

100mm × 100mm 阻性阳极 GEM探测器样机性能研究

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- 研究背景
- 阻性阳极读出方法
- 探测器样机研制与测试
- 总结展望

研究背景

- 传统气体探测器，如丝室等
 - 造价低廉、增益大、物质质量小、性能可调
 - 位置分辨率、计数率、老化等改进空间不大
 - 难以适应高能量、高亮度粒子物理实验需求

- 新型微结构气体探测器 MPGD

- Micro-Pattern Gaseous Detector
- 光刻技术的进步带来新的思路
- 保留传统气体探测器性能优点
- 位置分辨率和计数率能力极大提高
- 典型代表

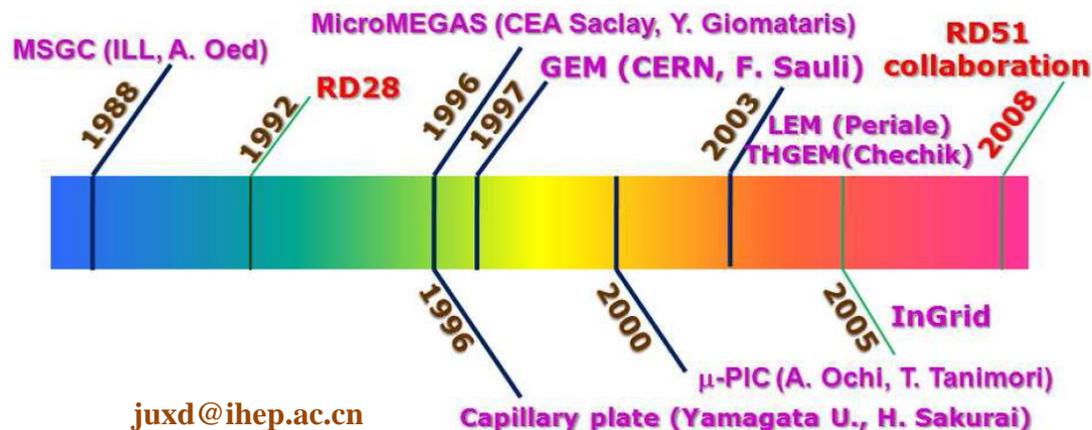
- ◆ MicroMegas
- ◆ Gas Electron Multiplier

- GEM 探测器

- 粒子物理实验
 - ◆ HERA-B、COMPASS、LHCb、TOTEM、KLOE-2、NA61/SHINE ……
- X 射线、中子成像等领域

- 高密度电子学通道数

- 信号横向扩散小
 - ◆ 1 – 3 mm
 - ◆ 条或块读出 + 重心法 \Rightarrow Pitch < 1 mm
- 高位置分辨率需求和潜力
 - ◆ COMPASS
 - ▶ $\sigma = 78.7 \mu\text{m} \Rightarrow$ Pitch = 400 μm



阻性阳极读出方法

- 电子学角度 👍👍👍

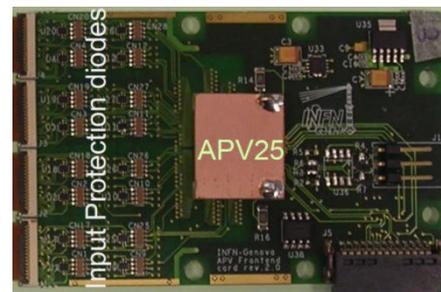
- ASIC \Rightarrow APV25

- 探测器角度

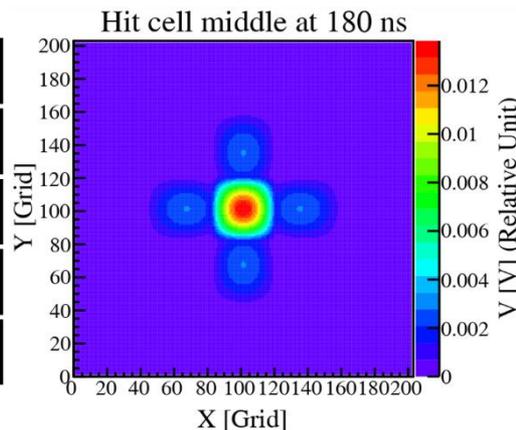
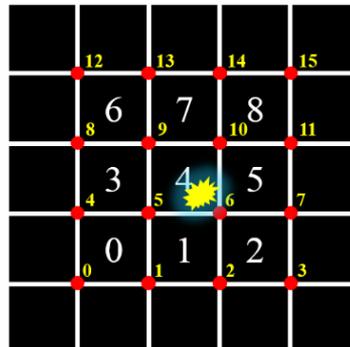
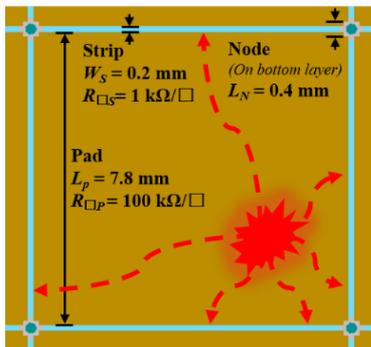
- 锯齿读出 Zigzag 👍
- 开关电容阵列 Switch Array
- 延迟线读出 Delay Line 👍
- 楔条阳极读出 WSA
- 阻性阳极读出 Resistive Anode
 - ◆ Pad: 高方阻
 - ◆ Strip: 低方阻
 - ◆ Node: 接前放
 - ◆ 阵列扩展 👍👍



IHEP 板极电荷灵敏前放 -- 8通道

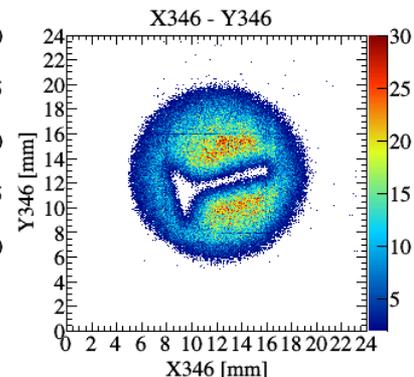
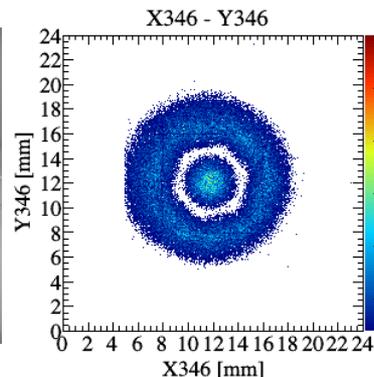
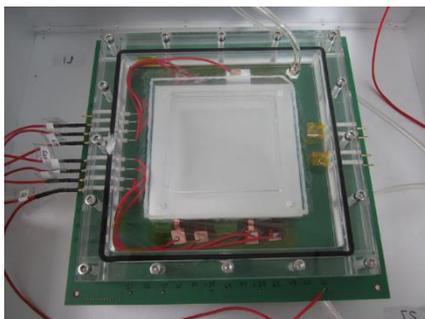


