测试束流与先进探测技术研讨会

VLAST原理样机研制及PS/SPS束流试验

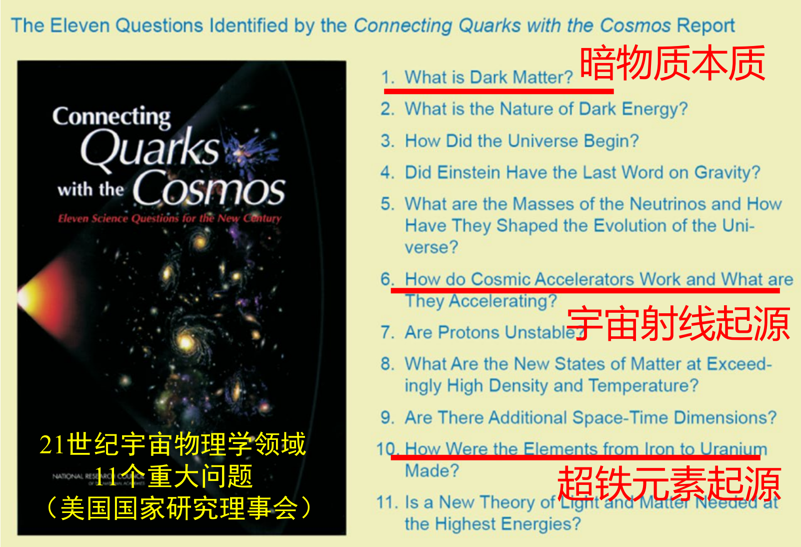
藏京京（临沂大学）

(on behalf of the VLAST collaboration)

提纲

1. VLAST原理样机研制
2. PS/SPS束流试验
3. 总结

甚大面积伽马射线VLAST：科学目标



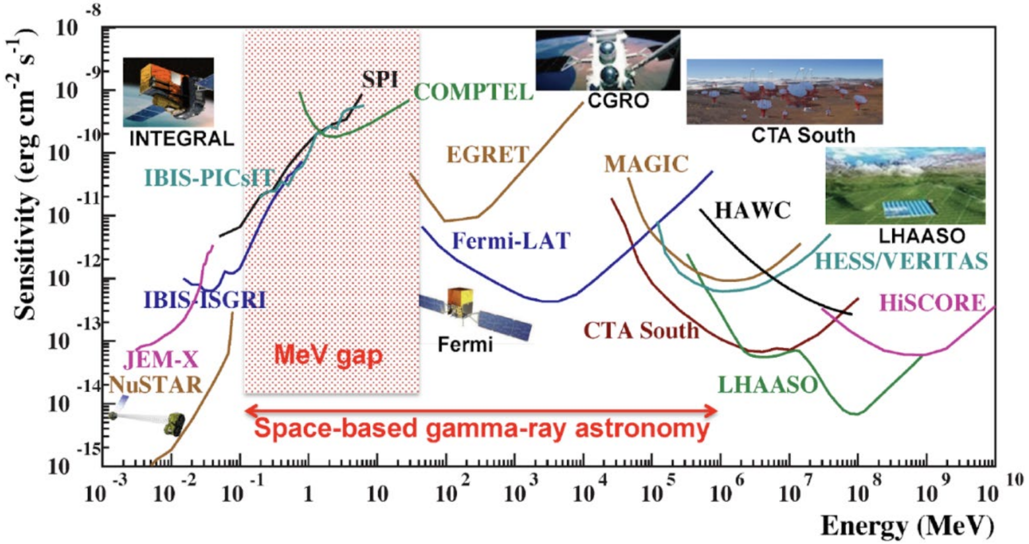
The Eleven Questions Identified by the *Connecting Quarks with the Cosmos* Report

Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

21世纪宇宙物理学领域
11个重大问题
（美国国家研究理事会）

1. What is Dark Matter? 暗物质本质
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protons Unstable? 宇宙射线起源
8. What Are the New States of Matter at Exceedingly High Density and Temperature?
9. Are There Additional Space-Time Dimensions?
10. How Were the Elements from Iron to Uranium Made?
11. Is a New Theory of Light and Matter Needed at the Highest Energies? 超铁元素起源



Credit:
ICRC2021

MeV-TeV的空间伽马射线探测在暗物质间接探测、宇宙线起源、超铁元素起源等方面蕴含着重大科学机遇！

甚大面积伽马射线VLAST：科学目标

国内外正在运行或提议的一些相空间伽马探测项目				
探测设施	伽马峰值接受度 (m^2 sr)	伽马能段范围	能量分辨率 (@10GeV)	角分辨本领 (@50GeV)
Fermi-LAT	~ 2	20 MeV-300 GeV	~6.0%	~ 0.10 deg
悟空号	~ 0.2	5 GeV-10 TeV	~1.5%	
AMS-100 (概念)	~30	0.1 GeV-10 TeV		~ 0.03 deg
APT	~20	1 MeV-10 TeV	~ 20%	~ 0.10 deg
HERD	~2	0.5 GeV-10 TeV	~1.5%	
VLAST	~10	1 MeV-10 TeV	~1.5%	~ 0.10 deg

甚大面积伽马射线VLAST：载荷配置

三大主载荷:

(a)反符合探测器:

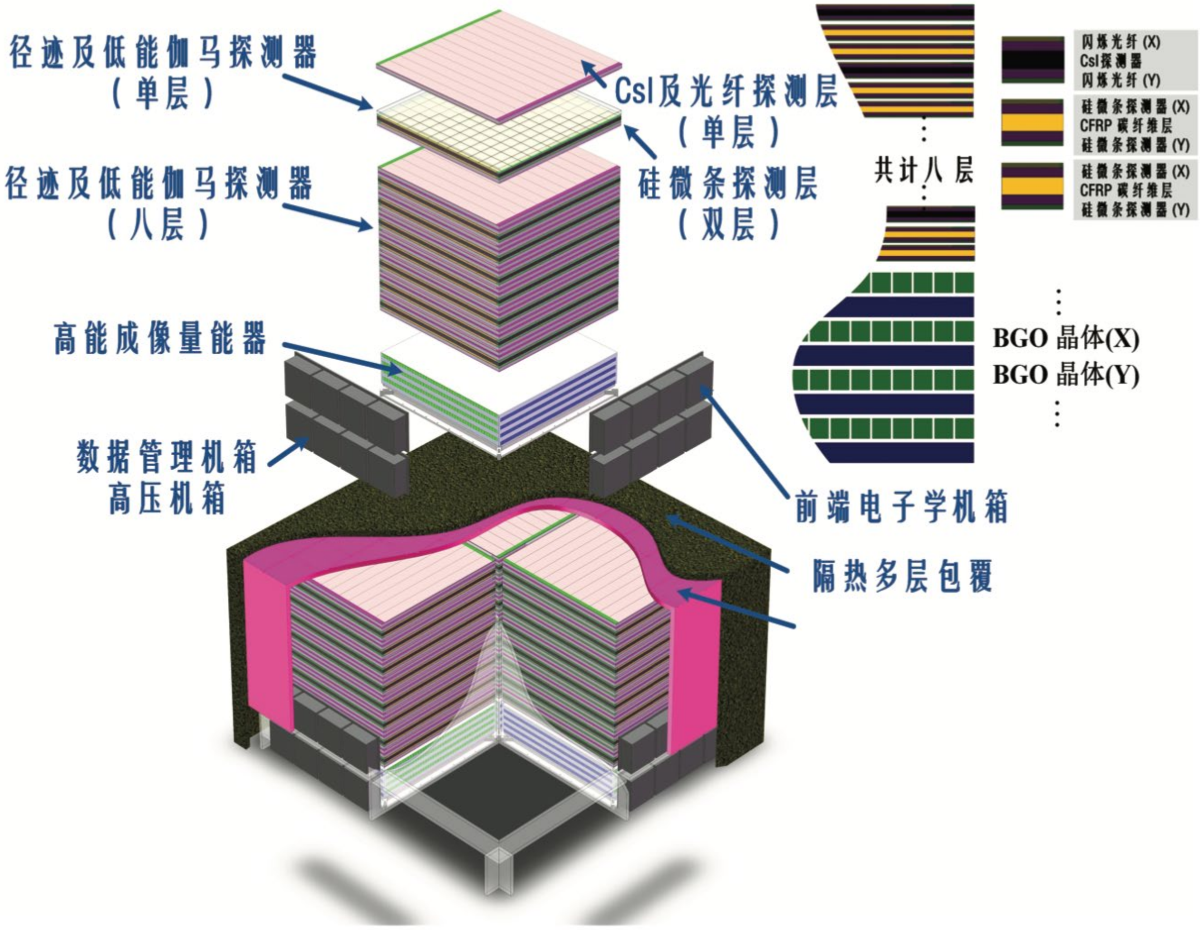
- ➢ 位于探测器的顶部及四周，用于区分光子和带电粒子

(b)径迹及低能伽马探测器:

- ➢ 用于测量高能光子（电子对）径迹和低能康普顿效应光子

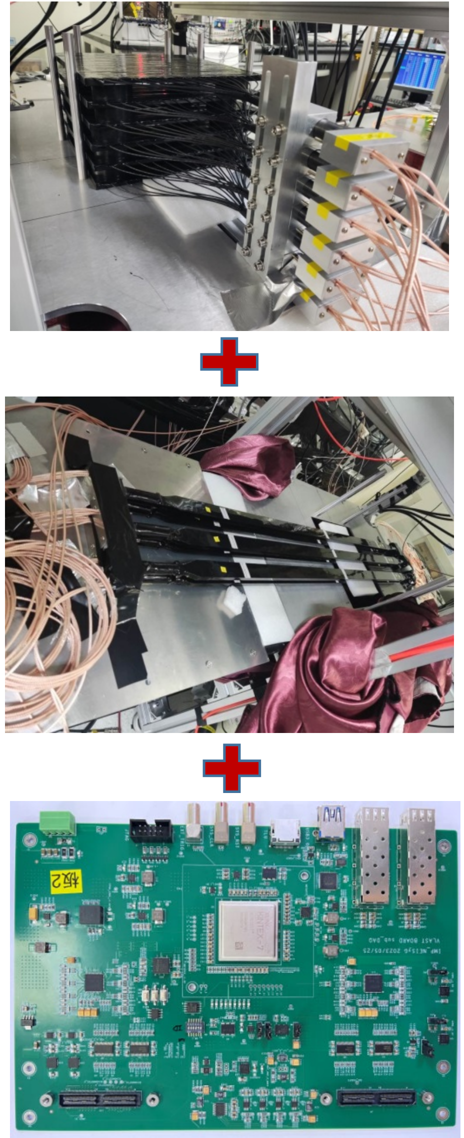
(c)高能成像量能器:

- ➢ 位于探测器的底部，用于测量入射高能粒子能量

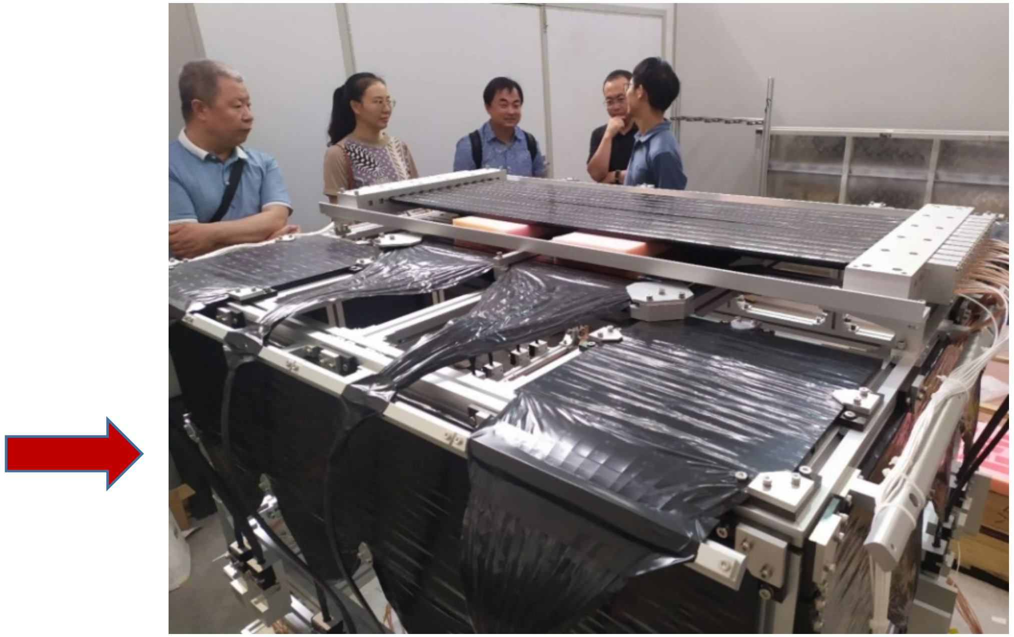

径迹及低能伽马探测器
（单层）
CsI及光纤探测层
（单层）
径迹及低能伽马探测器
（八层）
硅微条探测层
（双层）
共计八层
闪烁光纤 (X)
CsI探测器
闪烁光纤 (Y)
硅微条探测器 (X)
CFRP 碳纤维层
硅微条探测器 (Y)
硅微条探测器 (X)
CFRP 碳纤维层
硅微条探测器 (Y)
高能成像量能器
BGO 晶体(X)
BGO 晶体(Y)
数据管理机箱
高压机箱
前端电子学机箱
隔热多层包覆

VLAST是2×2的阵列，每个单元尺寸为1.2米!

VLAST技术预研进展：反符合探测器



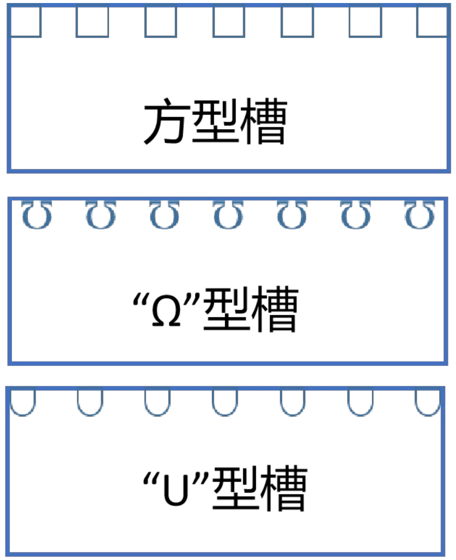
- 高性能反符合探测器
  - 两种方案：块状和条状的塑闪探测器
  - 特色：预埋波长位移转换光纤，降低探测效率对粒子击中位置的依赖性，消除模块化构型设计带来的探测灵敏死区；
  - 特色：多打拿极读出，兼顾核素测量；

