



兰州大学
LANZHOU UNIVERSITY



中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

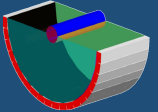
2024 年全国先进气体探测器研讨会

TPC-CsI(Tl) detection system for ($^3\text{He}, t$) reaction experiments in inverse kinematics

报告人：何志轩

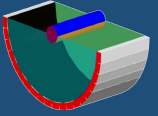
研究团队：张毅*，杨贺润，胡碧涛，谌盼姣，王婧妍，卜文娟

2024年7月 · 青岛

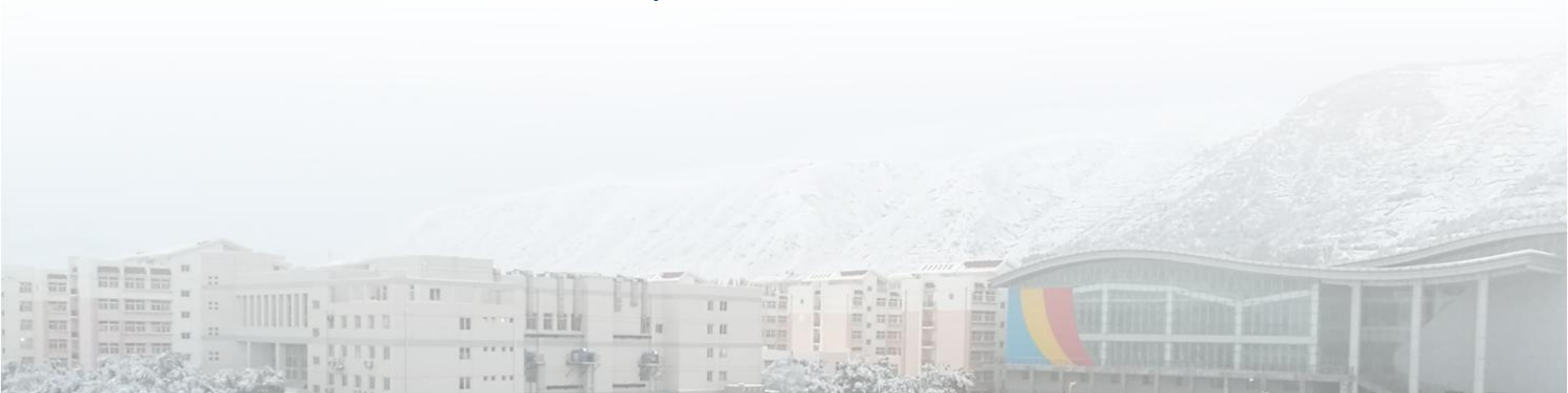


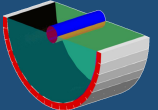
- I. 研究背景
- II. 探测器的搭建
- III. 性能测试
- IV. 总结与展望

白強不息 獨樹一幟

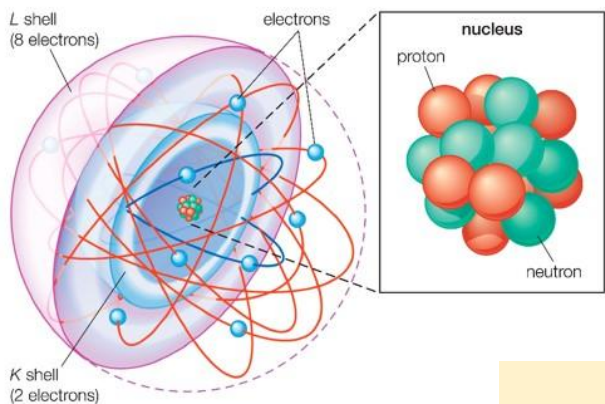


I. 研究背景





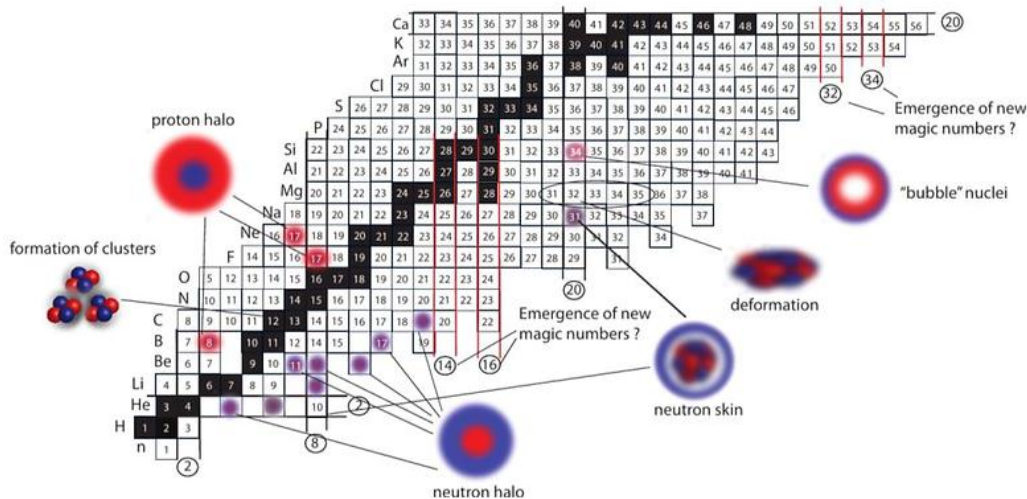
研究背景



双费米子量子多体系统

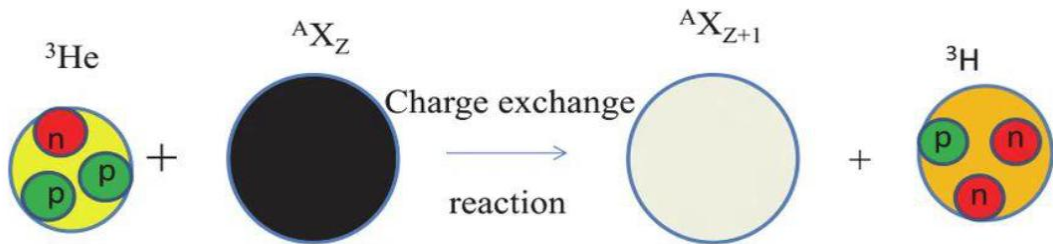
同位旋 $T_z = \frac{N - Z}{2}$

中子晕
中子皮
中子滴线



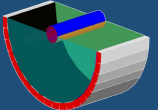
中能区电荷交换反应

$\Delta T_z = 1$

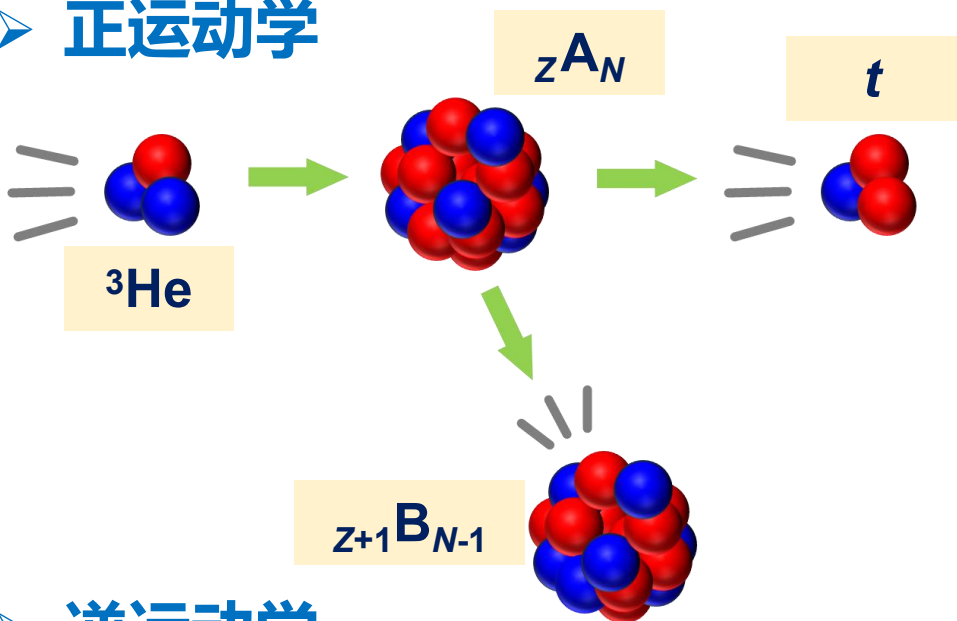


H. Lenske et al. PRL 62(13) (1989) 1457-1460

$E > 100 \text{ A MeV}$ → 直接反应，反应末态由同位旋矢量核子-核子 (NN) 散射描述的带电介子的 one-step 交换激发 → 直接获取核结构信息



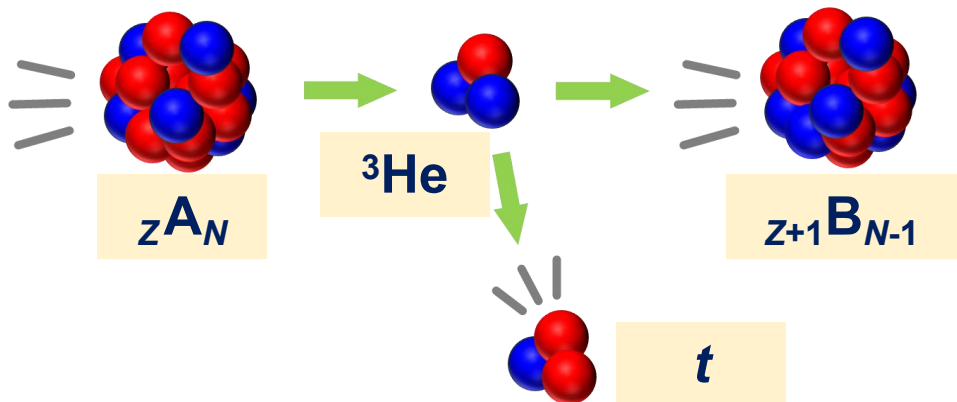
➤ 正运动学



- (p, n) or $({}^3\text{He}, t)$, $(t, {}^3\text{He})$
- ${}^{12}\text{C}$, ${}^{13}\text{C}$, ${}^{18}\text{O}$, ${}^{26}\text{Mg}$, ${}^{58}\text{Ni}$, ${}^{60}\text{Ni}$, ${}^{90}\text{Zr}$, ${}^{118,120}\text{Sn}$, ${}^{208}\text{Pb}$ @ 140 AMeV ${}^3\text{He}$, RCNP [Zegers2007]
- ${}^{12}\text{C}$, ${}^{10}\text{Be}$ @ 127 AMeV triton, NSCL [Daito1999]
- ${}^{13}\text{C}$, ${}^{26}\text{Mg}$, ${}^{88}\text{Sr}$, ${}^{100}\text{Mo}$, ${}^{45}\text{Sc}$, ${}^{56}\text{Fe}$ @ 115 AMeV triton, NSCL [Zegers2006, Zamora2019, Miki2017, Noji2015, Scott2014]

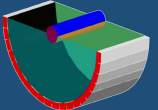
➤ 逆运动学

丰中子核、远离 β 稳定线的核



- **质心系·小角散射区** → 反应截面大，接近零动量转移 ($q = 0$)，蕴含物理丰富 → **逆运动学区·实验室系·大角散射区**
- 反冲核能量对散射角更敏感 → 精确测量