COMPASS 使用的 APV25 芯片 — 128 通道



- Resistive Anode GEM

- TGEM 原理探测器
 - ◆ 16 路, 3×3 Cell
- 阻性阳极的优化
- 重建算法的改进
- $100 \times 100 \text{mm}^2$ RAGEM 样机



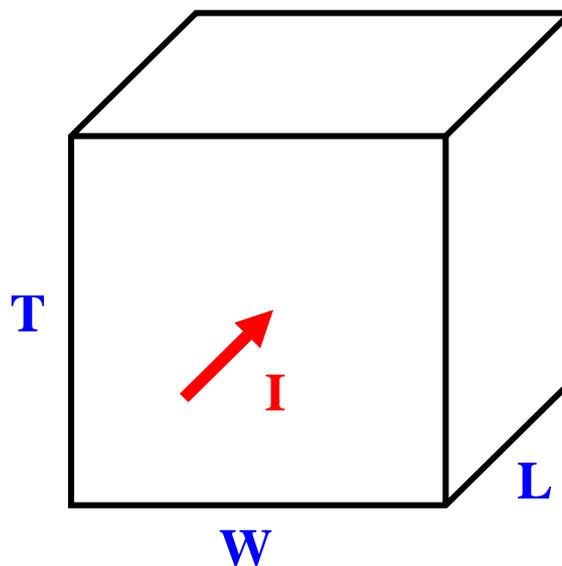
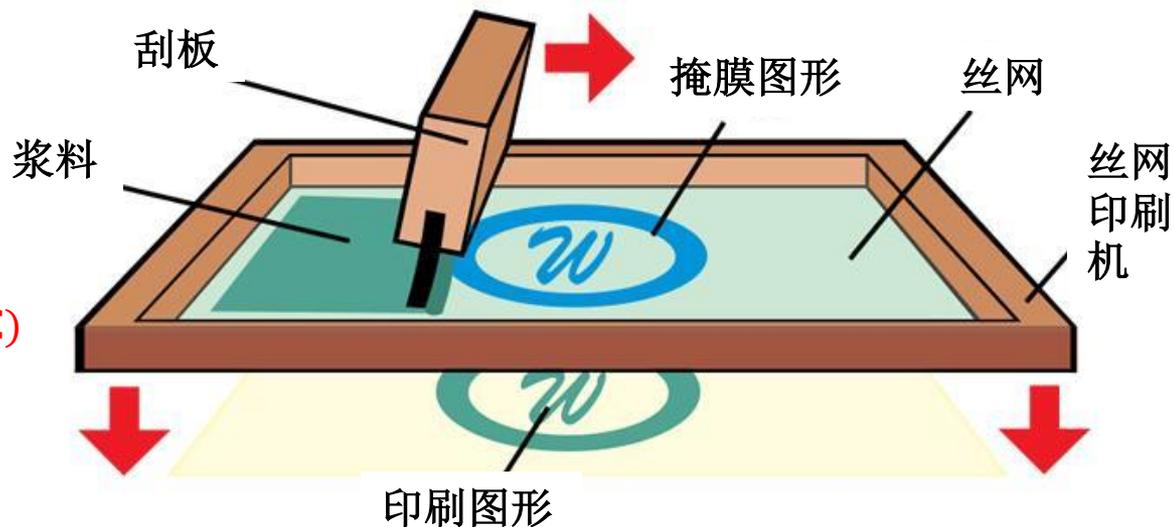
阻性阳极读出板设计与制作

● 厚膜电阻工艺

- 电阻浆料厚度: **2~20 μm**
- 导电相、玻璃相、有机载体
- 丝网印刷、烘干、**烧结(825 $^{\circ}\text{C}$)**

● 方阻 (面电阻率)

- $R = \frac{\rho_B L}{S} = \frac{\rho_B}{T} \frac{L}{W} = \rho_{\square} \frac{L}{W}$
- $\rho_{\square} = \frac{\rho_B}{T}$
- 方阻仅与材料特性和膜厚有关,
与膜的面积无关, 单位为: **Ω/\square**
- 厚膜电阻方阻值: **10~10 M Ω/\square**



RAGEM样机：阻性阳极读出板

- 背面导线层

- 过孔灌电阻浆、银浆

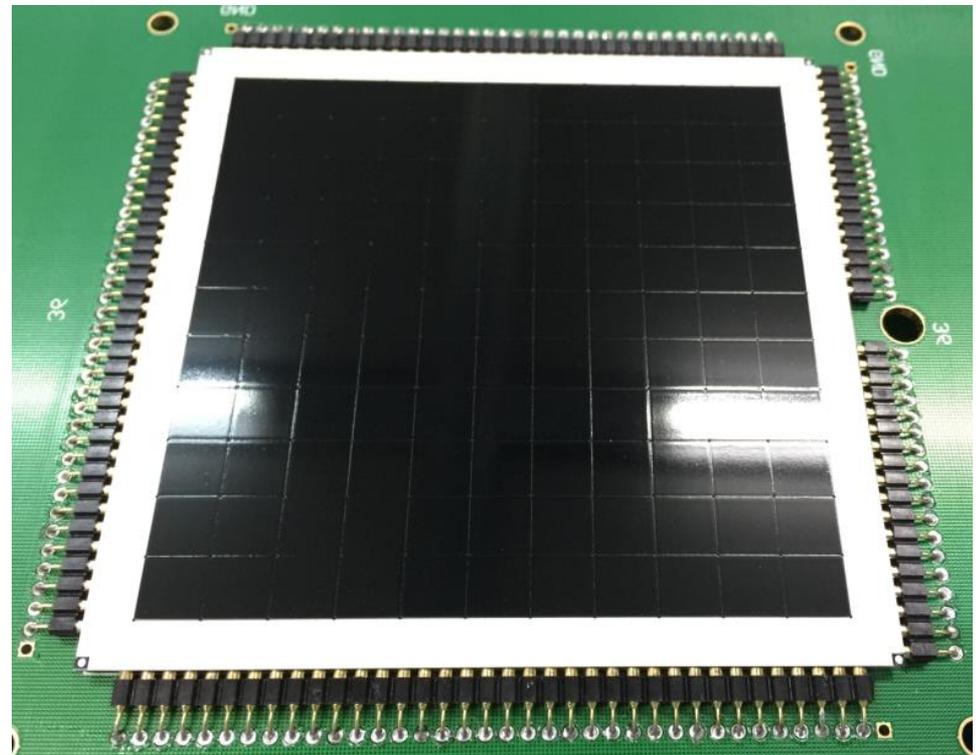
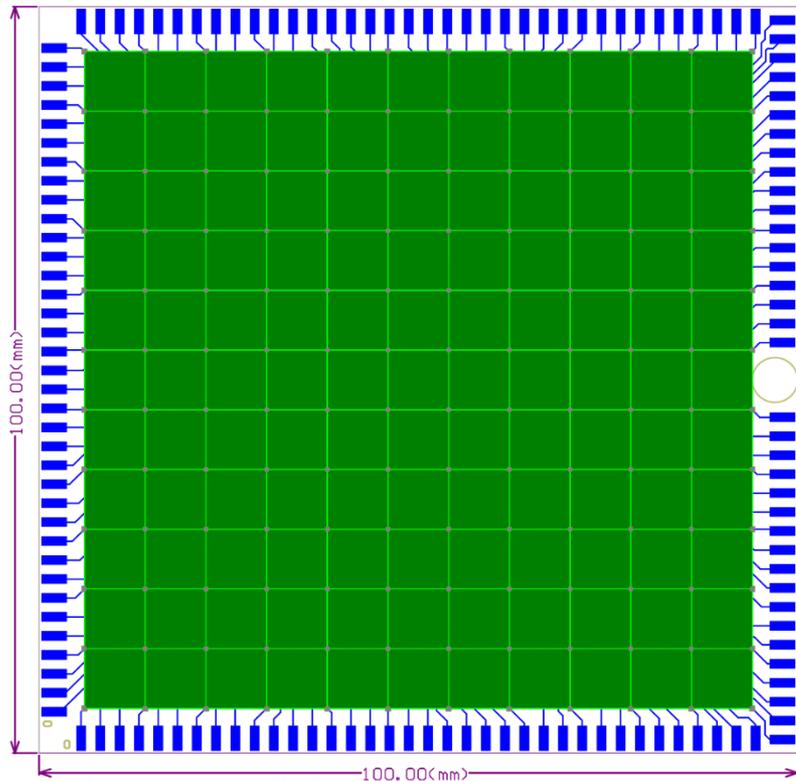
- 正面低方阻Strip