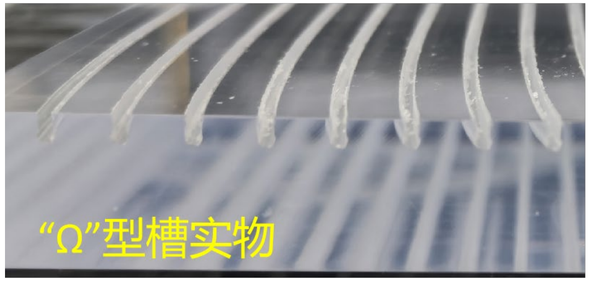


VLAST技术预研进展：反符合探测器

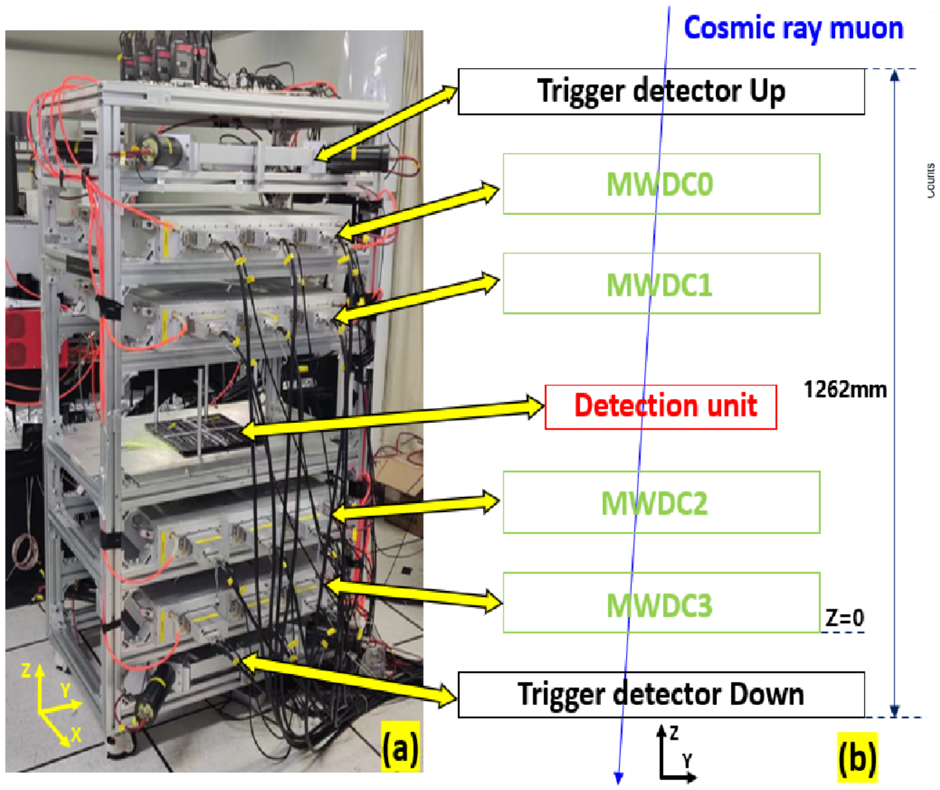
探测单元研制

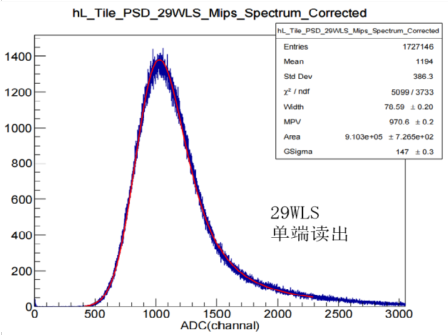
光纤嵌入构型工艺研究

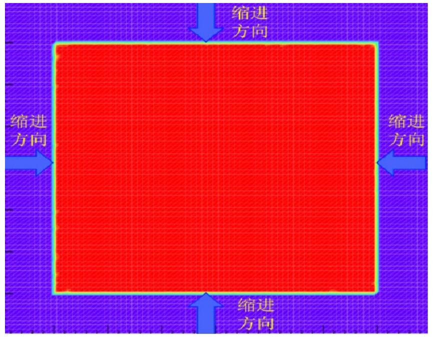


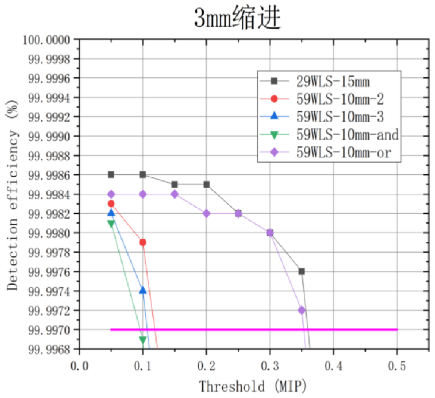


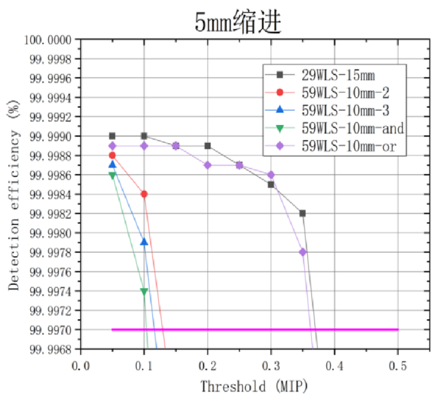
搭建宇宙线μ子测试平台，测试ACD单元的MIPs探测效率


Cosmic ray muon
Trigger detector Up
MWDC0
MWDC1
Detection unit
1262mm
MWDC2
MWDC3
Z=0
Trigger detector Down
Z
Y
X
(a)
(b)







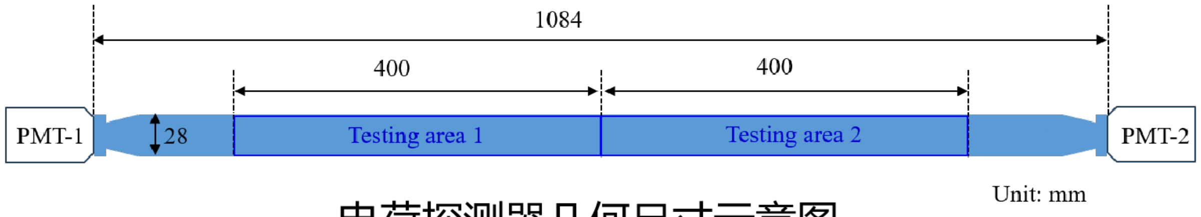


对于MIPs事件，单元可以在阈值为0.3MIPs情况下实现0.99997的极高探测效率指标！

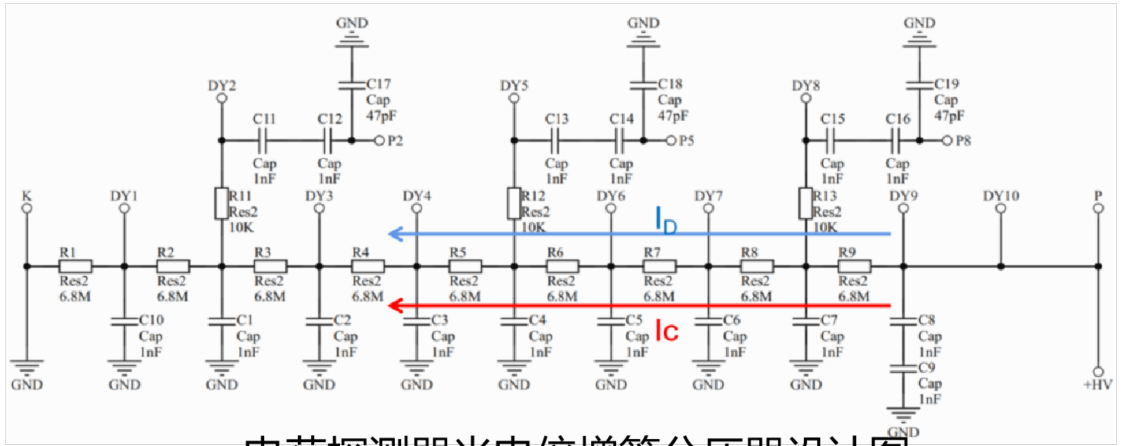
VLAST技术预研进展：反符合探测器

探测单元研制

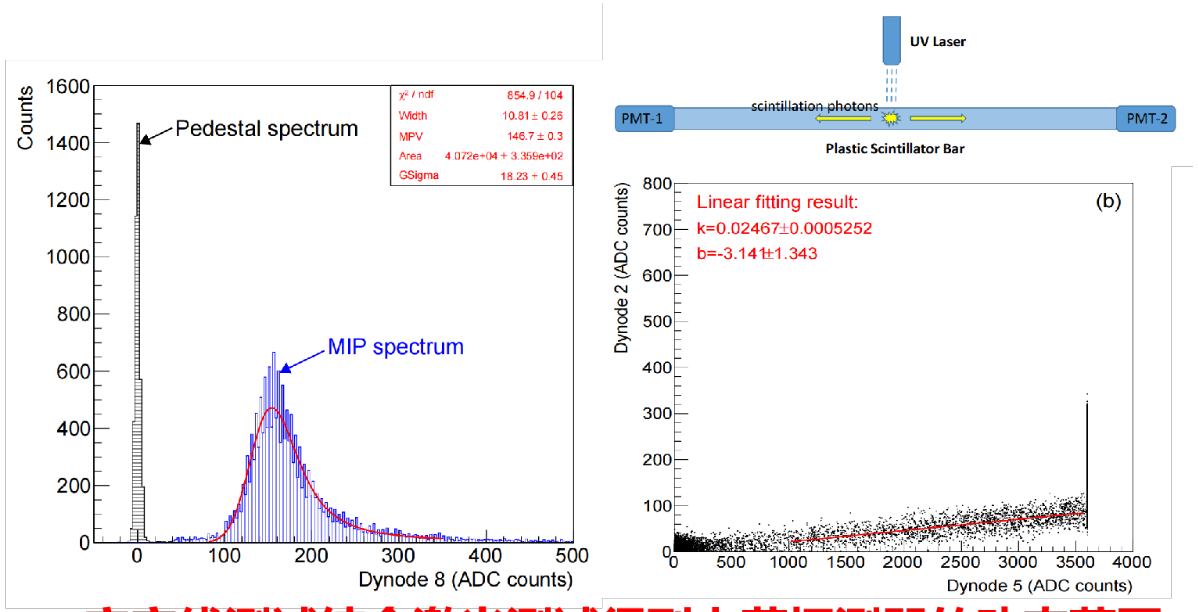
电荷探测器单元的大动态范围设计


1084
400
400
PMT-1
28
Testing area 1
Testing area 2
PMT-2
Unit: mm

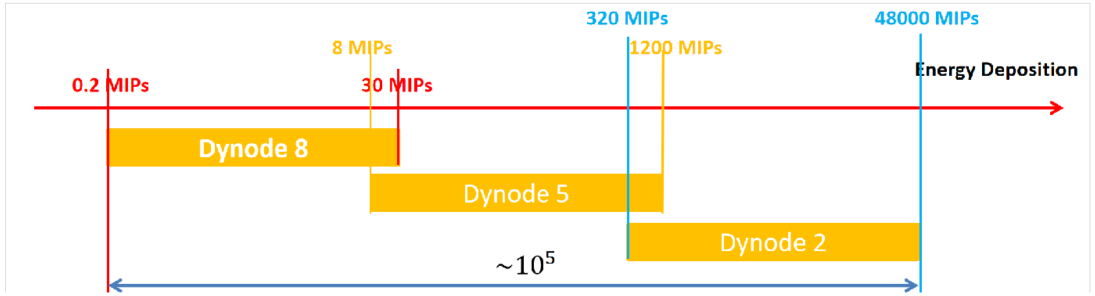
电荷探测器几何尺寸示意图


GND
C17 Cap 47pF
C18 Cap 47pF
C19 Cap 47pF
DY2
DY5
DY8
C11
C12
C13
C14
C15
C16
Cap 1nF
P2
P5
P8
K
DY1
R11 Res2 10K
R12 Res2 10K
R13 Res2 10K
DY3
DY4
DY6
DY7
DY9
DY10
P
I_D
R1 Res2 6.8M
R2 Res2 6.8M
R3 Res2 6.8M
R4 Res2 6.8M
R5 Res2 6.8M
R6 Res2 6.8M
R7 Res2 6.8M
R8 Res2 6.8M
R9 Res2 6.8M
I_C
C10 Cap 1nF
C1 Cap 1nF
C2 Cap 1nF
C3 Cap 1nF
C4 Cap 1nF
C5 Cap 1nF
C6 Cap 1nF
C7 Cap 1nF
C8 Cap 1nF
C9 Cap 1nF
+HV

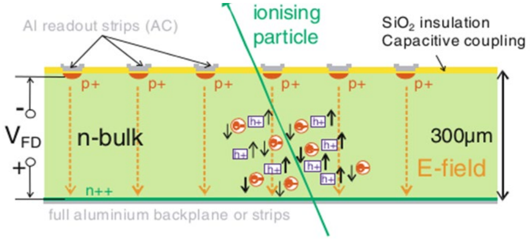
电荷探测器光电倍增管分压器设计图

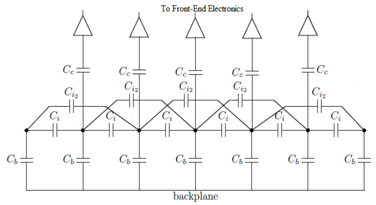


宇宙线测试结合激光测试得到电荷探测器的动态范围

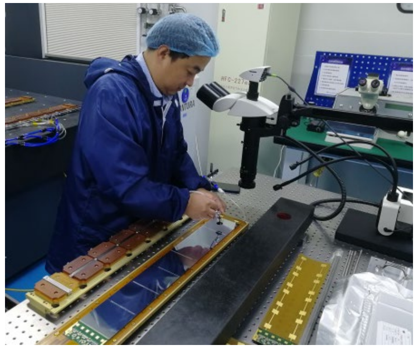

320 MIPs
48000 MIPs
8 MIPs
1200 MIPs
Energy Deposition
0.2 MIPs
30 MIPs
Dynode 8
Dynode 5
Dynode 2
~10⁵

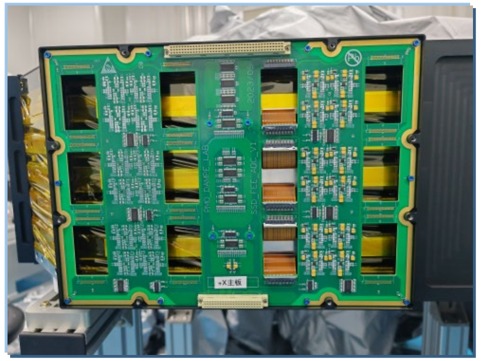
VLAST技术预研进展：径迹探测器

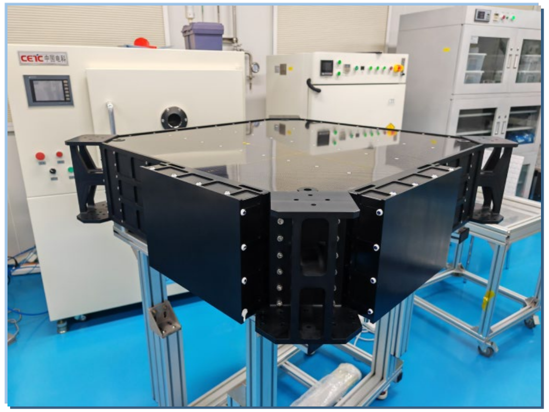

Al readout strips (AC)
ionising particle
SiO$_2$ insulation Capacitive coupling
p+
p+
p+
p+
p+
p+
V_{FD}
n-bulk
h+
300μm
E-field
n++
full aluminium backplane or strips


To Front-End Electronics
C_c
C_{i_2}
C_i
C_b
backplane

- 高灵敏的硅微条径迹探测器：
  - “悟空”号原有的一体化工装，硅微条越长平面度越差，超过100um的差异
  - 特色：采用“分体式”设计，配合光学导轨，通过三坐标仪测量校准平面度，获得高精度的封装工艺
  - 特色：多通道低噪声读出电子学的研制

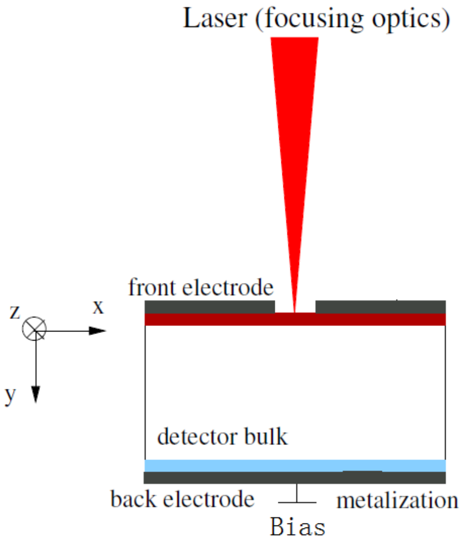




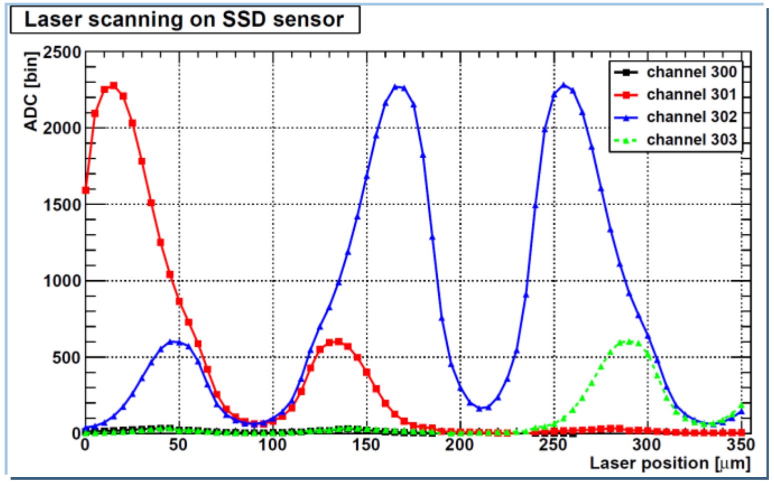


VLAST技术预研进展：径迹探测器

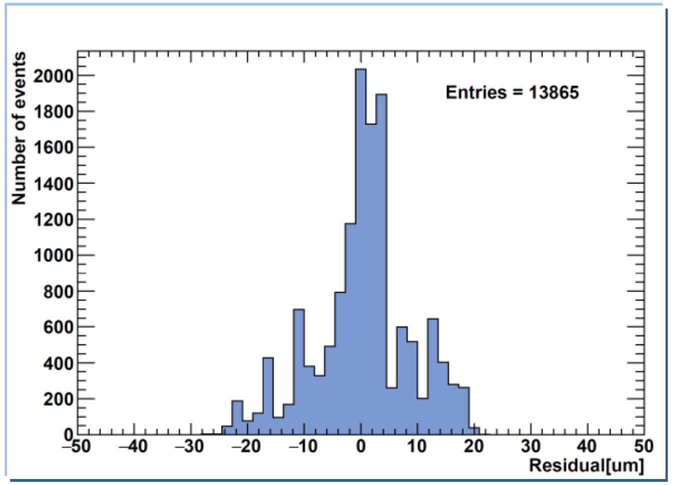
- 通过激光和束流测试探测器模块的位置分辨
  - 试验室条件下，激光模拟带电粒子，在硅探测器中沉积能量
  - 通过移动，扫描不同的硅微条的位置对激光信号的响应
  - 通过计算信号的在不同微条间的分配η计算位置分辨（<40um）



