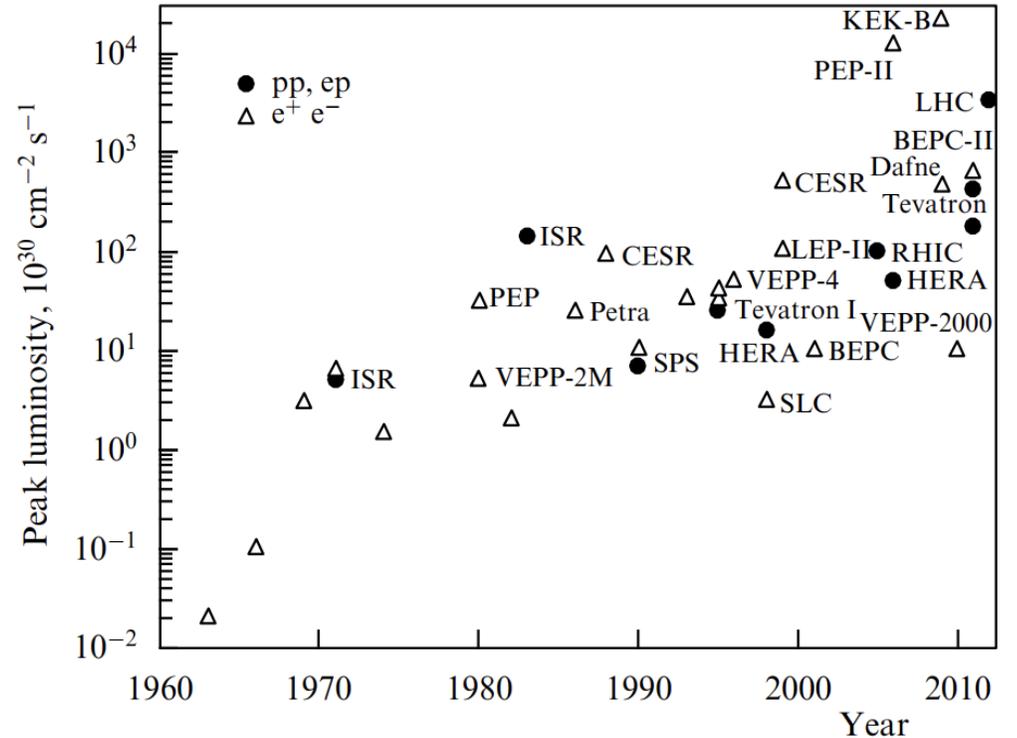
方向2:
液化惰性气体量能器

方向3:
闪烁体量能器



高亮度前沿对量能器的需求

- 高亮度实验是粒子物理发展的一个重要方向
 - 高的物理事例率
 - 极高的本底事例率
 - 事例堆积、辐照剂量
- 这对量能器提出了**新的需求与挑战**
 - 在极高的（本底）事例率下实现高精度测量
 - MHz?
 - 量能器的抗辐射能力
 - 百 kRad?

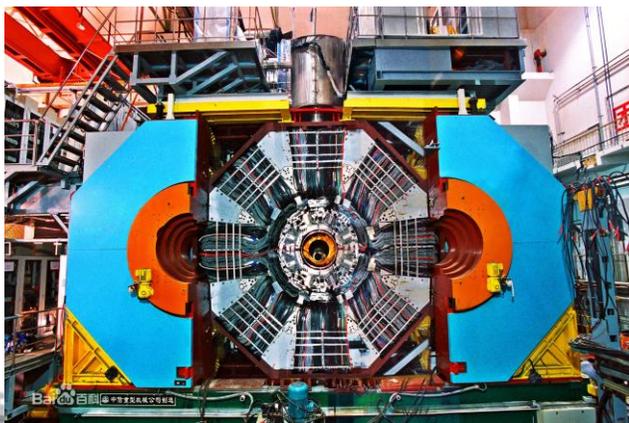


晶体量能器

- 晶体量能器能量分辨好、抗辐射性能优
- 是粒子物理实验电磁量能器的重要选择之一

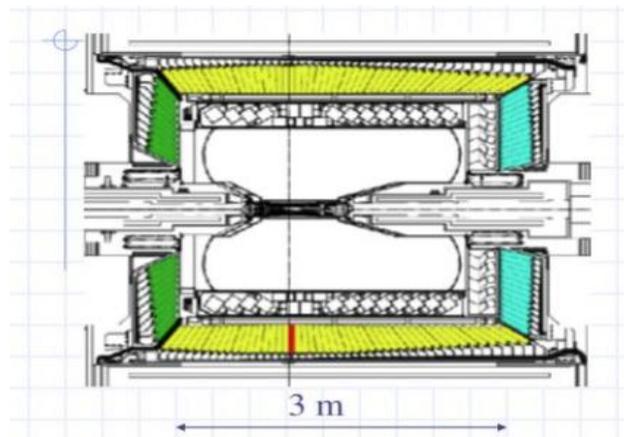
- BESIII 量能器

- CsI(Tl)全吸收型
- 能区: 20 MeV – 2 GeV
- 能量分辨: 优于2.5% @ 1 GeV
- 位置分辨: 6 mm @ 1 GeV



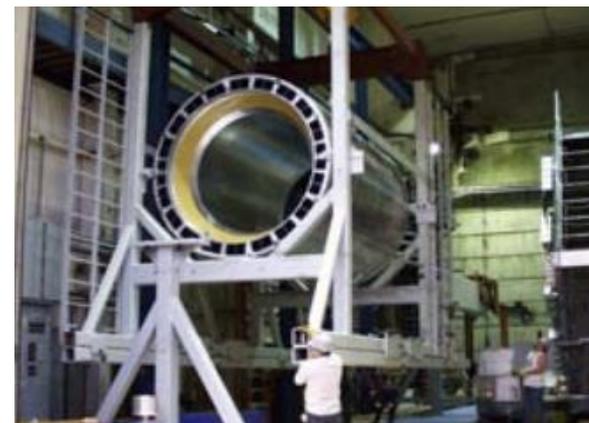
- BELLE 量能器

- CsI(Tl)全吸收型
- 能区: 20 MeV – 8 GeV
- 能量分辨: 优于2% @ 1 GeV
- 位置分辨: 6 mm @ 1 GeV



- Babar 量能器

- CsI(Tl)全吸收型
- 能区: 15 MeV – 8 GeV
- 能量分辨: 优于3% @ 1 GeV
- 角分辨: 4.16 mrad @ 1 GeV



下一代高亮度实验晶体量能器的选择

- 下一代晶体量能器
 - 要求晶体具有更快的发光衰减时间
 - 更高的抗辐照能力

Crystal	Pure Csl	LYSO	GSO	YAP	PWO	BaF:Y
Density (g/cm ³)	4.51	7.40	6.71	5.37	8.30	4.89
Melting Point (°C)	621	2050	1950	1872	1123	1280
Radiation Length (cm)	1.86	1.14	1.38	2.70	0.89	2.03
Moliere Radius (cm)	3.57	2.07	2.23	4.50	2.00	3.10
Refractive index	1.95	1.82	1.85	1.95	2.20	1.50
Hygroscopicity	Slight	No	No	No	No	No
Luminescence (nm)	310	402	430	370	425 420	300 220
Decay time (ns)	30 6	40	60	30	30 10	600 1.2
Light yield (%)	3.6 1.1	85	20	65	0.3 0.1	1.7 4.8
Dose rate dependent	No	No	TBA	TBA	Yes	No
D(LY)/dT (%/°C)	-1.4	-0.2	-0.4	TBA	-2.5	TBA
Experiment	KTeV Mu2e				CMS ALICE PANDA	
单价	0.5	4	-	-	1 (参考)	1.3