R.G.T. Zegers et al. PRL 99 (2007) 202501



➤ 电荷交换反应探测器 CExD

探测器的结构

- ^3He 气体靶
- TPC
- 闪烁体阵列

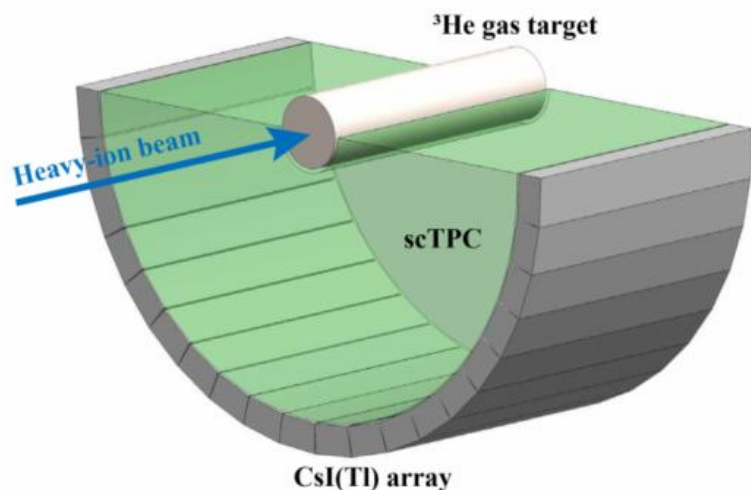
$\Delta E-E$

Geant4 模拟

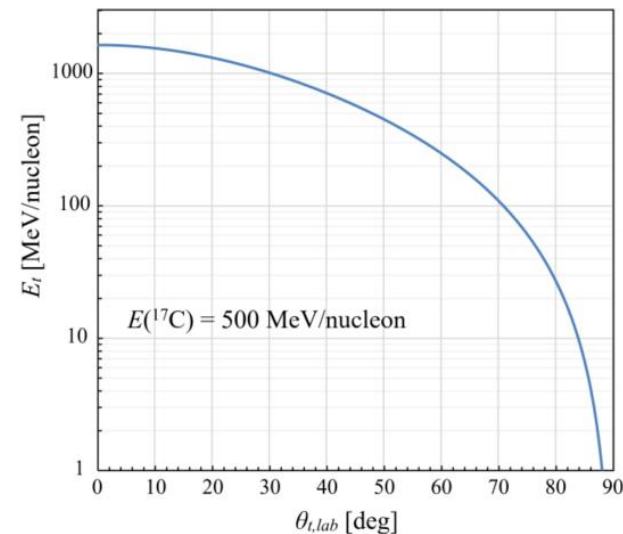
- 粒子鉴别能力
- 探测器死区损耗

运动学区间

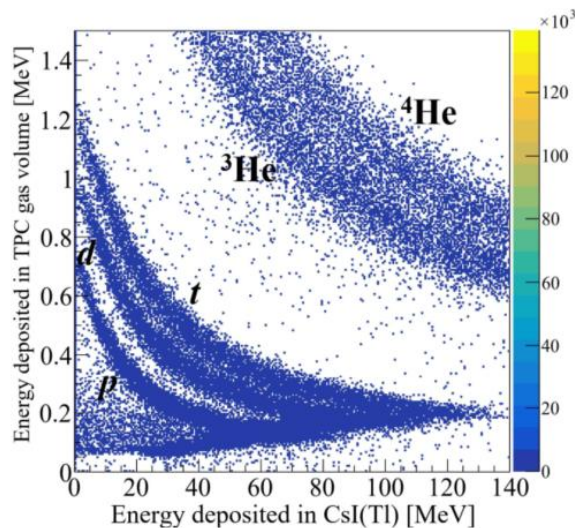
- 散射角: $76^\circ \sim 85^\circ$
- 散射能量: $20 \sim 140 \text{ MeV}$



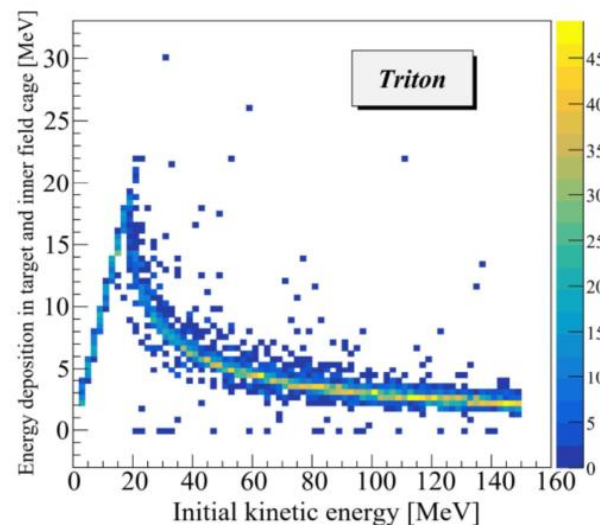
电荷交换反应探测器的整体设计



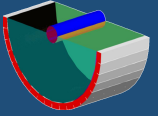
氚的散射动能 vs 实验室系氚的散射角



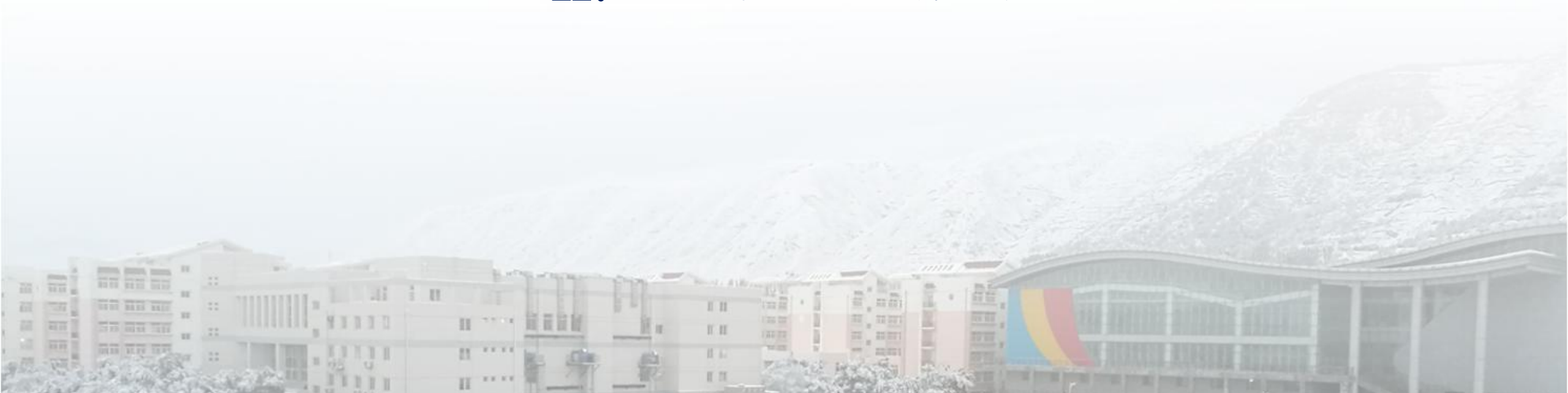
Geant4 模拟 $\Delta E-E$ 分布

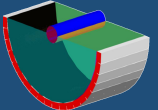


氚在 ^3He 气体, 不锈钢侧壁及内场笼侧壁中的能损 vs 氚的初始动能



II. 探测器的搭建





TPC 总体设计

TPC 结构

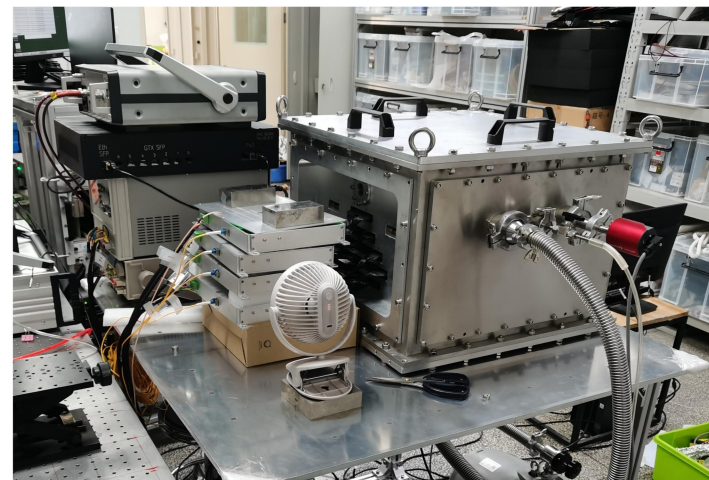
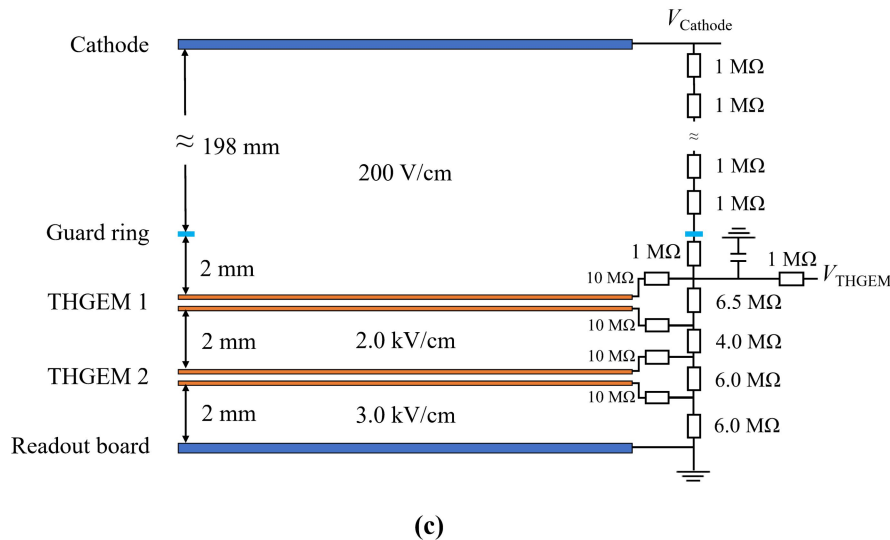
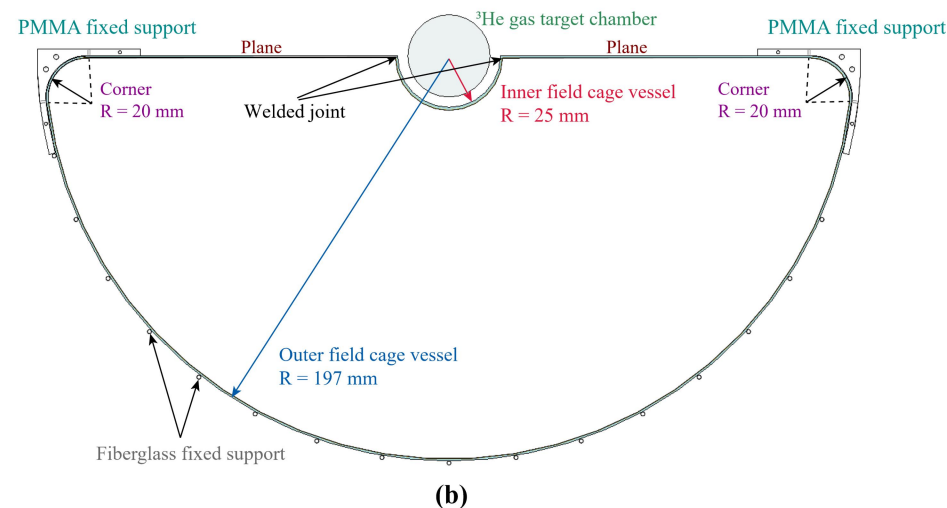
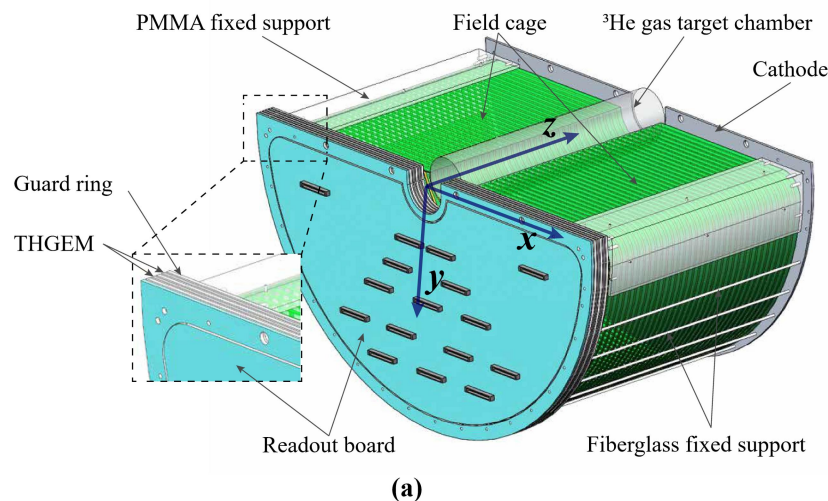
- 阴极
- 场笼
- THGEM
- 读出电极
- 电子学、数据获取