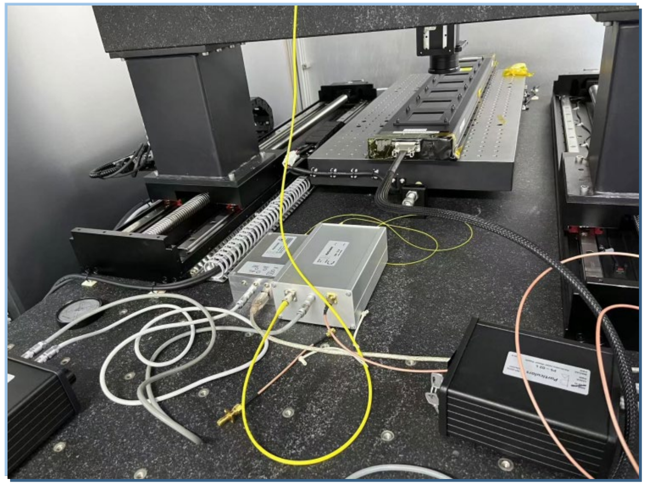
Laser (focusing optics)
front electrode
z
x
y
detector bulk
back electrode
metalization
Bias



微条的信号分布



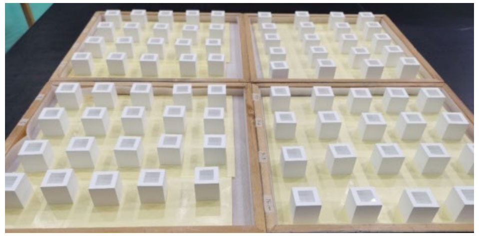
计算得到位置和移动位置的残差

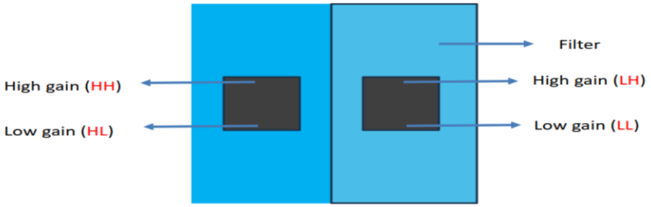


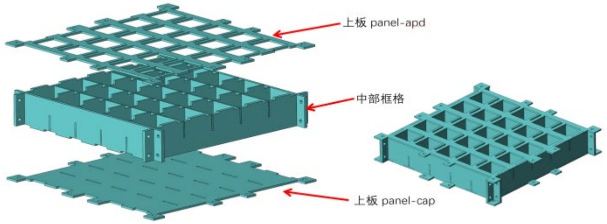
激光测试

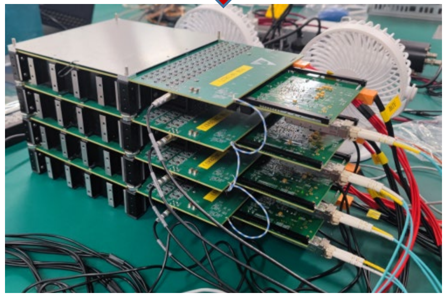
VLAST技术预研进展：电磁量能器—Cube

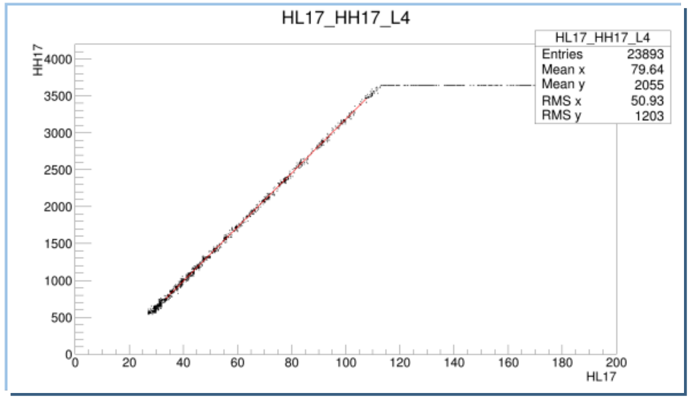
- 两条路线：3D高颗粒度量能器单元和条形量能器单元
- 高颗粒度量能器
  - **特色：**高颗粒度准确刻画簇射过程，提高粒子鉴别和能量分辨
  - 采用直接读出：解决了弱信号测量和大动态范围的串扰，探测单元实现了优于1.8X10^6 动态范围测量




Filter
High gain (HH)
High gain (LH)
Low gain (HL)
Low gain (LL)

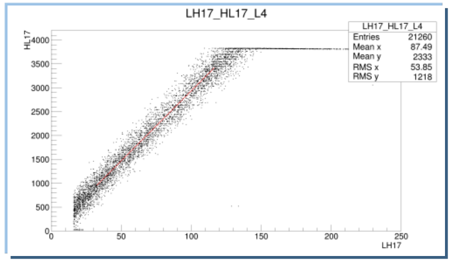

上板 panel-apd
中部框格
上板 panel-cap



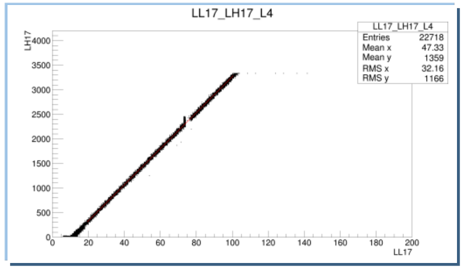


高增益/高低增益

中高增益/中低增益

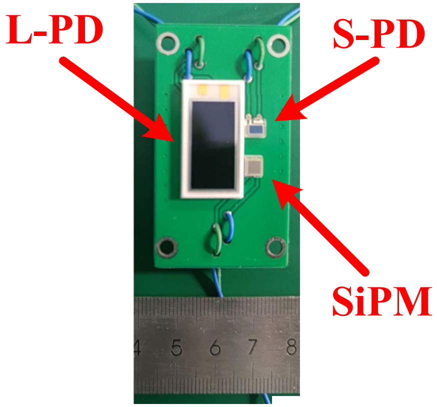


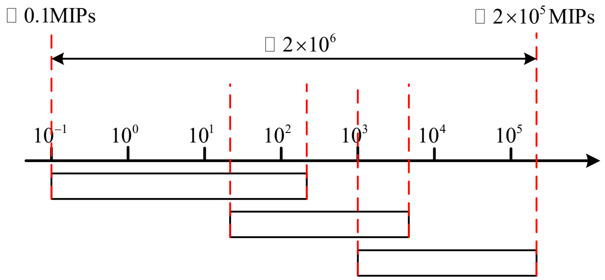
中低增益/低增益

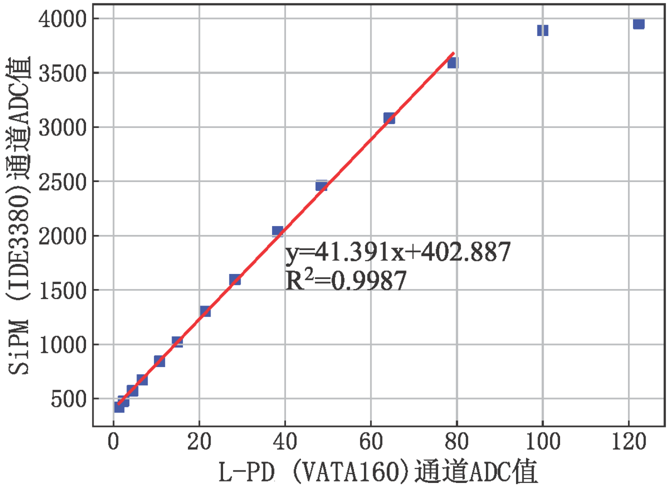


VLAST技术预研进展：电磁量能器—Bar

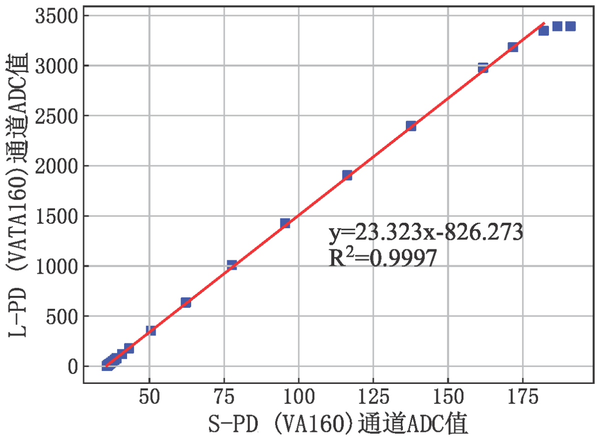
- 条形的“准3D”量能器单元优势是需要相对少的读出电子学
  - **特色：**利用3种不同增益的光电传感器实现大动态范围（>10^6）
  - 解决串扰、测量范围的线性扩展、标定等问题


L-PD
S-PD
SiPM
4 5 6 7 8

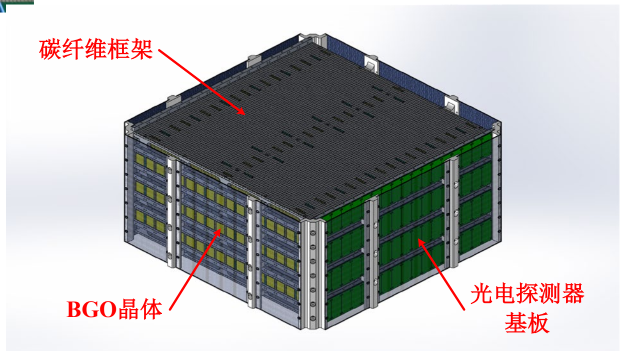

□ 0.1MIPs
□ 2×10⁵ MIPs
□ 2×10⁶
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵

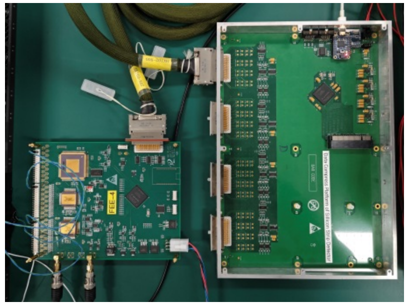


低能段与中能段增益

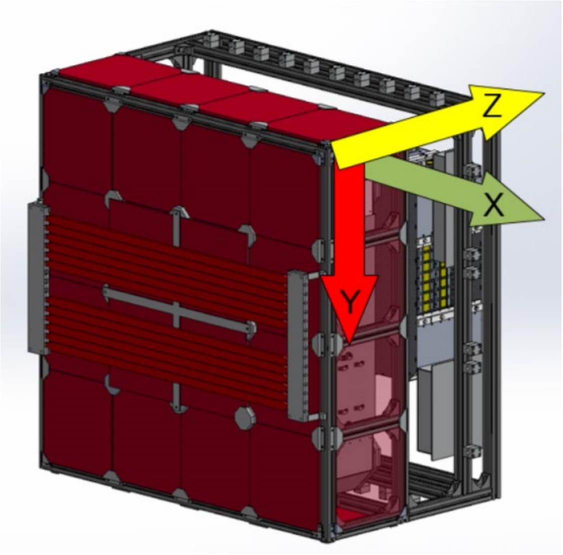


中能段与高能段增益

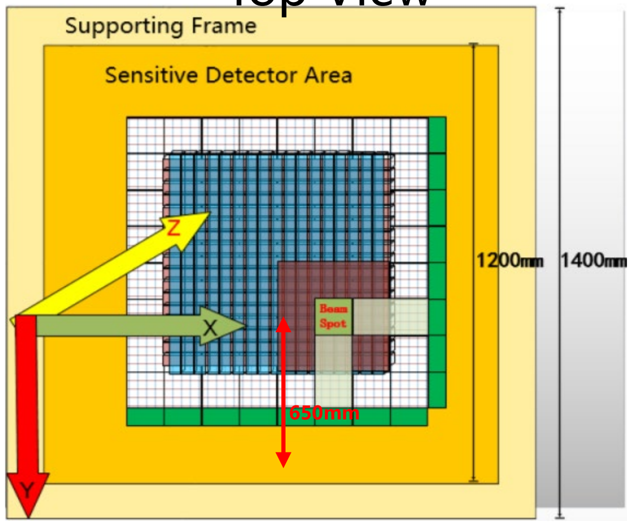

碳纤维框架
BGO晶体
光电探测器
基板



VLAST原理样机

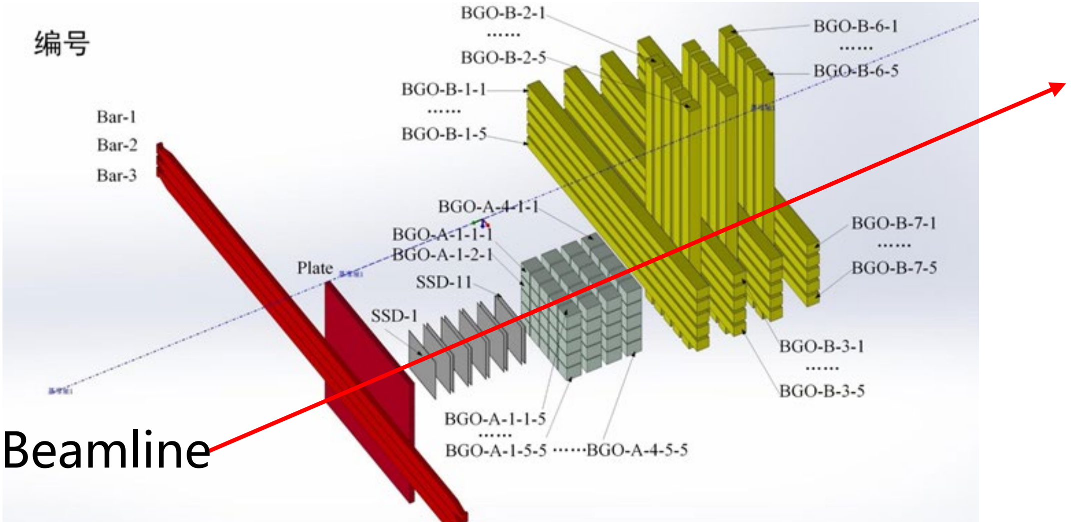


Top View


Supporting Frame
Sensitive Detector Area
Z
X
Y
Beam Spot
650mm
1200mm
1400mm

Dimension: $1.4m \times 1.4m \times 0.8m$

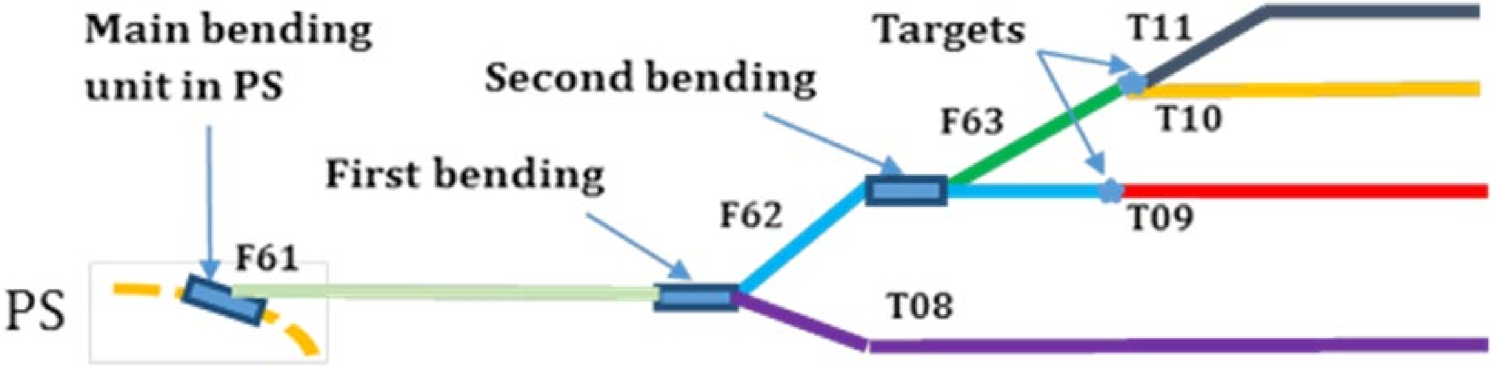
- ❖ Charge Detector: 12 PS bars
- ❖ Anti-coincidence Detector: 32 tiles
- ❖ Silicon Strip Tracker: 11 Layers
- ❖ BGO Calorimeter:
  - 10 Layers of 5x5 BGO cubes array
  - 7 Layers of 5 BGO bars
- ❖ CsI with wavelength shifted fiber
- ❖ Weight: **200kg**