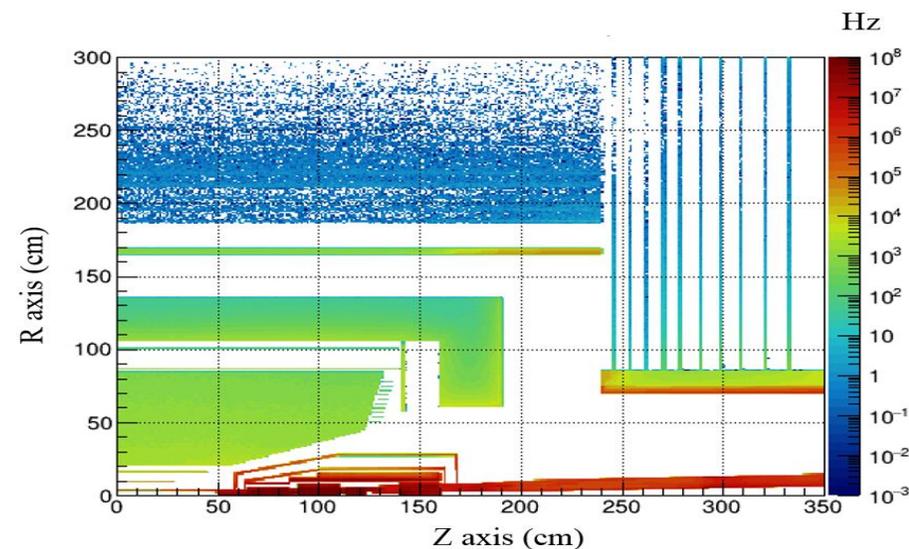
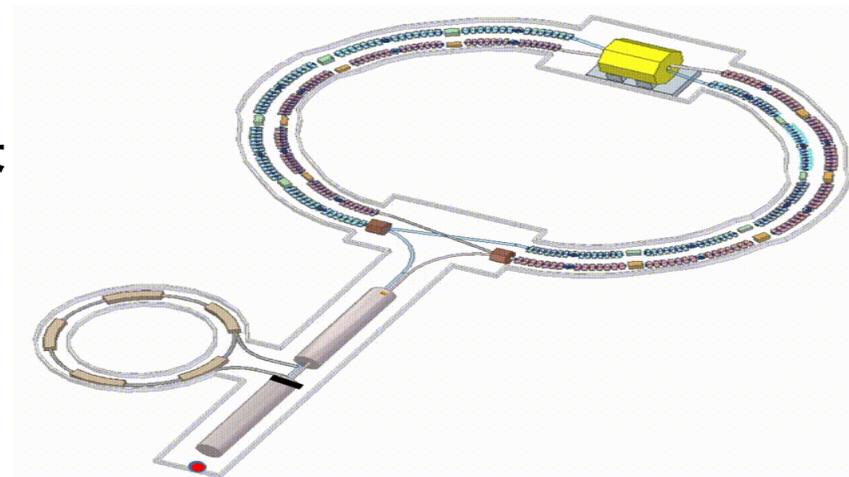


超级陶粲装置 (STCF)

Super Tau-Charm Facility

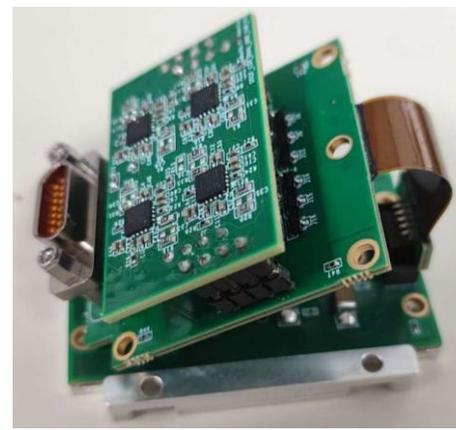
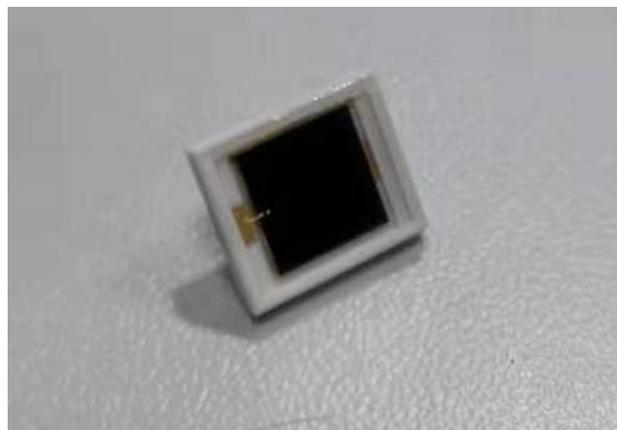
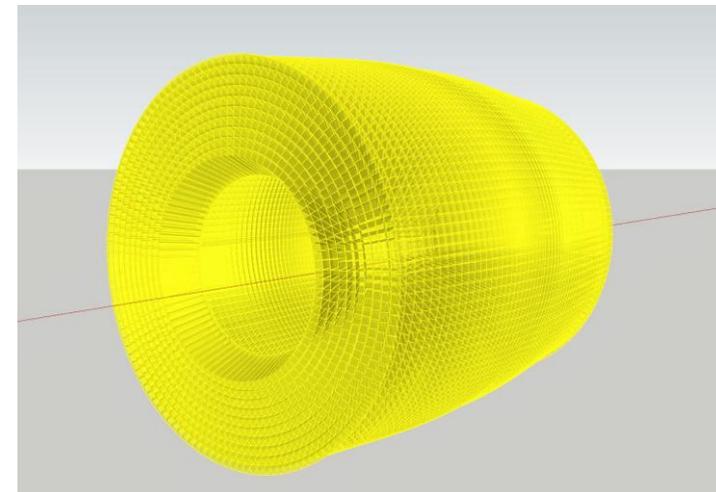
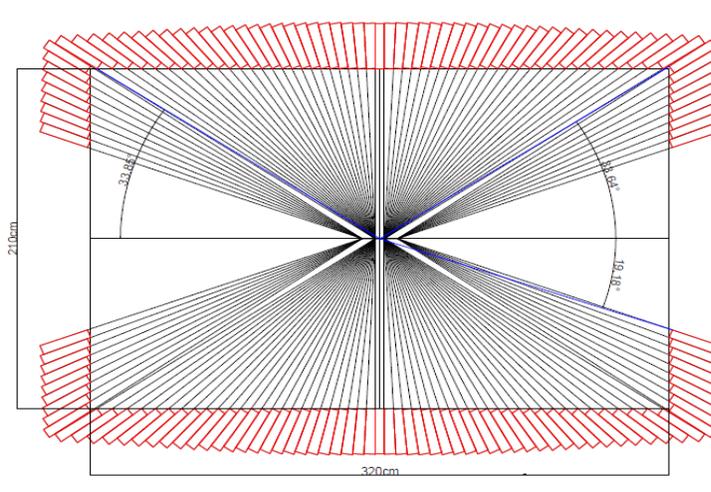
- ◆ 对称型双环对撞机： 注入器~300米， 对撞主环~800米
- ◆ 质心能量： 2-7 GeV,
亮度： $> 0.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ @ 4 GeV
- ◆ 具有进一步提升亮度和实现极化束流的潜力