- 过孔与Strip的电气连接

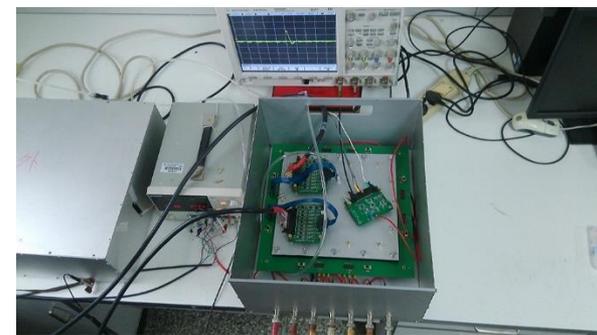
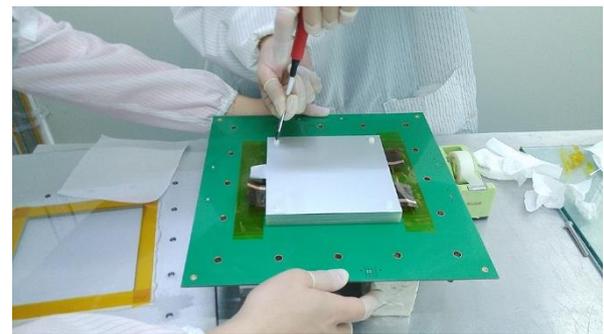
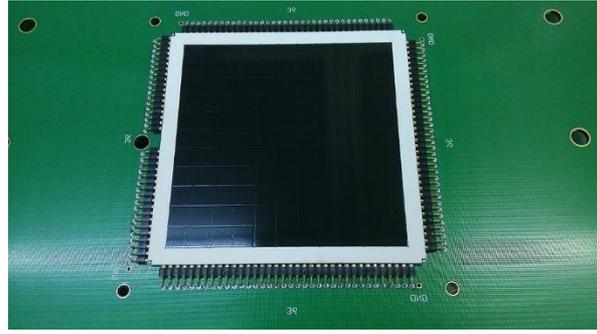
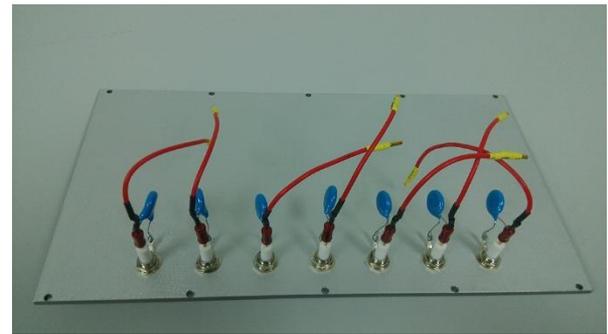
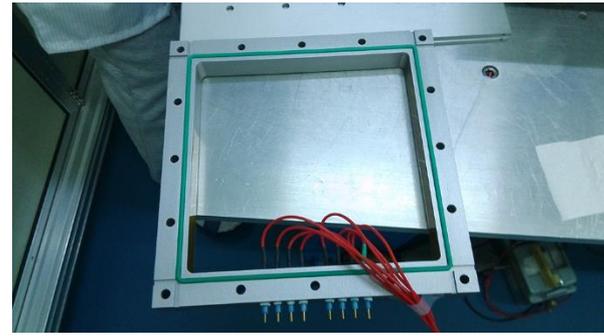
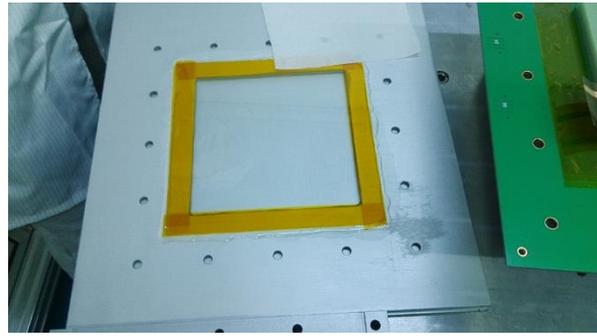
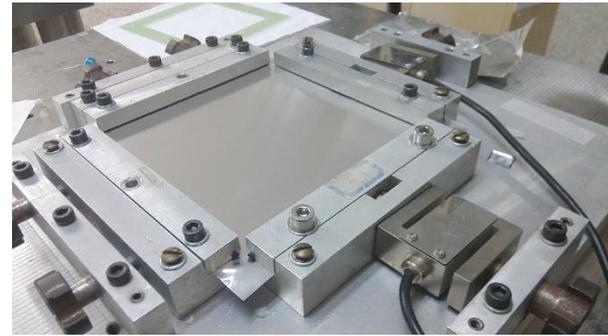
- 正面高方阻Pad

- Pad与Pad的电气连接

N_{Cell} (1-side)	W_{Pad} (mm)	W_{Strip} (mm)	$R_{\square P}$ (k Ω / \square)	$R_{\square S}$ (k Ω / \square)	ϕ_{Hole} (mm)	$T_{Ceramic}$ (mm)
11	7.85	0.25	200	1	0.3	1