编号
Bar-1
Bar-2
Bar-3
Plate
SSD-1
SSD-11
BGO-A-1-1-1
BGO-A-1-2-1
BGO-A-4-1-1
BGO-A-1-1-5
……
BGO-A-1-5-5 ……BGO-A-4-5-5
BGO-B-1-1
……
BGO-B-1-5
BGO-B-2-1
……
BGO-B-2-5
BGO-B-6-1
……
BGO-B-6-5
BGO-B-7-1
……
BGO-B-7-5
BGO-B-3-1
……
BGO-B-3-5
Beamline

提纲

1. VLAST原理样机研制
2. PS/SPS束流试验
3. 总结

PS束流基本情况

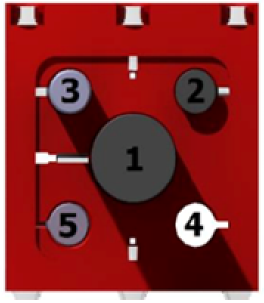

Main bending unit in PS
Second bending
Targets
T11
T10
F63
First bending
F62
T09
F61
PS
T08

Spill duration: 0.4 second flat top
Usually : **1-2 cycles per minute per East Destination, Max 6 East cycles / 40 seconds**

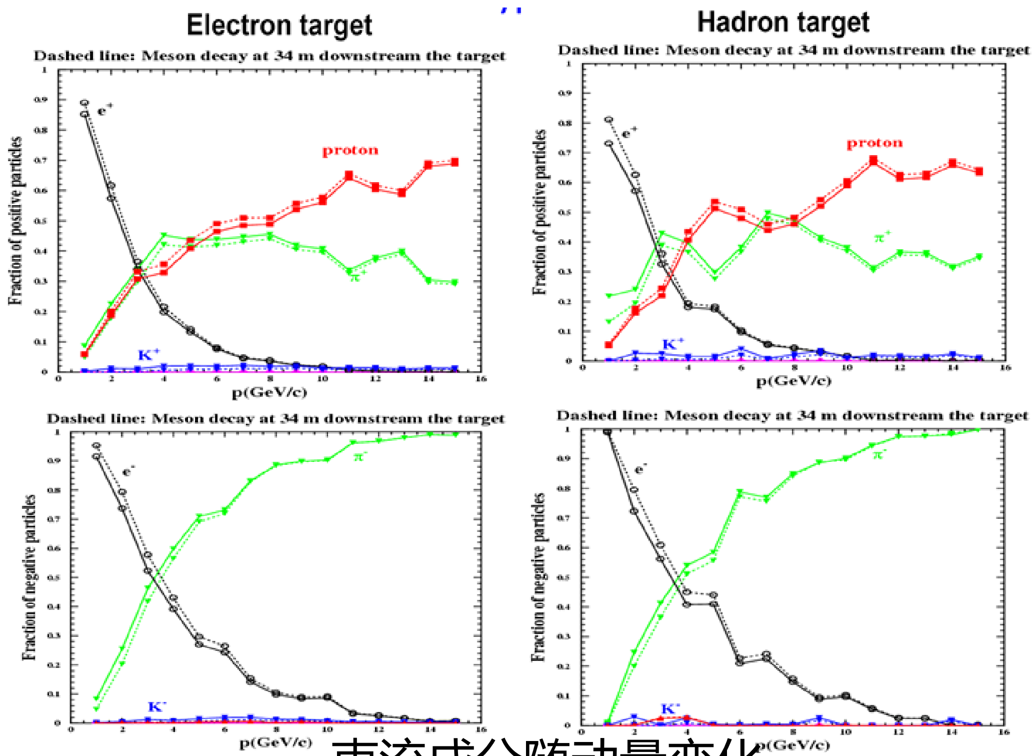
Parameter	**T09 Target**	**T10/T11 Target**	
Beam Line	T09	T10	T11
Secondary beam Max Momentum (GeV/c)	15	11.5	3.5
Δp/p (%)	±0.7 to ±15.0	±0.7 to ±15.0	±0.7 to ±15.0
Maximum intensity/spill (hadrons/electrons)	~10^6	~10^6	~10^6
Available particle types	Pure electrons (T09) or mixed/pure hadrons or pure muons		

PS束流基本情况

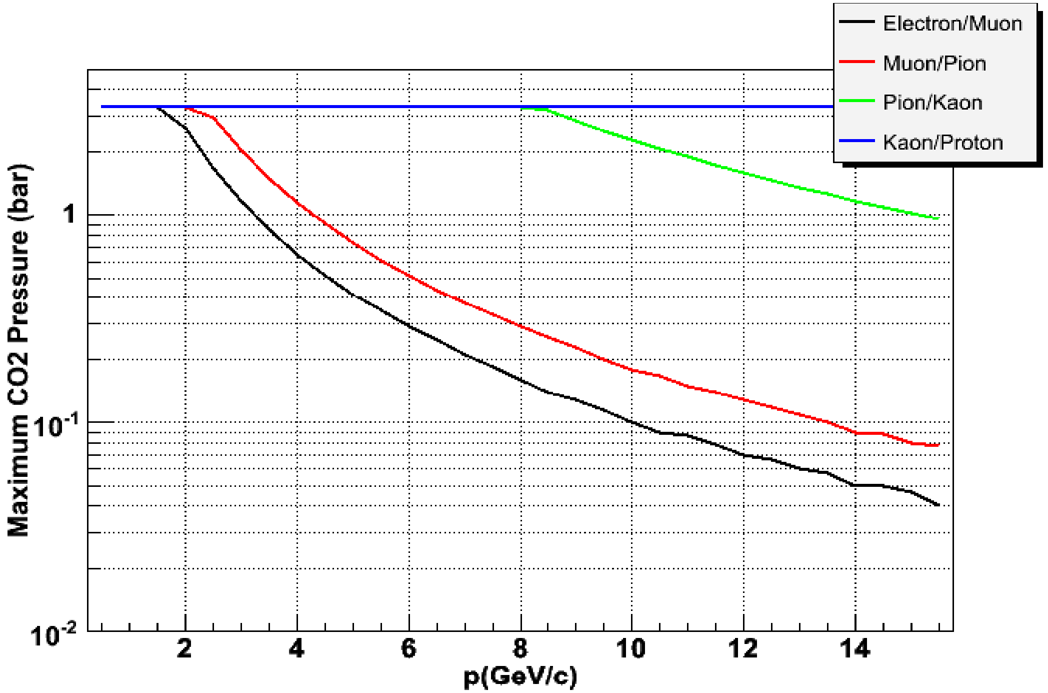
Head	Material	Length (mm)	Diameter (mm)	Comments
1	Be	200	10 + Al case	Electron enriched
	W	3		
2	Al	100	10	Electron enriched
	W	3		
3	Al	200	10	Hadron
4	Air	-	-	Empty
5	Al	20	10	Hadron



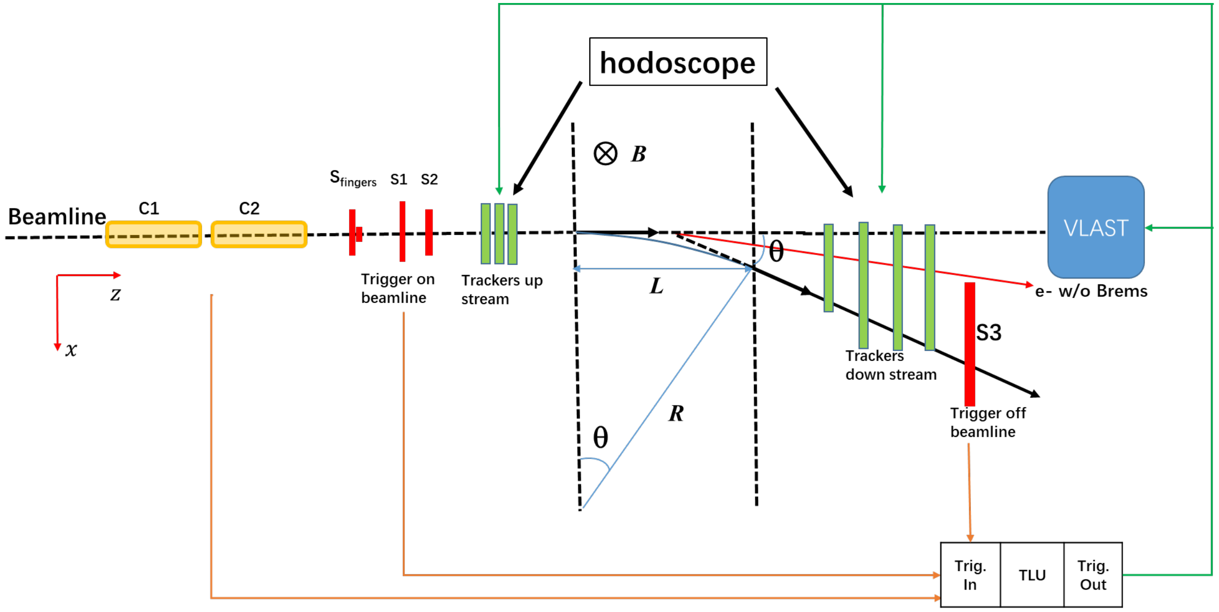
- 阈式契伦科夫探测器C1、C2
  - ✓ C1：高压契伦科夫，最高15bar，气体：CO_2
  - ✓ C2：低压契伦科夫，最高3.5bar，气体：CO_2

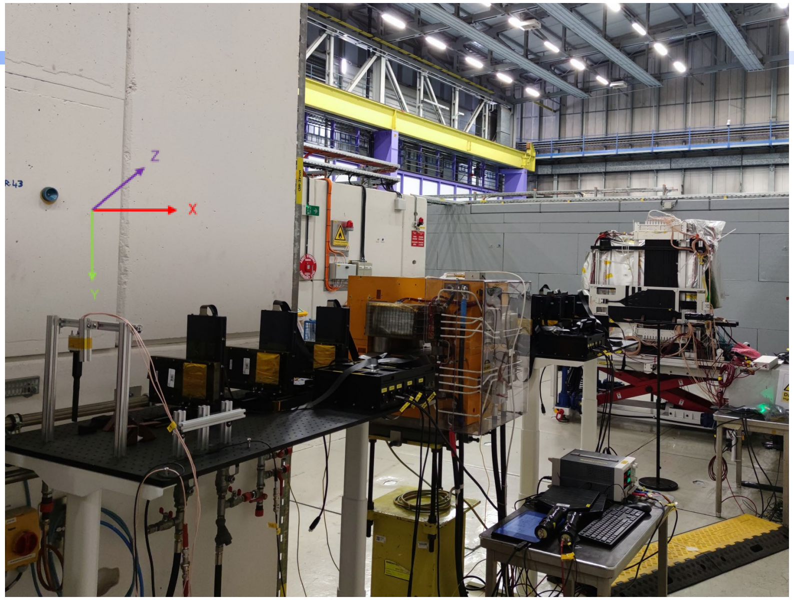


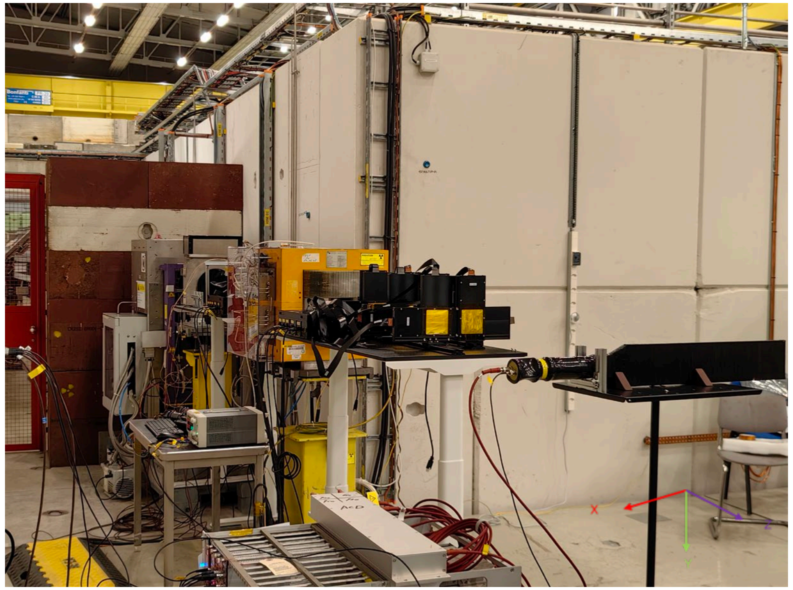
束流成分随动量变化



PS束流试验装置

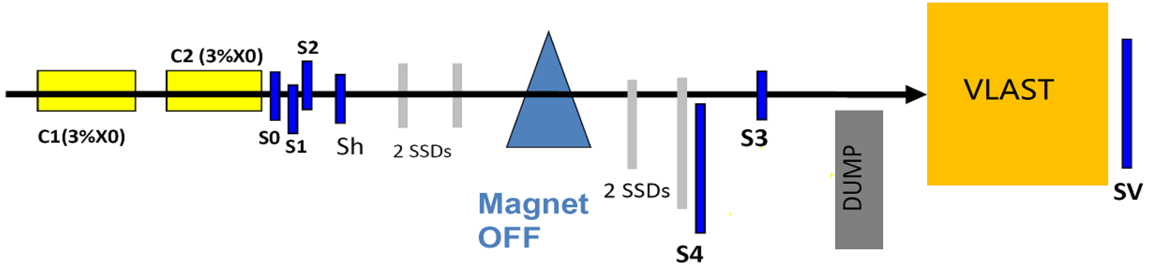

hodoscope
⊗ B
$S_{fingers}$
S1
S2
Beamline
C1
C2
z
x
Trigger on beamline
Trackers up stream
L
θ
R
θ
VLAST
e- w/o Brems
S3
Trackers down stream
Trigger off beamline
Trig. In
TLU
Trig. Out


z
x



PS束流试验方案——缪子束流

- 试验目的：采用Muon对探测器单元进行MIPs能量刻度，同时利用Muon粒子径迹进行探测器的校准工作。
- 束流：电子靶、负电成分。准直器MCH1与MCV1关闭，理论上只有mu可以通过。实际mu样本中可能存在强子污染，无电子污染，可以将C1、C2气压设置黑线与红线之间，排除π-束流，也可以通过离线数据分析，剔除发生簇射的π-。
- 外触发设置：