- High Event Rate: ~ MHz background event rate
- Precise Energy Resolution: $< 2.5\%$ @ 1 GeV
- Good Position Resolution: ~ 5 mm @ 1 GeV
- Good Time Resolution: 300 ps @ 1 GeV



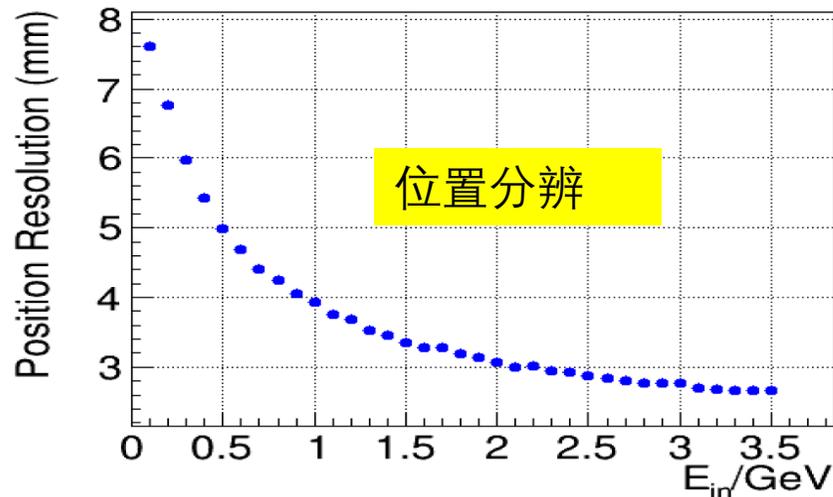
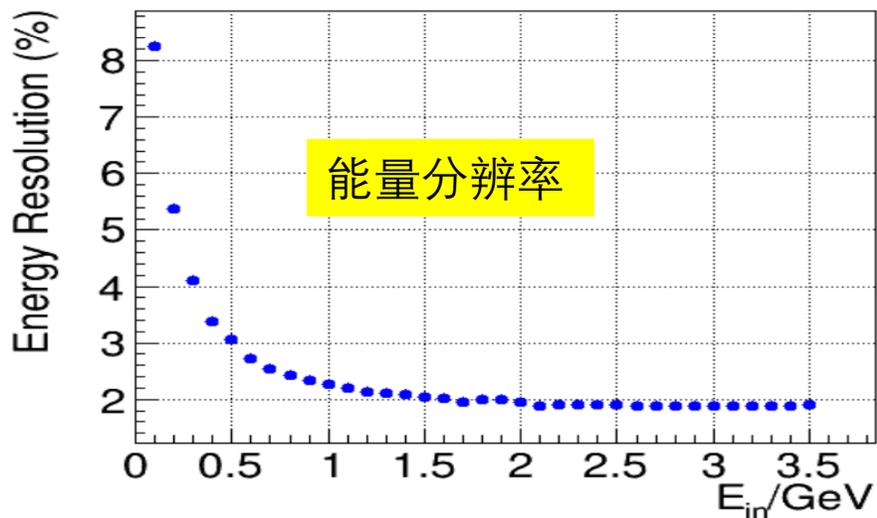
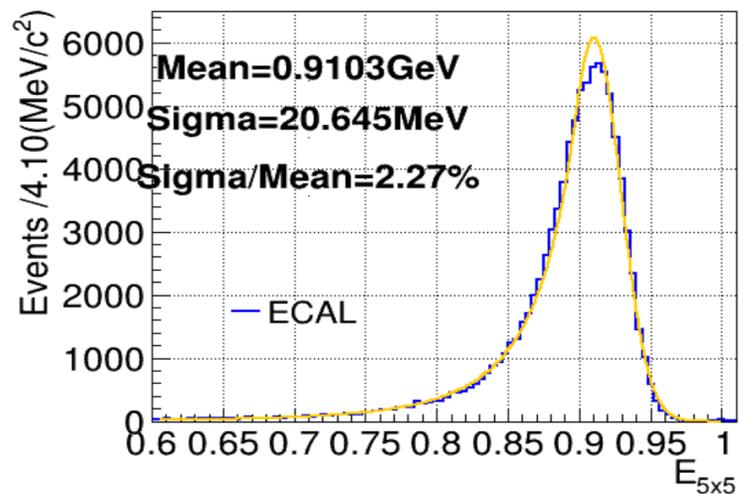
电磁量能器回顾

- 纯碘化铯晶体
 - 晶体数: 8670
- 雪崩光二极管
 - 大面积阵列拼装
- 电荷灵敏方案, 波形采样读出



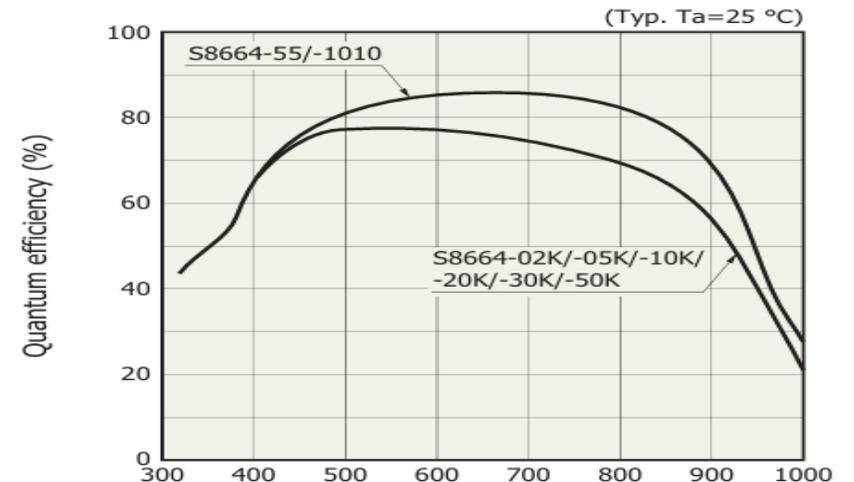
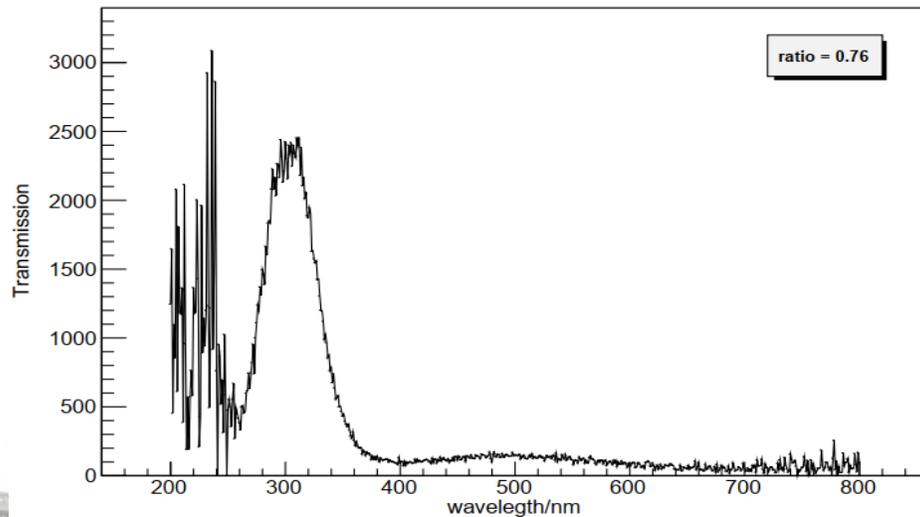
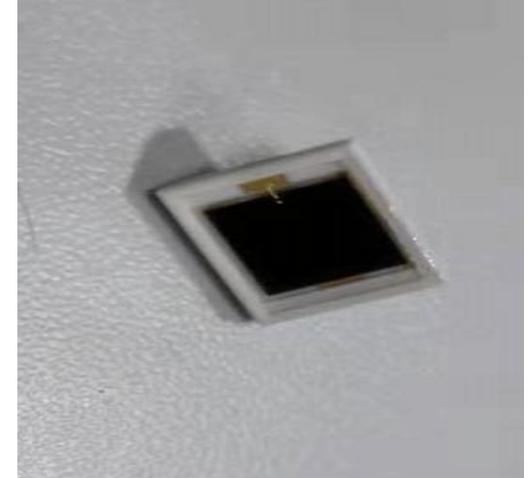
电磁量能器性能模拟研究

