MARVEL实验的气体微像素探测器研究

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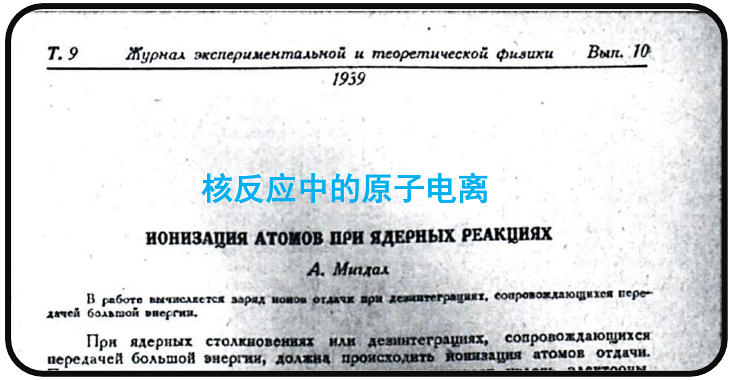
July, 23th, 2026 Huizhou

MigdAl pRocess Validation by nEutruaL scattering

University of Chinese Academic of Sciences

Migdal 效应


Т. 9 Журнал экспериментальной и теоретической физики Вып. 10
1939

核反应中的原子电离

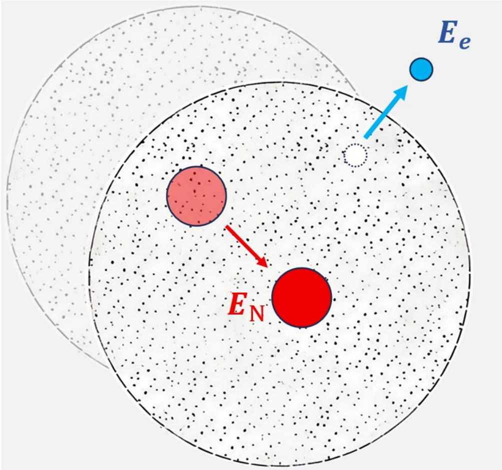
ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал

В работе вычисляется заряд ионов отдачи при дезинтеграциях, сопровождающихся передачей большой энергии.

При ядерных столкновениях или дезинтеграциях, сопровождающихся передачей большой энергии, должна происходить ионизация атомов отдачи.

（本文计算了伴随有大能量转移的核衰变过程中，反冲离子的电荷。）

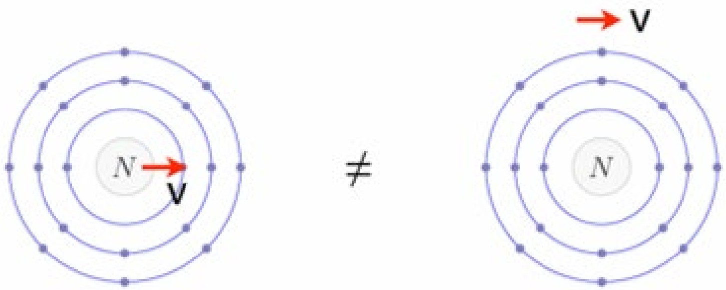


关键假设:反冲核库伦场变化时间尺度远小于核外电子运动弛豫时间

Migdal计算采用的方案:

$$|\Phi'_{ec}\rangle = \underbrace{e^{-im_e\sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}}_{\text{核反冲}}|\Phi_{ec}\rangle$$

电离概率： $\mathcal{P} = |\langle\Phi^*_{ec} \mid \Phi'_{ec}\rangle|^2$

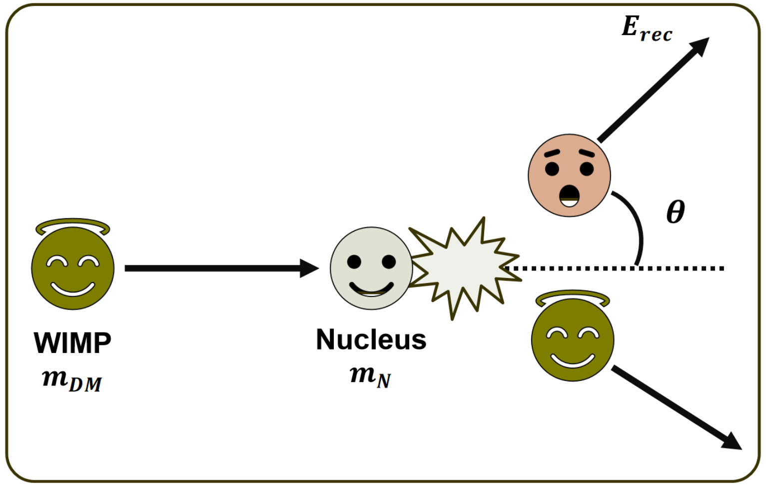


Ibe的框架优化:

$$iT_{FI} \simeq F_A(q_A^2)\mathcal{M}(q_A^2) \times Z_{FI}(\mathbf{q}_e) \times i(2\pi)^4 i(p_F - p_I)$$

- 原子散射
- 保证能动量守恒

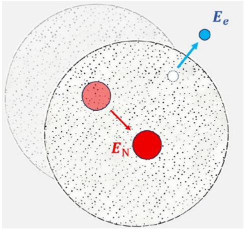
暗物质直接探测

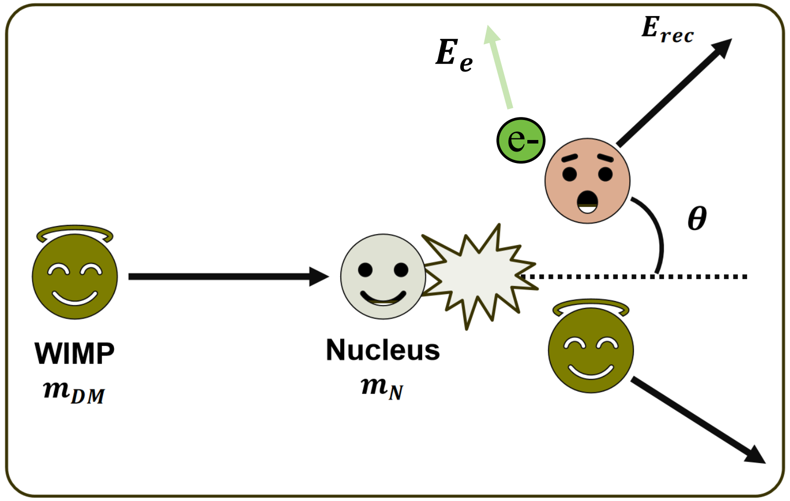


$$m_{DM} = 10\ \mathrm{GeV/c^2};\ v = 220km/s;$$
$$m_N = 131\ \mathrm{GeV/c^2}$$

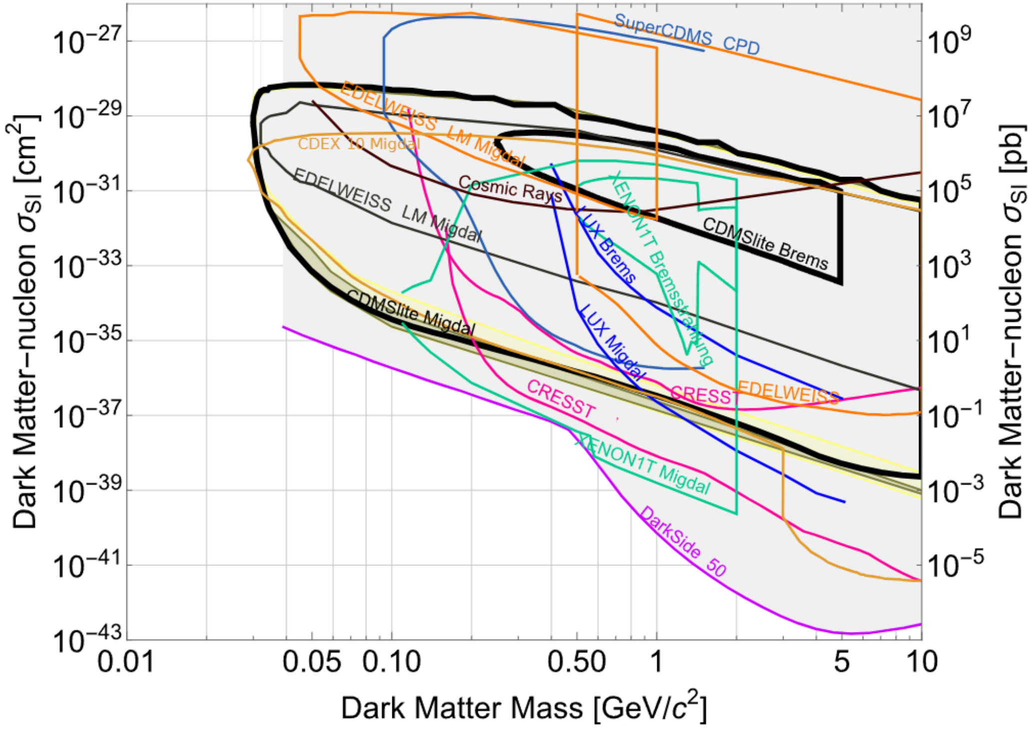
$$E_{rec} \leq \frac{4m_{DM}\, m_N}{(m_{DM} + m_N)^2} E_{DM} = 0.7\ \mathrm{keV_{nr}}$$

引入Migdal效应



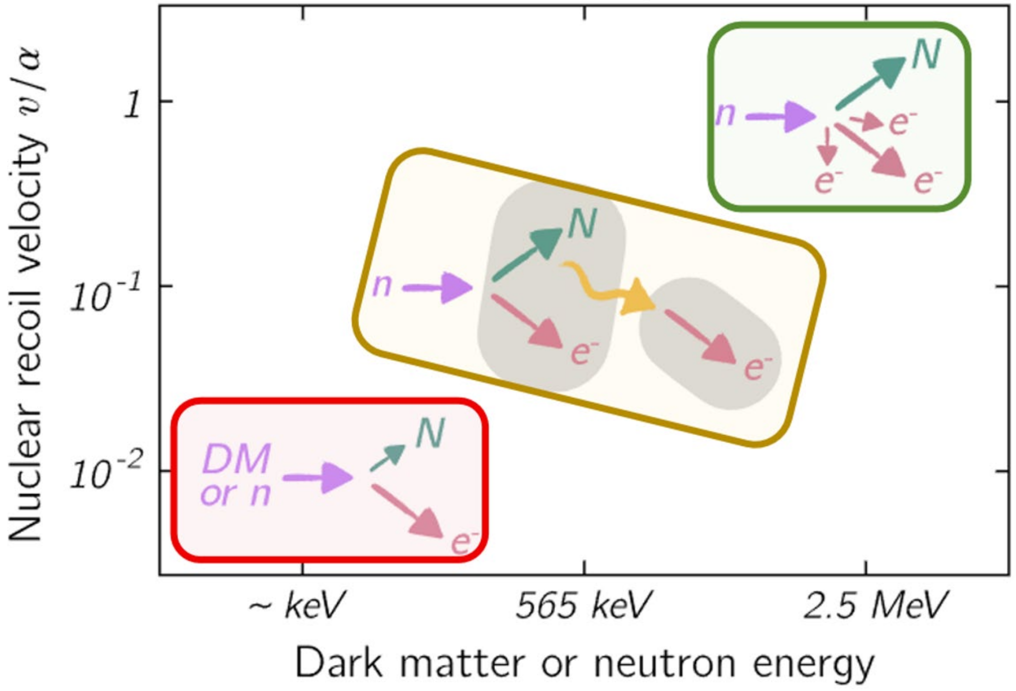


$$E_e \leq \frac{m_N}{m_{DM} + m_N} E_{DM} = 2.5\ \mathrm{keV_{ee}}$$



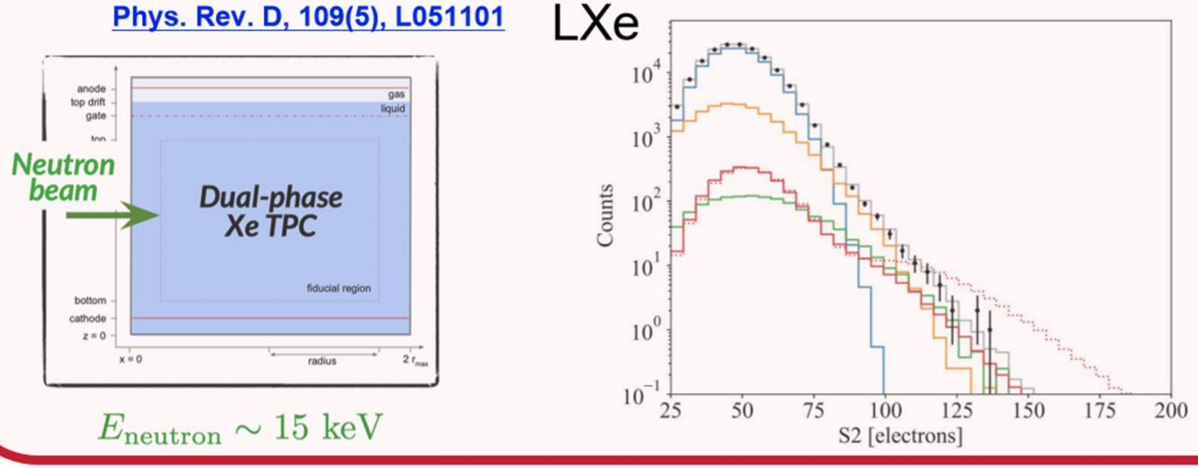
Migdal效应直接探测实验

[Phys. Rev. D,107, 035032](#)



[Phys. Rev. D, 109(5), L051101](#)

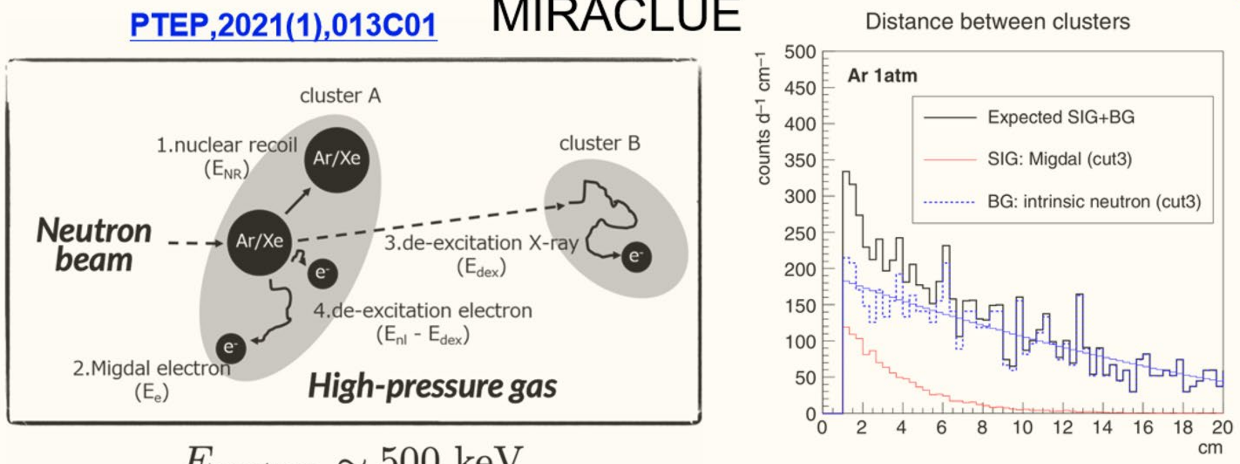
LXe



$E_{\mathrm{neutron}} \sim 15$ keV

[PTEP,2021(1),013C01](#)