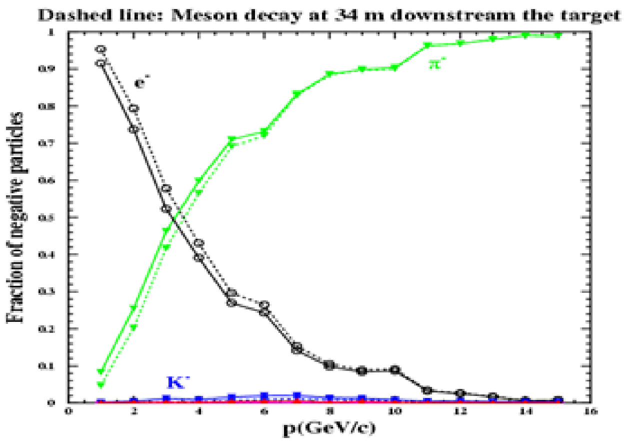

C1(3%X0)
C2 (3%X0)
S2
S0
S1
Sh
2 SSDs
Magnet
OFF
2 SSDs
S4
S3
DUMP
VLAST
SV

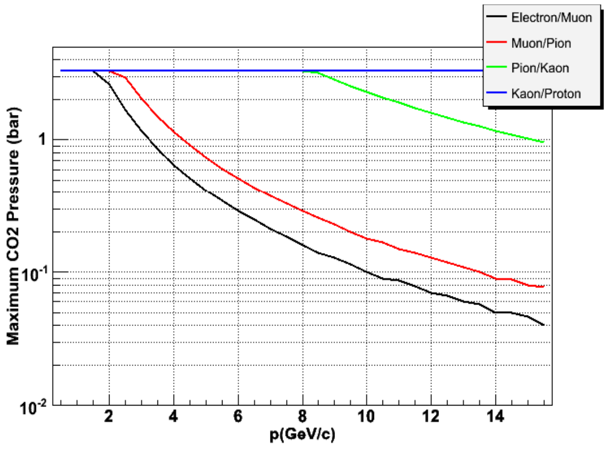
触发逻辑：$\mathrm{TRIG} = S_1 S_2 \overline{S_h} C_1 C_2 S_3 S_V$

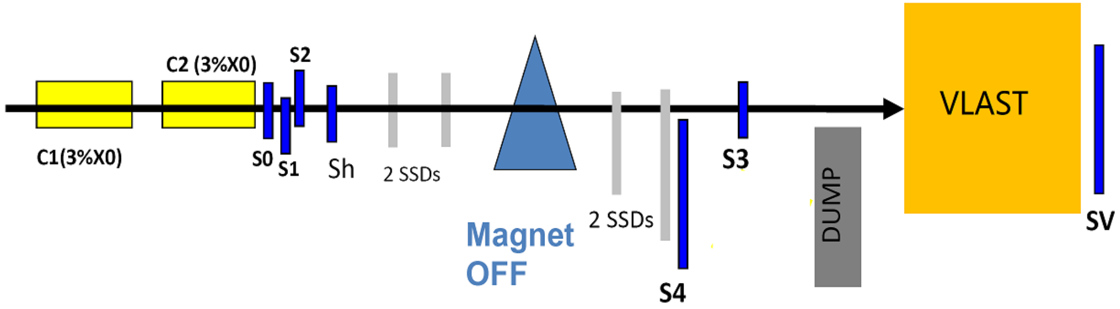
注意事项：减小温度影响，建议6个小时刻度一次。

PS束流试验方案——电子束流

- 试验目的：探测器对电子的能量分辨与能量线性
- 束流：电子靶、负电成分。电子能量0.5GeV-12GeV。C1与C2气压设置黑线以下，由于电子束流中，随着能量的增加，π-和k-强子的污染逐渐变得严重，在2-3GeV时，强子污染10^{-6}，但是10GeV以上，即使经过C1、C2甄别，强子污染仍可高达50%。
- 外触发设置：



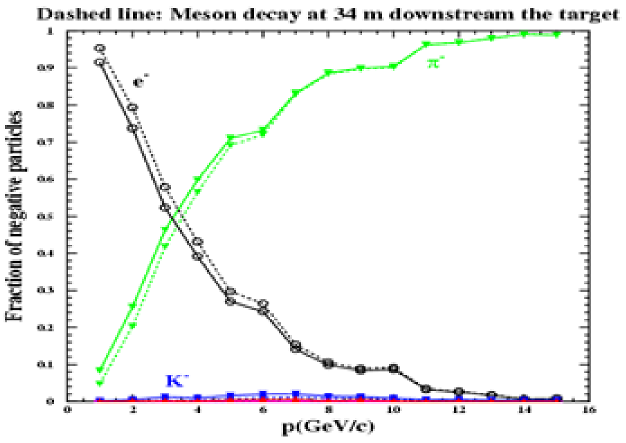


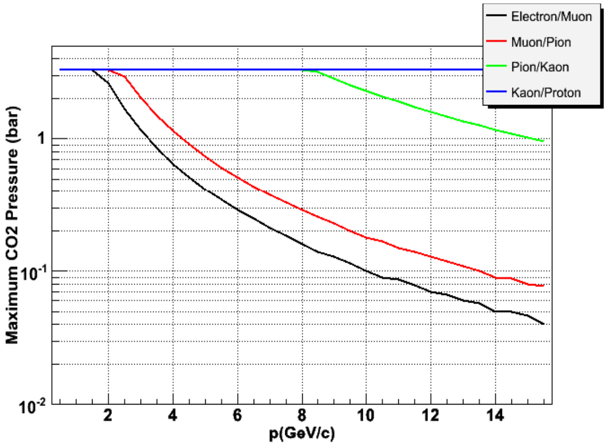

C1(3%X0)
C2 (3%X0)
S0
S1
S2
Sh
2 SSDs
Magnet OFF
2 SSDs
S4
S3
DUMP
VLAST
SV

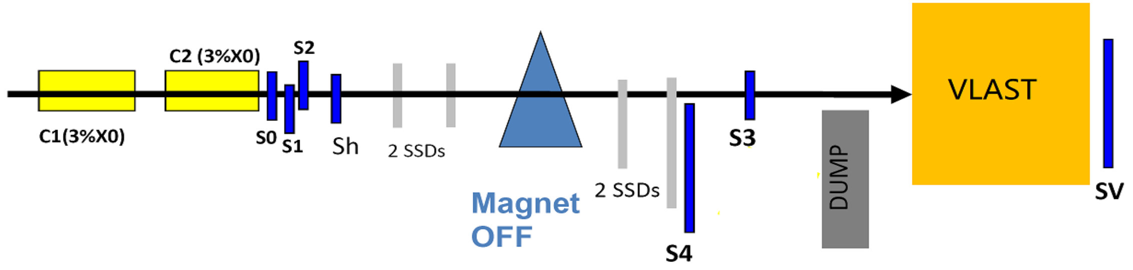
触发逻辑：$\mathrm{TRIG} = S_1 S_2 \overline{S_{\mathrm{h}}} C_1 C_2 S_3 \overline{S_V}$

PS束流试验方案——π-束流

- 试验目标：测量强子能量分辨，同时可以利用强子的MIPs样本刻度探测器。
- 束流：电子靶、负电成分。主要成分为e-、π-、和少量k-，在8-10GeV附近，束流90%以上为π-，C1、C2设置红黑线之间。
- 外触发设置：



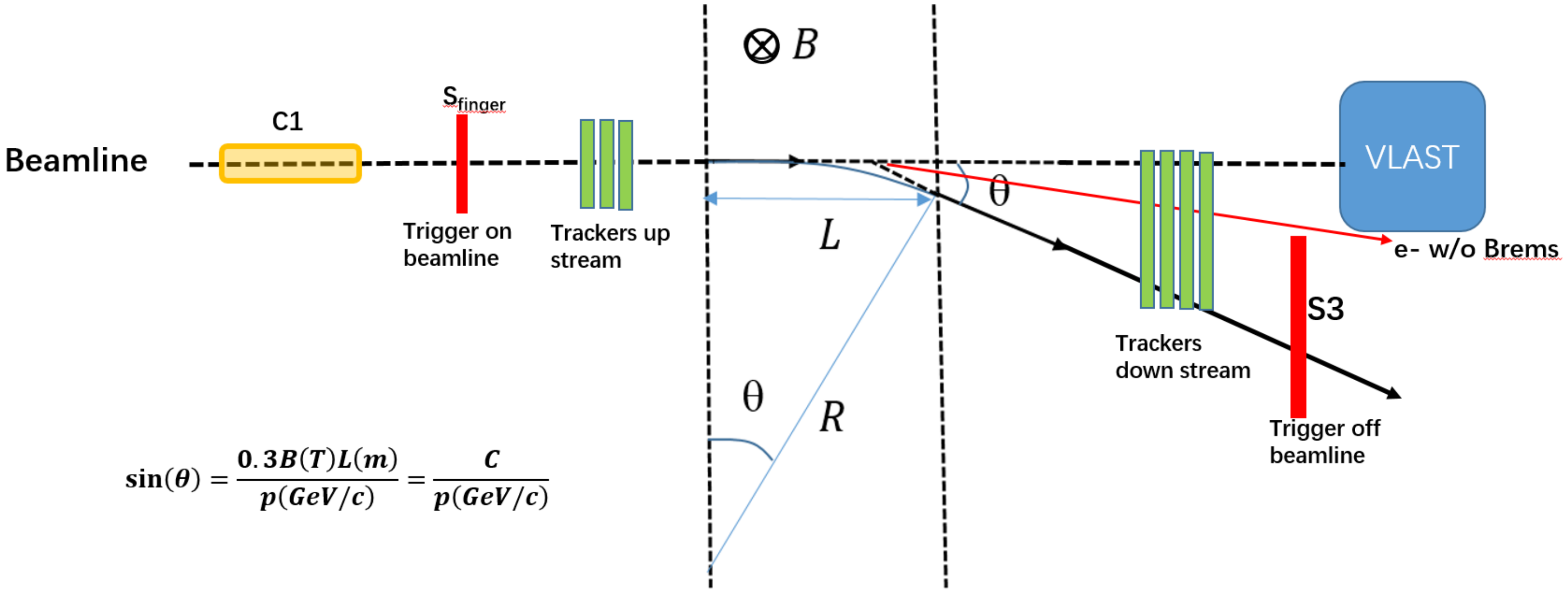



C1(3%X0)
C2 (3%X0)
S0
S1
S2
Sh
2 SSDs
Magnet OFF
2 SSDs
S4
S3
DUMP
VLAST
SV

触发逻辑：$\mathrm{TRIG} = S_1 S_2 \overline{S_{\mathrm{h}} + C_1 + C_2}\, S_3$

PS束流试验方案——光子束流

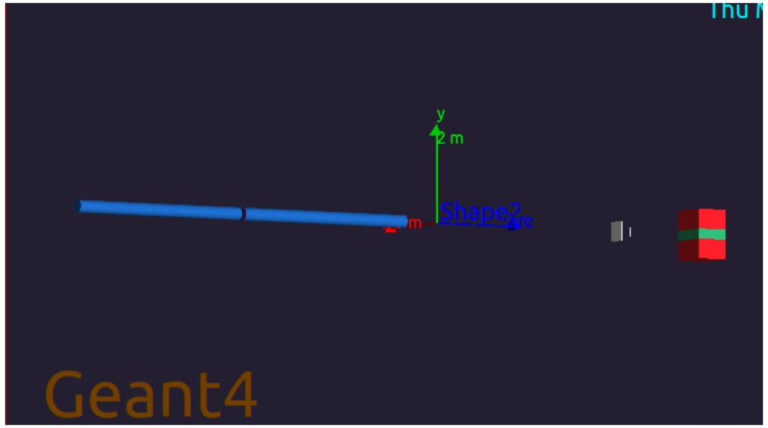
- 试验目标：研究对探测器对光子的响应以及物理性能指标，如能量分辨、线性、veto效率等。
- 束流：与电子束流相同。光子由电子在Tracker前空气中韧致辐射产生，通过用户磁铁偏转电子束流，得到纯净光子束流。
- 外触发设置：

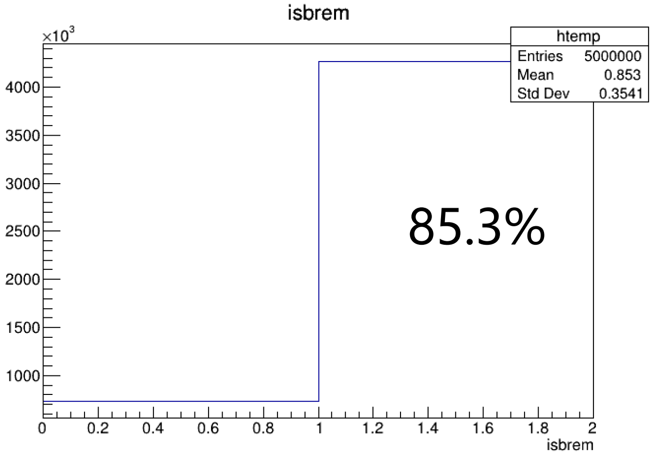

⊗ B
Beamline
C1
S_finger
Trigger on beamline
Trackers up stream
L
θ
θ
R
VLAST
e- w/o Brems
S3
Trackers down stream
Trigger off beamline

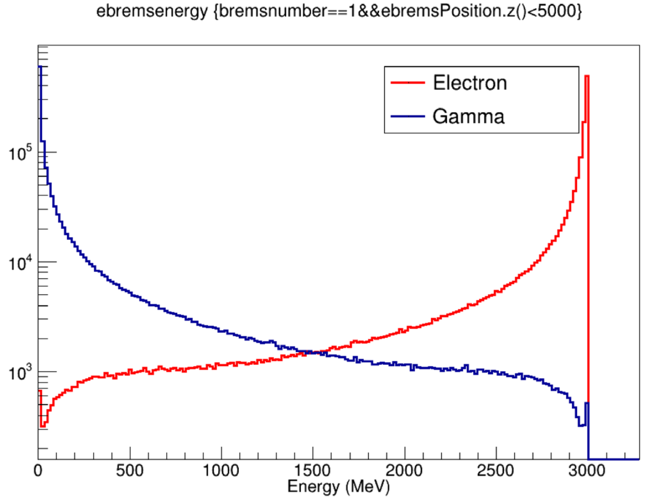
$$\sin(\theta) = \frac{0.3B(T)L(m)}{p(GeV/c)} = \frac{C}{p(GeV/c)}$$