- 能量分辨率~2.5% @ 1 GeV
- 位置分辨~5 mm @ 1 GeV



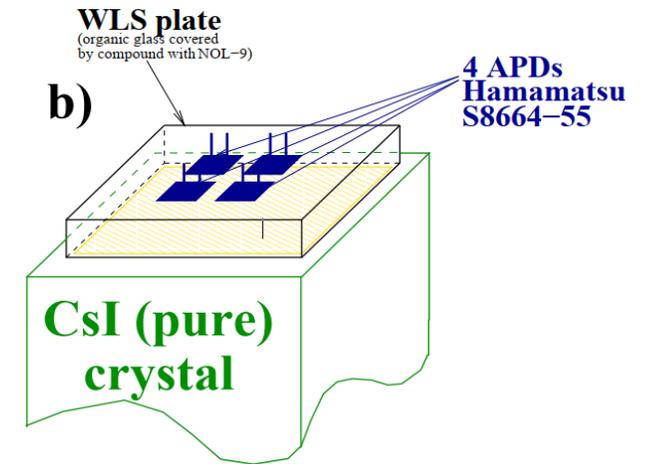
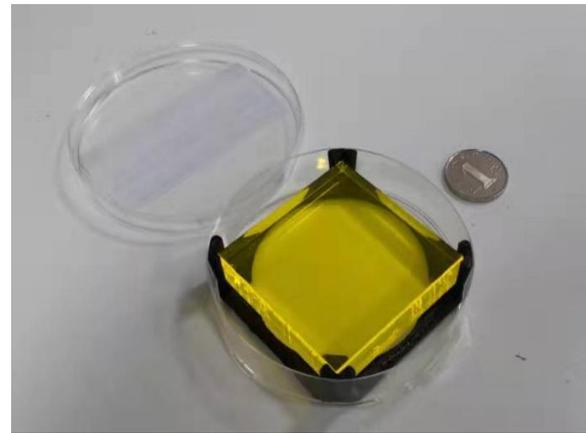
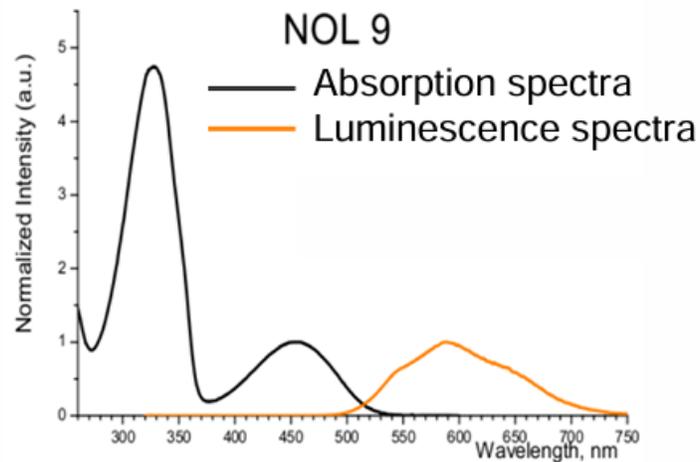
pCsI 光输出优化

- pCsI 晶体光衰减时间: 6ns (f), 30ns (s)
- 荧光产额: 1.1 (f), 3.6 (s)
- 发光波段在310 nm附近, 与常规APD的QE匹配度不好
 - QE~40%@310 nm



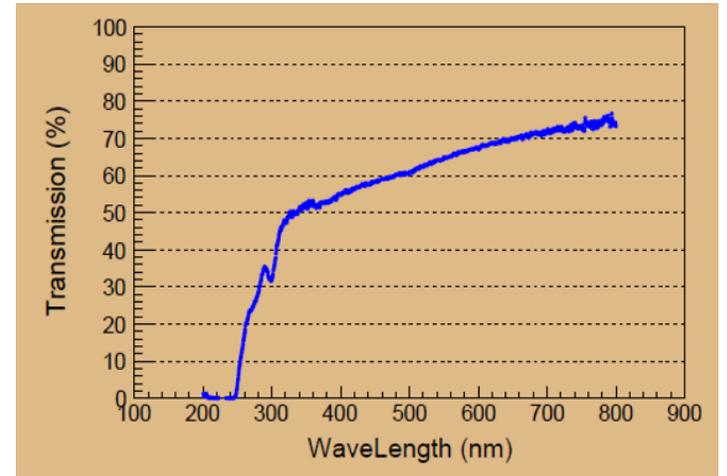
pCs | 光输出优化

- BELLE II 实验组尝试了一种新型的波长位移材料, NOL-9
- 可以把 ~ 310 nm的荧光转换到588nm, 与APD更好匹配, 取得了很好的效果
- 光产额提高到 ~ 100 pe/MeV

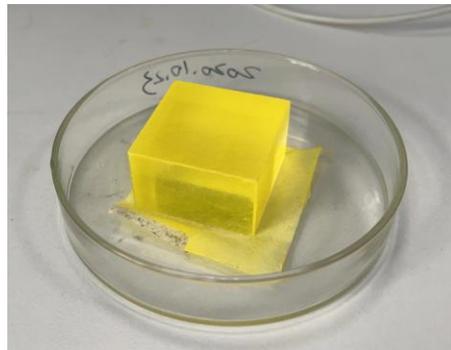
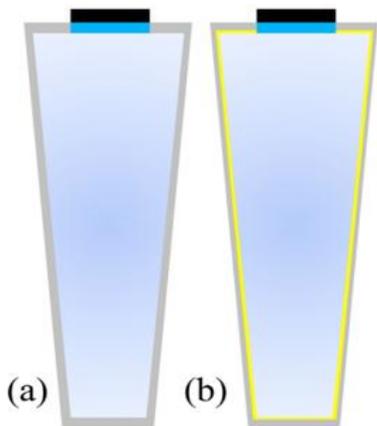