TPC 作用

- **三维径迹**
- **能损 ΔE**

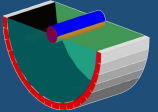
TPC 尺寸

- 漂移区长度: 200 mm
- 传输区长度: 2 mm
- 感应区长度: 2 mm
- 内半径: 25 mm
- 外半径: 197 mm

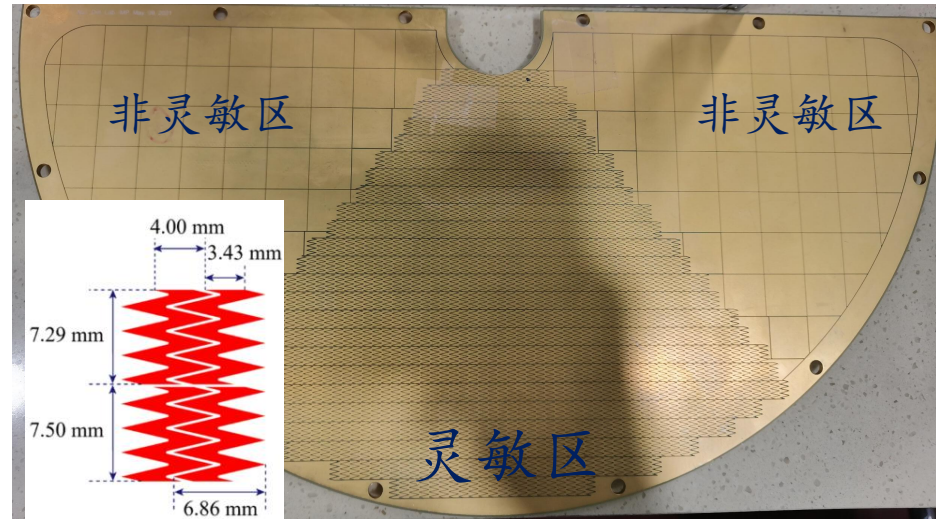
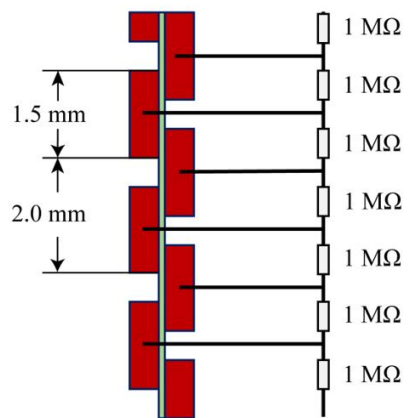


CExD-TPC 的总体设计及测试

Z.X. He et al. EPJC 83 (2023) 1092

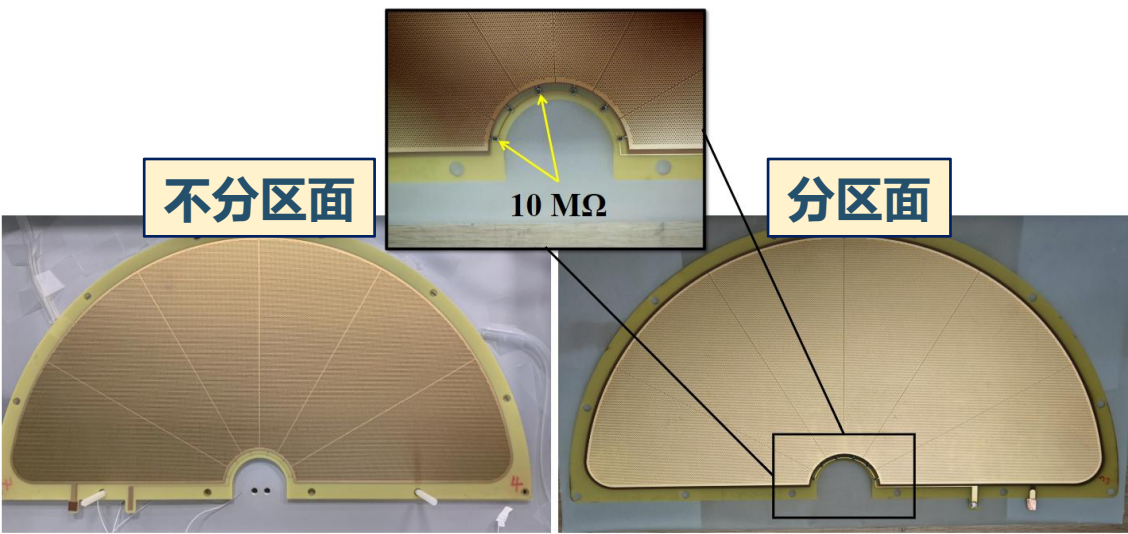


TPC 的搭建

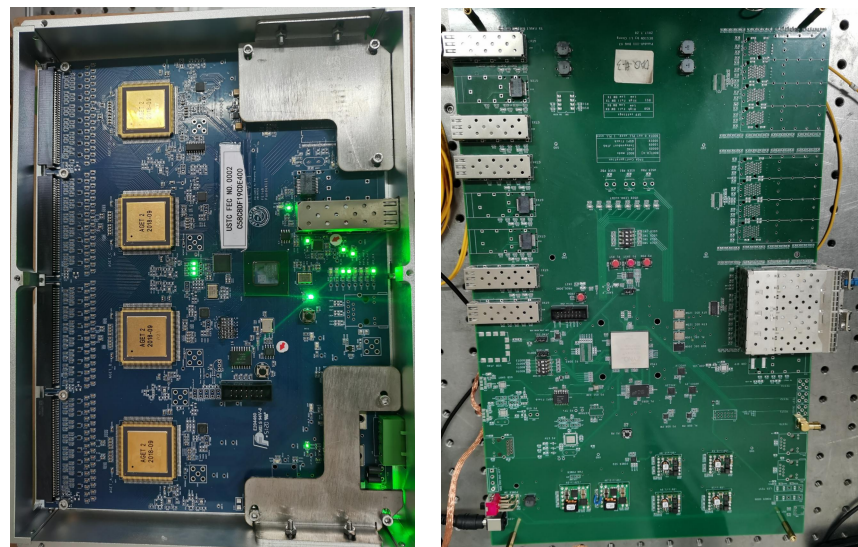


场笼电极及实物图

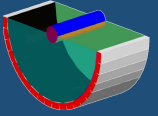
Readout board



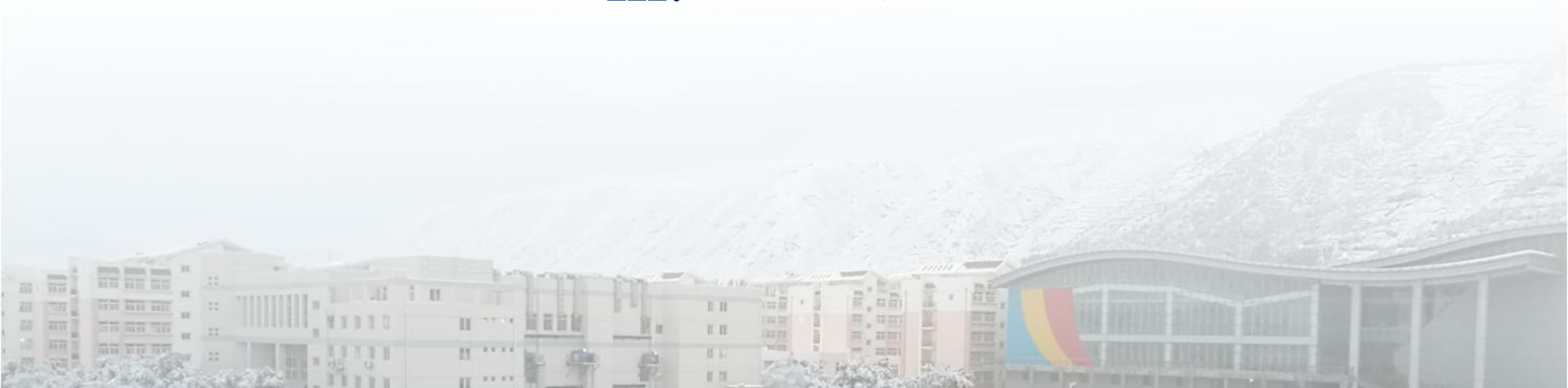
经过分区处理的 THGEM

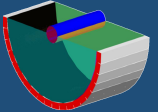


AGET 读出电子学



III. 性能测试





➤ 波形拟合函数选取

$$f(t) = B + A \left(\frac{t - t_0}{\tau} \right)^3 \exp \left(-\frac{t - t_0}{\tau} \right) \Theta(t - t_0)$$