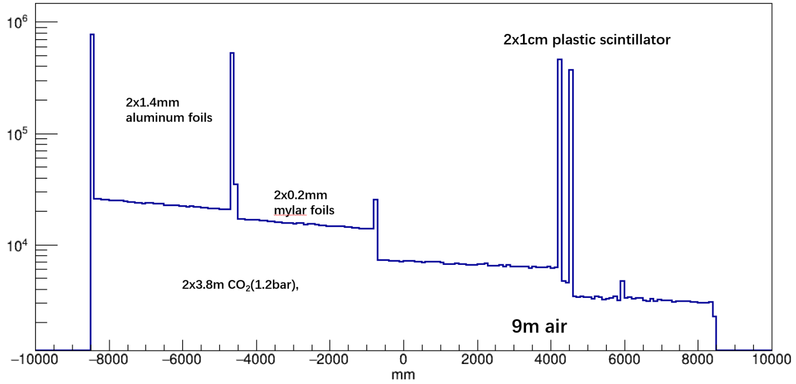
Trigger Logic=C1&S$_{\text{finger}}$&S3

PS束流电子韧致辐射模拟



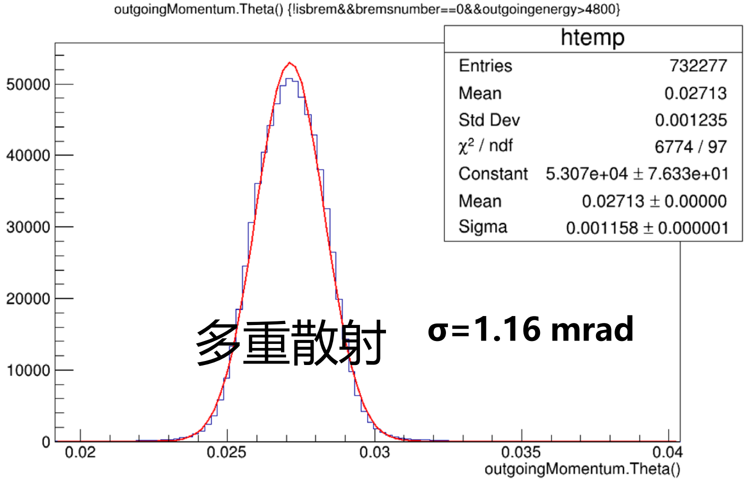




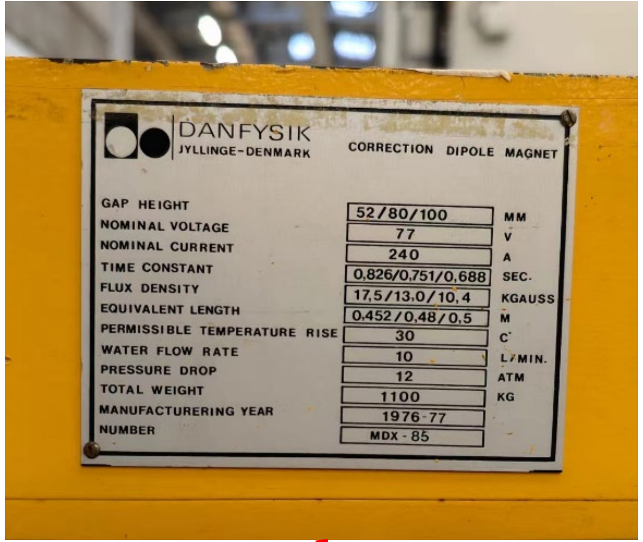


Material Budget

	材料	厚度(mm)	辐射长度(mm)	等效辐射长度(X0)	占比
C1	铝膜	1.4	88.97	0.015736	0.060364
	二氧化碳	3280	1.97E+05	0.016692	0.064033
	铝膜	1.4	88.97	0.015736	0.060364
	空气	1685	3.04E+05	0.005545	0.02127
C2	mylar	0.25	88	0.002841	0.010898
	二氧化碳	3115	1.97E+05	0.015852	0.060812
	mylar	0.25	88	0.002841	0.010898
触发	塑闪	5	2.70E+02	0.018519	0.07104
丝室	丝室	0.005	1	0.005000	0.019181
finger	塑闪	10	270	0.037037	0.142079
S2	塑闪	10	270	0.037037	0.142079
S1	塑闪	10	270	0.037037	0.142079
SSD*14	硅(320um)	4.48	94	0.047660	0.182829
铝膜*14	铝(20um)	0.28	88.97	0.003147	0.012073
大厅空气	空气	7965	303900	0.026209	0.100543
			总厚度	0.260679	

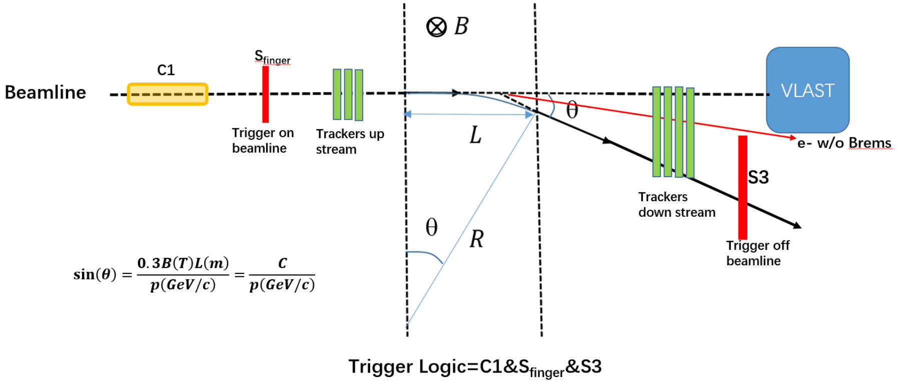


PS束流-用户磁铁刻度



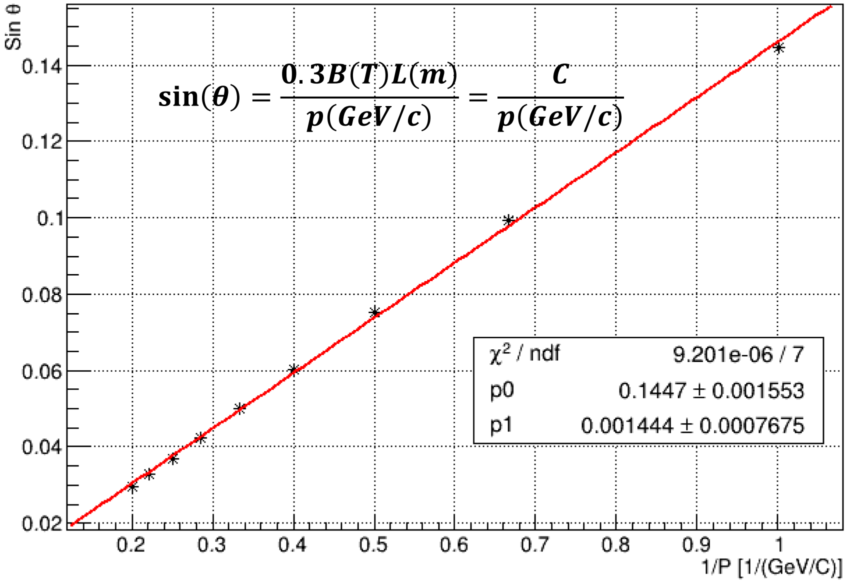
DANFYSIK
JYLLINGE-DENMARK
CORRECTION DIPOLE MAGNET

GAP HEIGHT	52/80/100	MM
NOMINAL VOLTAGE	77	V
NOMINAL CURRENT	240	A
TIME CONSTANT	0,826/0,751/0,688	SEC.
FLUX DENSITY	17,5/13,0/10,4	KGAUSS
EQUIVALENT LENGTH	0,452/0,48/0,5	M
PERMISSIBLE TEMPERATURE RISE	30	C'
WATER FLOW RATE	10	L/MIN.
PRESSURE DROP	12	ATM
TOTAL WEIGHT	1100	KG
MANUFACTURERING YEAR	1976-77	
NUMBER	MDX - 85	



$$\sin(\theta) = \frac{0.3B(T)L(m)}{p(GeV/c)} = \frac{C}{p(GeV/c)}$$

Trigger Logic=C1&S_{finger}&S3

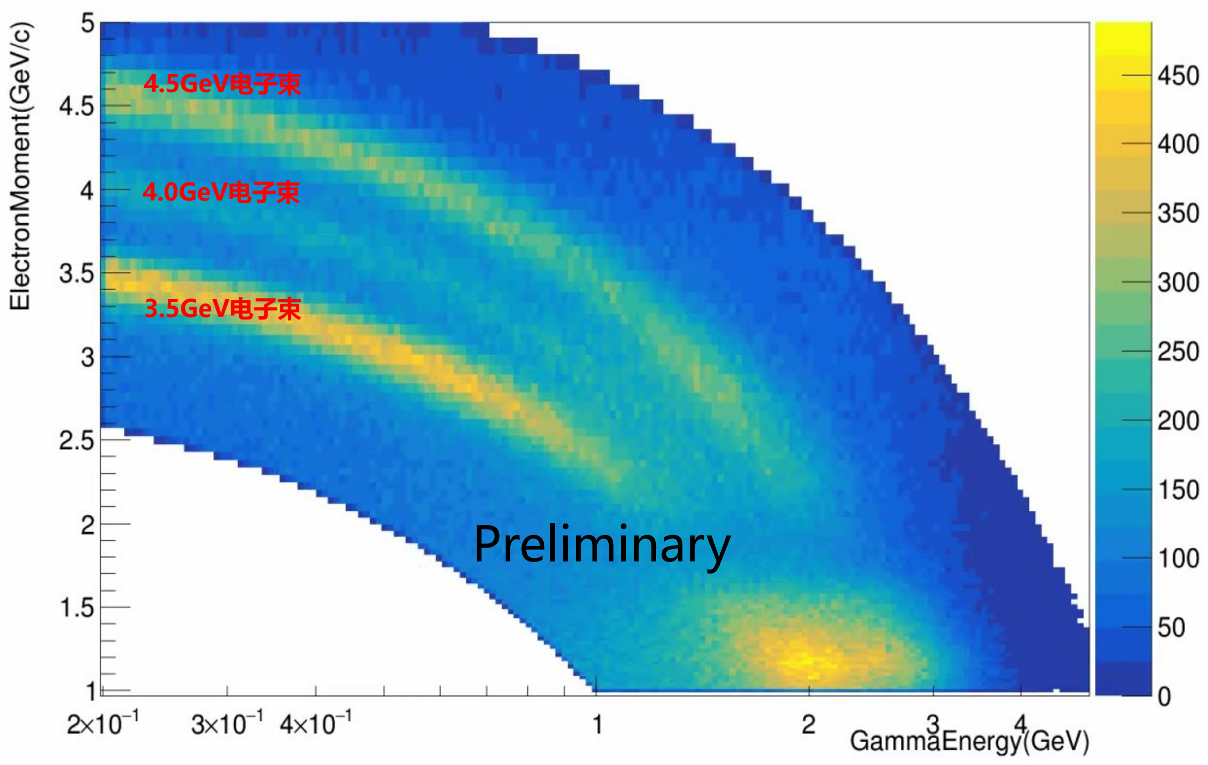


$$\sin(\theta) = \frac{0.3B(T)L(m)}{p(GeV/c)} = \frac{C}{p(GeV/c)}$$

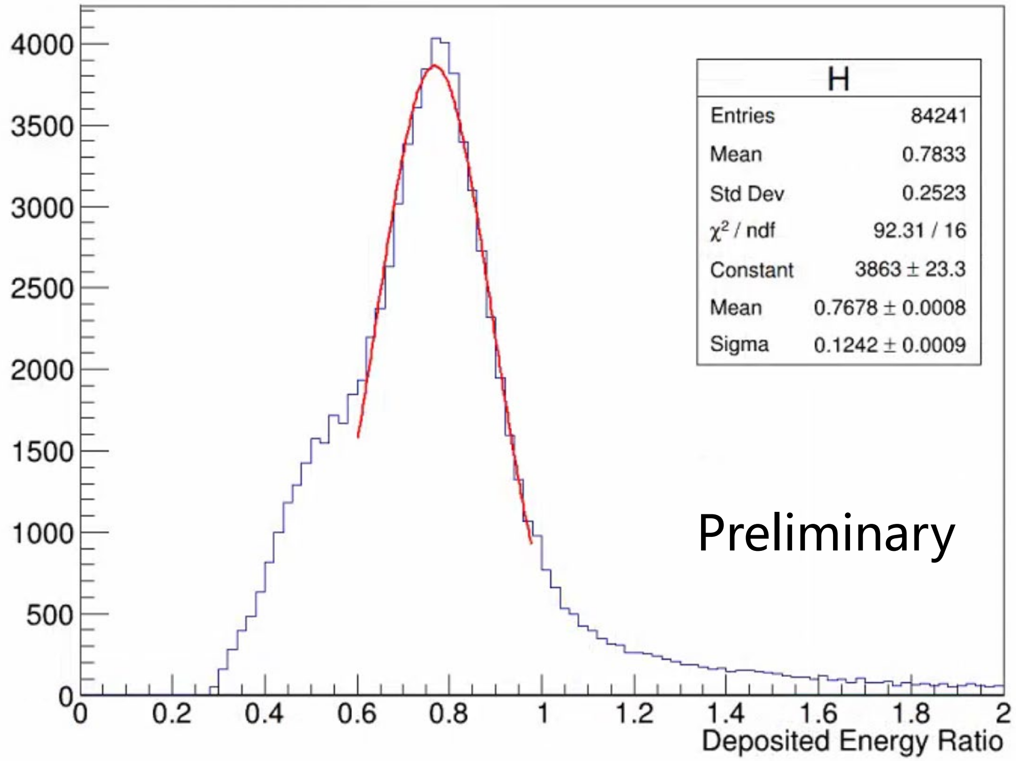
电子能量（GeV)	电子偏转角度（rad)	电子偏转角度（°)	磁场后2米位置横向偏转距离（cm)	磁场后3米位置横向偏转距离（cm)	磁场后5米位置横向偏转距离（cm)
0.1	0.933248	53.47	160.71	241.07	401.78
0.3	0.422854	24.23	82.07	123.11	205.18
0.5	0.263712	15.11	52.13	78.20	130.33
0.7	0.190518	10.92	37.87	56.81	94.68
0.9	0.148890	8.53	29.67	44.50	74.17
1.1	0.122117	7.00	24.36	36.54	60.91
1.3	0.103475	5.93	20.66	30.99	51.65
1.5	0.089758	5.14	17.93	26.89	44.82
1.7	0.079245	4.54	15.83	23.75	39.58
1.9	0.070933	4.06	14.17	21.26	35.44
2.1	0.064197	3.68	12.83	19.25	32.08
2.3	0.058628	3.36	11.72	17.58	29.30
2.5	0.053948	3.09	10.78	16.18	26.96
2.7	0.049958	2.86	9.99	14.98	24.97
2.9	0.046518	2.67	9.30	13.95	23.25
3.1	0.043521	2.49	8.70	13.05	21.75
3.3	0.040886	2.34	8.17	12.26	20.44
3.5	0.038552	2.21	7.71	11.56	19.27
3.7	0.036470	2.09	7.29	10.94	18.23
3.9	0.034602	1.98	6.92	10.38	17.30
4.1	0.032915	1.89	6.58	9.87	16.45
4.3	0.031385	1.80	6.28	9.41	15.69
4.5	0.029991	1.72	6.00	9.00	14.99
4.7	0.028716	1.65	5.74	8.61	14.36
4.9	0.027544	1.58	5.51	8.26	13.77
5.1	0.026464	1.52	5.29	7.94	13.23

PS束流试验——光子束流试验结果

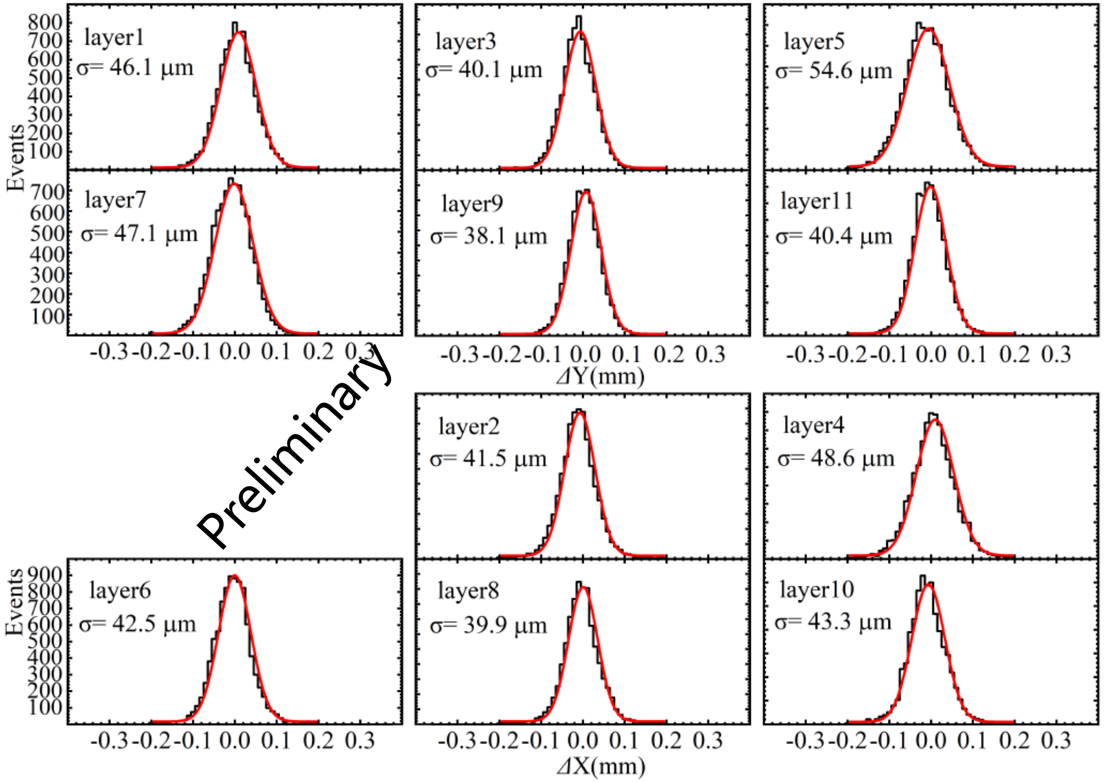
Magnet: -180A

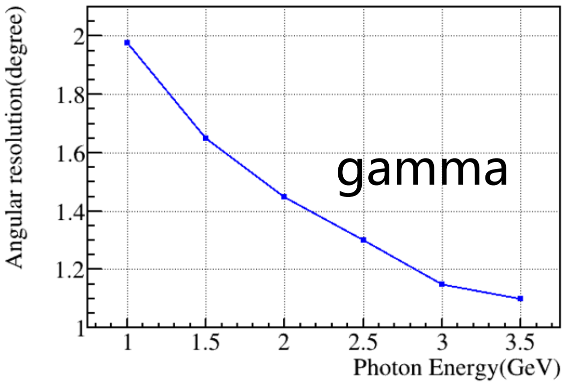


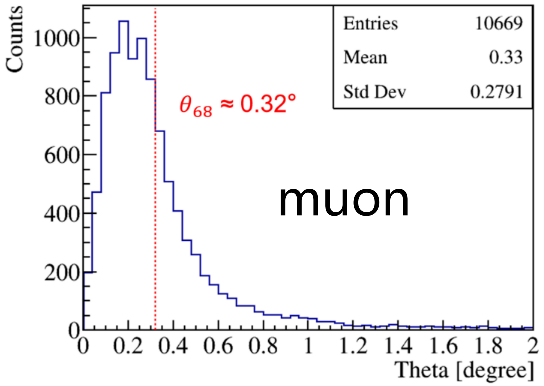
Deposited Energy / (Beam Moment-Electron Moment)