新的尝试

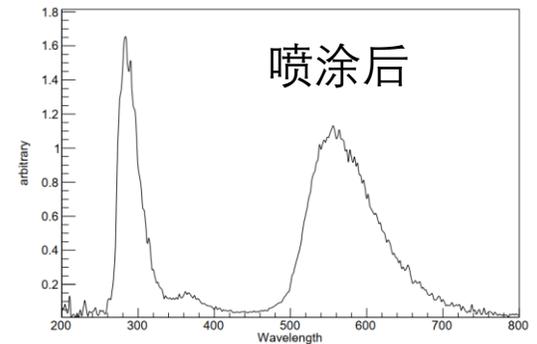
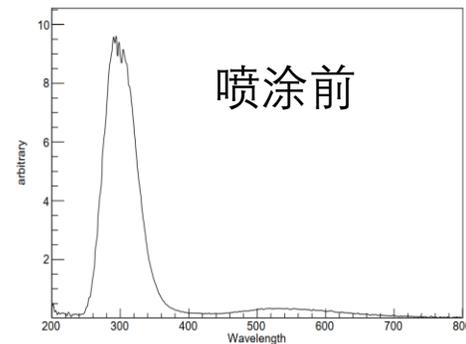
- 对于大尺寸晶体，晶体的荧光**自吸收效应**不能忽略
 - ~30%@310nm
 - ~70%@600nm
- 可以把晶体表面喷涂NOL波长位移材料，在荧光光子第一次与晶体表面作用时就被转换
 - 模拟结果显示，光产额可以提高近2倍