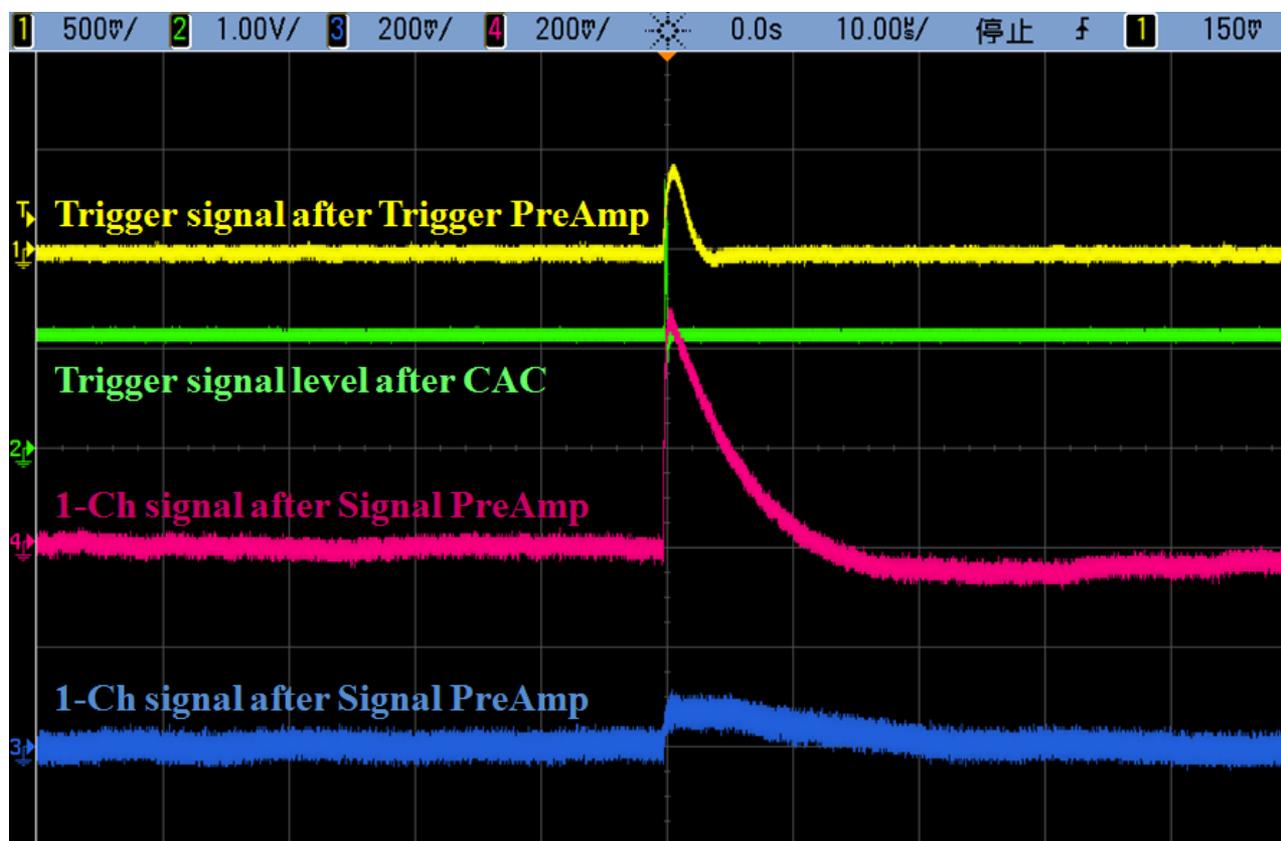
RAGEM样机：制作图片



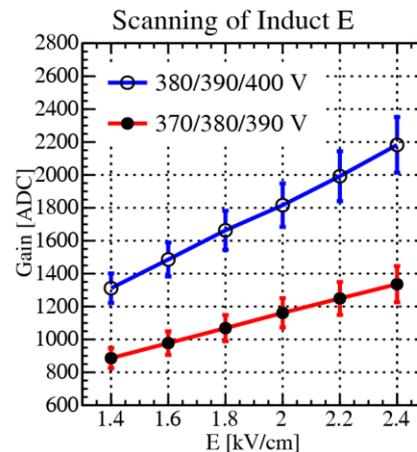
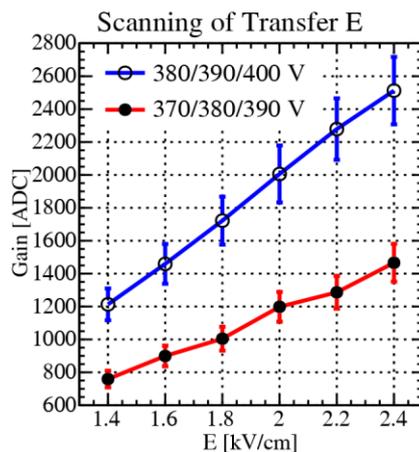
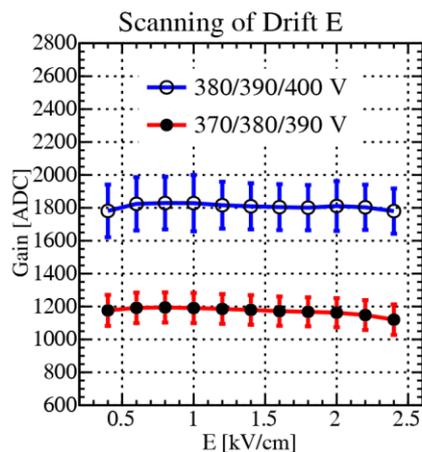
RAGEM样机：探测器信号

- 触发信号

- 第三层GEM膜下表面信号，本身噪声大，毛刺多 → 防止多次触发 → 设置 $VetoTime = 2\mu s$
- 触发信号、触发电平、通道信号一一对应 → 触发质量和触发数量



RAGEM样机：工作点设置



● 工作点扫描

- $G = (\epsilon_{i1} \cdot G_1 \cdot \epsilon_{o1}) \cdot (\epsilon_{i2} \cdot G_2 \cdot \epsilon_{o2}) \cdot (\epsilon_{i3} \cdot G_3 \cdot \epsilon_{o3})$
- 膜上高压对增益影响最大
- 漂移区场强 \Rightarrow 入孔率
- 传输区场强 \Rightarrow 入孔率和出孔率
- 感应区场强 \Rightarrow 出孔率

● 工作点设置

- 膜上压差: 380/370/370 V
- Gap 场强: 1.0/2.0/2.5/4.0 kV/cm

探测器电极	高压(V)	位置(mm)
Cathode (CAT)	-3370	10.0
GEM1 Top (G1T)	-3020	6.50
GEM1 Bottom (G1B)	-2640	
GEM2 Top (G2T)	-2240	4.50
GEM2 Bottom (G2B)	-1870	
GEM3 Top (G3T)	-1370	2.50
GEM3 Bottom (G3B)	-1000	
Anode (ANO)	0	0.0