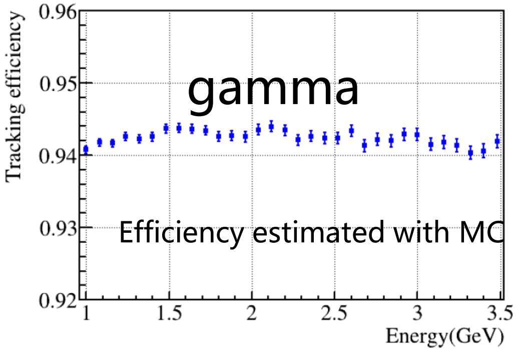


PS束流试验——光子束流试验结果

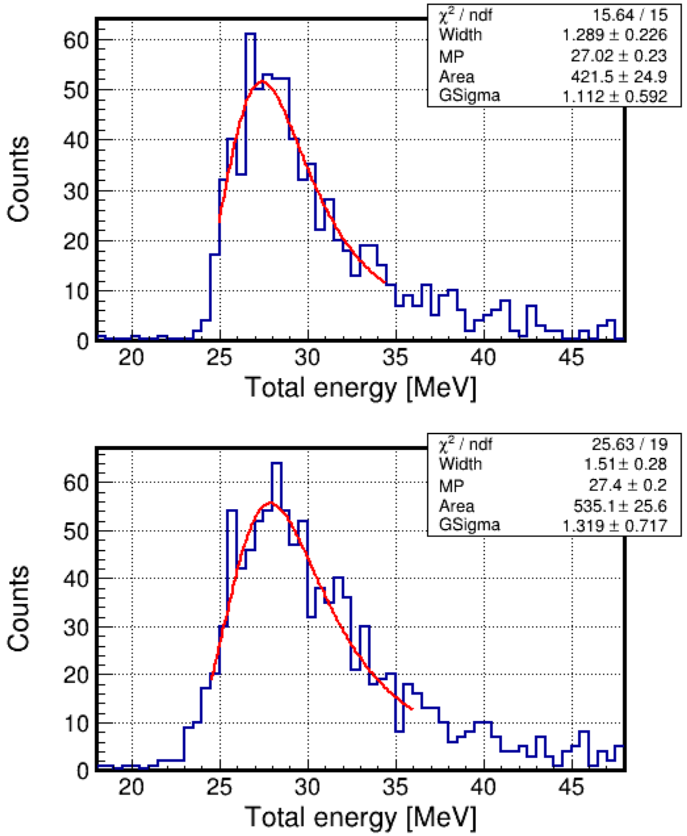






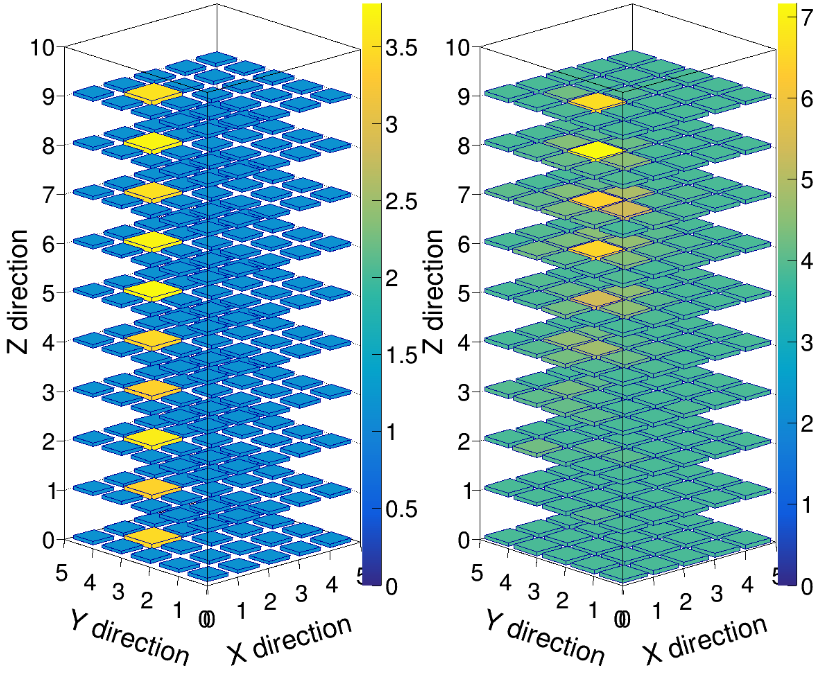


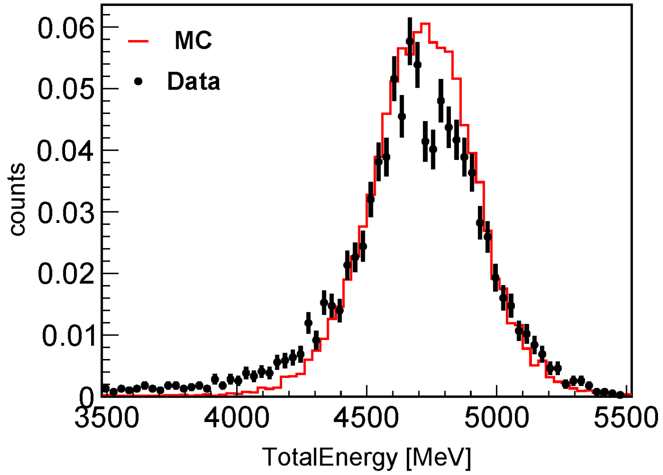
PS束流试验——电子及缪子束流试验结果



MIPs 的典型结果:
(上) Geant4 模拟; (下) 束流数据

Muon 事例与电子事例的可视化展示



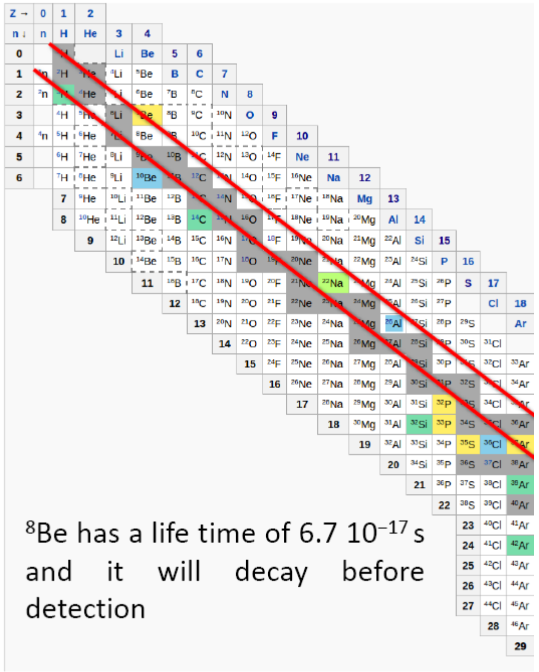


5 GeV/c 电子能谱

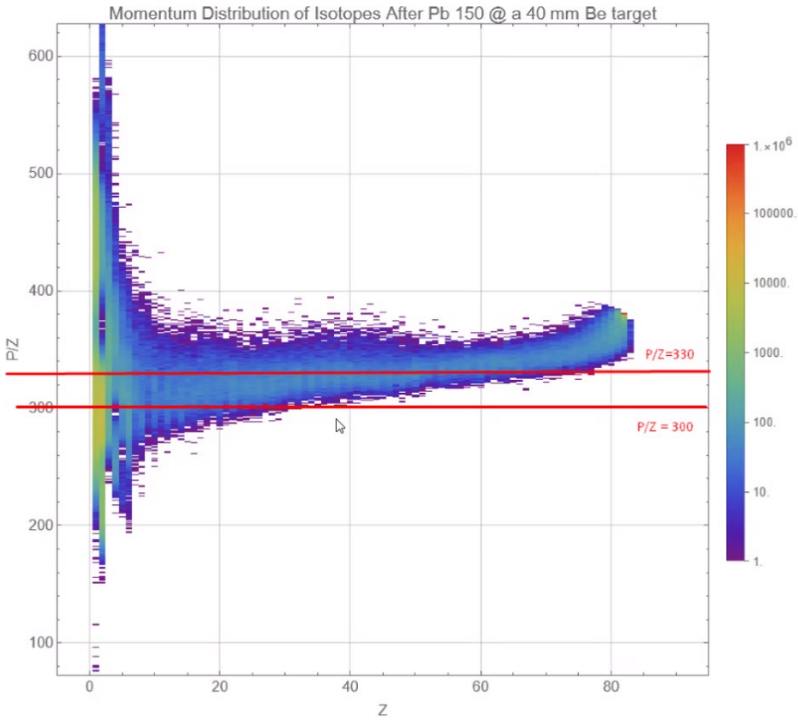
SPS-H8核碎片束线基本情况

- Beam originates from the T4 target, shared with the H6 and P42 beamlines
  - Available momenta: <10-400 GeV/c
  - Magnetic spectrometers with maximum δp/p : 0.1 - 1.5% (not for muons)
  - Momentum selection, not particle species selection
- Spill duration: flat-top ~4.8s for protons, ~9.0s for ions, 1-2 spills / supercycle (~3000/day)

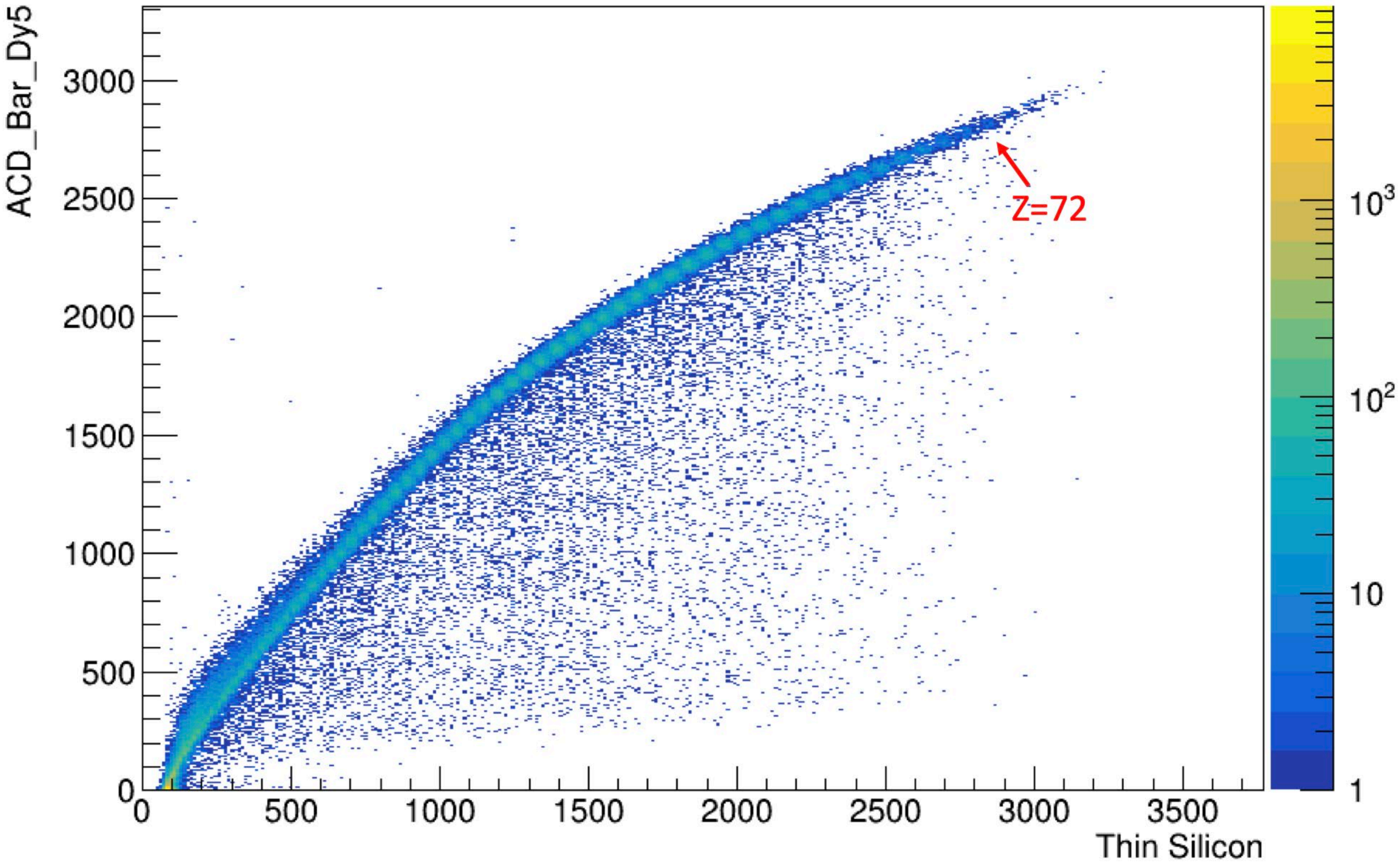
^{8}Be 的寿命只有6.7*10^{-17}s，在到达探测器之前已经衰变。在电荷重建过程中，可以将这个缺口作为电荷测量的一个基准，来确定其他电荷。