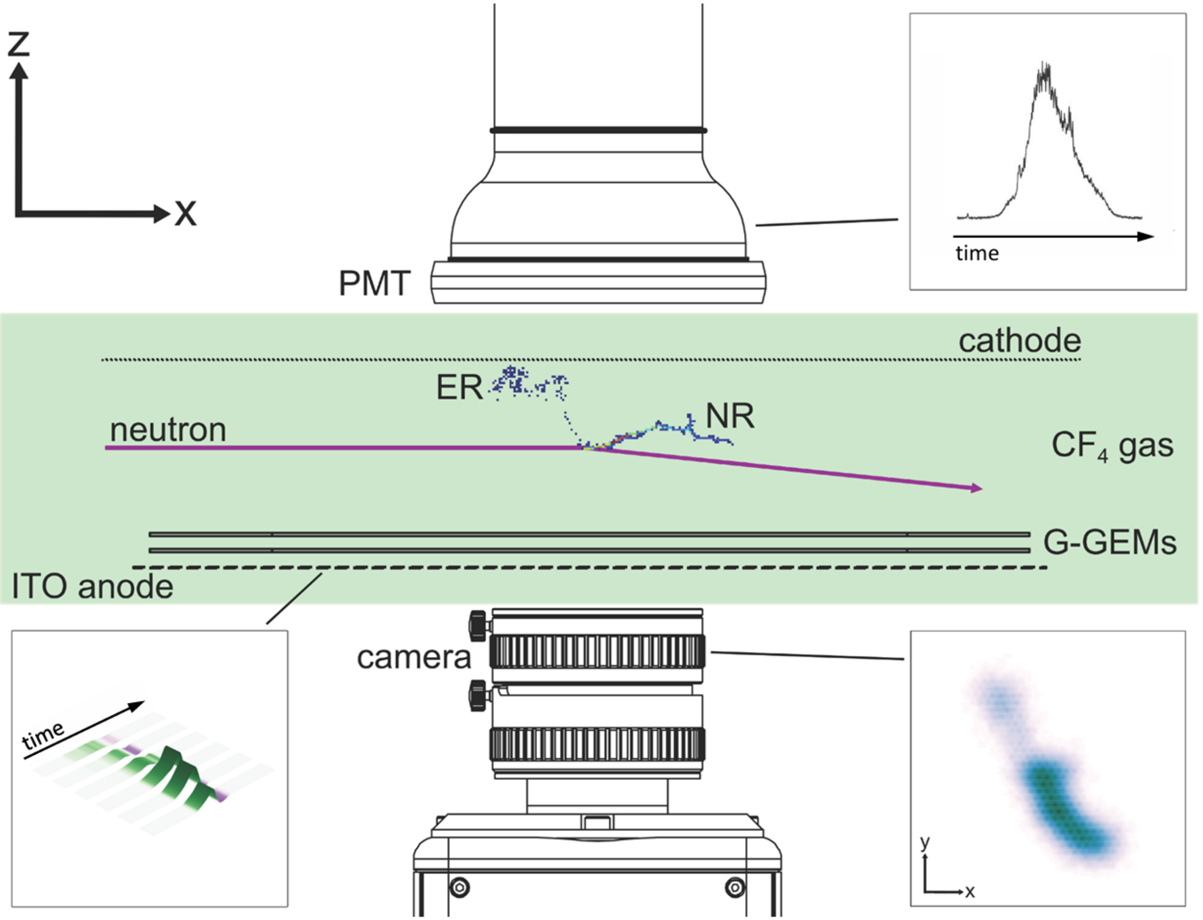
MIRACLUE



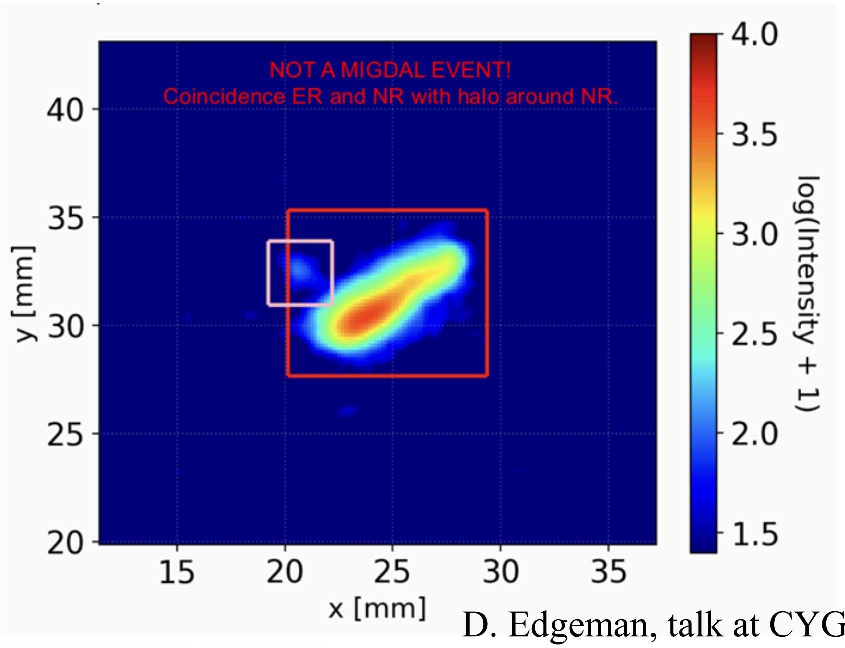
$E_{\mathrm{neutron}} \sim 500$ keV

Migdal效应直接探测实验

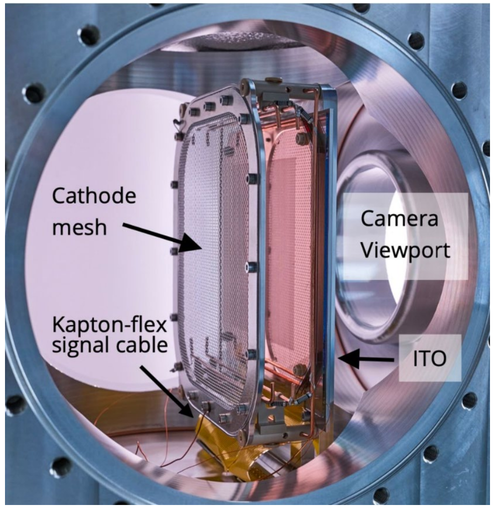
MIGDAL



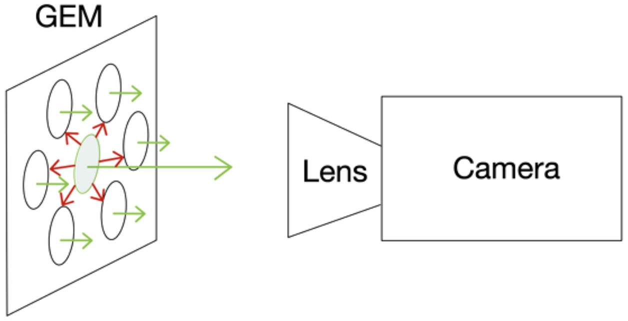
Astropart. Phys.151 (2023), 102853



D. Edgeman, talk at CYGNUS Workshop 9, 23 Feb 2026.

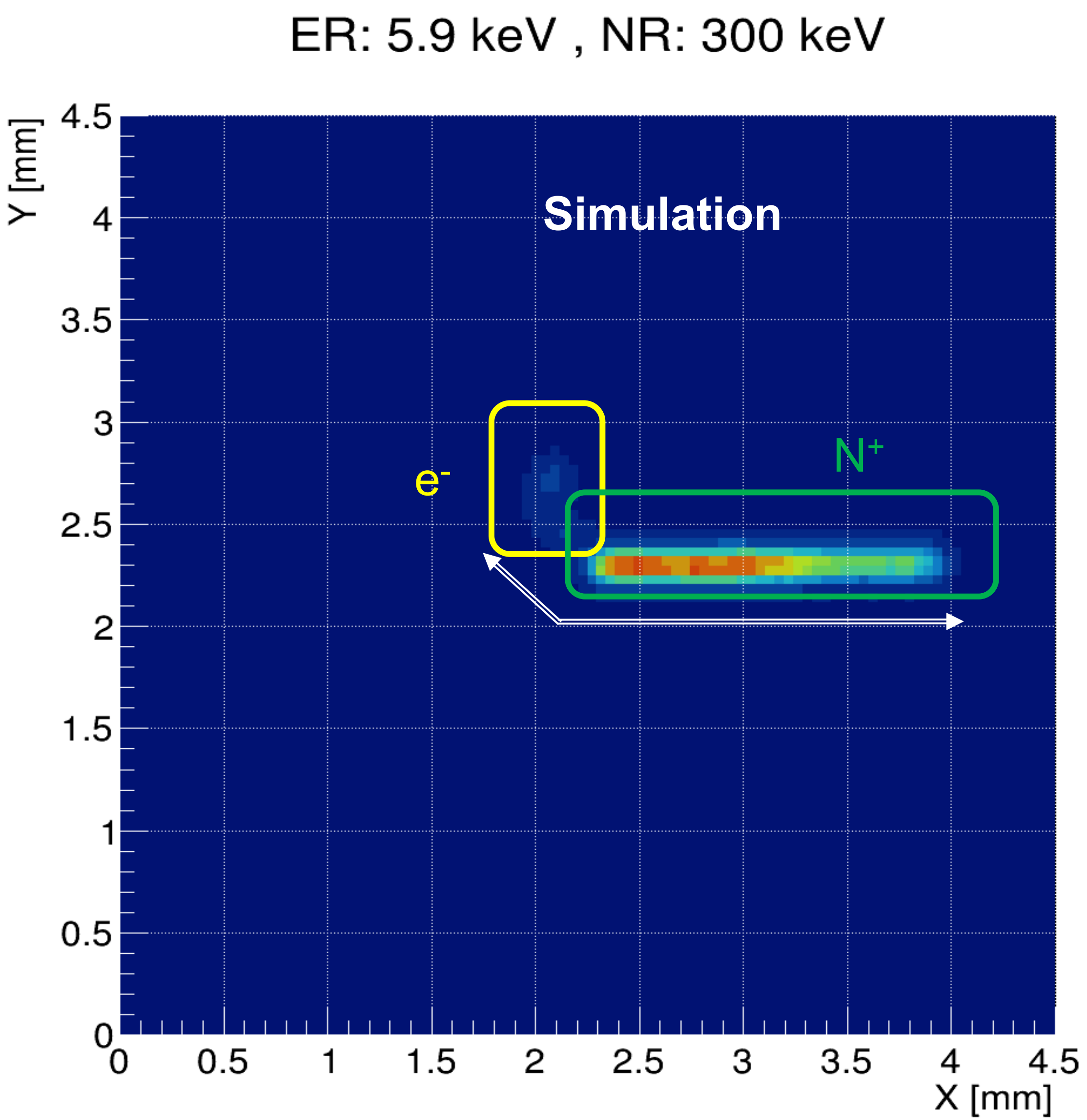


P. Majewski, talk at 9th CYGNUS Workshop, 25 Feb 2026.



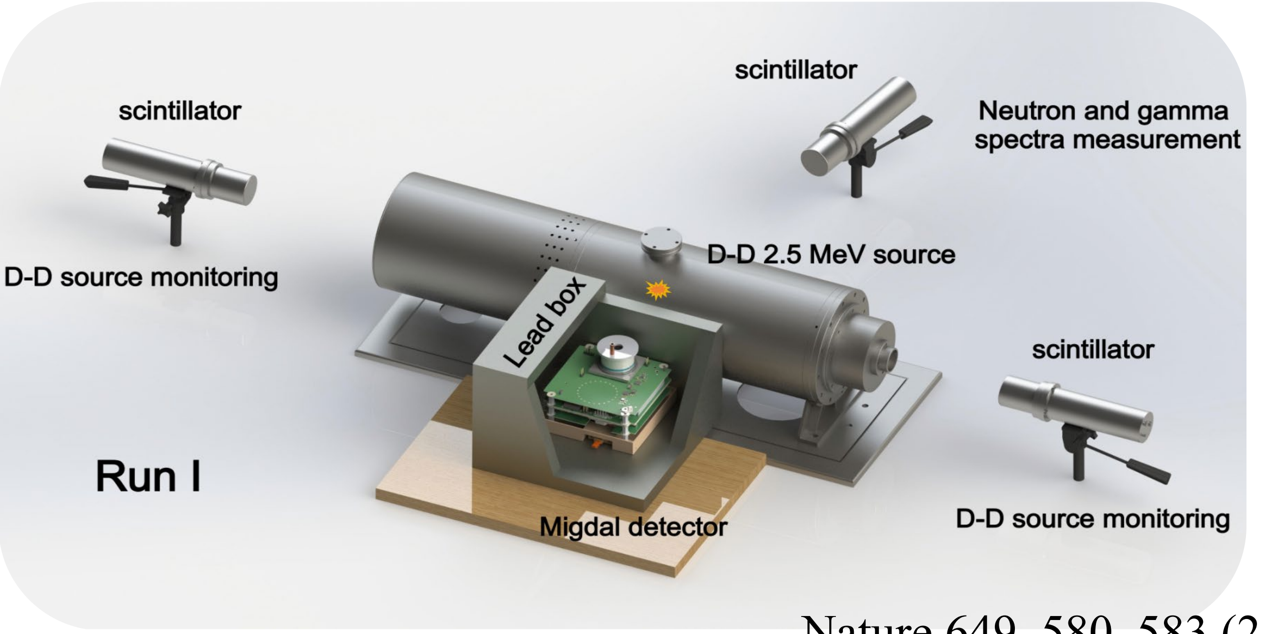
arXiv:2604.27399

探测器需求