28cm长pCsl晶体荧光传输效率



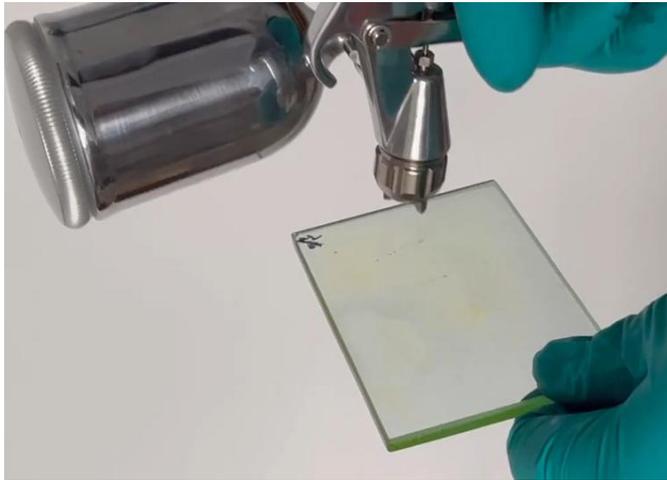
pCsl喷涂尝试



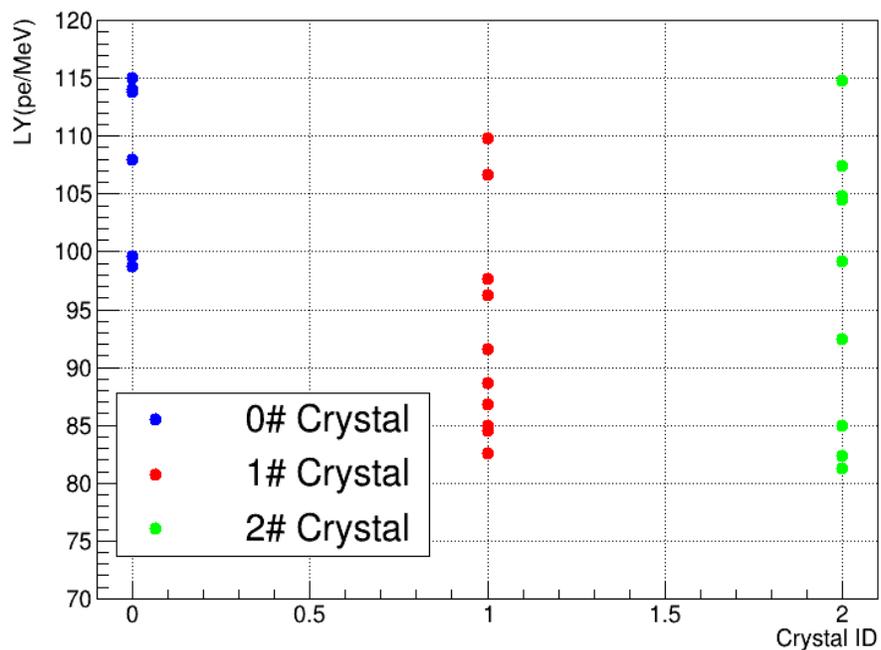
长波段光子大量增加

pCsl晶体喷涂

- 利用喷枪摸索喷涂工艺
- 把WLS材料喷涂在晶体表面
 - 玻璃、小晶体、大晶体



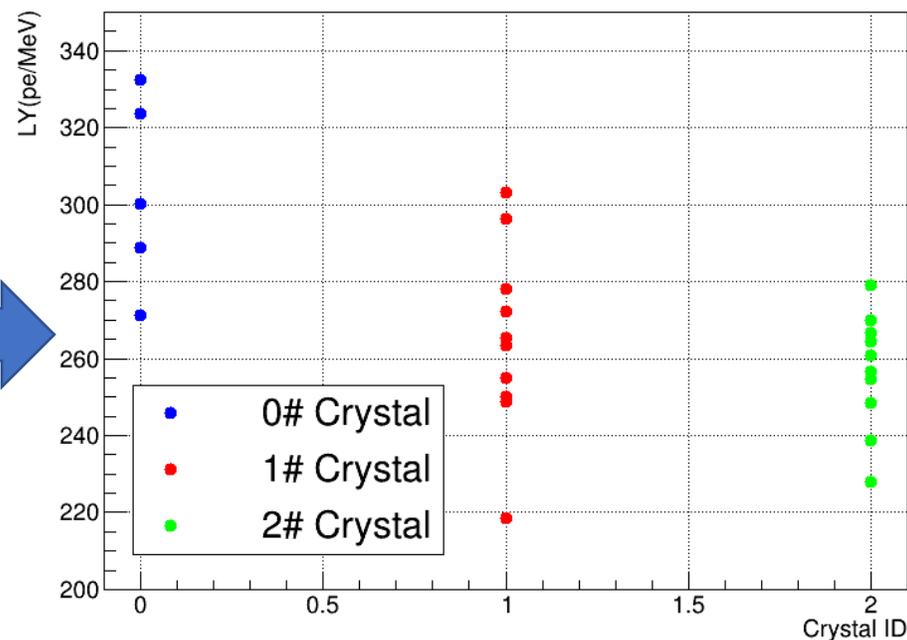
pCsI晶体荧光输出产额



喷涂WLS前

0#型号晶体平均光产额: 108.2 pe/MeV
1#型号晶体平均光产额: 92.4 pe/MeV
2#型号晶体平均光产额: 98.7 pe/MeV

喷涂
前后



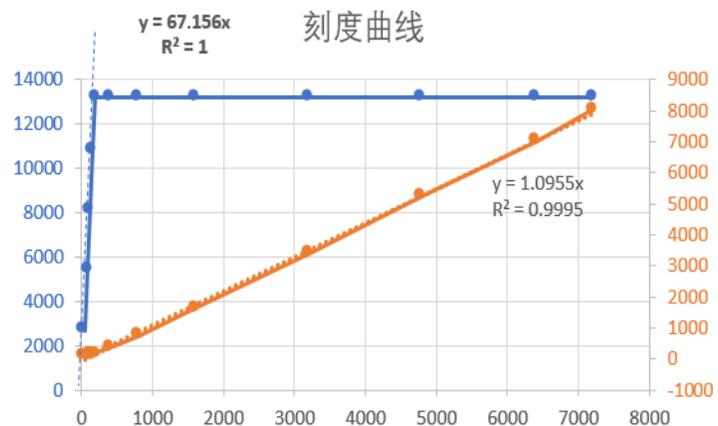
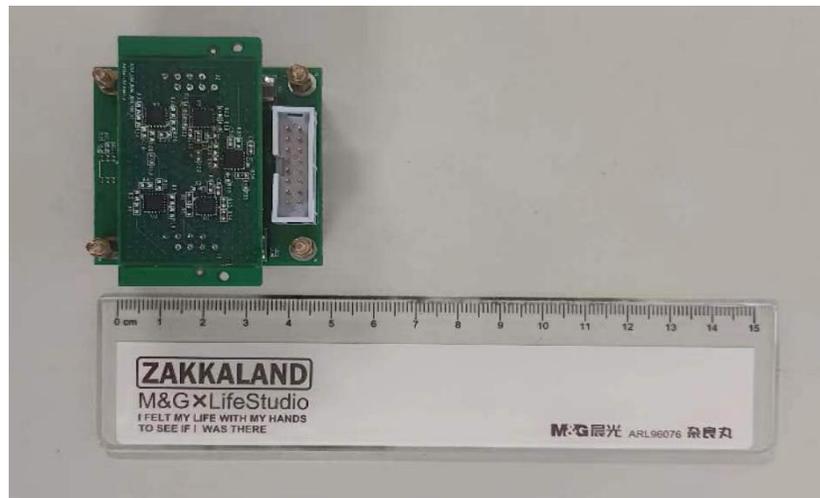
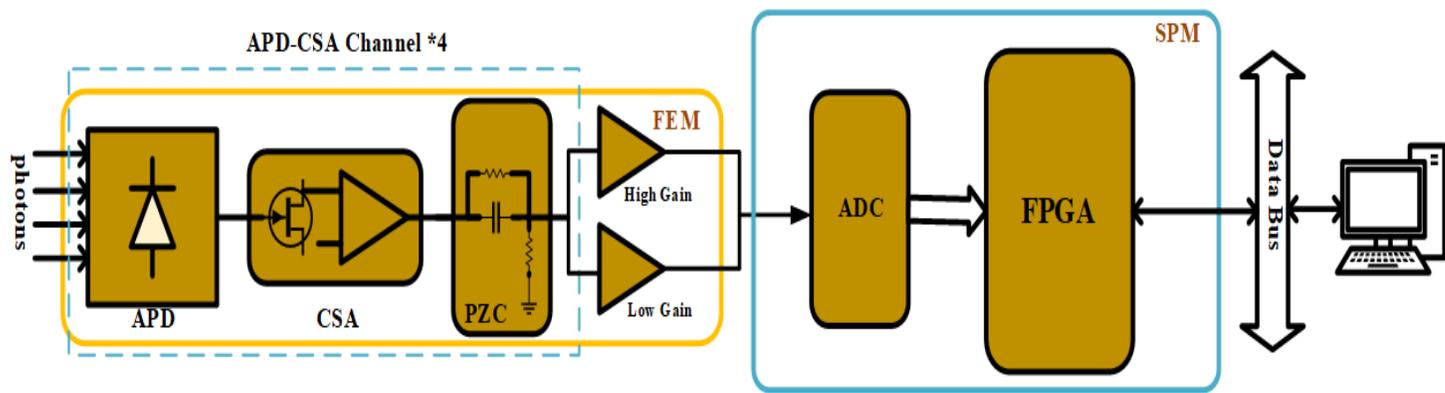
喷涂WLS后

0#型号晶体平均光产额: 302.8 pe/MeV
1#型号晶体平均光产额: 265.7 pe/MeV
2#型号晶体平均光产额: 256.7 pe/MeV



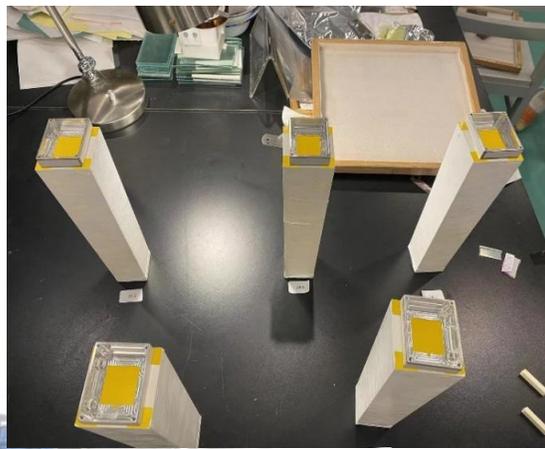
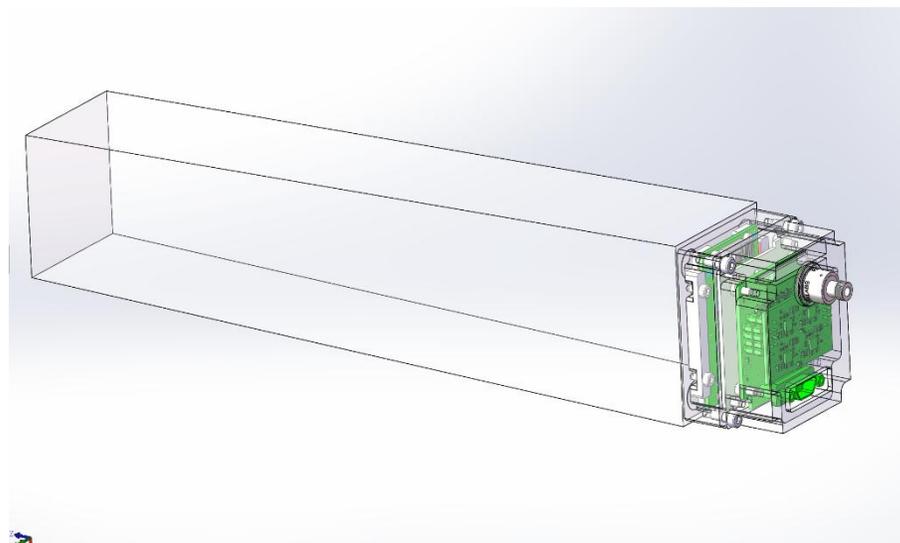
读出电子学的设计

- 低噪声大动态范围测量读出电子学
 - 采用电荷灵敏方案
 - 波形采样读出
 - 噪声水平：小于1 MeV
 - 动态范围：大于1000倍



- 晶体的封装

- 晶体表面包裹一层镀铝的mylar膜 (Al-Mylar) 进行电磁屏蔽
- Al-Mylar与前放盒良好接触
- 封装后的晶体, 初步结果显示光产额下降 <math><10\%</math>
 - 耦合面部分区域粘接前放盒导致