RAGEM样机：能量分辨率与增益均匀性

● ^{55}Fe (5.9 keV) 放射源

■ $E_{Full} = 1400 \sim 1500$ ADC

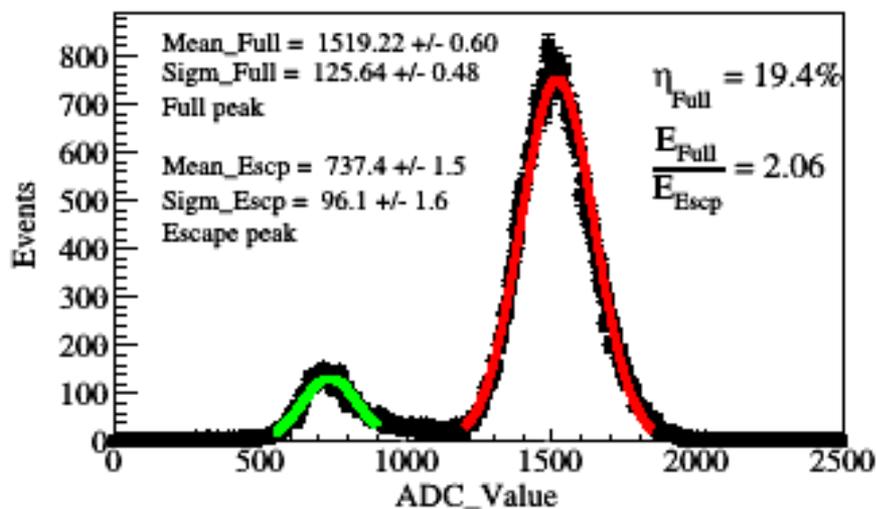
- ◆ $\sim 1 \times 10^4$
- ◆ $\bar{\sigma} < 7\%$ @ 11 Cells

■ $\eta = 19.4\%$

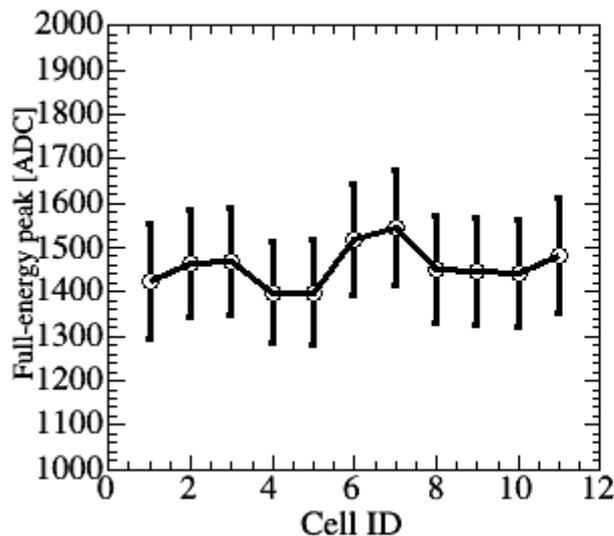
- ◆ $\bar{\eta} \approx 20\%$

■ $\frac{E_{Full}}{E_{Escape}} = 2.06$ (1.97)

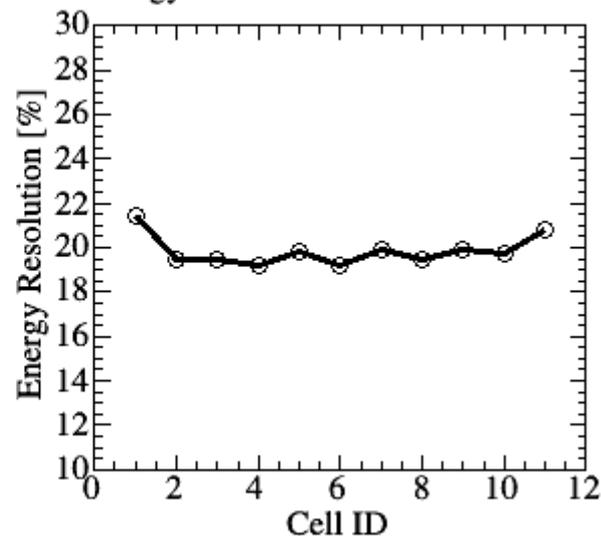
Energy Spectrum of Fe-55@Ar/CO2(70/30), All nodes of Pad 5_5



Gain scan of 11 cells



Energy Resolution scan of 11 cells



RAGEM样机：探测器位置分辨率

● 基本原理

- 实验分布 $M(x')$ 表示为真实分布 $T(x)$ 与探测器位置分辨函数 $R(x, x')$ 的卷积

◆ $M(x') = T(x) \otimes R(x, x') = \int_{-\infty}^{\infty} T(x) R(x, x') dx$ Spatial resolution with slit width = 0.04mm

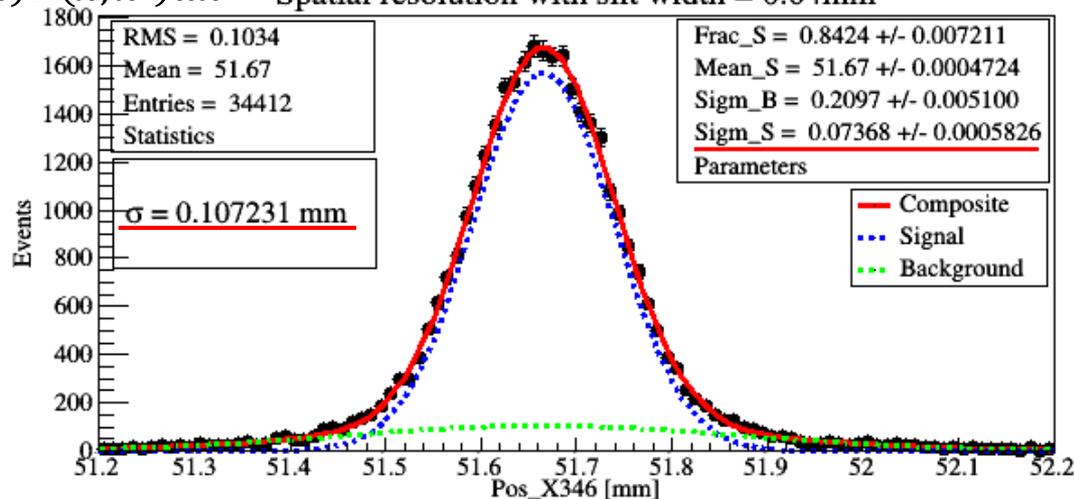
◆ $R(x, x') = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(x-x')^2}{2\sigma^2}\right]$