B represents the baseline

A is related to the amplitude of the waveform

t_0 is the start time

τ is the shaping time of the electronics

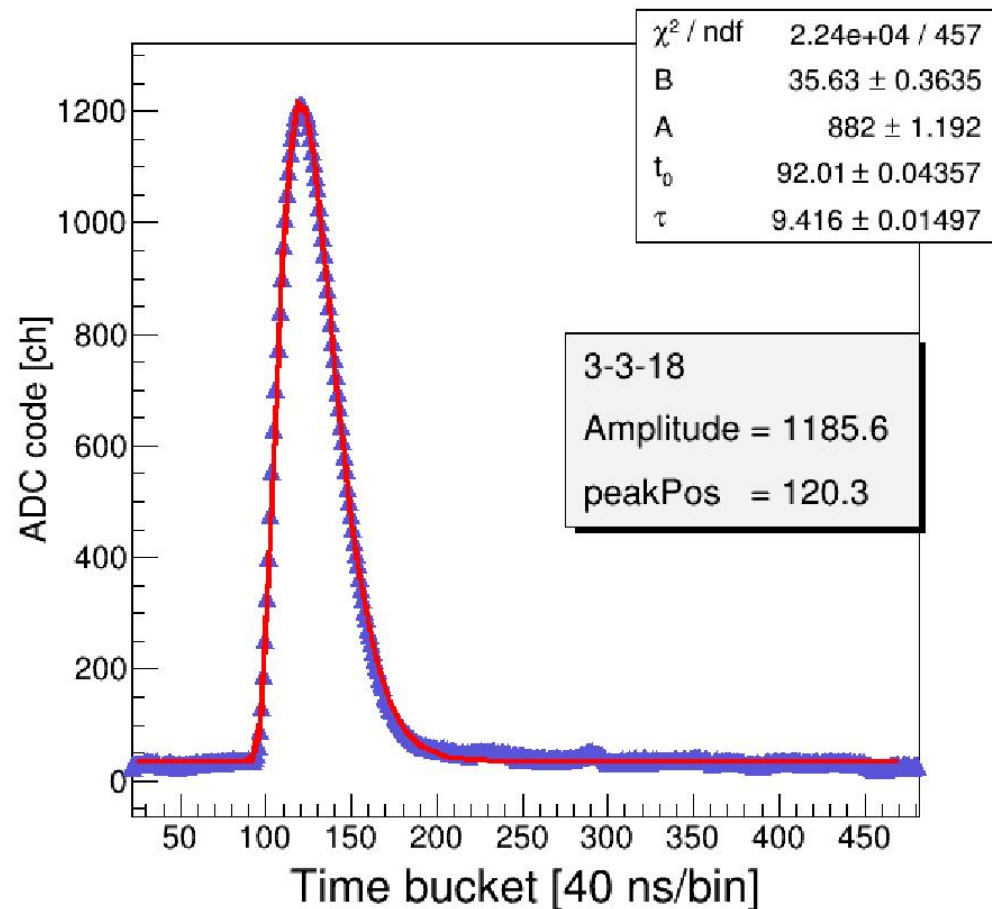
Θ is the Heaviside step function

$$\Theta(x) = \begin{cases} 0, & x < 0 \\ \frac{1}{2}, & x = 0 \\ 1, & x > 0 \end{cases}$$

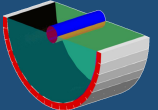
Y. Li et al. NIM A 1060 (2024) 169045

Z. Chen et al. JINST 17 (2022) P05032

⁵⁵Fe 源 X-ray 信号波形拟合



输出波形及拟合函数

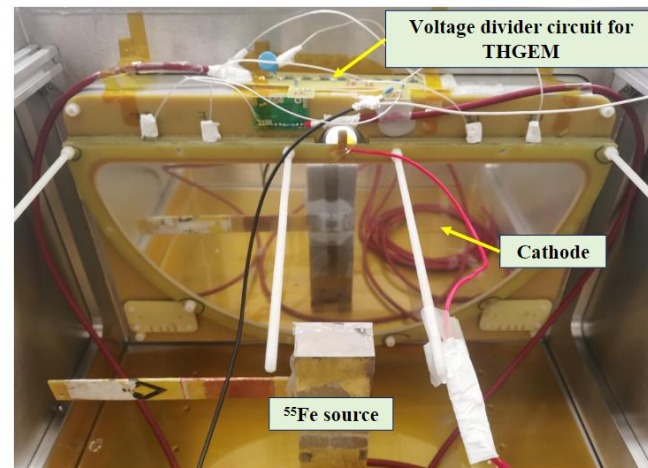


➤ X-ray 刻度增益非均匀性

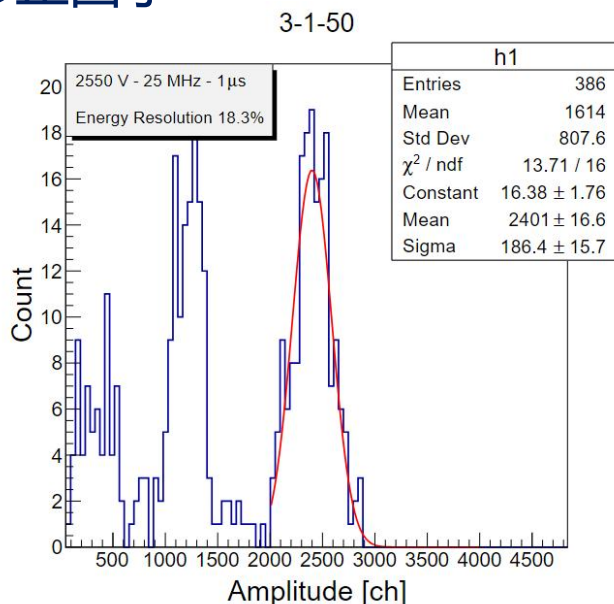
- ^{55}Fe 放射源
- 能量分辨: $\sim 18\%$ @ 5.9 keV
- 增益不均与性
- 增益修正因子