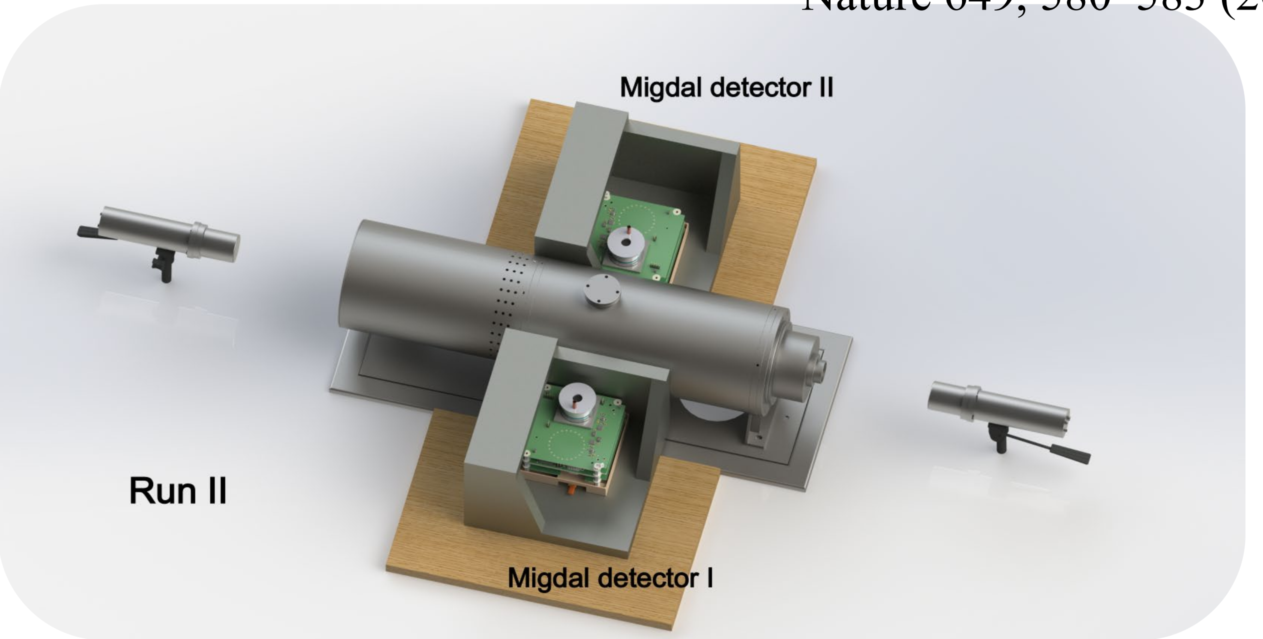


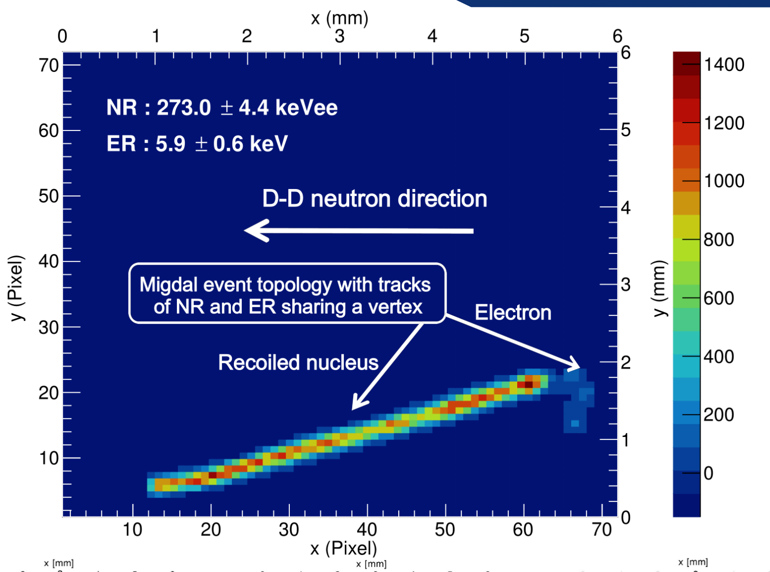
- 电子~keV，核子~百keV
  - 好的能量分辨
  - 大的动态响应范围
- 电子与核子径迹共顶点
  - 好的顶点分辨能力
- 降低潜在本底水平
  - 好的时间分辨

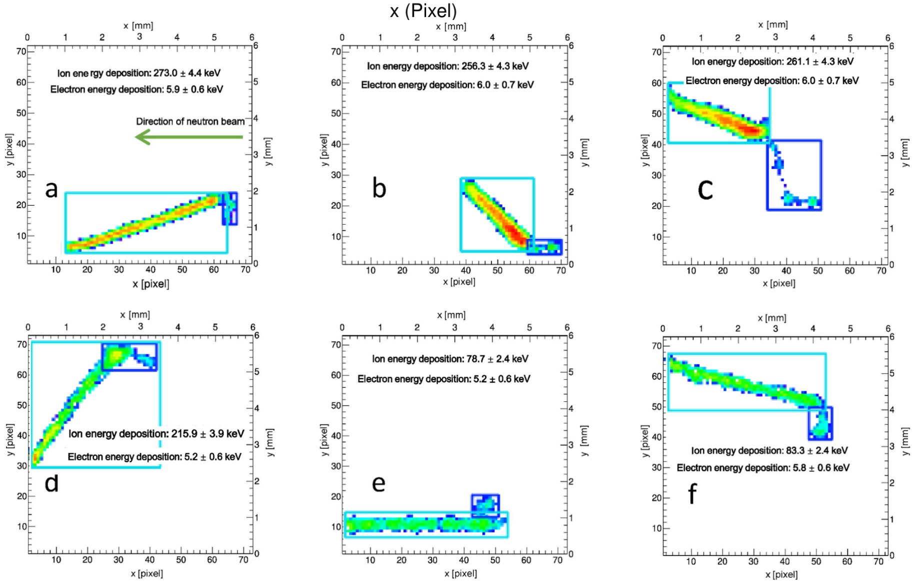
MARVEL实验



Nature 649, 580–583 (2026)

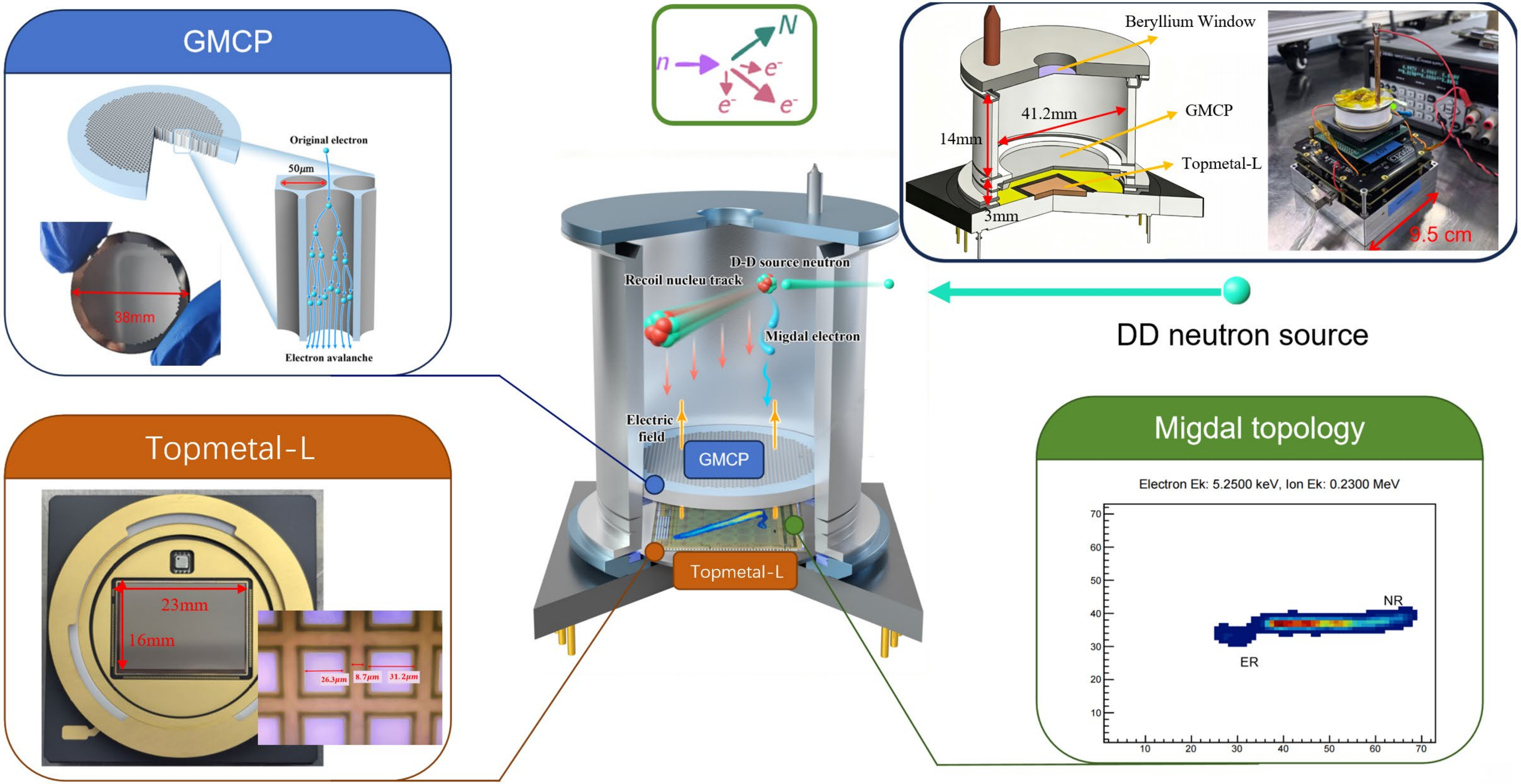




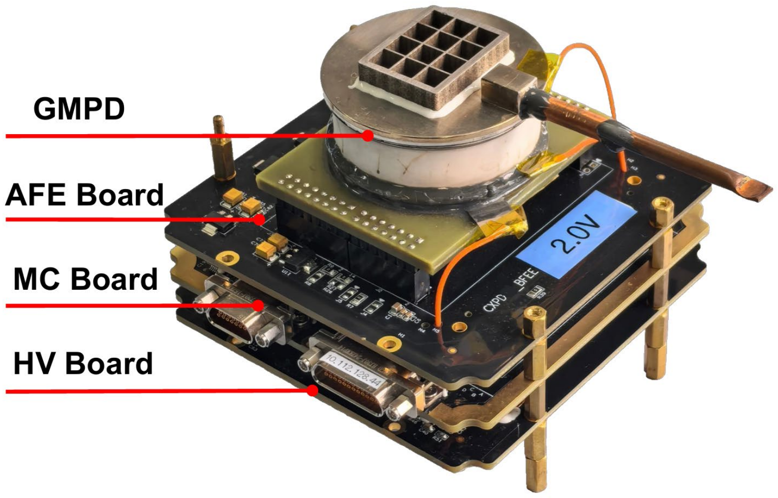


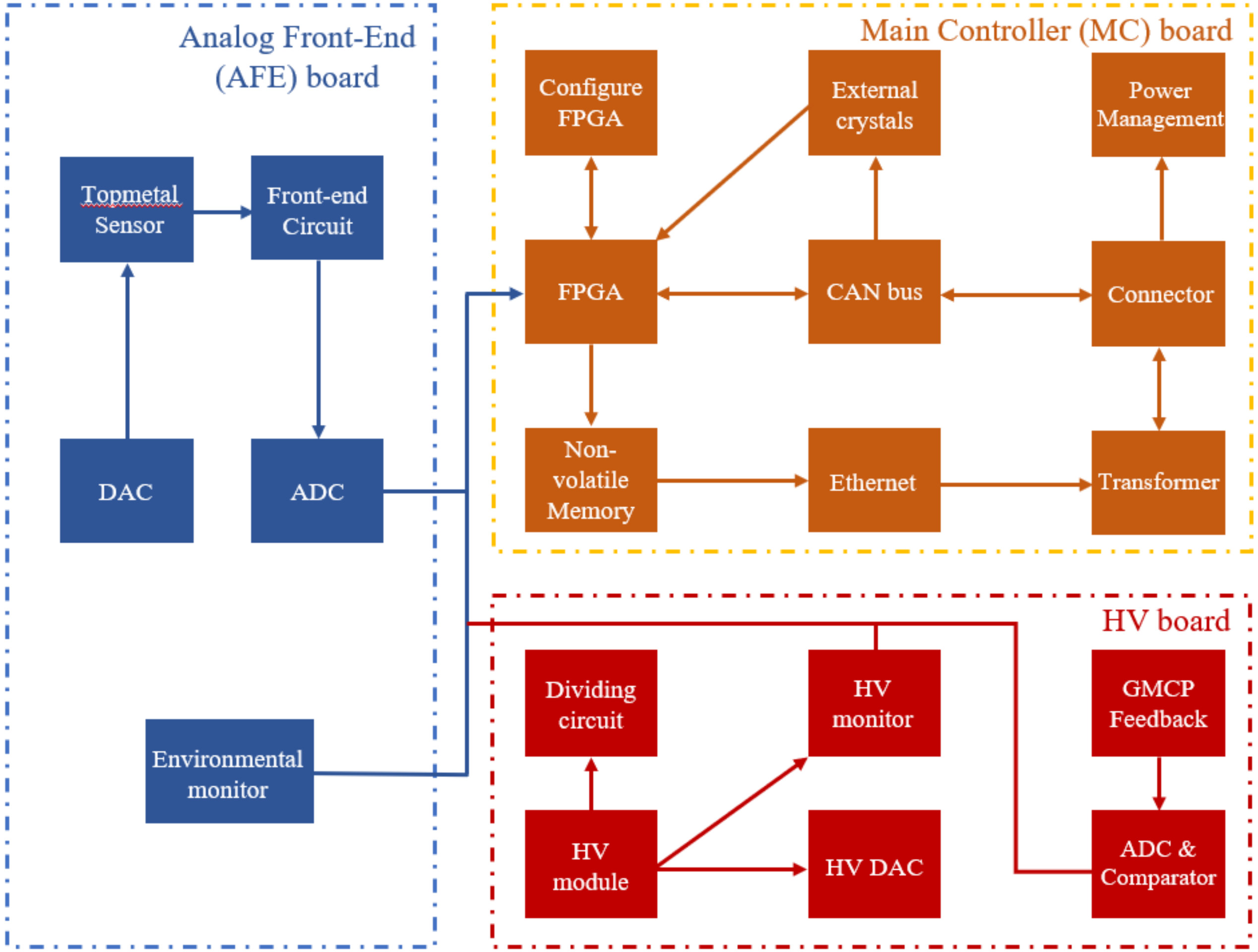
$$P_{\text{Migdal}}(5\text{keV} < \text{ER} < 10\text{keV}, \text{NR} > 35\text{keV}_{\text{ee}}) = 4.9^{+2.6}_{-1.9} \times 10^{-5}$$