● 双高斯拟合法

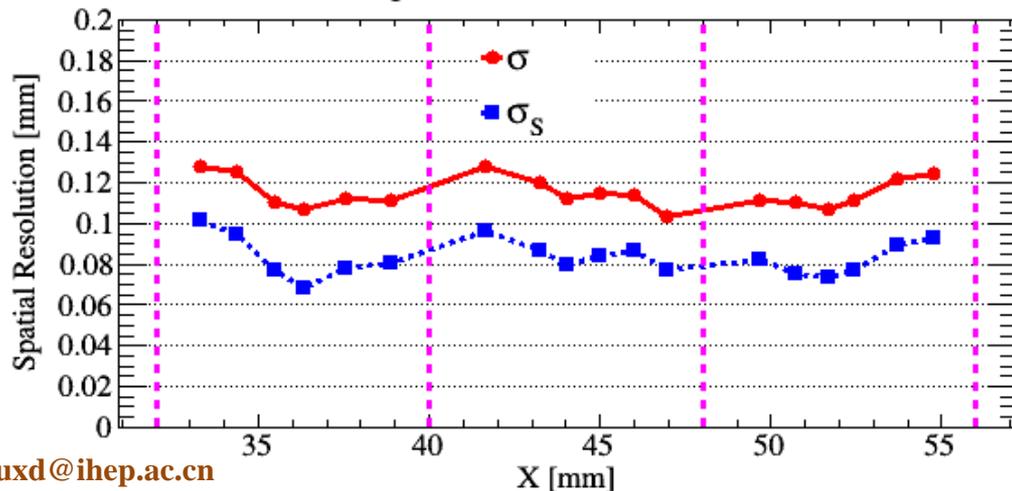
- 假设真实分布为 δ 分布

■ $M(x') = T(x) \otimes R(x, x')$
 $= \int_{-\infty}^{\infty} \delta(x - x_0) R(x, x') dx$
 $= R(x_0, x')$

- X光机 + 40 μm Slit
- $\sigma = 107.2 \mu\text{m}$ @ 8 mm Cell
- $\bar{\sigma} < 120 \mu\text{m}$ @ 8 mm Cell



Spatial Resolution Scan



$$f(x) = a \cdot g_S(x) + (1 - a) \cdot g_B(x)$$

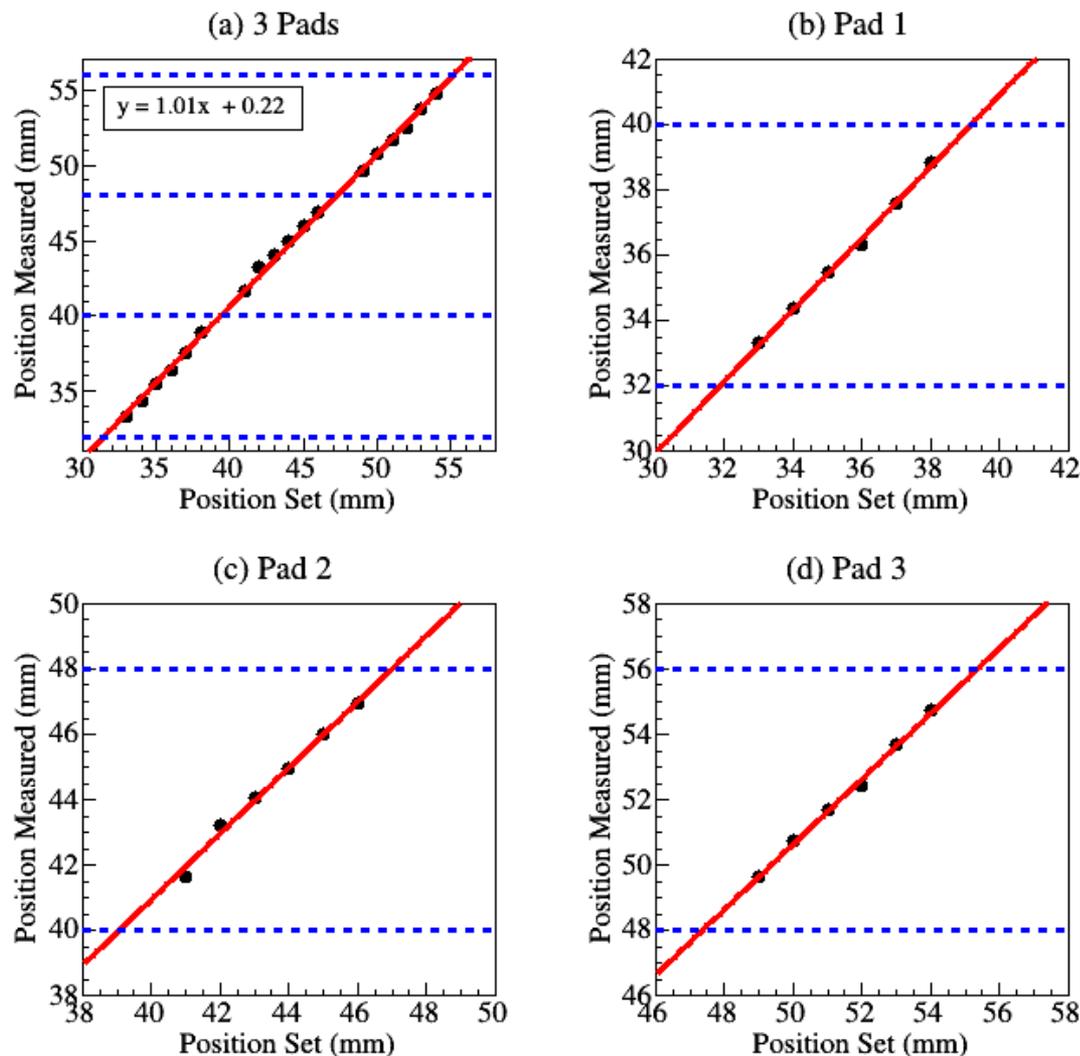
$$g_S(x) = N(\mu_S, \sigma_S)$$

$$g_B(x) = N(\mu_B, \sigma_B)$$

$$\sigma^2 = \int (x - \mu)^2 f(x) dx = a \cdot \sigma_S^2 + (1 - a) \cdot \sigma_B^2$$