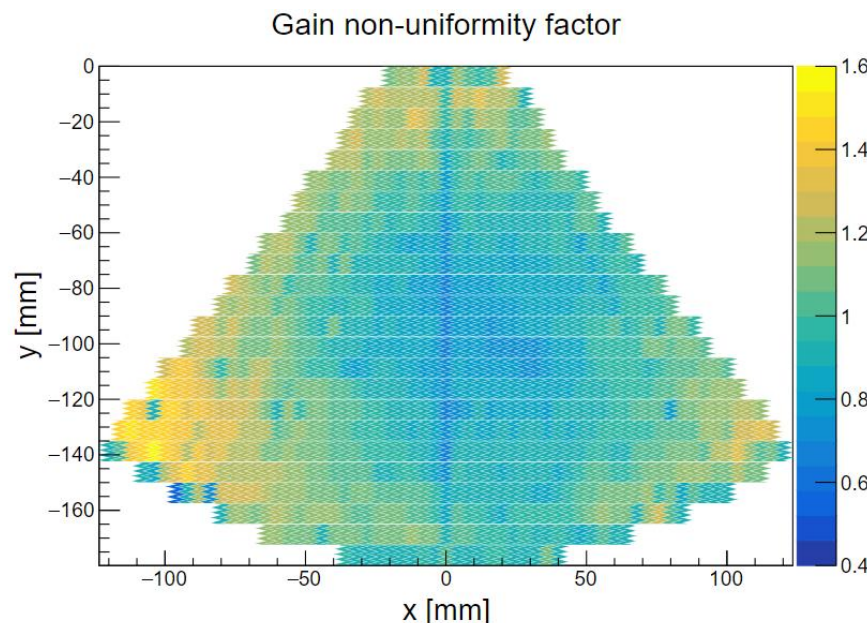
^{55}Fe 源测试示意图



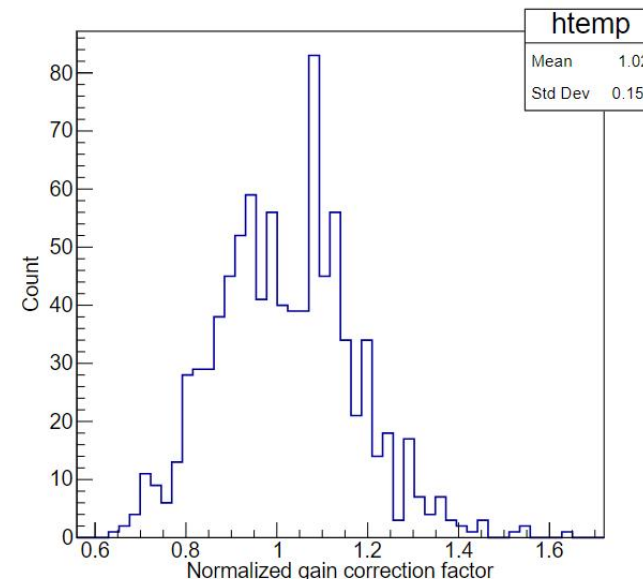
^{55}Fe 源测试



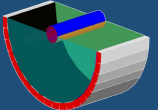
一个 Pad 上的 X-ray 能谱



增益不均匀性分布



归一化增益修正因子



➤ 漂移速度测试

H. Yi et al. CPC 38 (2014) 126002

• 激光

- 两束激光
- 反推激光径迹至顶点

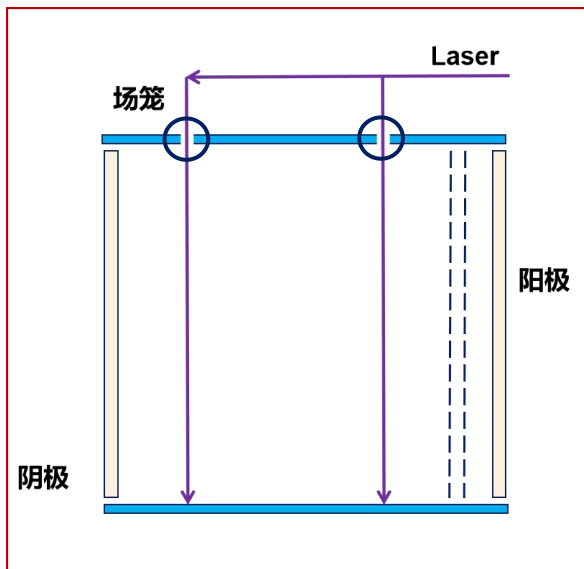
• 宇宙线

- 随机入射
- 漂移时间的分布体现漂移区的总长度

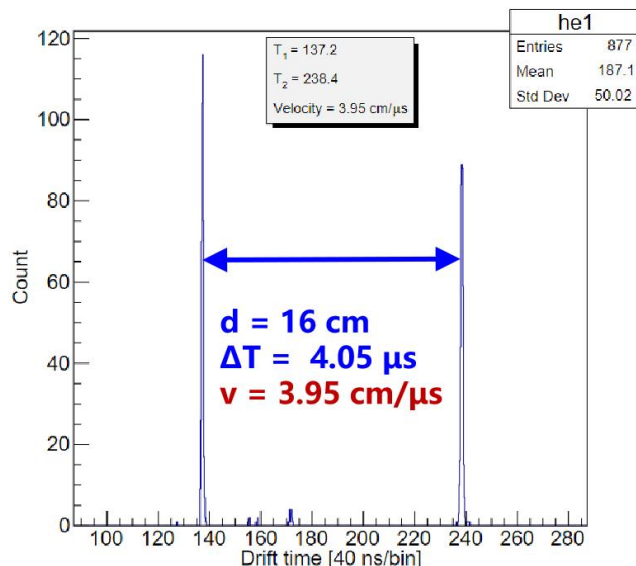
边缘函数

$$f(t) = B + A \frac{e^{-t/\tau_1}}{1 + e^{(t-T_0)/\tau_2}}$$

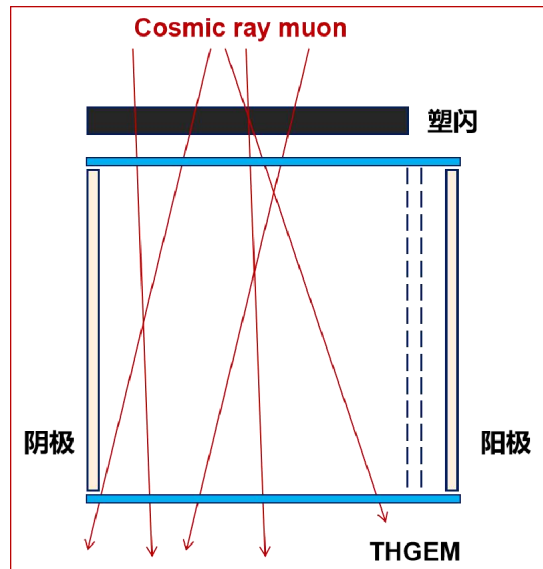
T_0 : 斜率最大的点



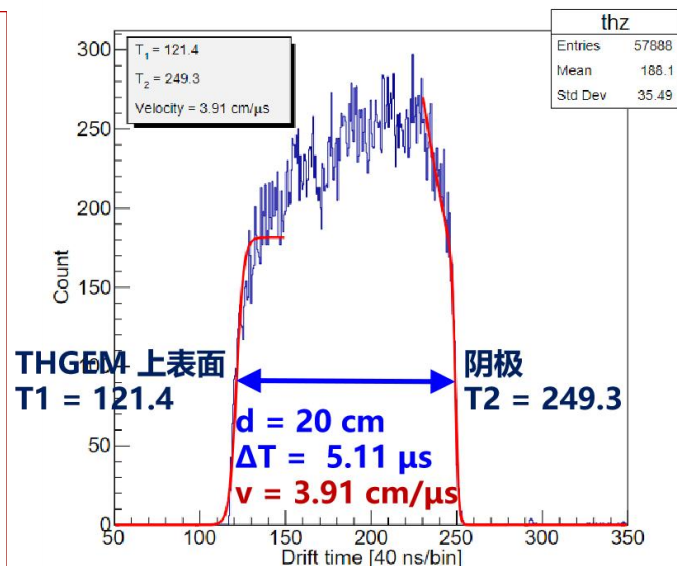
激光测试示意图



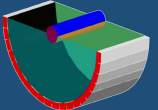
激光准直孔处的漂移时间分布



宇宙线测试示意图

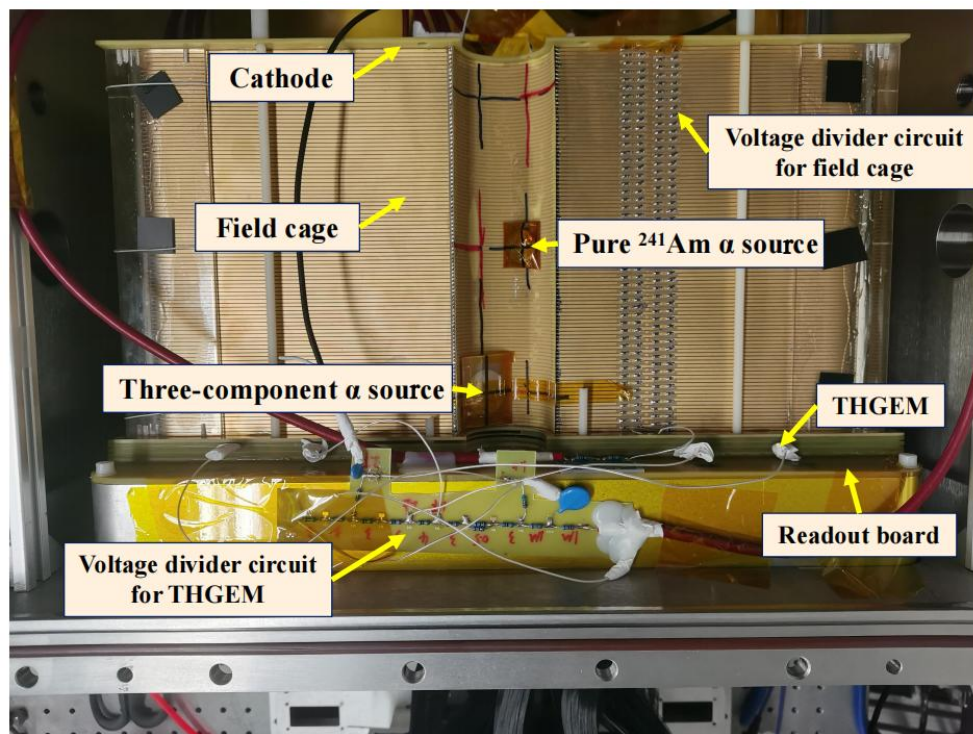


宇宙线径迹的漂移时间分布

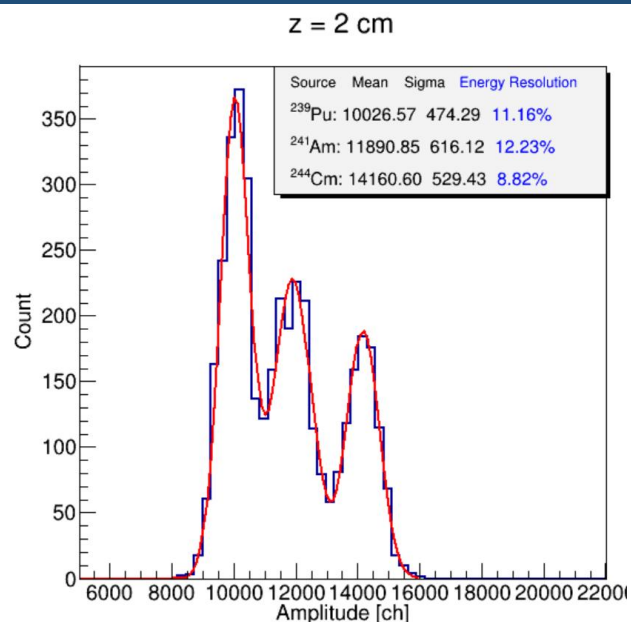


Alpha 源测试能量分辨

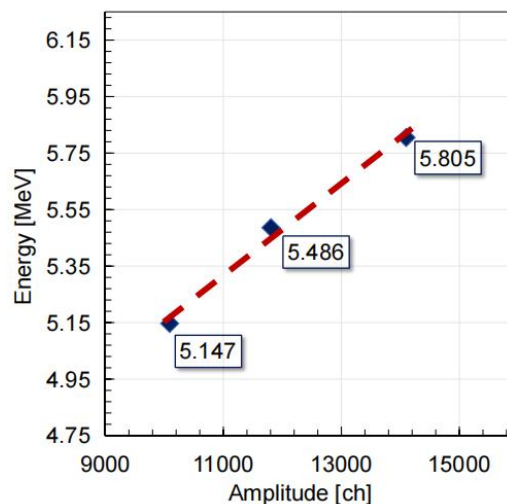
- ^{241}Am α 源 (5.486 MeV)
- 三组分 α 源 ^{239}Pu (5.157 MeV), ^{241}Am (5.486 MeV) and ^{244}Cm (5.805 MeV)



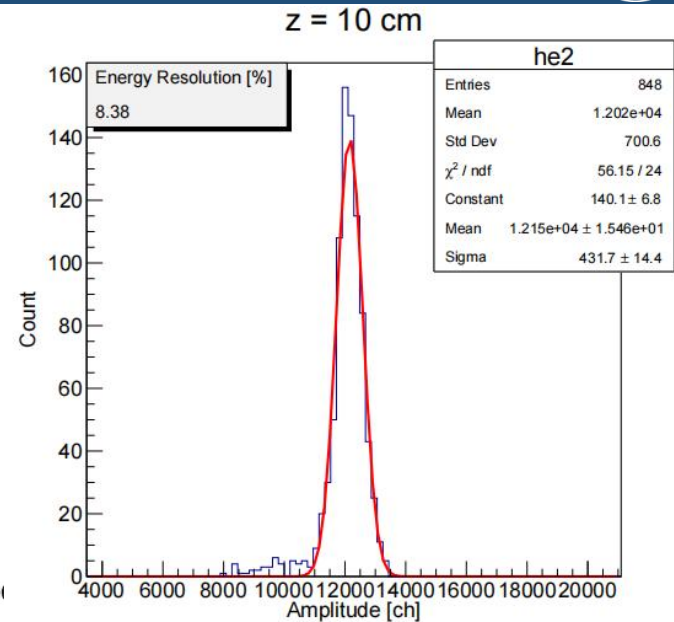
α 源测试现场



三组分 α 源能谱



能量沉积 vs 电荷量

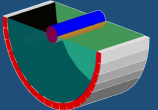


^{241}Am α 源能谱

能量分辨 8% @ ~5 MeV

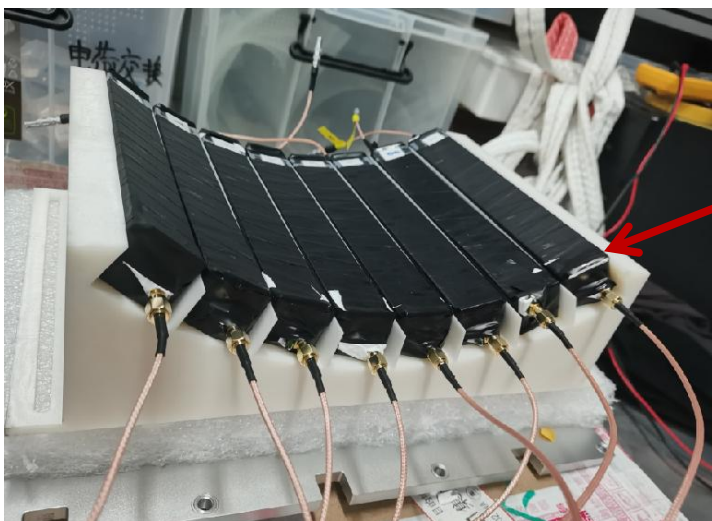
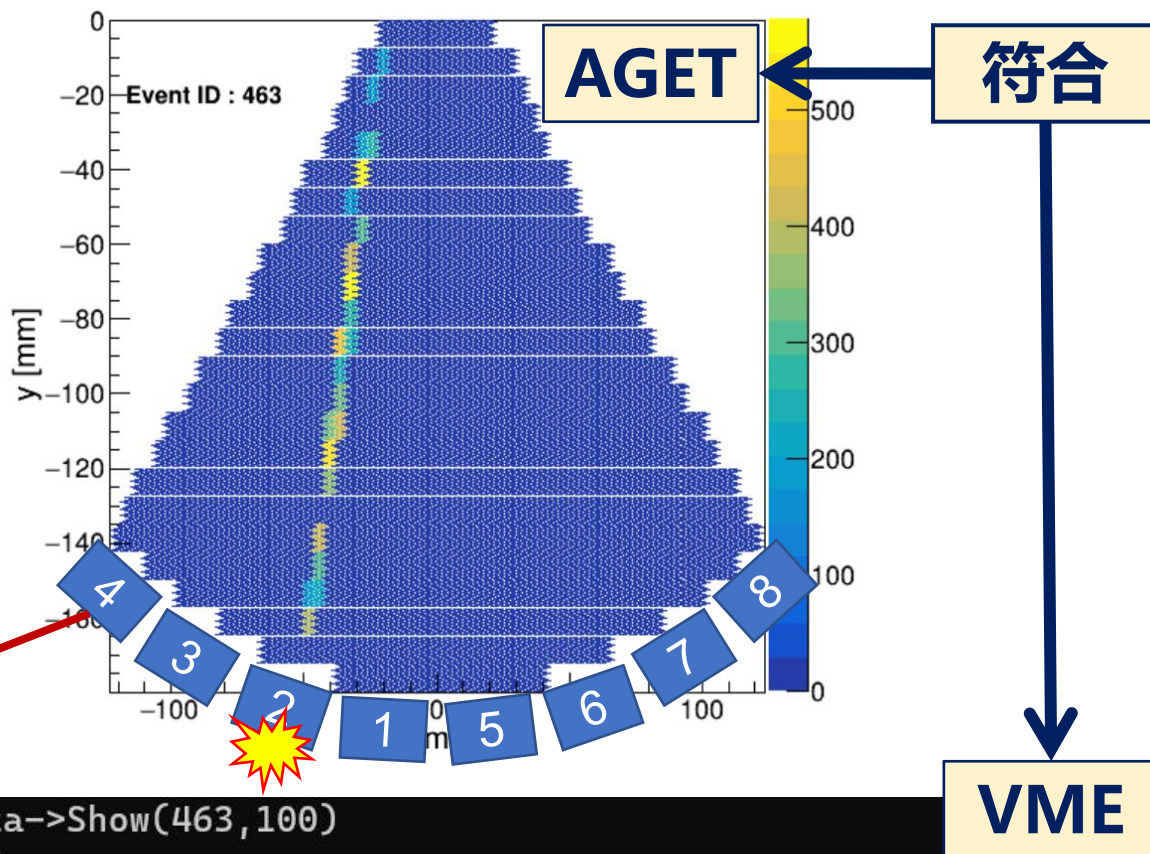
能量沉积 vs 电荷量