样机的组装，及束流测试台的加工

● ECAL样机

- 5 × 5 晶体阵列
- PXI 机箱控制
- 温控装置



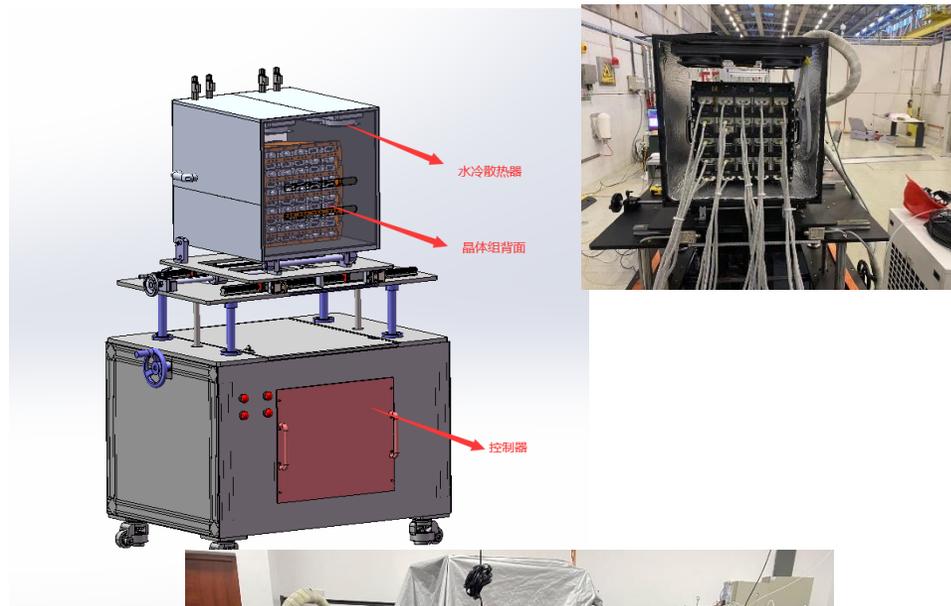
样机结构



PXI



制冷机



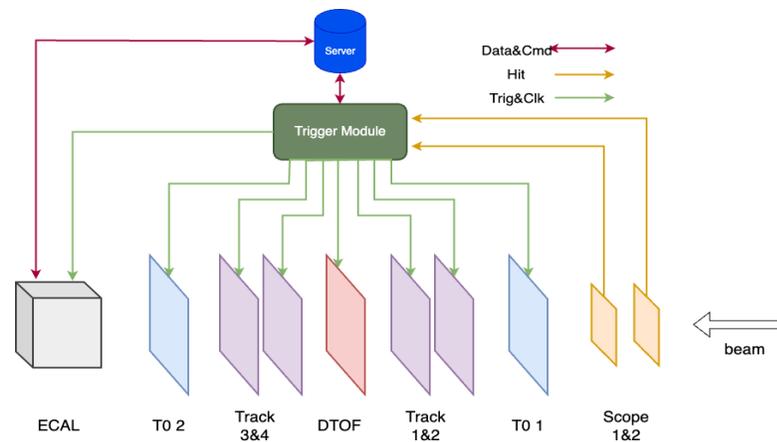
ECAL 样机

束流测试

● 束流测试

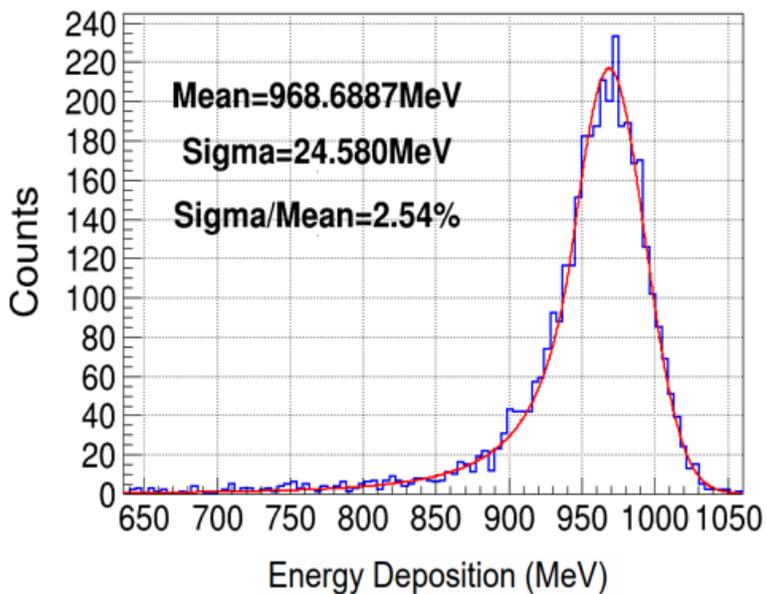
- CERN PS T09 beam line
- Multi-system beam test
 - T0 Detector
 - Track Detector
 - PID Detector——DToF
 - ECAL
- Beam particle and momentum

Particle	Momentum
μ^+	$\sim 5 \text{ GeV}/c$
e^+	$0.5\text{-}5 \text{ GeV}/c$
$hadron^+$	$1\text{-}5 \text{ GeV}/c$

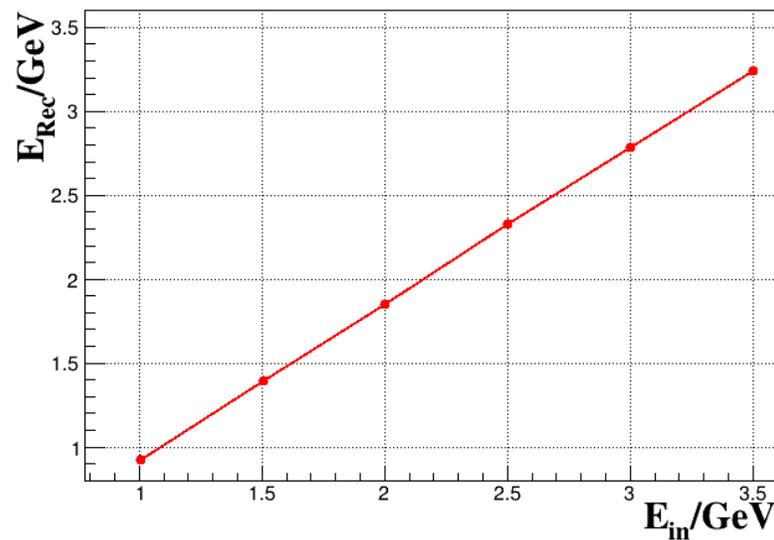


性能研究——能量响应

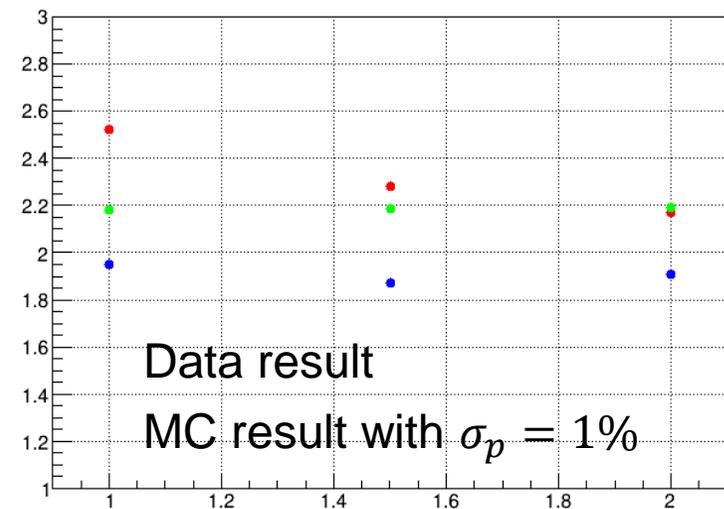
- 1 – 3.5 GeV电子
- 能量分辨率 ~ 2.5% @ 1 GeV
- 能量分辨率曲线比MC略差
 - 没有考虑束线上的物质质量及束流能散