气体微像素探测器


GMCP
Original electron
50μm
38mm
Electron avalanche
Topmetal-L
23mm
16mm
26.3μm
8.7μm
31.2μm
n
N
e-
e-
e-
D-D source neutron
Recoil nucleu track
Migdal electron
Electric field
GMCP
Topmetal-L
Beryllium Window
41.2mm
GMCP
14mm
Topmetal-L
3mm
9.5 cm
DD neutron source
Migdal topology
Electron Ek: 5.2500 keV, Ion Ek: 0.2300 MeV
NR
ER
70
60
50
40
30
20
10
10
20
30
40
50
60
70

电子学系统





- 参数配置
- FPGA预处理
- 数据传输

- 提高高压
- 高压监控、GMCP监控
- 高压保护
- GMCP信号采集及数字化

- Topmetal像素信号采集及数字化
- 气压、温度环境监测

动态响应与径迹成像

- 反冲核 ~百keV
- 电子 ~ keV

跨2量级动态范围

- 反冲核 ~ cm
- 电子 ~ mm

读出区域 ~ cm

- Migdal电子连续能谱

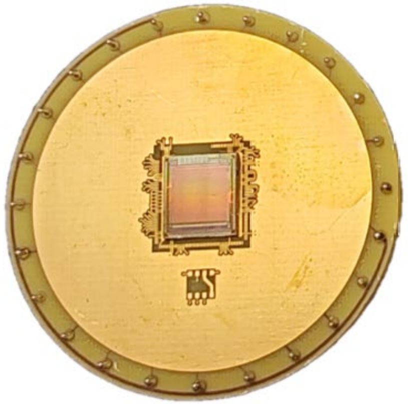
良好的信号—能量对应关系

动态响应与径迹成像

	Topmetal-II⁻	Topmetal-L
芯片尺寸 [mm²]	8 × 9	17 × 24
有效面积 [mm²]	6 × 6	16.02 × 23.04
像素阵列	72 × 72	356 × 512
像素密度 [像素/mm²]	145	494
功率密度 [W/cm²]	2.778	0.195
像素增益 [μV/电子]	–	76.04
等效噪声电荷（ENC）[电子]	13.9	22.8
读出模式	卷帘门	卷帘门 / 哨兵模式
单帧时间开销	2.6 ms/帧	0.73 ms/帧（哨兵模式）

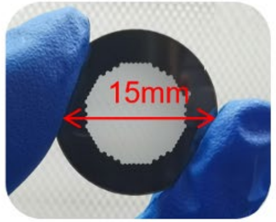
$6 \times 6\text{mm} \rightarrow 16 \times 23\text{mm}$

$83\mu m$ pixel size $\rightarrow$ $45\mu m$ pixel size

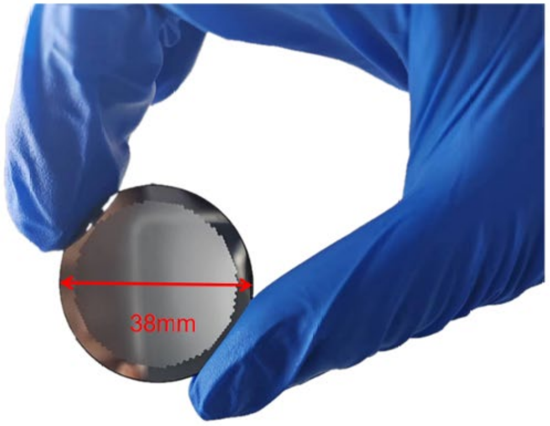


Topmetal-II

Topmetal-L

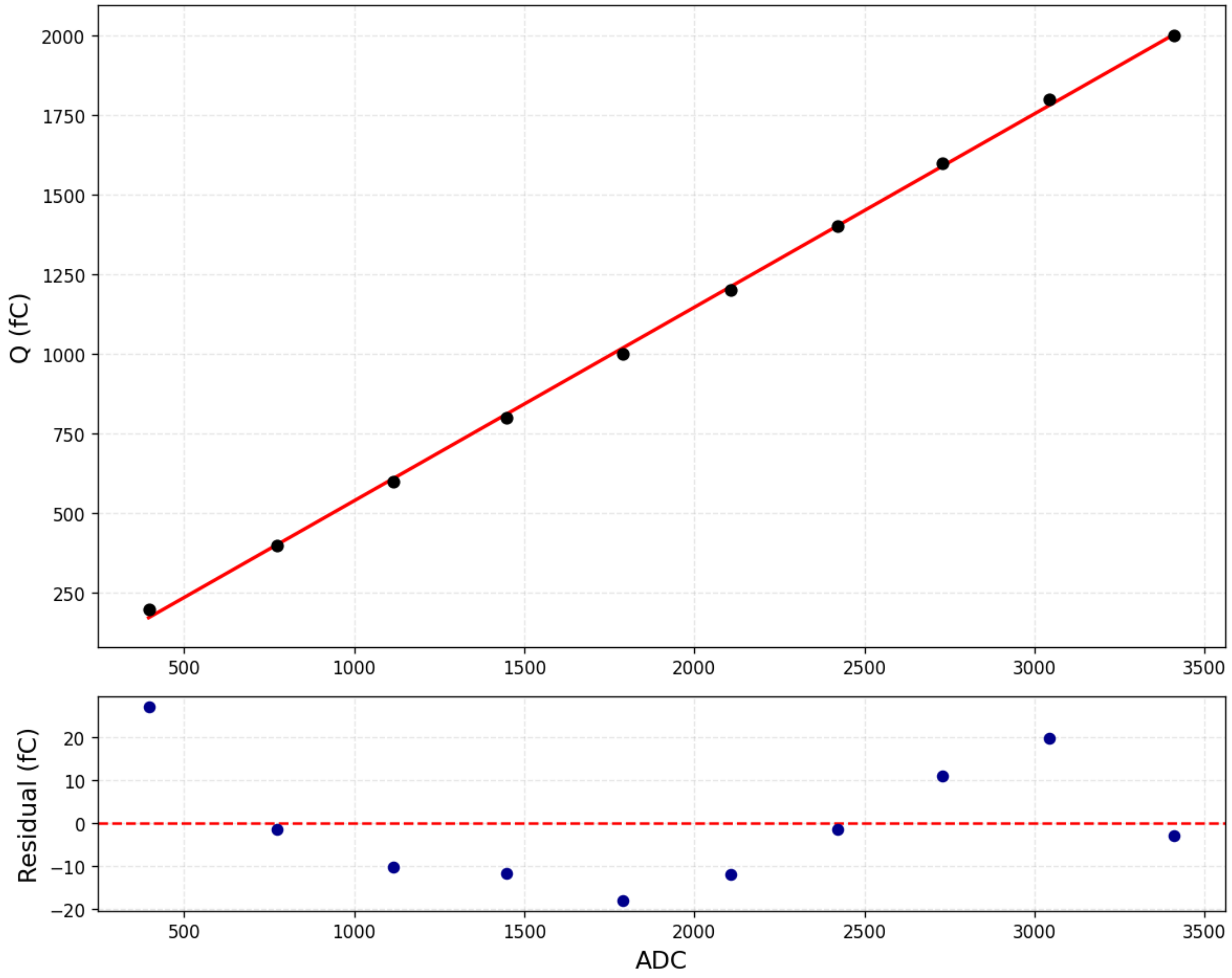


GMCP



Larger GMCP

动态响应与径迹成像



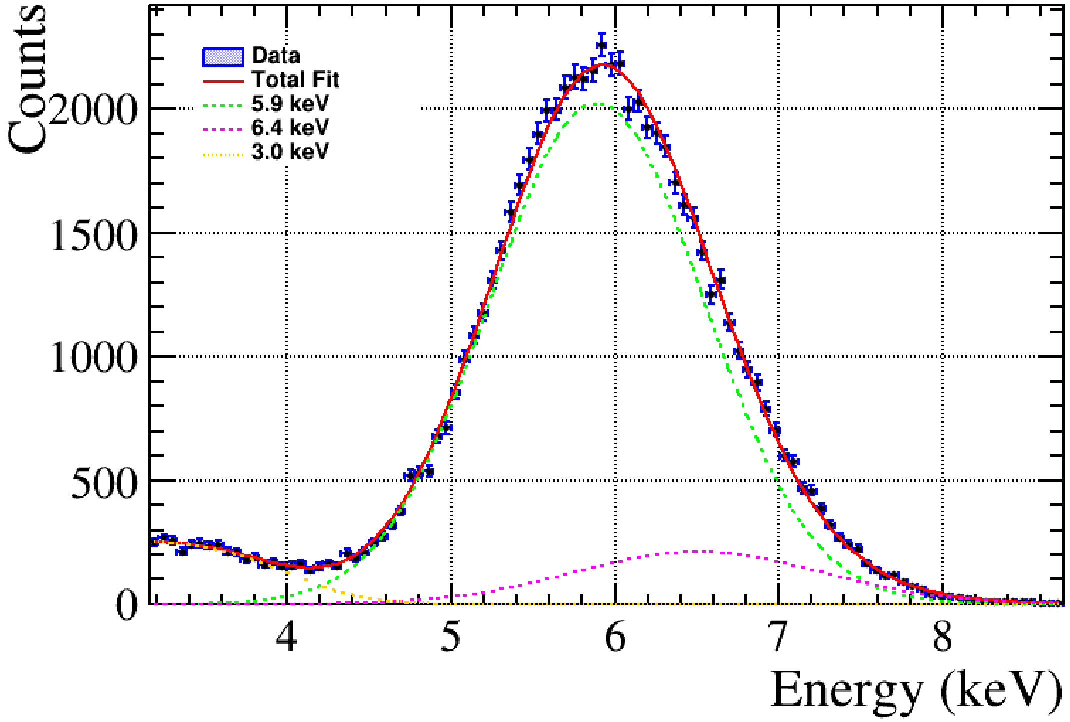
多道全区域良好线性

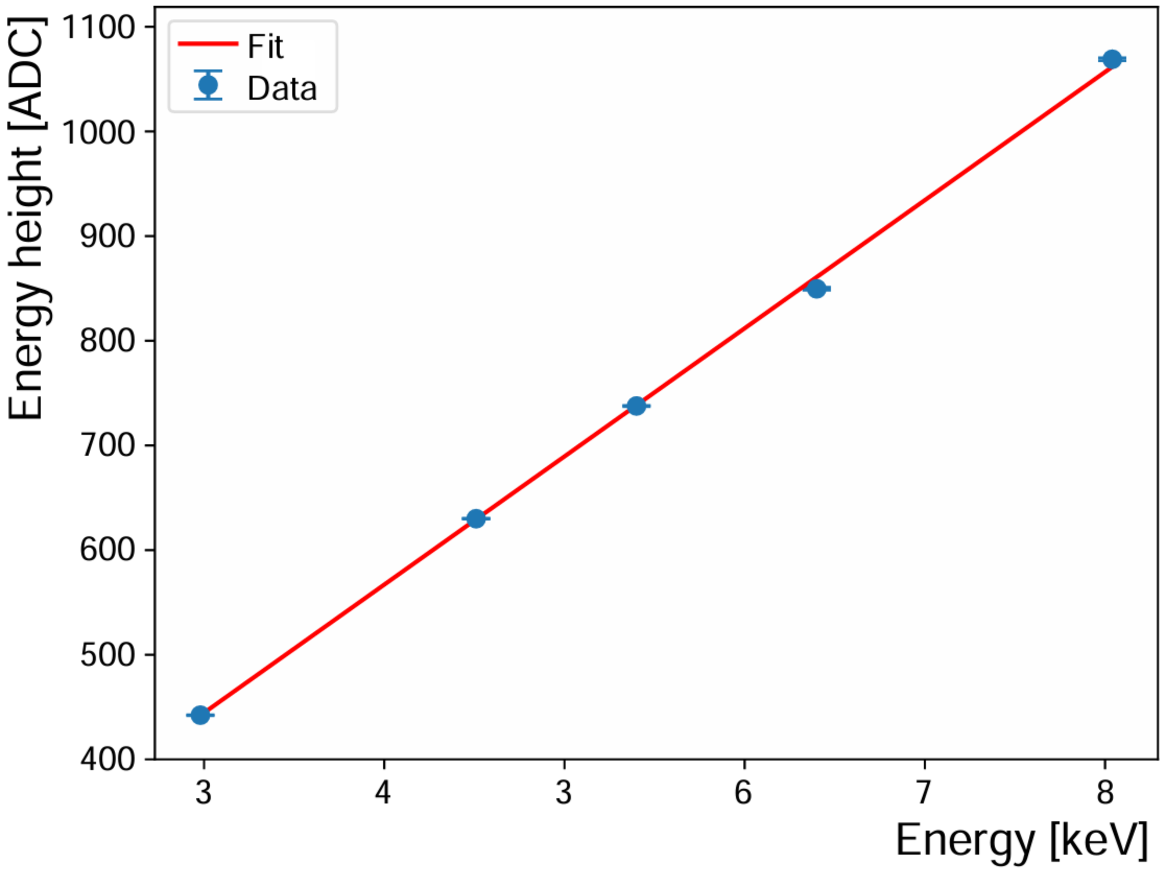
广域稳定动态范围

动态响应与径迹成像

^{55}Fe源产生X射线入射探测器

谱线	能量
^{55}Fe K_α	5.9 keV
^{55}Fe K_β	6.4 keV
Ar K系特征X射线	3.0 keV





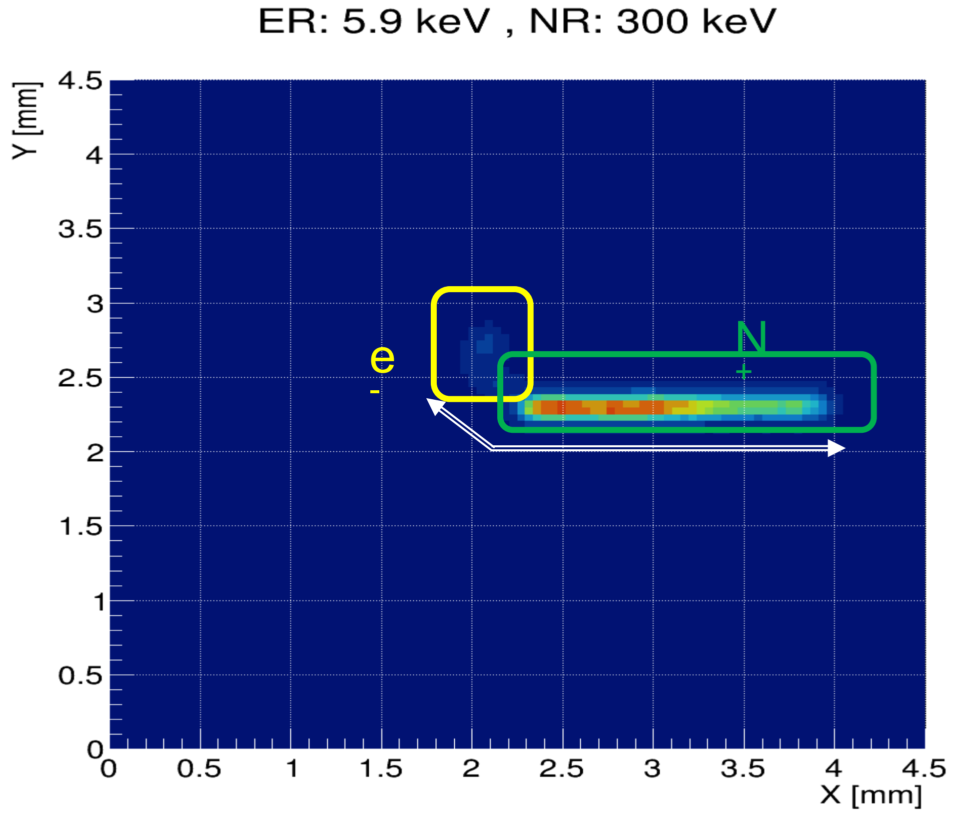
Preliminary Energy Resolution ~26%@5.9keV

对不同能量信号线性对应

准确电子能量获取

顶点分辨

The key to identify Migdal events:
A shared vertex !