^{8}Be has a life time of 6.7 10^{-17} s and it will decay before detection

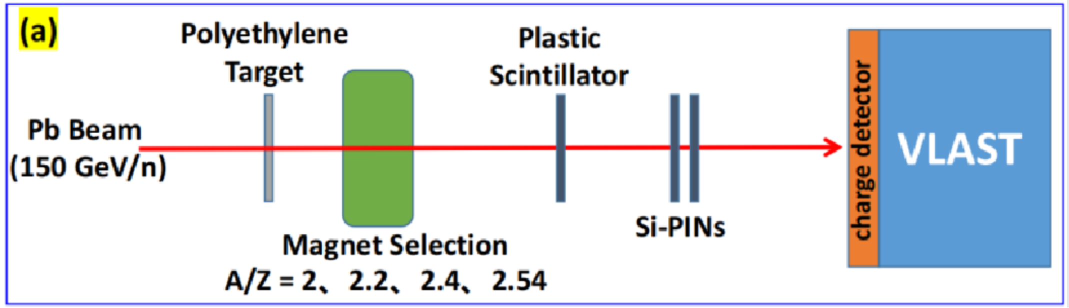


SPS-H8束流试验测试结果

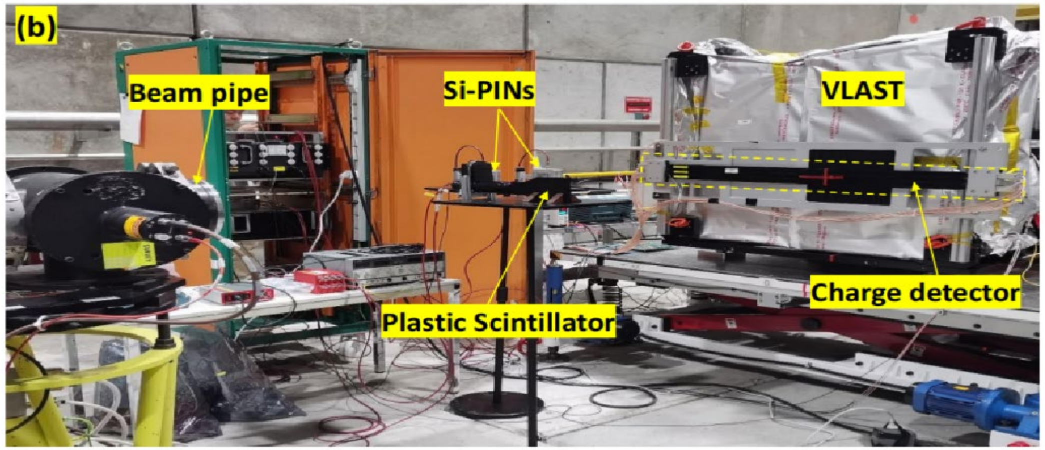


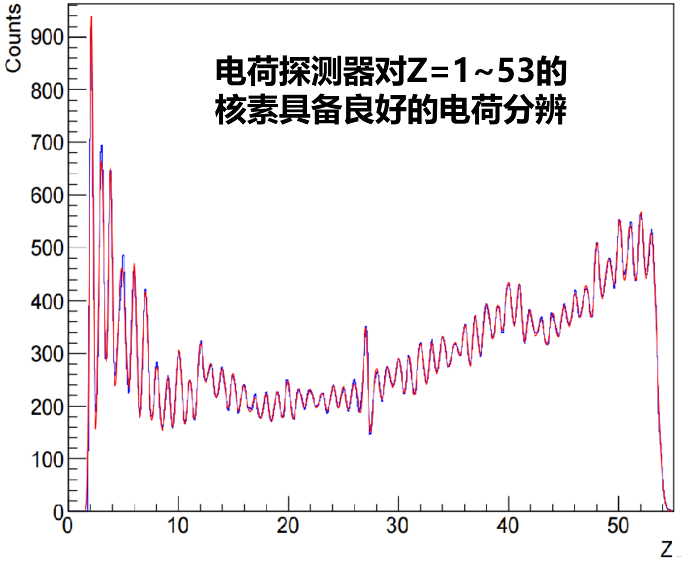
SPS-H8束流试验测试结果

试验目标：利用SPS-H8束流线产生的核碎片研究电荷测量能力及QUENCH效应
束流：A/Z=2、2.2、2.4、2.54的Pb碎片
外触发设置：

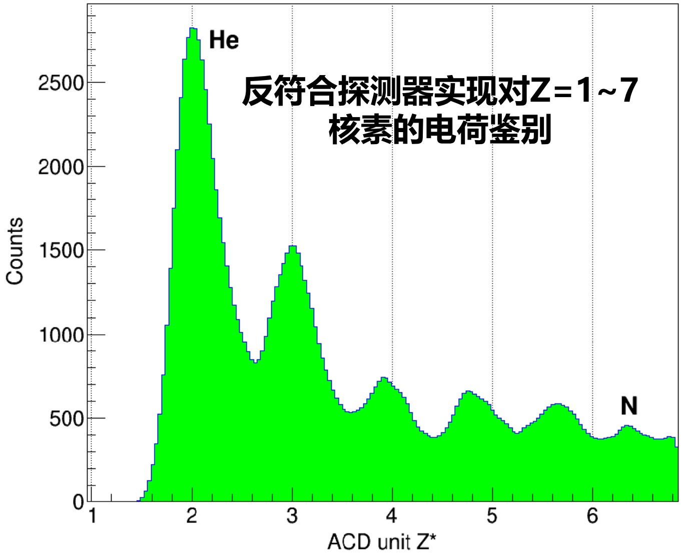

(a)
Polyethylene Target
Plastic Scintillator
Pb Beam (150 GeV/n)
charge detector
VLAST
Si-PINs
Magnet Selection
A/Z = 2、2.2、2.4、2.54

Si1、Si2为硅Pin探测器，用于标记碎片粒子。


(b)
Beam pipe
Si-PINs
VLAST
Charge detector
Plastic Scintillator



电荷探测器对Z=1~53的核素具备良好的电荷分辨

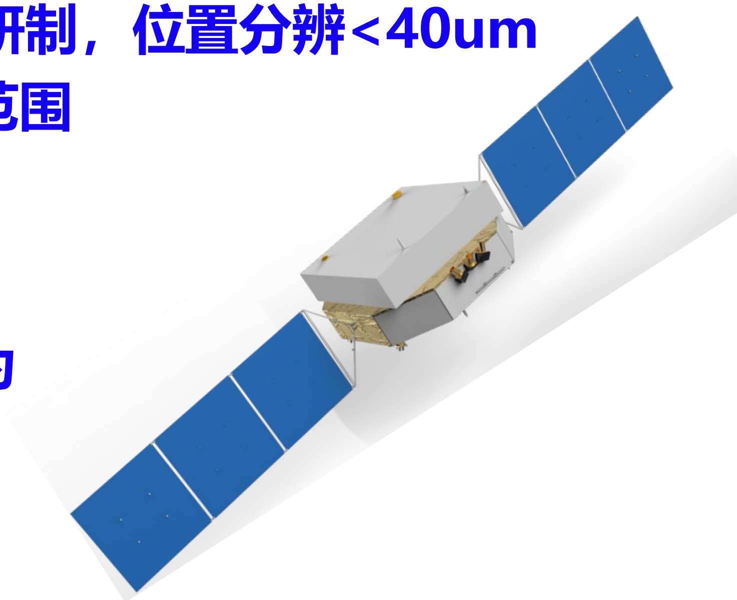


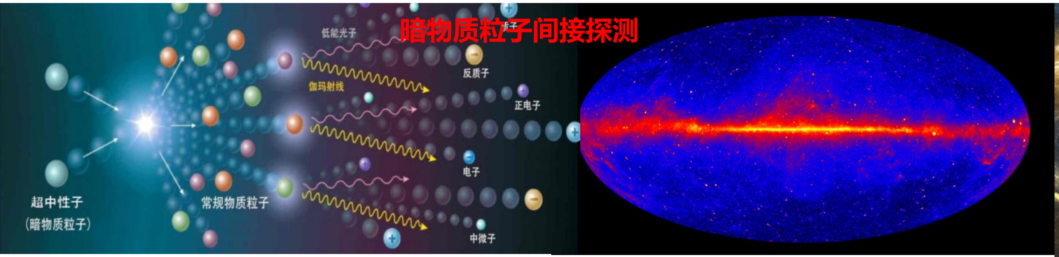
反符合探测器实现对Z=1~7核素的电荷鉴别

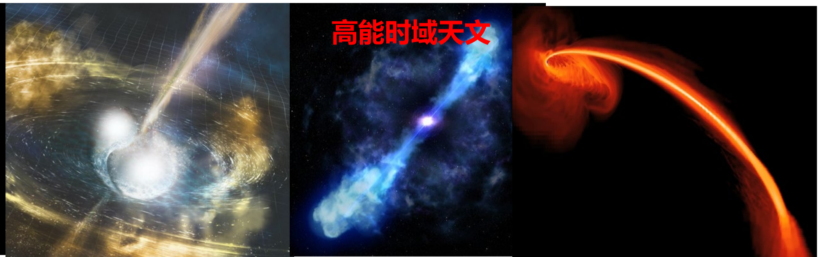
电荷分辨(0.15e@He)满足Z=1~40电荷测量指标要求！

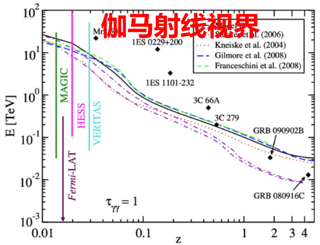
总结

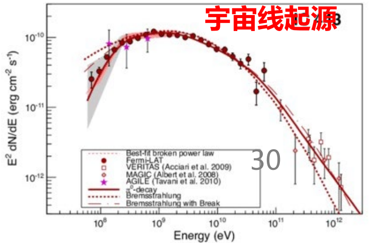
- **VLAST完成了部分技术预研工作，搭建一个小型原理样机（2024年）**
  1. 反符合探测器——Tile形ACD的MIPs事件实现0.99997的极高探测效率指标，Bar形电荷测量完成10^5大动态范围读出设计
  2. 径迹探测器——高精度的封装工艺与多通道低噪声读出电子学的研制，位置分辨<40um
  3. 电磁量能器——采用PD、APD、SiPM信号读出方案，10^6动态范围
- **原理样机进行了PS和SPS束流试验**
  1. 成功完成了电子、π-、gamma和核碎片束流试验
  2. 完成部分测试数据的离线分析，后续将继续分析和理解探测器行为



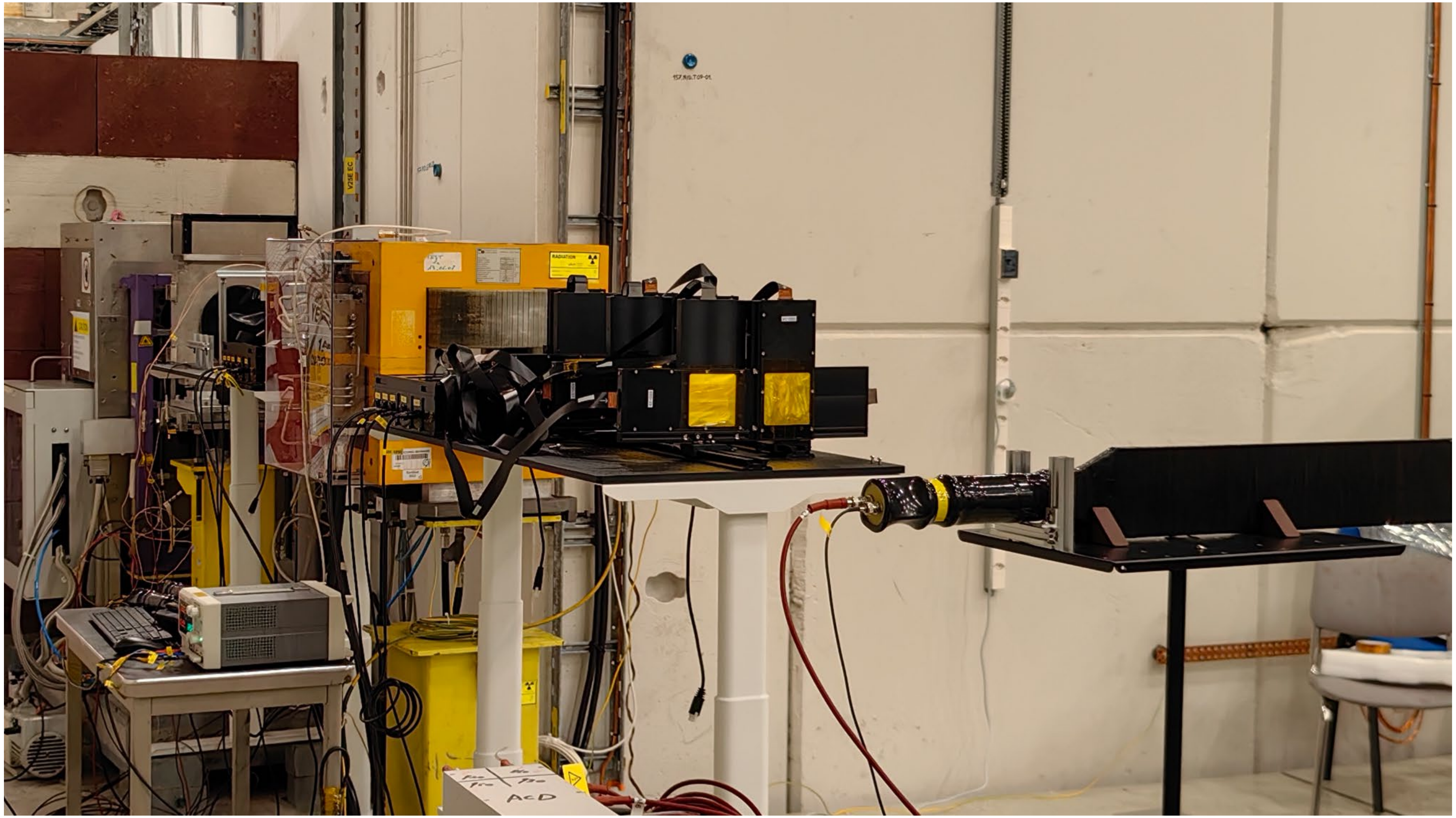

暗物质粒子间接探测
超中性子
(暗物质粒子)
常规物质粒子
低能光子
伽马射线
反质子
正电子
电子
中微子


高能时域天文


伽马射线视界

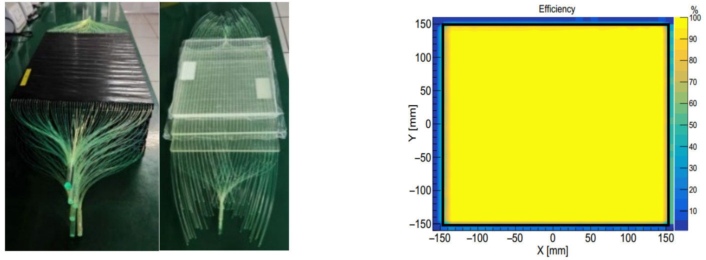

宇宙线起源

Backup

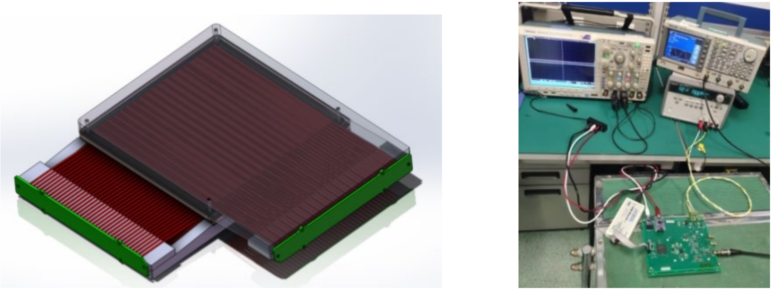


VLAST技术预研进展——2025

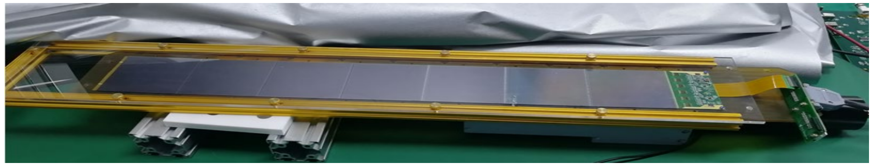
- **高探测效率的塑闪反符合技术**
  - 不同位置能够达到均匀的探测效率，同时保证在高计数率下工作
  - 单元>99.97%探测效率和原始事件率>10 kHz/m^2的信号采集处理
  - 对单个塑闪单元模块嵌入波长位移转换光纤，实现单个模块99.9%的效率
- **大面积高分辨的碘化铯CsI读出及康普顿散射光子数据处理技术**
  - 大面积的CsI晶体能量读出的同时完成信号的位置测量
  - 灵敏单元测量范围50keV-10MeV，位置分辨好于2mm
  - 已完成方案设计和读出电子学原型测试，正进行模块研制
- **高灵敏度高分辨的硅微条探测器封装技术**
  - 单个Ladder面积从悟空号的40cm×10cm增大到70cm×10cm，解决大面积封装带来的工艺挑战以及低功耗的读出电子学
  - 研制了70cm长模块，但未环境验证；正ASIC芯片设计，准备流片
- **大面积成像量能器读出技术**
  - 实现平方米级高能成像量能器，并达到~10^6探测单元动态范围
  - 已初步研制米量级的长BGO晶体和相应的读出电子学原型
  - 同时进行高颗粒度晶体方案预研：小尺寸晶体+APD/PD读出



反符合探测器单元和效率测试初步结果



CsI读出单元和波形数字化信号采集系统



硅微条探测器ladder

高颗粒度晶体

~1米的BGO晶体及大动态范围读出电子学