幅度 vs 漂移距离



TPC-CsI(Tl) 宇宙线联调

- TPC 用 AGET 获取
- CsI(Tl) 用 VME 的 V785 ADC 获取
- 触发:
 - CsI(Tl) 信号 → TTL 信号 → **AGET、VME**

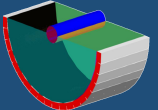


双端读出的 8 根 CsI(Tl) 晶体

```

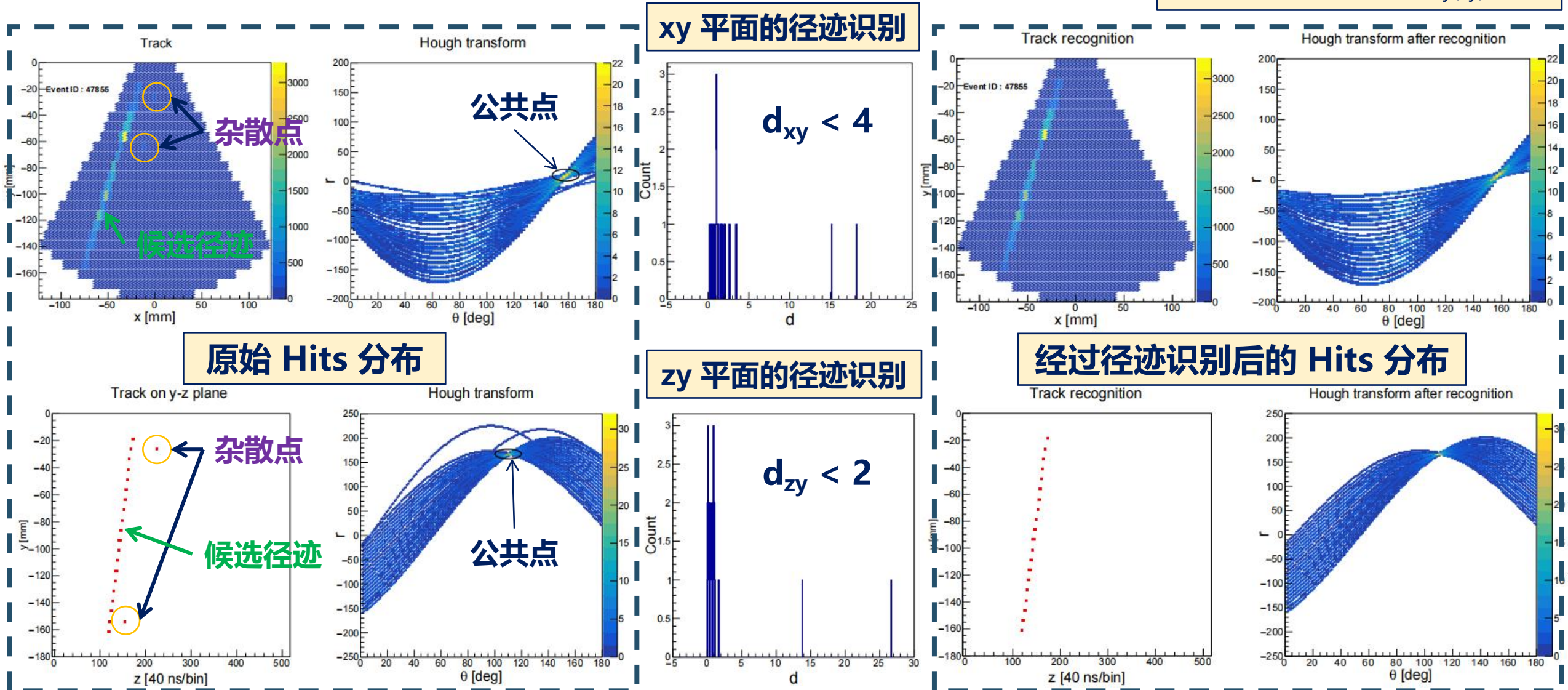
root [164] RawData->Show(463,100)
=====> EVENT:463
Mod102_TModV785 = (TModV785*)0x5579ba1e8140
fGeo              = 2
fCrateNum         = 1
MaxChannel        = 32
chdata[32]        = 49, 74, 75, 46, 65, 64, 94, 52, 95, 82,
                    88, 57, 95, 85, 81, 84, 490, 462, 3750, 1154,
                    164, 347, 480, 344, 153, 347, 96, 125, 33, 80,
                    100, 54
  