Energy spectrum of 1 GeV e^+



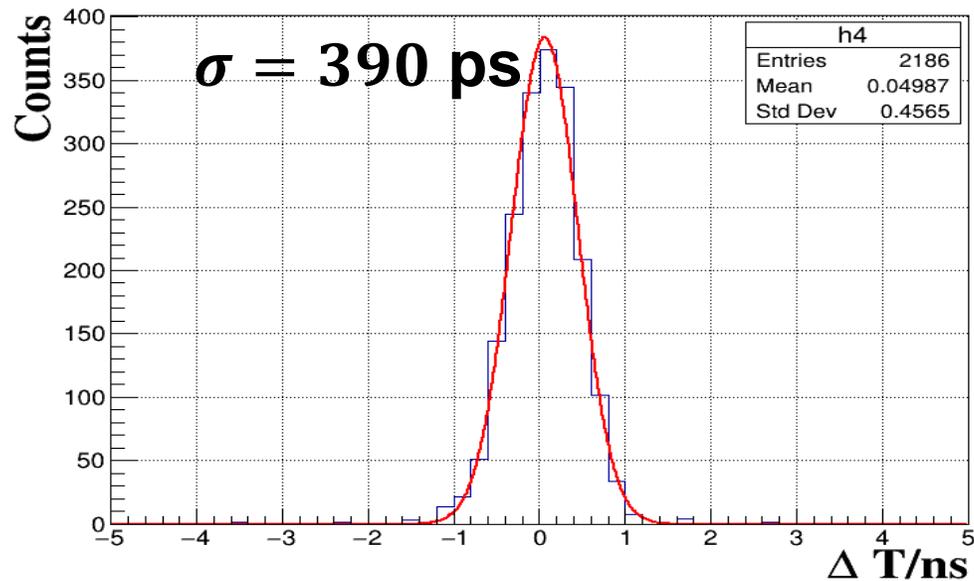
Energy linearity



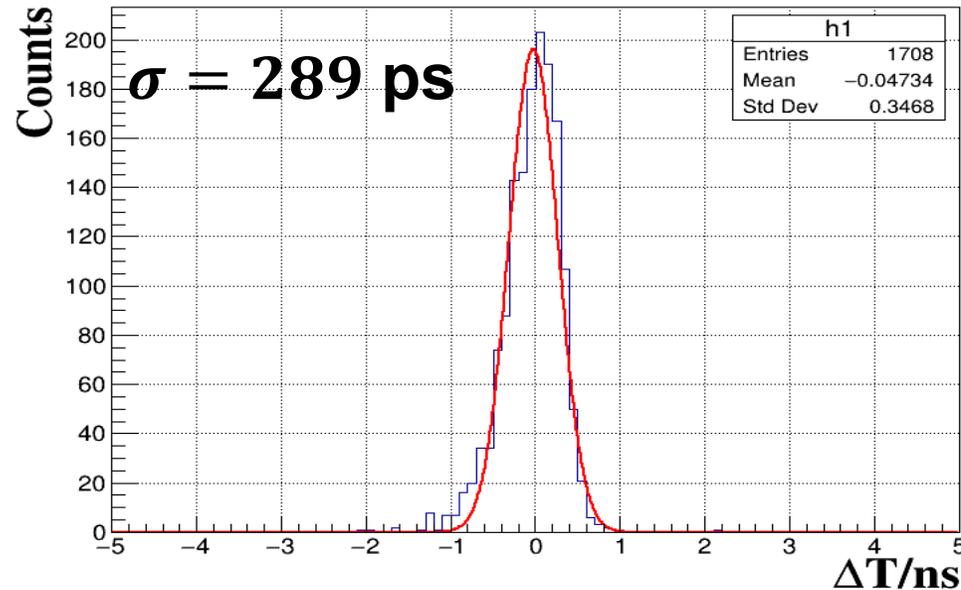
Energy resolution vs. Energy

性能研究——时间响应

- 利用束线上的T0探测器（时间分辨45 ps）进行时间测量
- Muon (~180 MeV能量沉积), $\sigma_t \sim 390$ ps
- 1 GeV 电子, $\sigma_t \sim 290$ ps
 - 发现簇射起始点位置与时间重建的关系，后期还可以进一步修正



Time reconstruction results of MIPs



Time reconstruction results of 1 GeV e^+



- 量能器是粒子物理实验谱仪的重要探测器之一
- 下一代粒子物理实验，高能量前沿和高亮度前沿对量能器有着不同的需求
 - 高能量前沿：高颗粒度量能器
 - 高亮度前沿：晶体型快响应量能器
- 研制了不同类型的量能器样机，并开展了束流测试
- 高颗粒度强子量能器样机
 - 实现了 $4\text{cm} \times 4\text{cm}$ 的颗粒度，对强子能量分辨好于 $60\% @ 1 \text{ GeV}$
- 新型晶体量能器
 - 基于pCsl晶体实现能量分辨 $2.5\% @ 1 \text{ GeV}$
 - 时间分辨好于 $300 \text{ ps} @ 1\text{GeV}$



总结

- 量能器是粒子物理实验谱仪的重要探测器之一
- 下一代粒子物理实验，高能量前沿和高亮度前沿对量能器有着不同的需求
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谢谢!

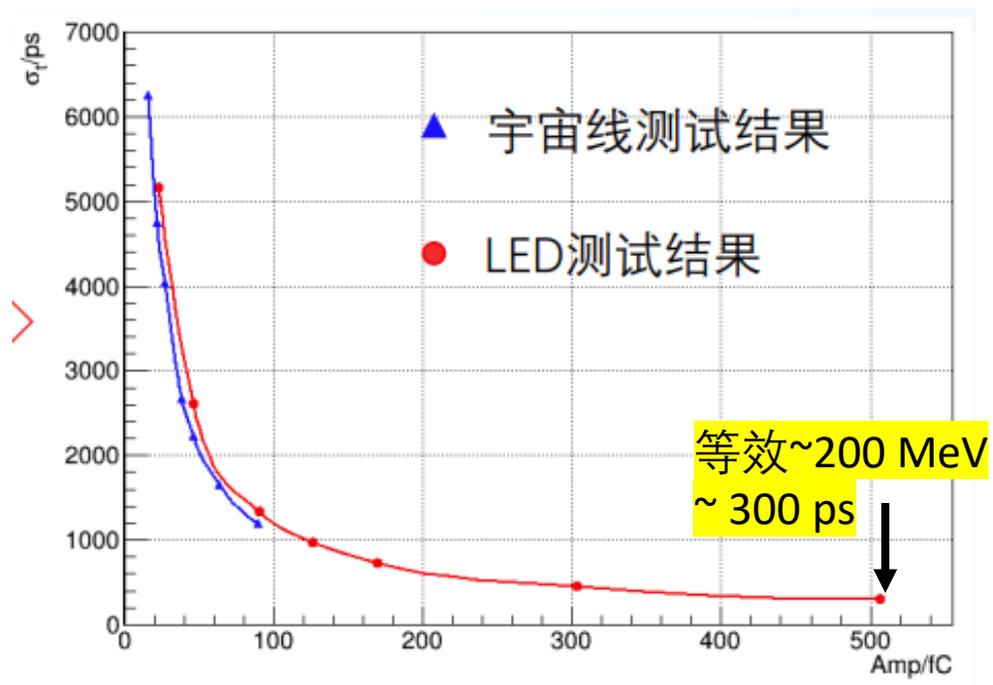


backup



性能研究——时间性能

宇宙线及LED测试



束流测试