$(\mu_B = \mu_S)$

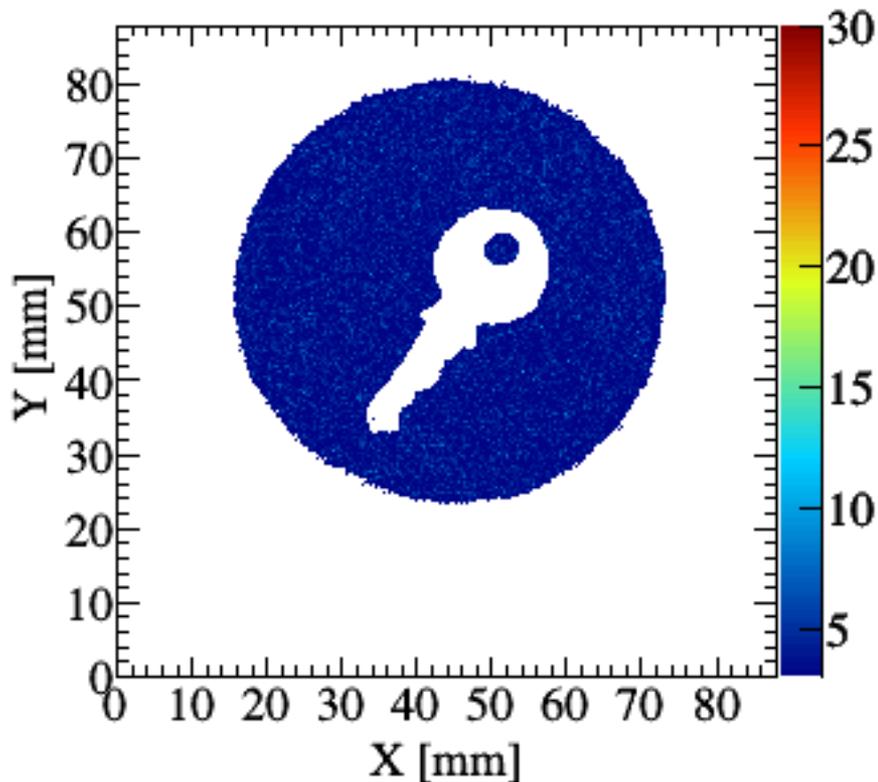
RAGEM样机：探测器位置线性



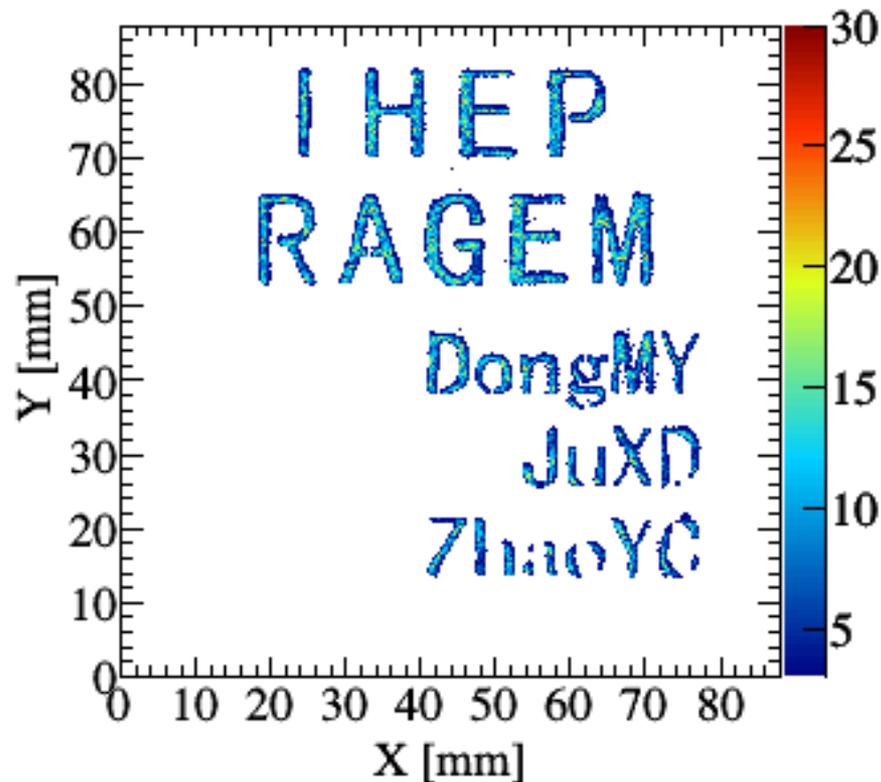
$$\delta = \frac{\sqrt{\langle (x_M - x_F)^2 \rangle}}{L} \times 100\% = 2.58\%$$

RAGEM样机：探测器二维成像能力

钥匙成像



3D打印的字母mask成像



总结和展望

● 总结

- 研究了阻性阳极读出方法用于 GEM 探测器的可行性
 - ◆ 连续的二维成像能力、抑制探测器打火
 - ◆ 阻性阳极的优化设计、重建算法的改进
- 制作了 $100 \times 100 \text{ mm}^2$ 的探测器样机，用铁源和X光机进行了测试
 - ◆ 好的能量分辨率($\sim 20\%$)和好的增益均匀性 ($< 7\%$)
 - ◆ 好的位置分辨率($\sim 120 \mu\text{m} @ 8 \text{ mm Cell}$)和好的位置线性 ($< 1.1\%$)
 - ◆ 良好的二维成像性能
 - ◆ 有效节省电子学
 - ▶ 当前位置分辨率和灵敏面积下，相较条读出结构，节省约一半电子学 ($169 \text{ vs } 334$)

● 展望

- 为 RAGEM 匹配一套集成度较高的电子学，进行同步辐射实验
- 适用于类似结构的其它探测器，已在厚GEM探测器上尝试
- 进一步增大Cell尺寸，用于中子成像等
 - ◆ $\sigma \sim 300 \mu\text{m} @ 36 \text{ 路} @ 20 \times 20 \text{ mm}^2 \text{ Cell} @ 100 \text{ mm}^2 \text{ Area}$

谢谢

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鞠旭东.基于GEM探测器的阻性阳极读出方法研究. PhD thesis, 中国科学院大学, 2016.

RAGEM样机：探测器计数率分析

- 单Cell总计数率

Electronics	CAMAC	VME	704GEM
Rate (Hz)	~ 100	> 3k	> 5k

- 三套电子学系统

- ◆ 目前最高为 5 kHz

- RC 时间常数

- ◆ $\tau \approx 400 \text{ ns} @ R_p = 200 \text{ K}\Omega/\square @ W_{Cell} = 8 \text{ mm}$
- ◆ 防止脉冲堆积，间隔三倍时间常数 $\Rightarrow 4 \times 10^6 \text{ Hz}$

- 示波器信号波形和模拟结果

- ◆ 信号上升时间 $\Rightarrow >100 \text{ kHz}$
- ◆ $2 \mu\text{s}$ 时间窗 $\Rightarrow 500 \text{ kHz}$