反冲核径迹：

- cm级别长度
- 大沉积能量
- 明显衰减特征

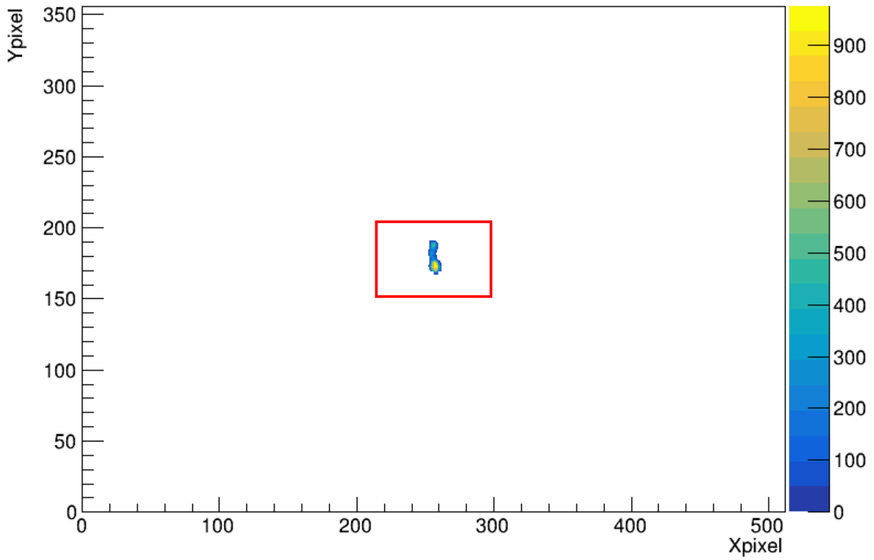
电子径迹：

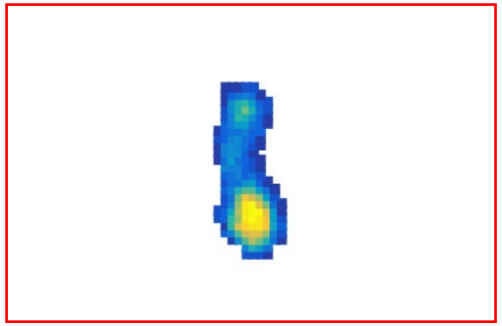
- mm级别长度
- 小沉积能量
- 布拉格峰特殊分布

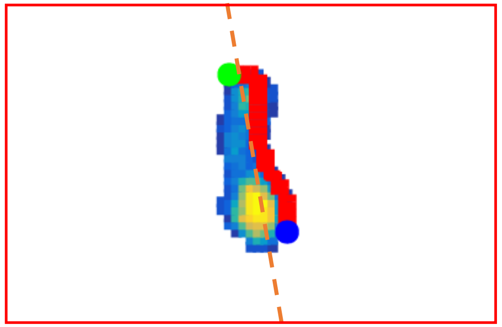
顶点分辨～百μm

顶点重建

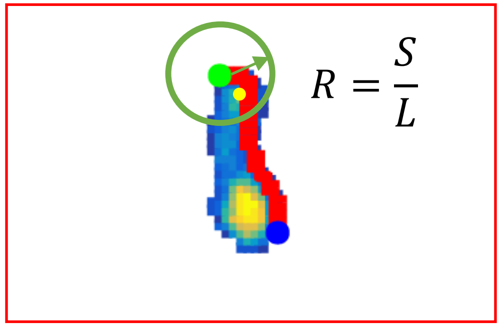
基于团簇拓扑数学特性，重建顶点







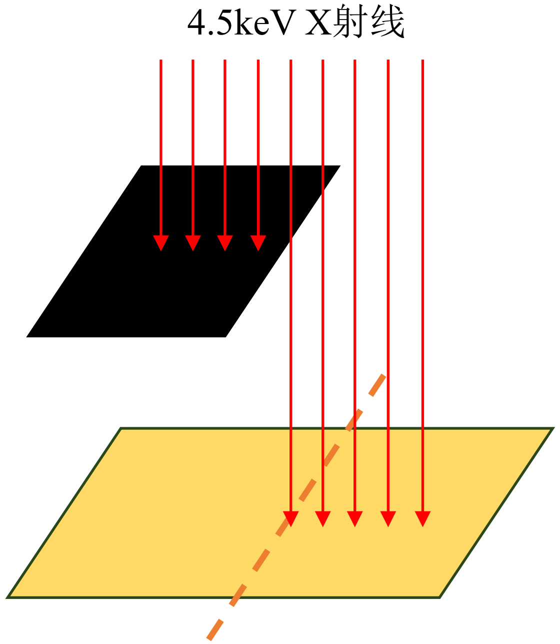
- 径迹面积 S
- 在径迹边缘点中，寻找满足两点间最短路径最长的两个点
- 蓝点：高能端点
- 绿点：低能端点
- 最短路径长度为 L

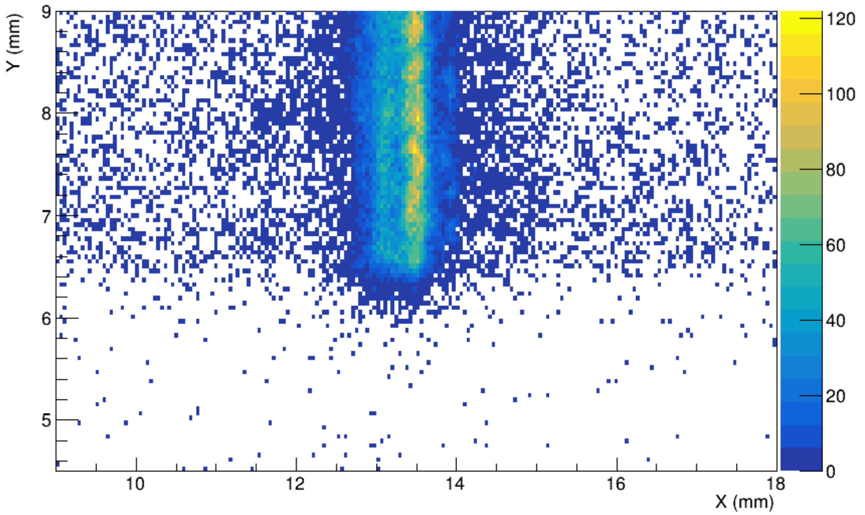


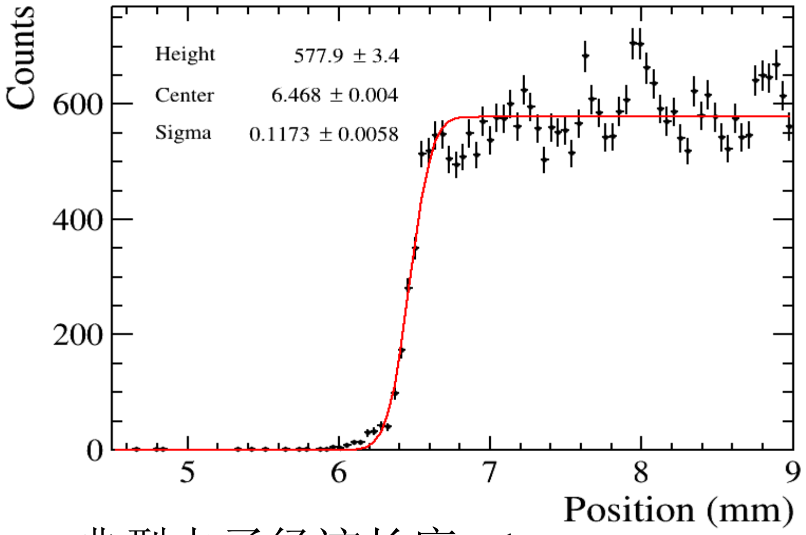
- 低能端点为圆心
- $R = \frac{S}{L}$作为半径
- 加权平均得到顶点

顶点分辨

采用铜板遮蔽探测器顶部一半的铍窗，使用4.5keV 准直X射线入射。







典型电子径迹长度 ~1mm

重建光电子顶点，分界面处满足误差函数，σ值对应顶点位置分辨能力。

一期探测器

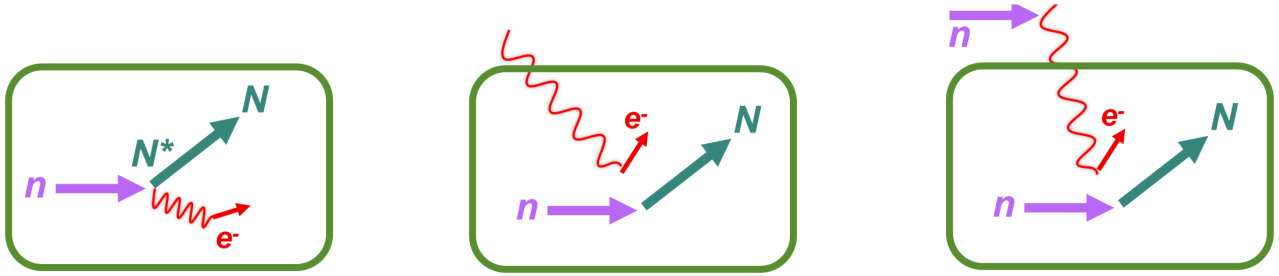
$\sigma_{old} = 150\ \mu m$

VS

$\sigma_{position} = 117.3\ \mu m$ @ 4.5keV

时间分辨

主要本底：Radom track conincidence



I　　II　　III

MARVEL一期

	NR	Compton e-	photonEle
I	1	4.32×10^{-5}	1.06×10^{-5}
II	1	6.06×10^{-6}	$\sim 3.63 \times 10^{-8}$
III	1	3.11×10^{-6}	7.15×10^{-7}

Faster readout time, less background.

时间分辨 ~ 百ns

数据获取时间

GMCP:

单通道高速读出粒子时间信息与能量信息

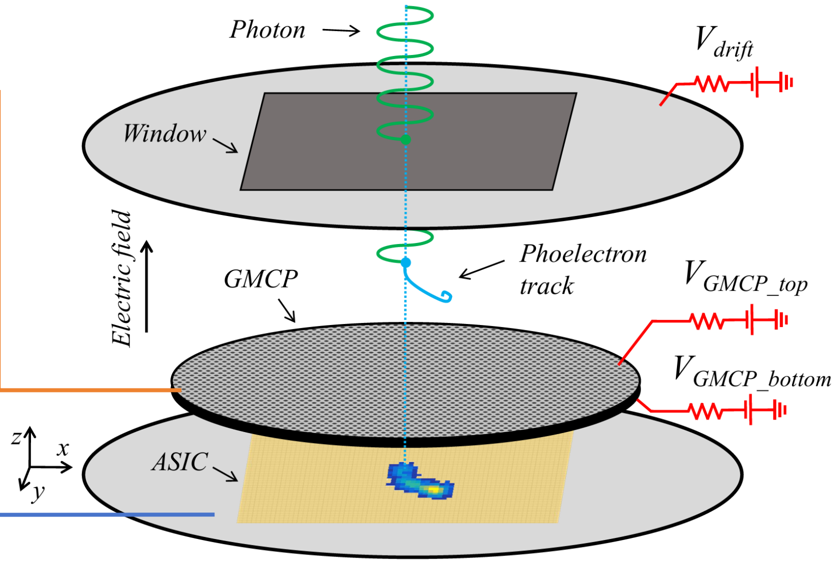
100 MHz (10 ns) 时钟

Topmetal-L:

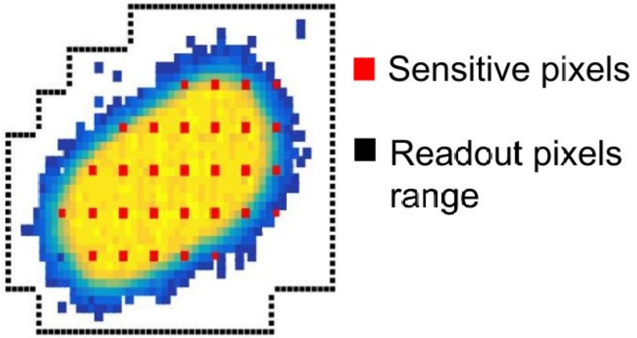
扫描模式：感兴趣区域读出模式（ROI），实现径迹成像

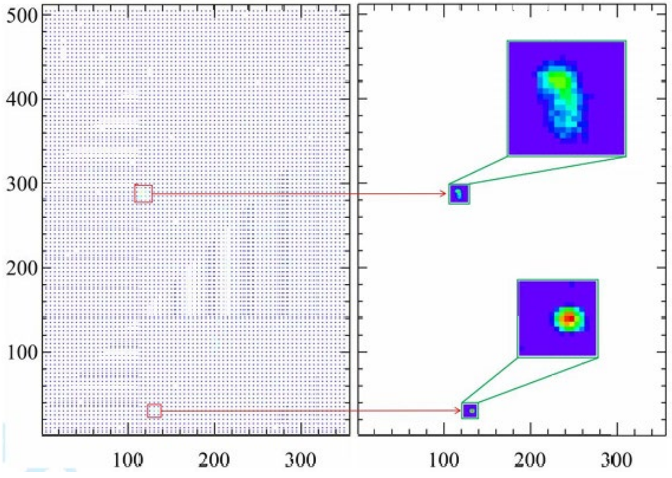
哨点扫描 → 哨点触发 → 确定读出区域 → 扫描读出 → 哨点扫描

哨点扫描 0.73 ms一帧



arXiv 2511.09863 (2025)





arXiv:2511.15130 （2025）

ROI VS Rolling shutter

数据压缩比例：

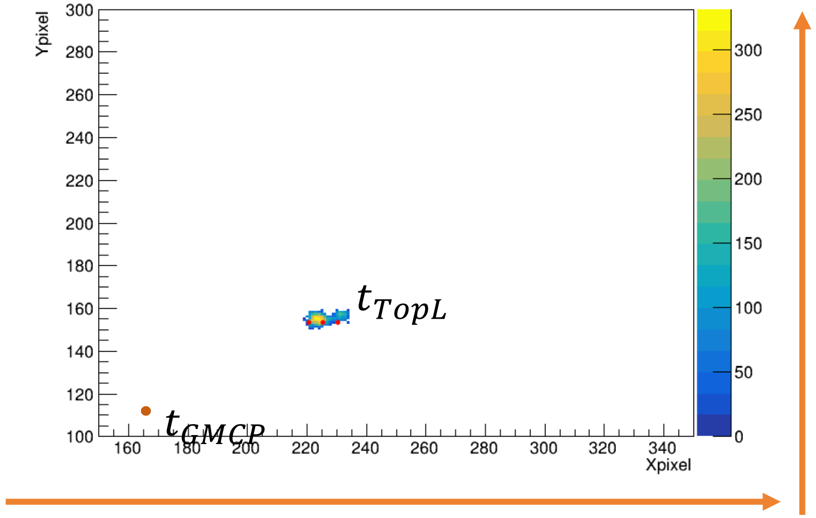
0.5% for electron track

9% for ion track

每帧时间开销：快25倍

时间符合

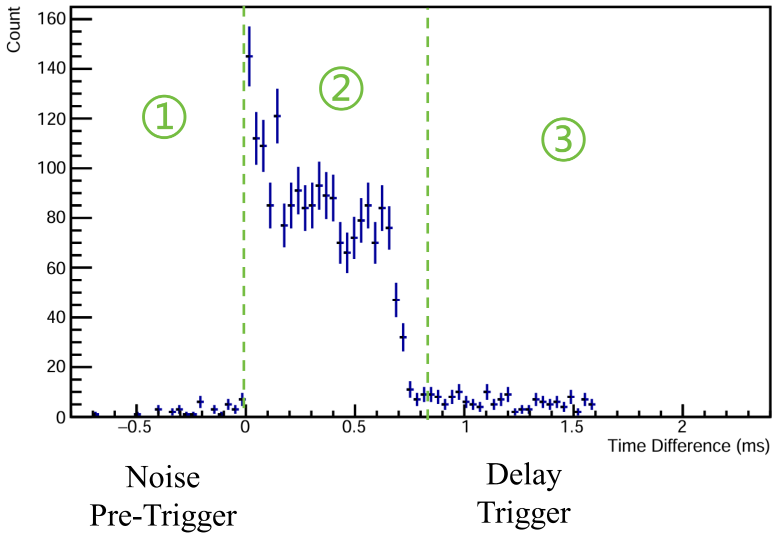
GMCP 10ns时钟 VS Topmetal-L ~0.73ms/帧



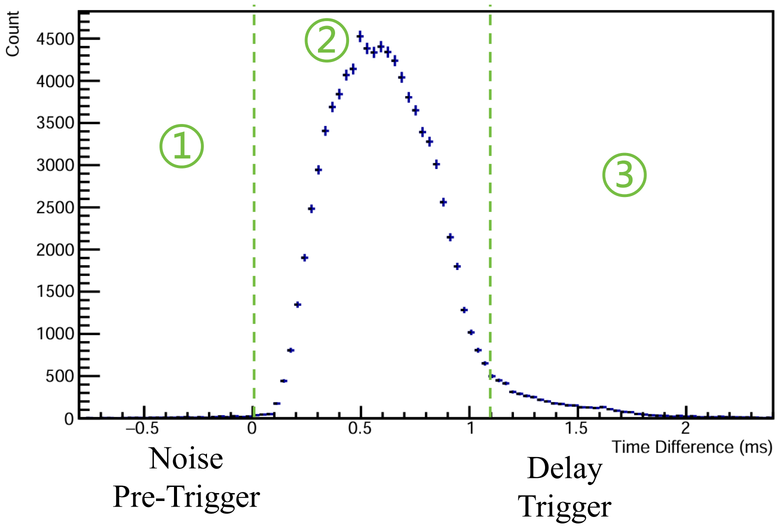
扫描方向

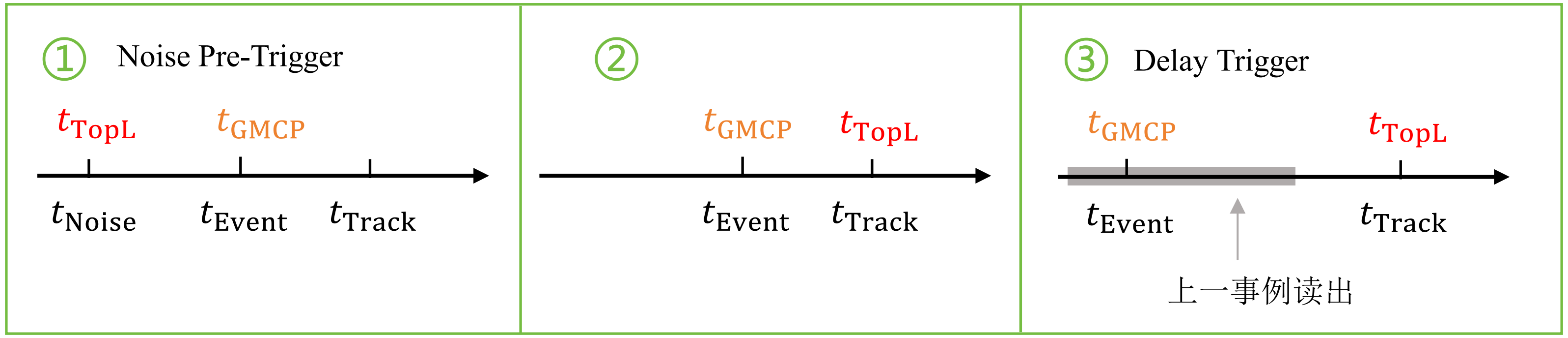
在Topmetal记录的时间戳附近，
寻找对应的GMCP数据.

核子径迹
符合效率：99.92%

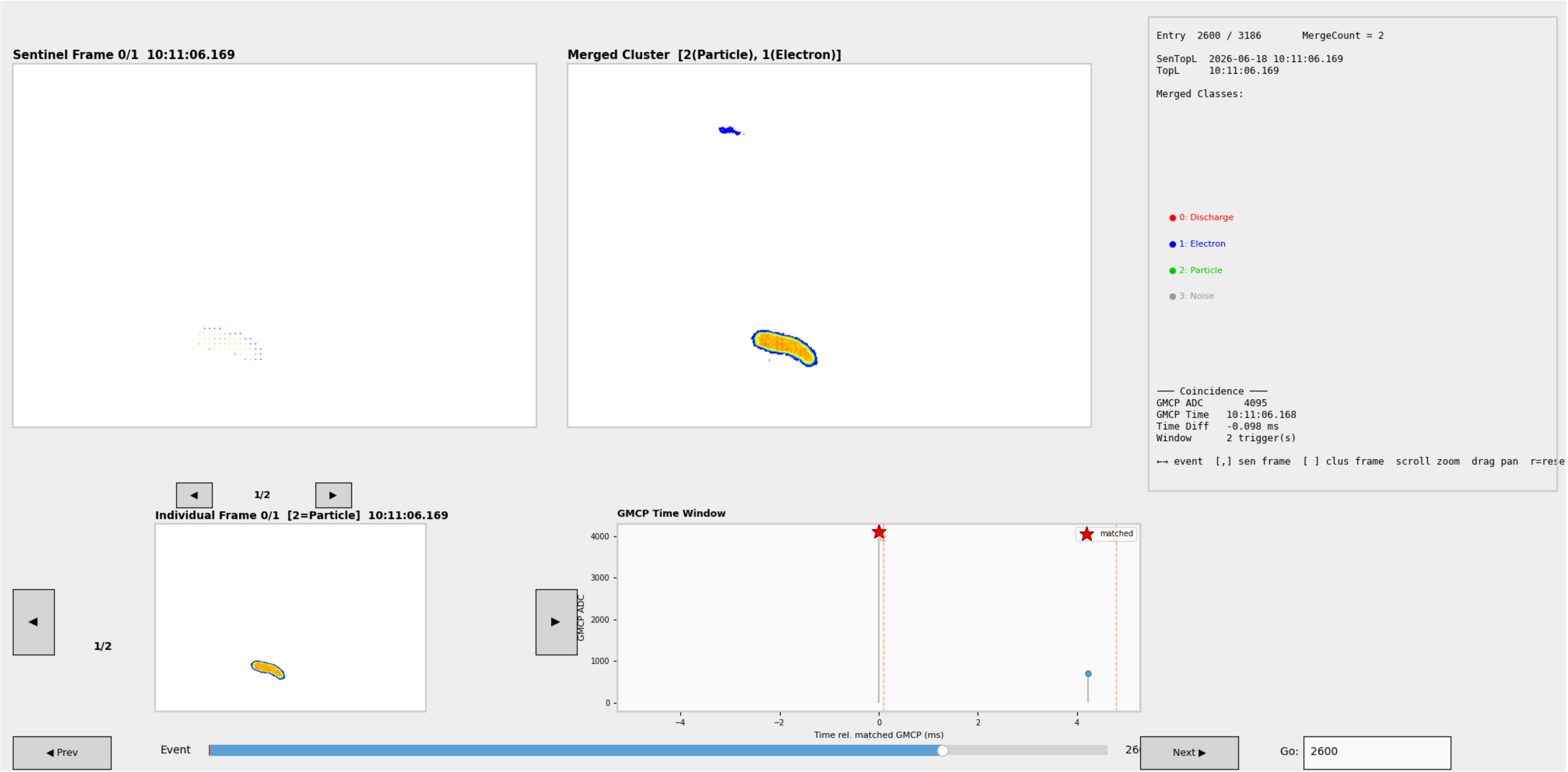


^{55}Fe源光电子径迹
符合效率：99.96%





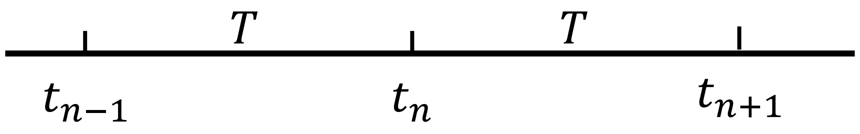
时间符合


Sentinel Frame 0/1 10:11:06.169
Merged Cluster [2(Particle), 1(Electron)]
Entry 2600 / 3186   MergeCount = 2
SenTopL 2026-06-18 10:11:06.169
TopL   10:11:06.169
Merged Classes:
0: Discharge
1: Electron
2: Particle
3: Noise
—— Coincidence ——
GMCP ADC   4095
GMCP Time   10:11:06.168
Time Diff   -0.098 ms
Window   2 trigger(s)
←→ event [,] sen frame [ ] clus frame scroll zoom drag pan r=rese
1/2
Individual Frame 0/1 [2=Particle] 10:11:06.169
1/2
GMCP Time Window
matched
GMCP ADC
Time rel. matched GMCP (ms)
◀ Prev
Event
Next ▶
Go:
2600

时间分辨

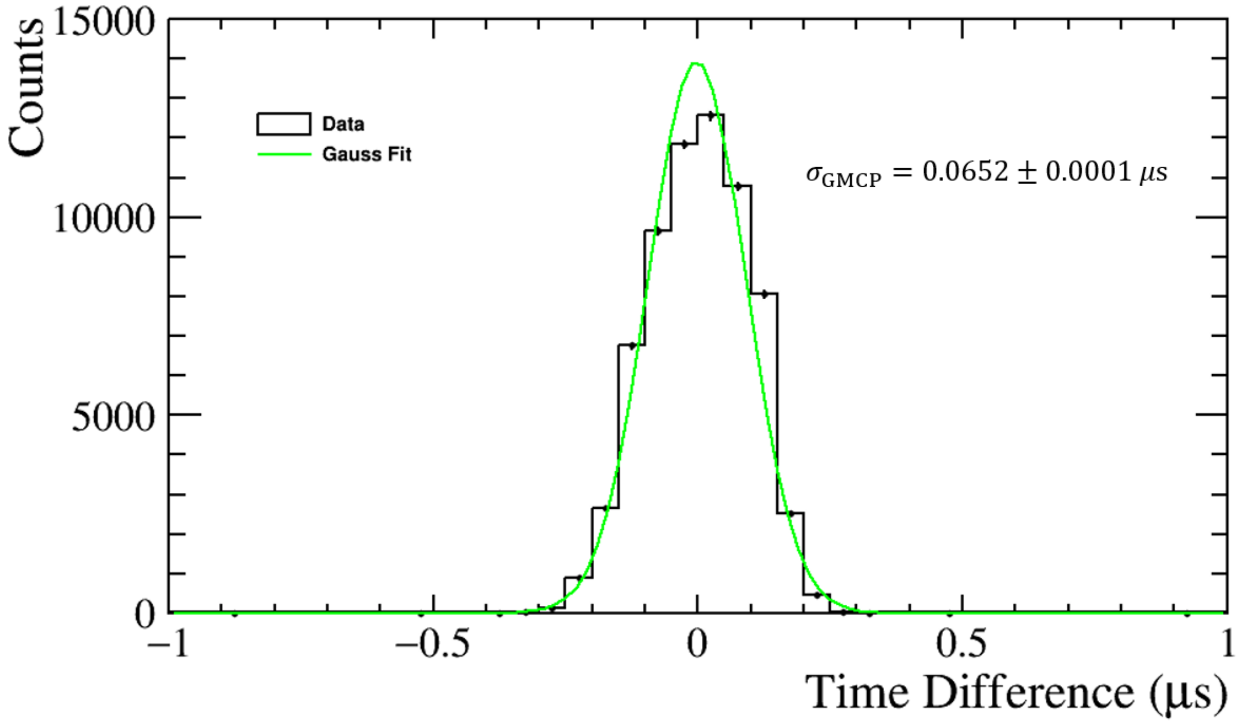
信号发生器注入周期为T的方波信号：

$$f(x)=\frac{1}{\sqrt{2\pi(\sigma_T^2+2\sigma_{GMCP}^2)}}\exp\left[-\frac{(x-\mu)^2}{2(\sigma_T^2+2\sigma_{GMCP}^2)}\right]$$ ，$\sigma_T \ll \sigma_{GMCP}$