```

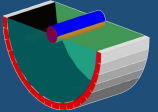
Scin-2



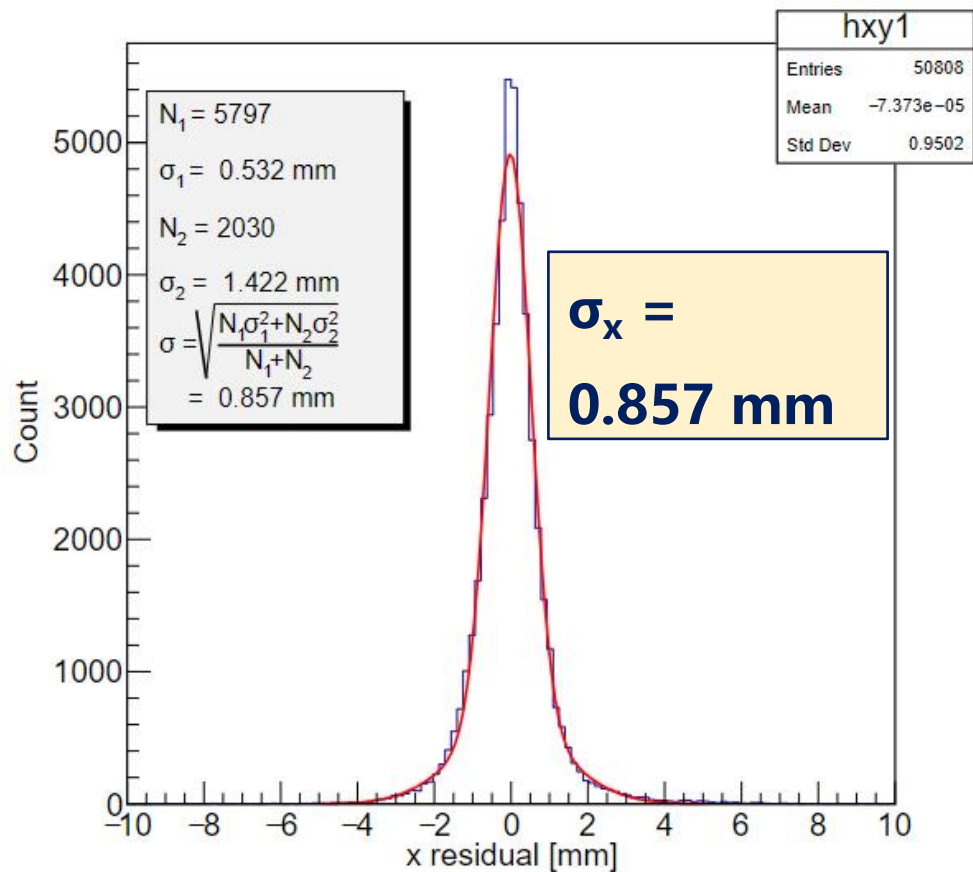
局限性：适用于单粒子径迹
审慎选择 $d_{xy(z)}$ 值

基于 Hough 变换的径迹识别和径迹重建

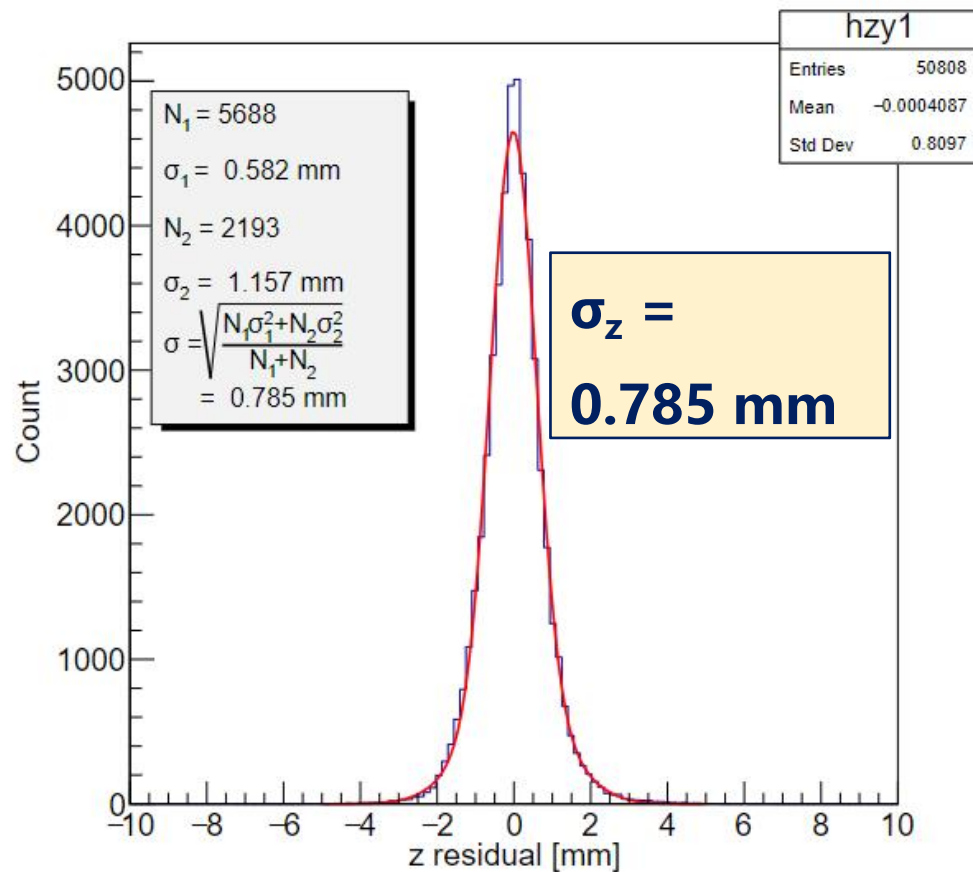




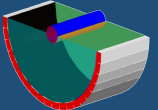
宇宙线 Muon 的径迹分辨



径迹在 xy 平面的径迹分辨

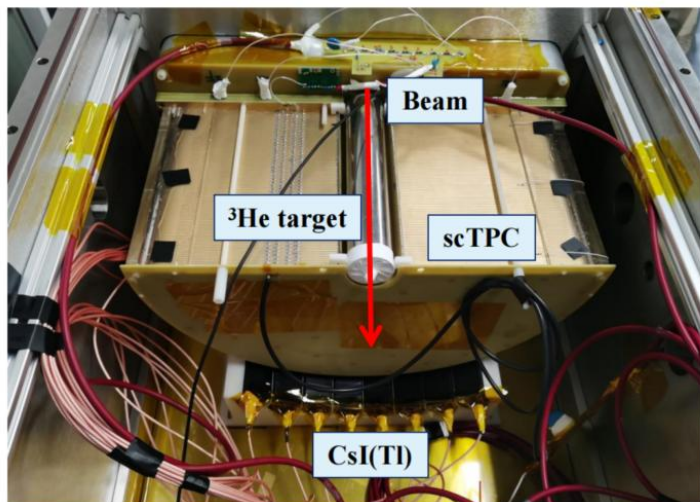


径迹在 zy 平面的径迹分辨

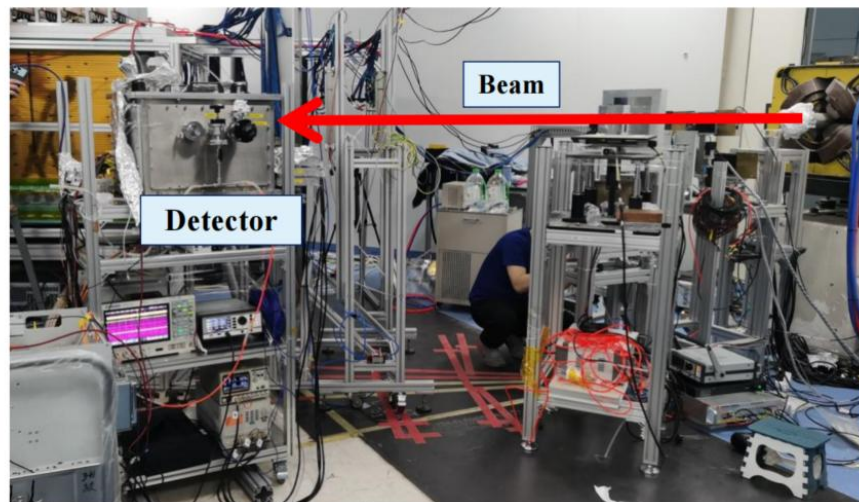


束流测试

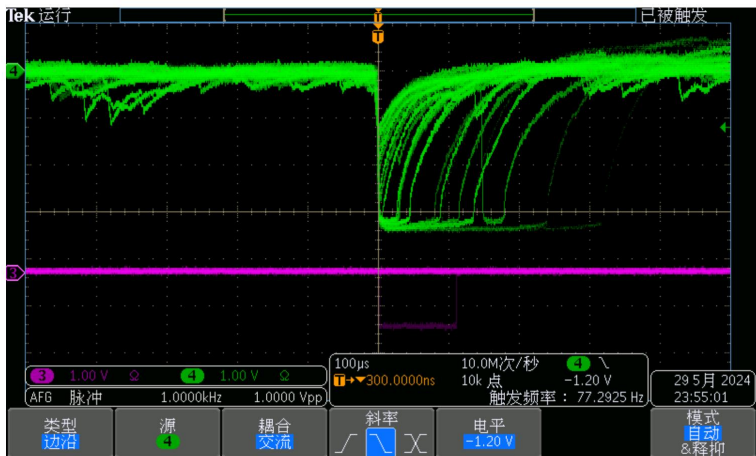
- 350 MeV/u Kr 束流
 - 2024 年 6 月 @ HIRFL
 - 主束, 10^5 pps
- 束流打 ^3He 靶
 - TPC + CsI(Tl) 阵列