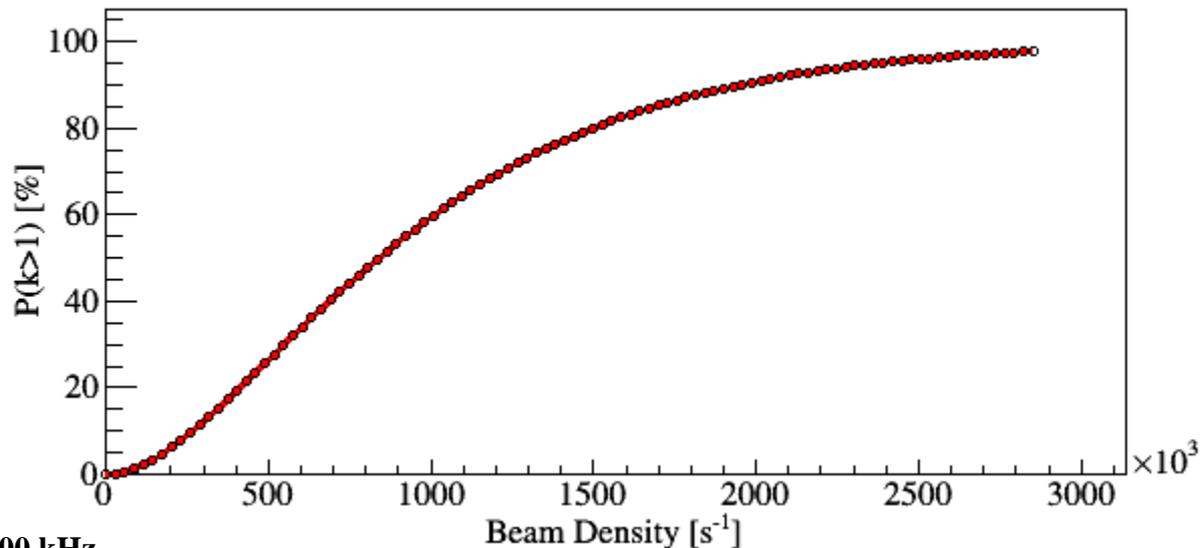
- 单位面积内的计数率

- 多次击中问题

- 泊松分布

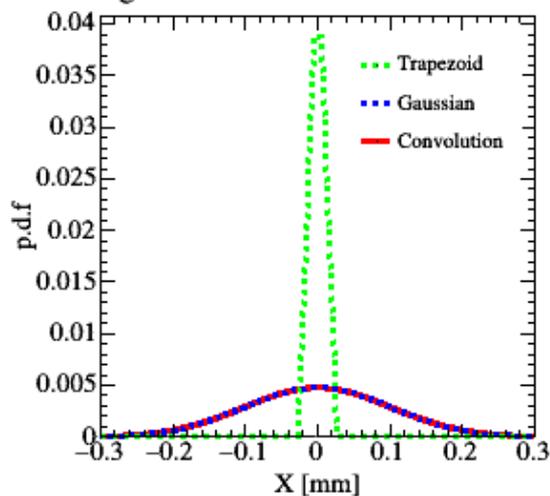
- ◆ $P(X = k) = \frac{\lambda^k}{k!} e^{-\lambda}$
- ◆ $\lambda = \varepsilon \cdot \Delta t \cdot s \cdot I_0$
- ◆ $3 \times 3 \text{ Cell}, P(k > 1) = 1.8\% @ 100 \text{ kHz}$

Multi-hit Percent vs Beam Density

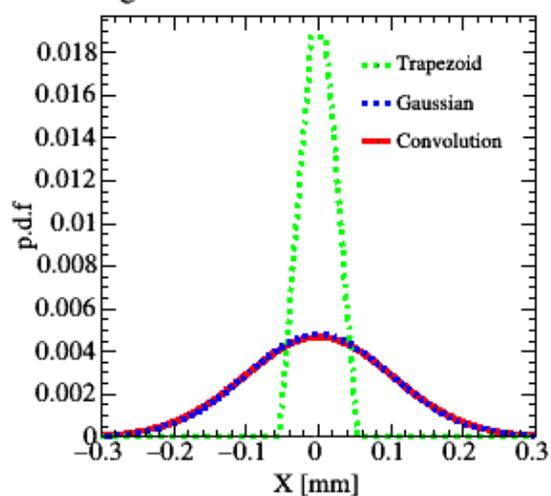


RAGEM样机：探测器位置分辨率

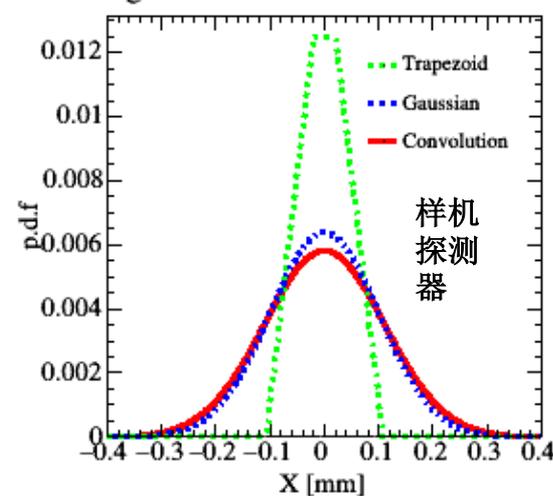
Sigma = 100um and Slit = 10um



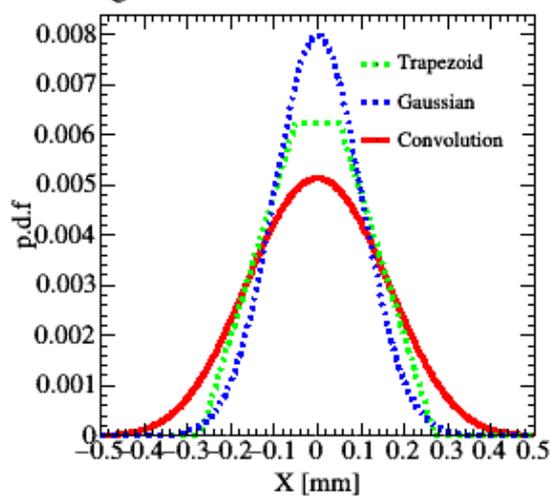
Sigma = 100um and Slit = 20um



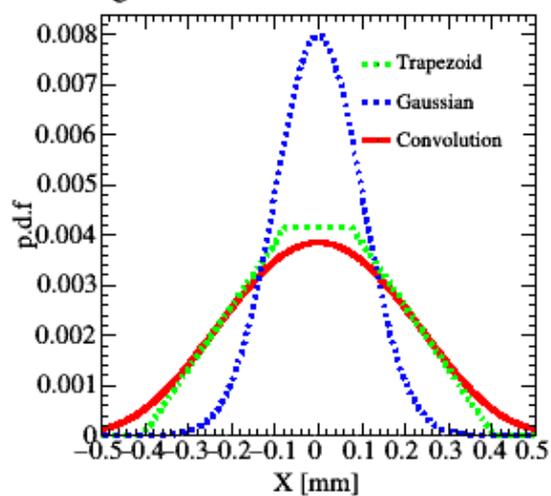
Sigma = 100um and Slit = 40um



Sigma = 100um and Slit = 100um



Sigma = 100um and Slit = 150um



Sigma = 100um and Slit = 200um