将测得的t_n前后相减，得到周期测量值，该测量值的误差来源于信号发生器本身的误差以及探测器时间分辨能力。

即满足$Var(t_{n+1}-t_n)=\sigma_T^2+2\sigma_{GMCP}^2$

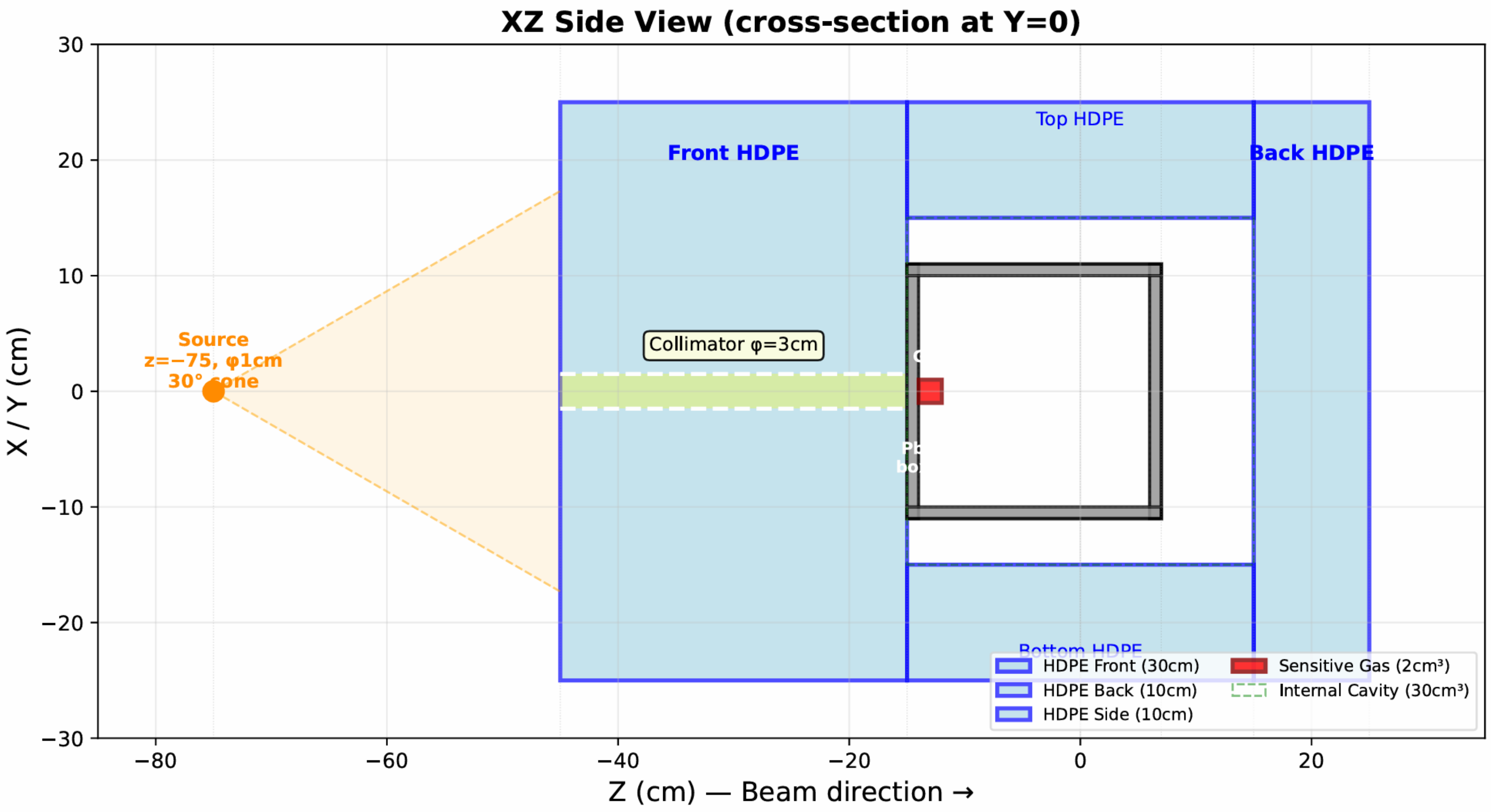


一期探测器
$\sigma_{old}=262$ ns

VS

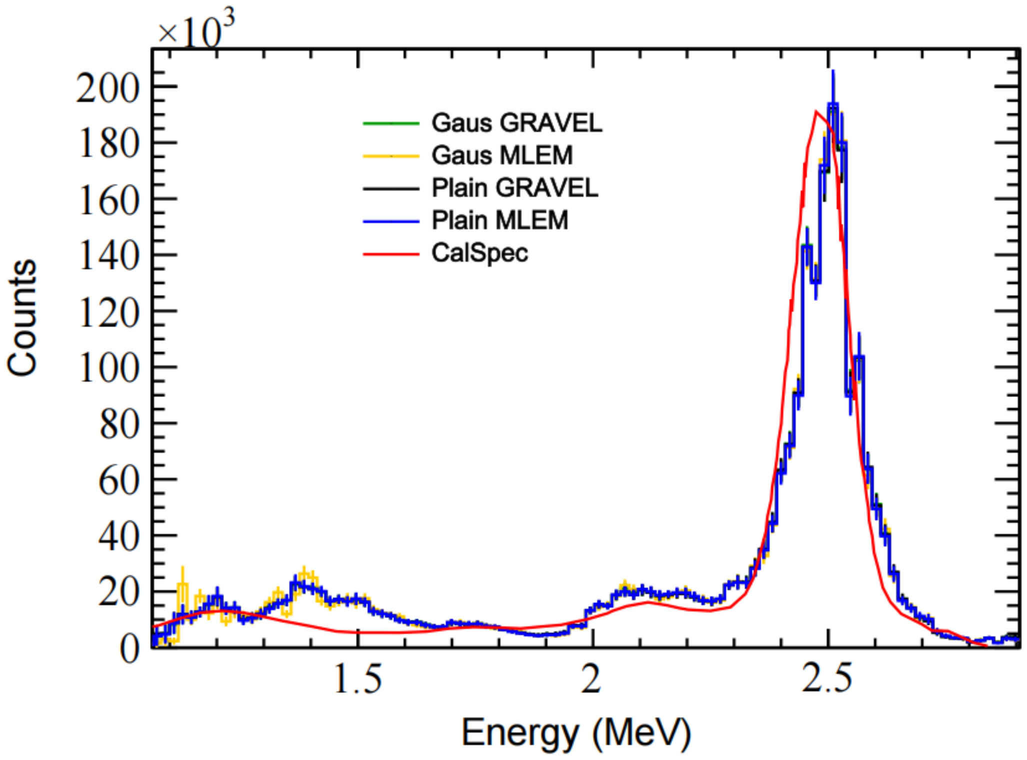
$\sigma_{time}=\sigma_{GMCP}=65$ ns

束流预实验


XZ Side View (cross-section at Y=0)
Source
z=−75, φ1cm
30° cone
Collimator φ=3cm
Front HDPE
Top HDPE
Back HDPE
Bottom HDPE
HDPE Front (30cm)
HDPE Back (10cm)
HDPE Side (10cm)
Sensitive Gas (2cm³)
Internal Cavity (30cm³)
X / Y (cm)
Z (cm) — Beam direction →
30
20
10
0
−10
−20
−30
−80
−60
−40
−20
0
20