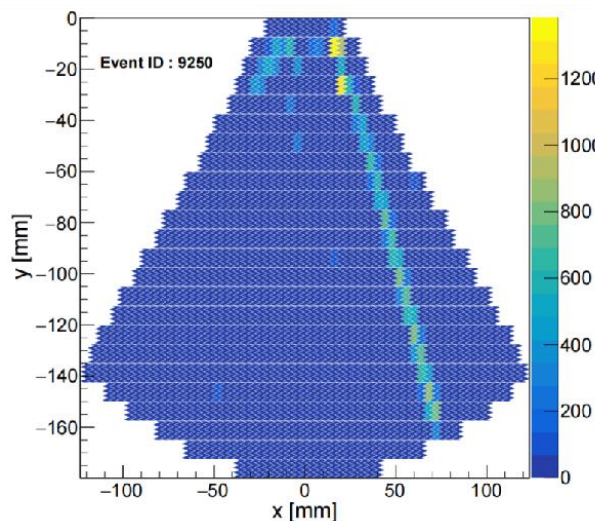
完全安装的探测系统



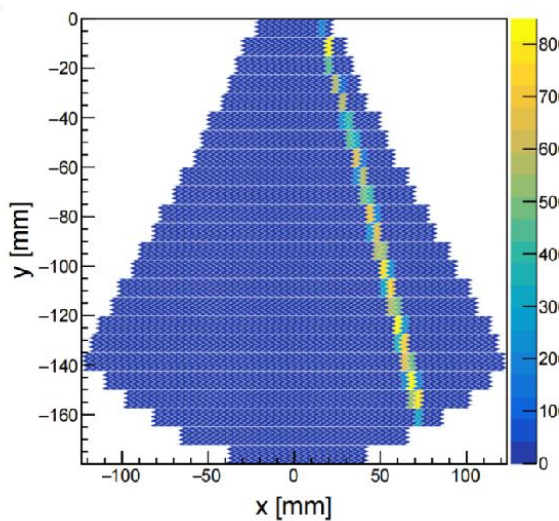
束流测试现场



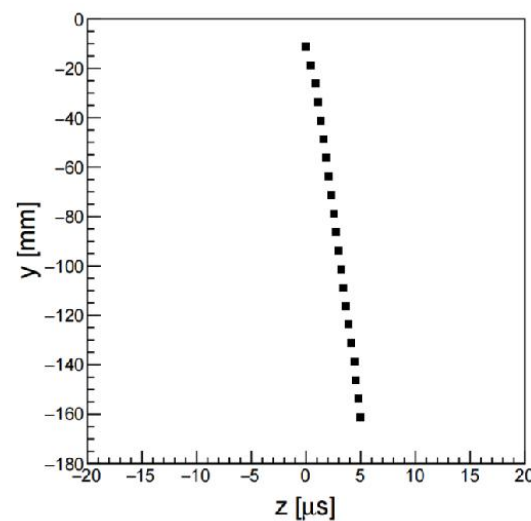
TPC 的多个束流信号



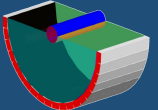
未经识别的原始 Hits 在读出平面 (xy 平面) 的投影



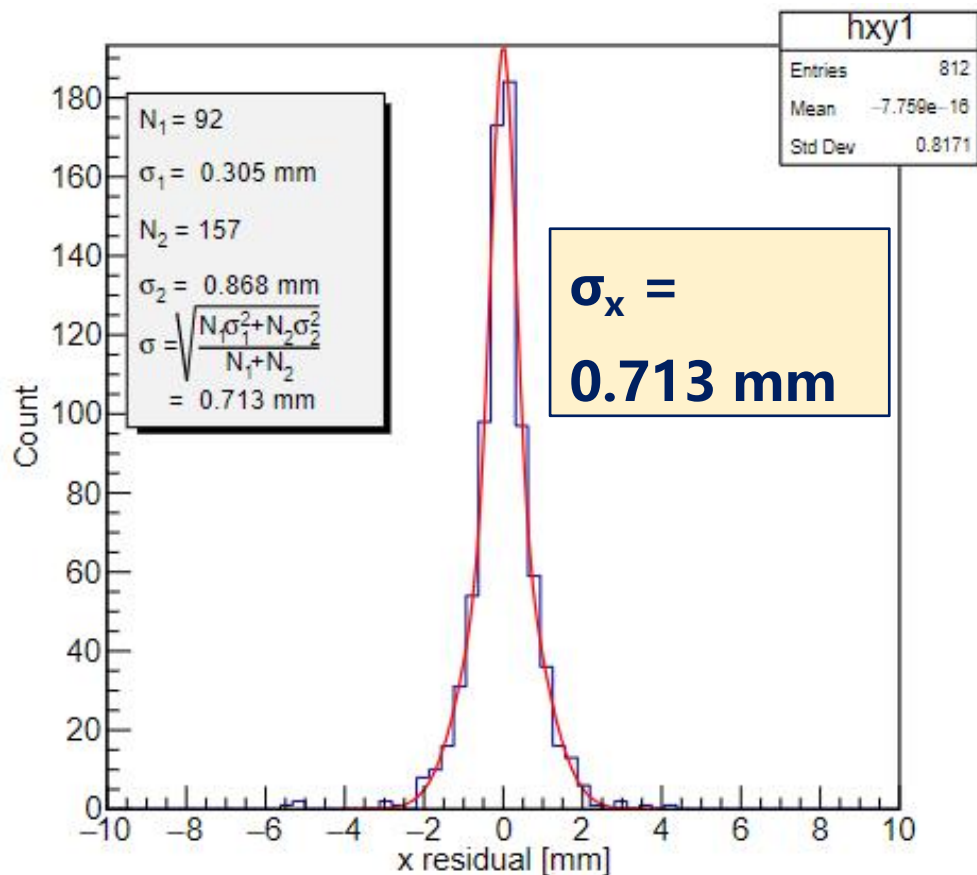
经过识别的 Hits 在读出平面 (xy 平面) 的投影



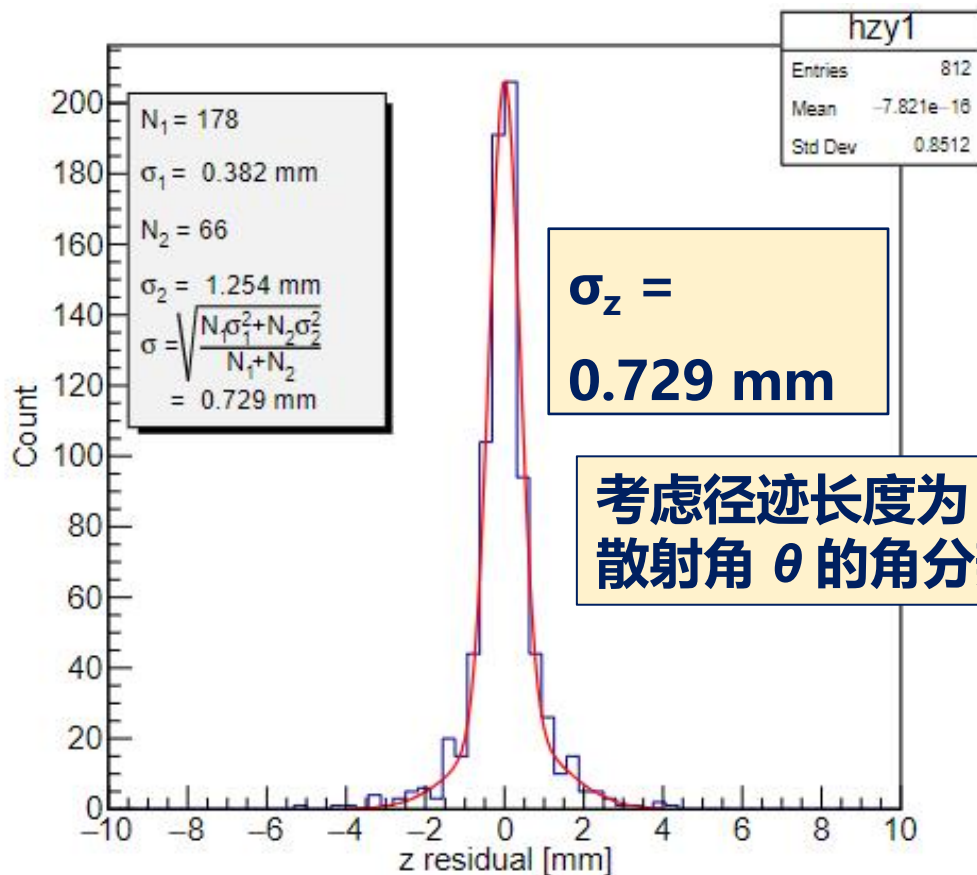
经过识别的 Hits 在漂移平面 (zy 平面) 的投影



束流实验次级粒子的径迹分辨

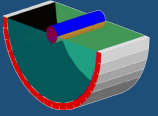


径迹在 xy 平面的径迹分辨

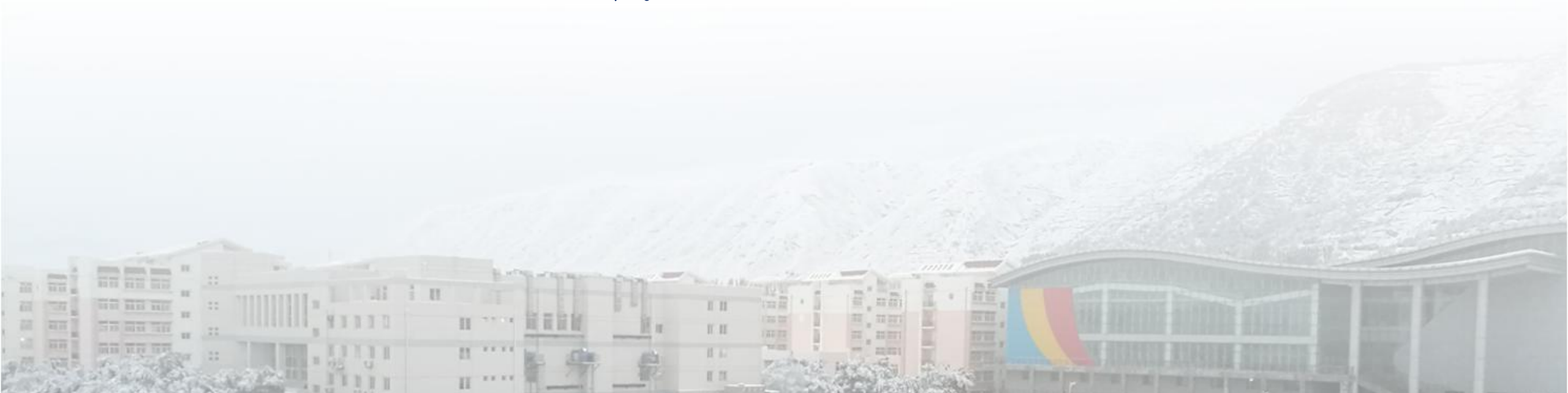


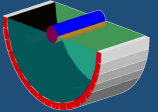
径迹在 zy 平面的径迹分辨

考虑径迹长度为 20 cm
散射角 θ 的角分辨好于 0.2°



IV. 总结与展望



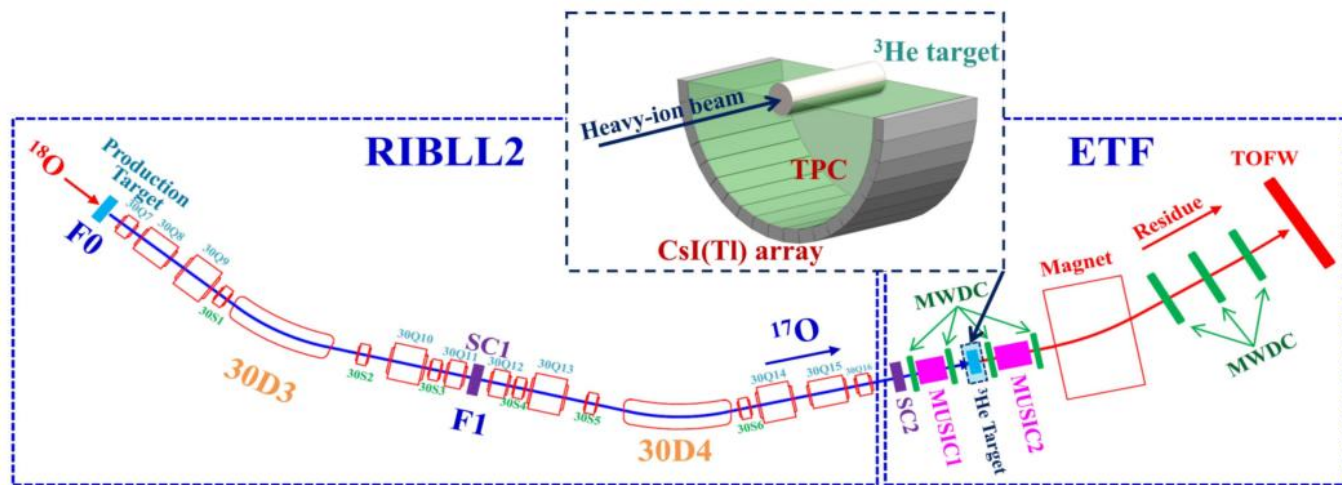


总结

- 搭建探测器
- 电子漂移速度, 增益修正因子
- 能量分辨, 位置分辨
- TPC-CsI(Tl) 联调: 触发合适
- 束流测试: 工作正常

展望

- RIBLL2-ETF 束流实验 (2025年之前)
- HIAF-HFRS 束流实验 (2025年之后)
- 极化 ^3He 靶电荷交换反应实验



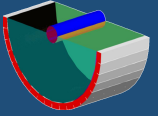
Acknowledgments

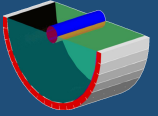
- ▶ 感谢中国科学院近代物理研究所段利敏研究员、余玉洪研究员、王世陶研究员、魏向伦副研究员、鲁辰桂副研究员、马朋副研究员，清华大学博士研究生秦智的指导和帮助
- ▶ 感谢各位老师的建议和批评指正
- ▶ 感谢会务组



THANKS!

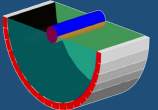
何志轩 (hezhx21@lzu.edu.cn)



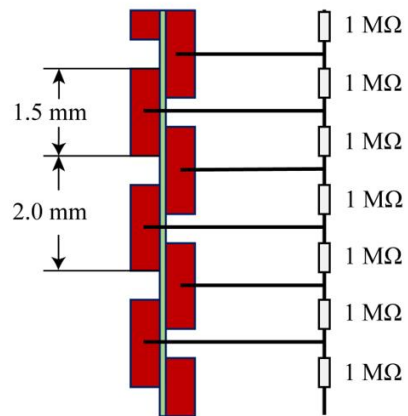


Backup





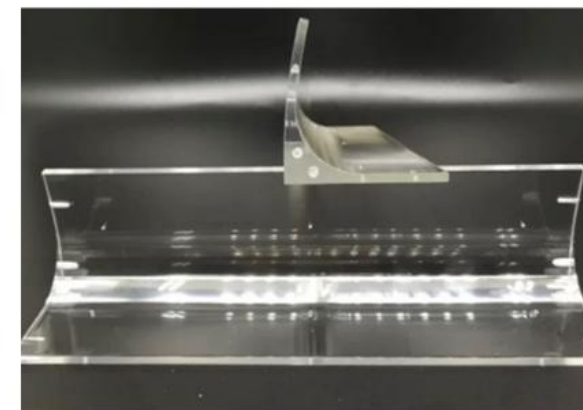
场笼的搭建



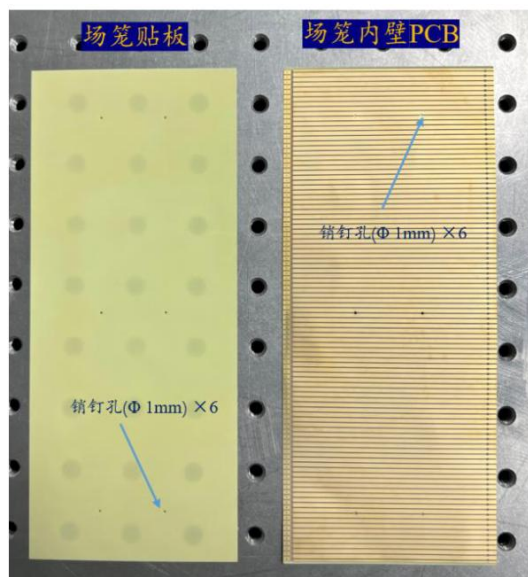
镜像电极设计



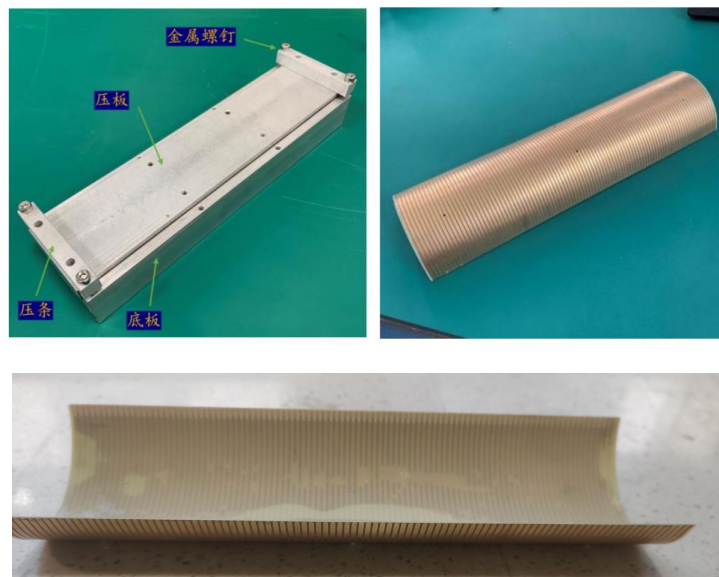
场笼 PCB



有机玻璃支架



内场笼制作和成品



内外场笼及电阻串焊接



场笼实物图