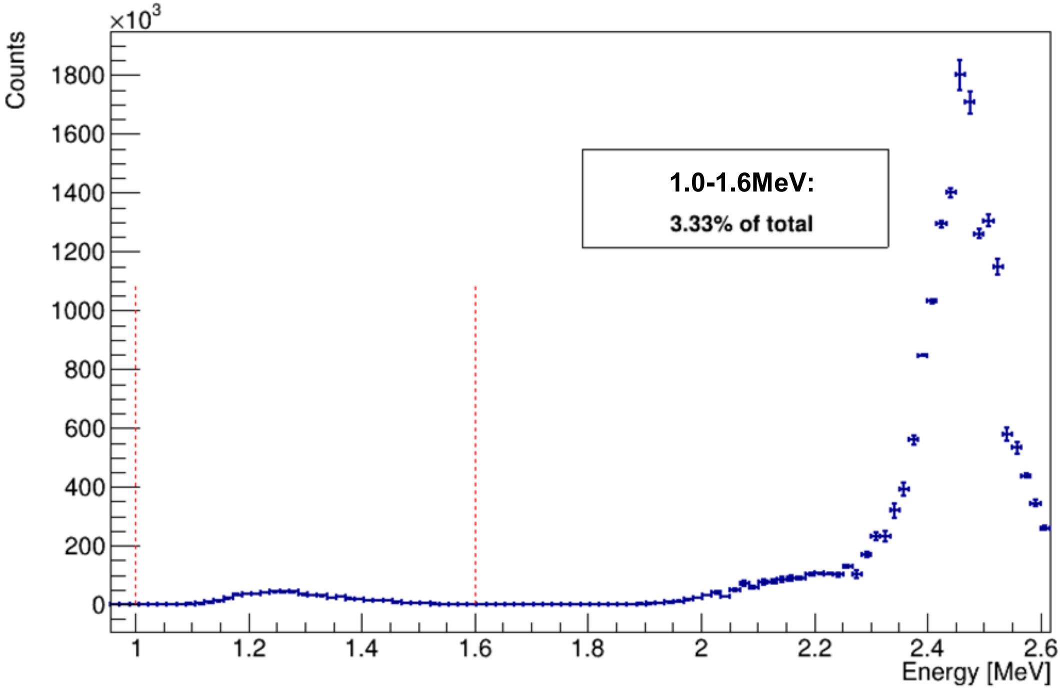
束流预实验

MARVEL一期实验中子能谱



低能部分～30%

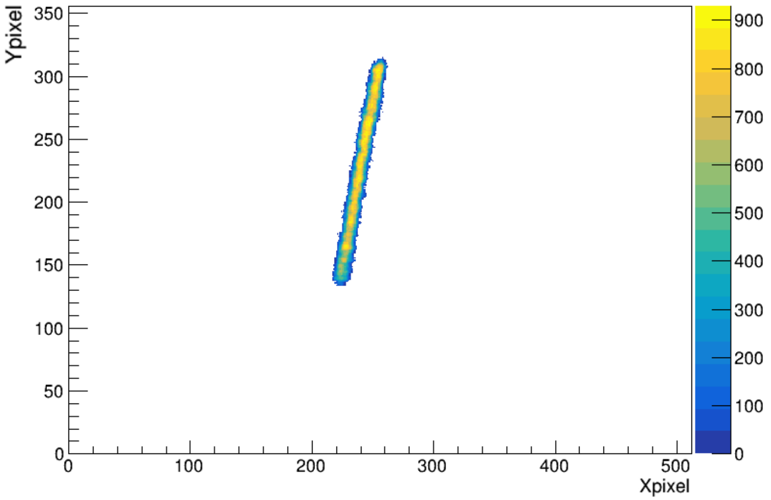
束流预实验中子能谱

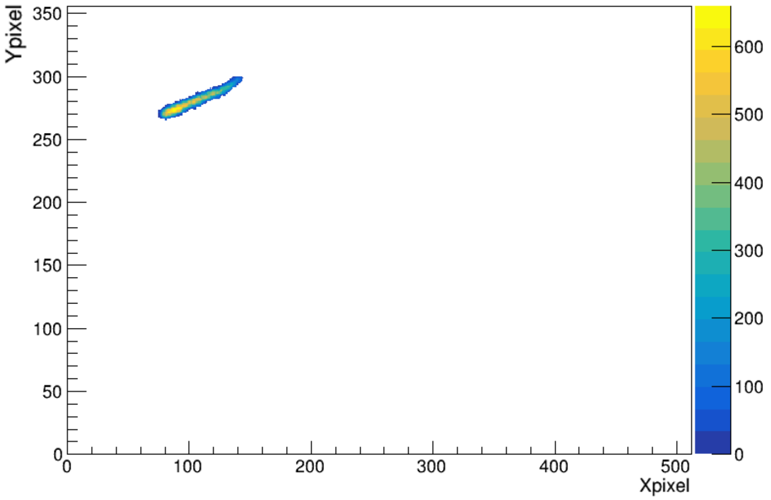


低能部分～3%

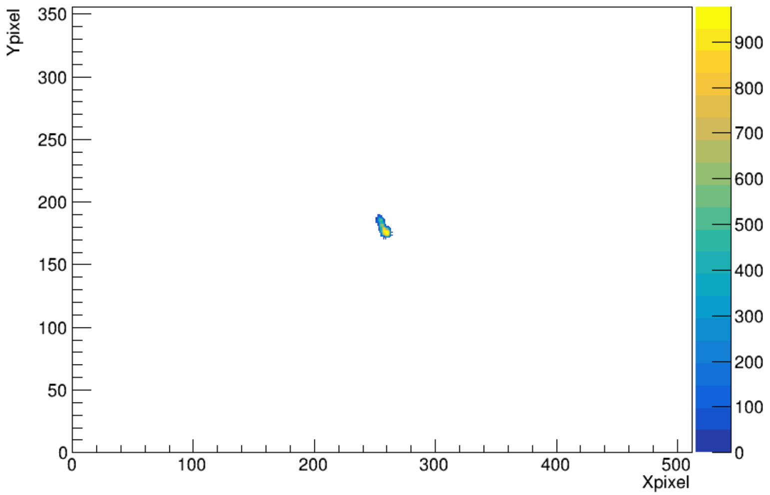
束流预实验

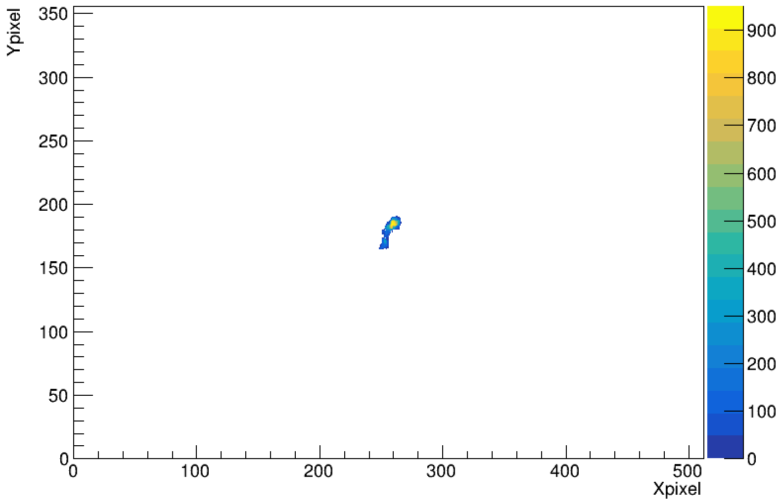
核子径际





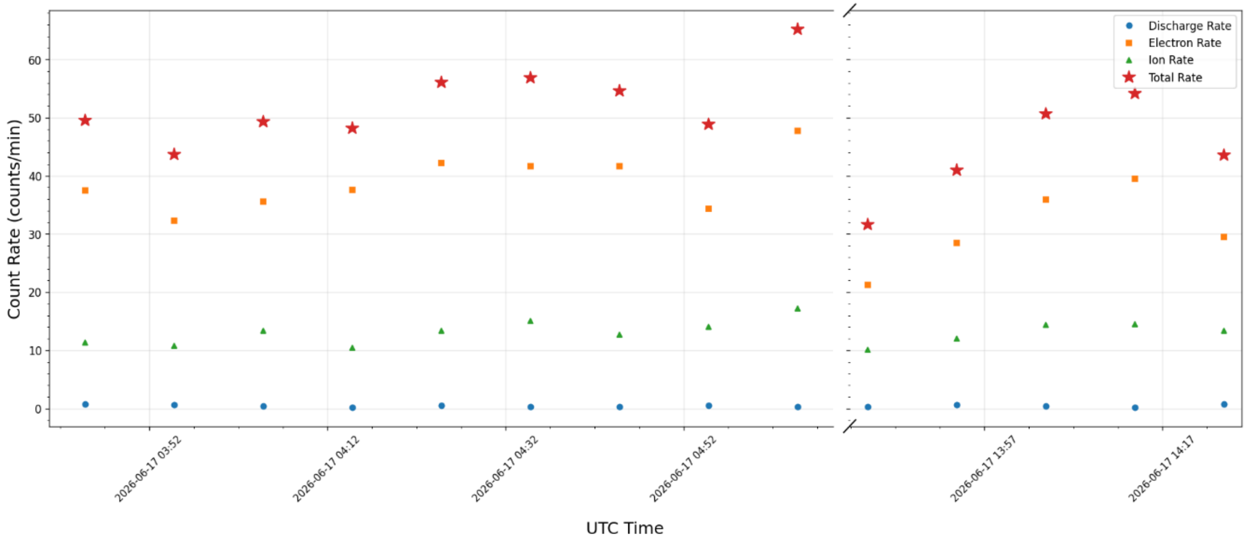
电子径迹



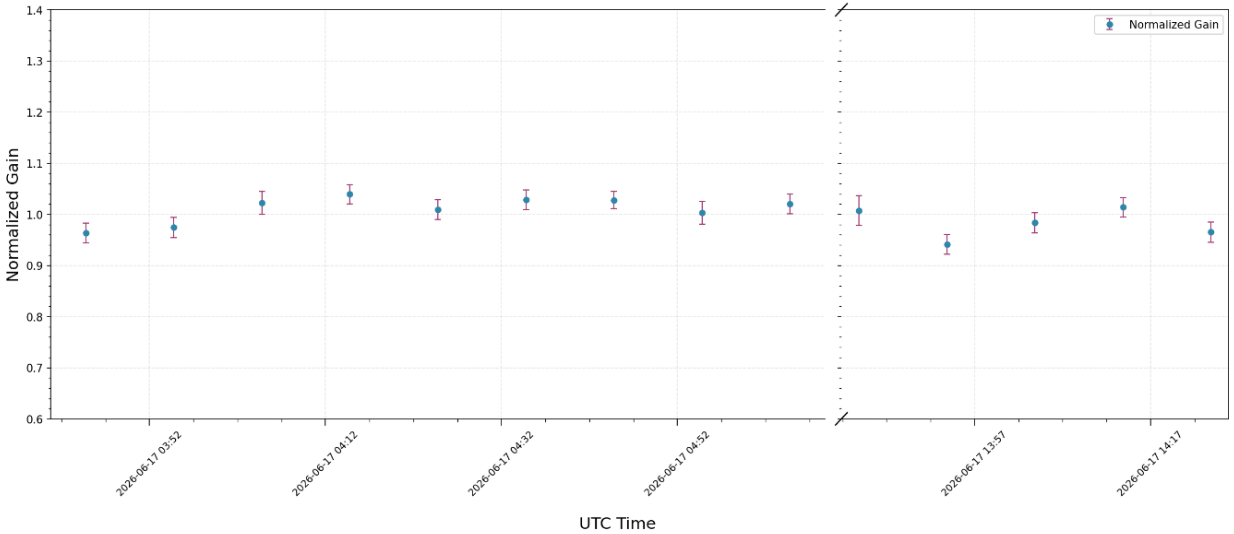


束流预实验

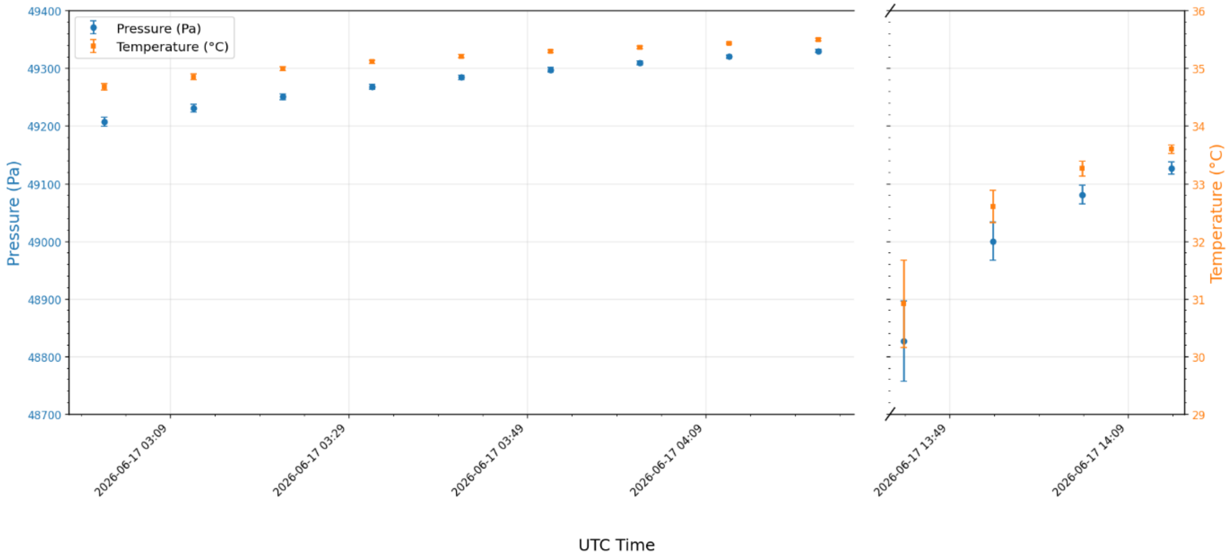
计数率



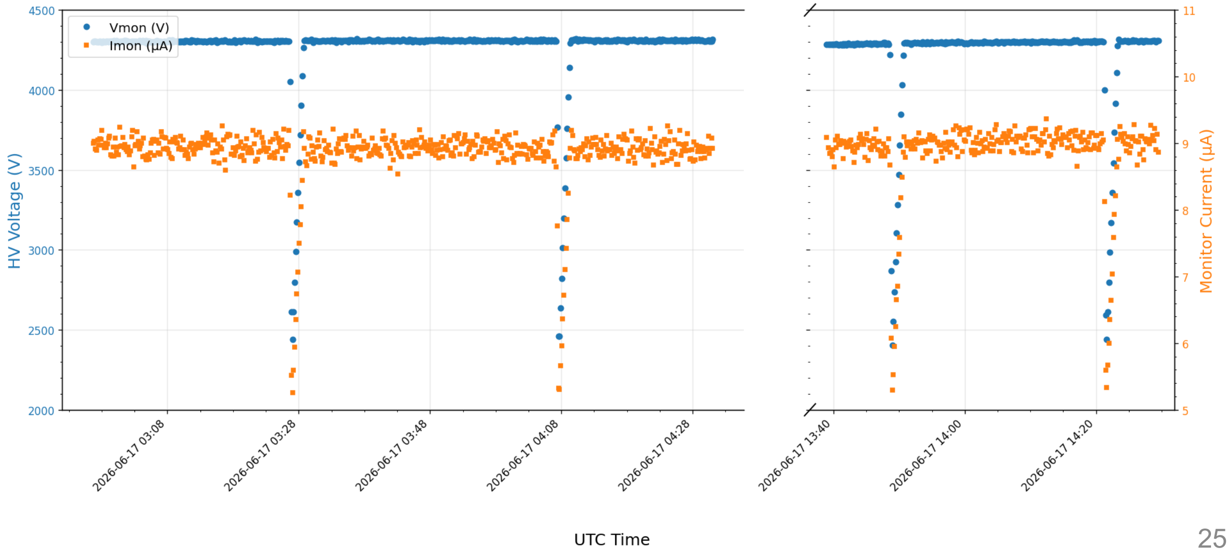
增益



气压 温度

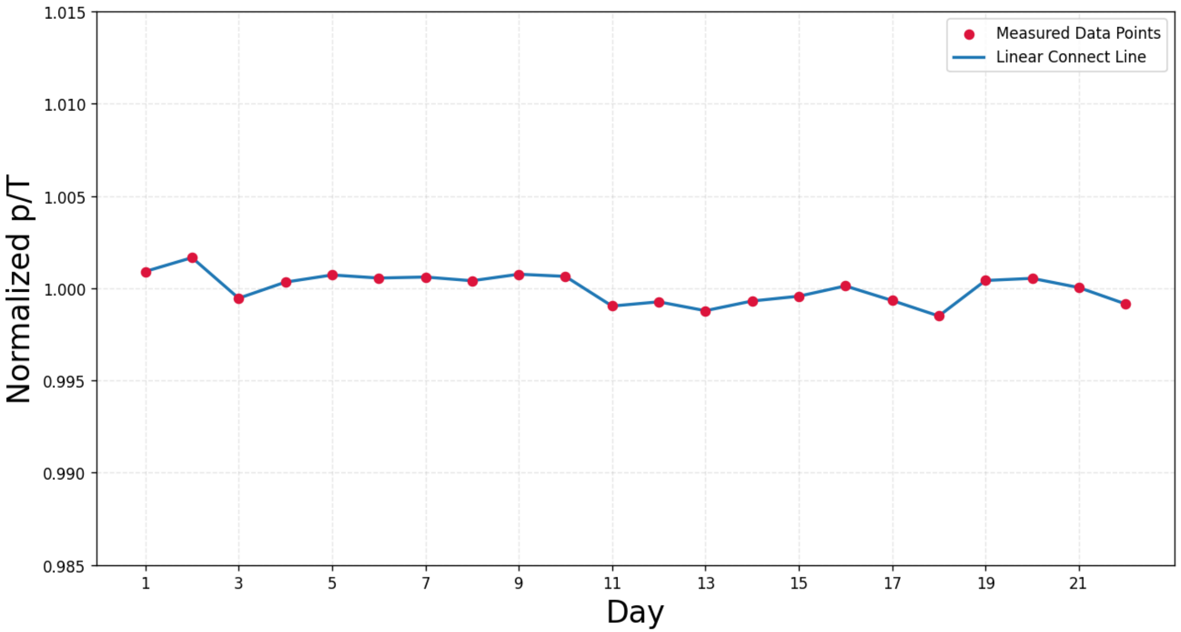


高压 电流

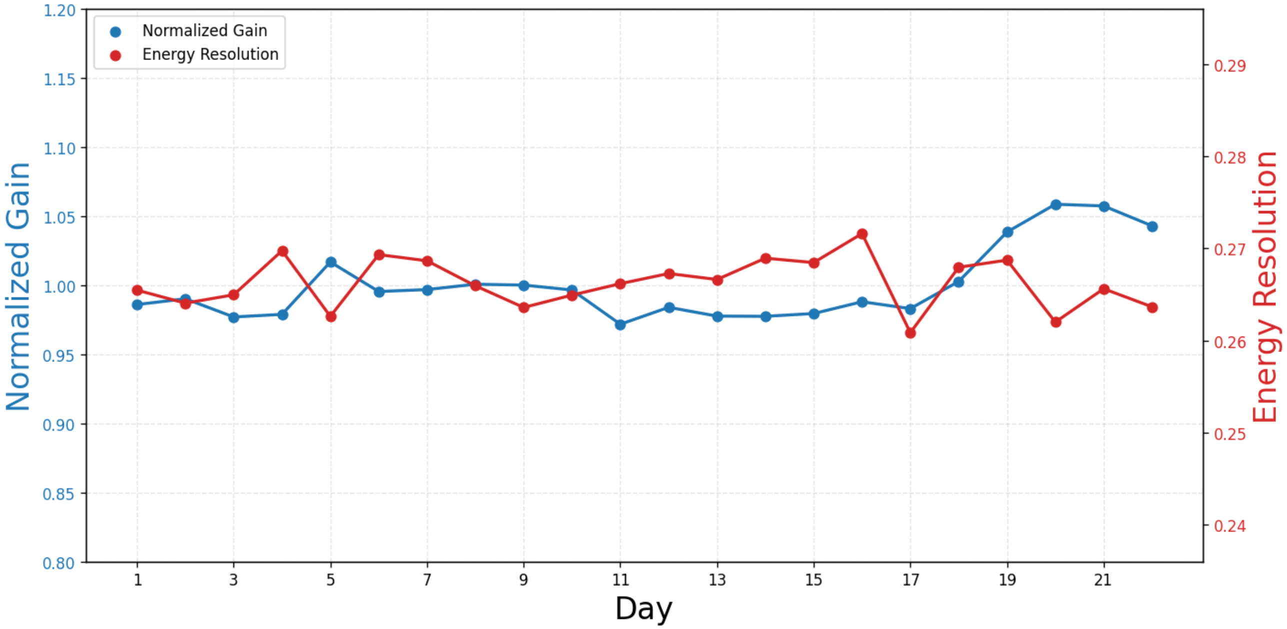


长期运行稳定性

气压-温度长期测试稳定性
(<3%)



增益-能量分辨长期测试稳定性
(< 6%)



展望

$a\%Ar\text{-}b\%CO_2$/ $a\%He\text{-}b\%CO_2$
dual-detector combined measurement

Parameters	Description
a,*b*	gas composition ratio
σ	nuclear neutron scattering cross section
ϕ	flux
N	Number of events

Ratio of Migdal cross section to neutron-nucleus scattering cross section:

$$r_i = \frac{\int \frac{d\sigma_i}{dE_{NR}} p(E_{NR}) dE_{NR}}{\int \frac{d\sigma_i}{dE_{NR}} dE_{NR}} = \frac{\int \frac{d\sigma_i}{dE_{NR}} p(E_{NR}) dE_{NR}}{\sigma_i}$$

$$\sigma_{\mathrm{Ar}} r_{\mathrm{Ar}} = \frac{k_B T}{\phi t L P} \left(\frac{N_{\mathrm{ArMigdal}}}{a_{\mathrm{Ar}} \eta_{\mathrm{Ar}}} - \frac{N_{\mathrm{HeMigdal}}}{a_{\mathrm{He}} \eta_{\mathrm{He}}} \right)$$

- Larger sensitive volume
- Smaller pixel size
- Superior vertex resolution
- Superior time resolution
- Improved neutron energy spectrum

谢谢！