

中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

HIRFL-CSR 外靶实验 (CEE) : 探测器建设、 软件平台与物理展望

张亚鹏

中国科学院近代物理研究所

2026年7月13-19日, 广州



CEE合作组

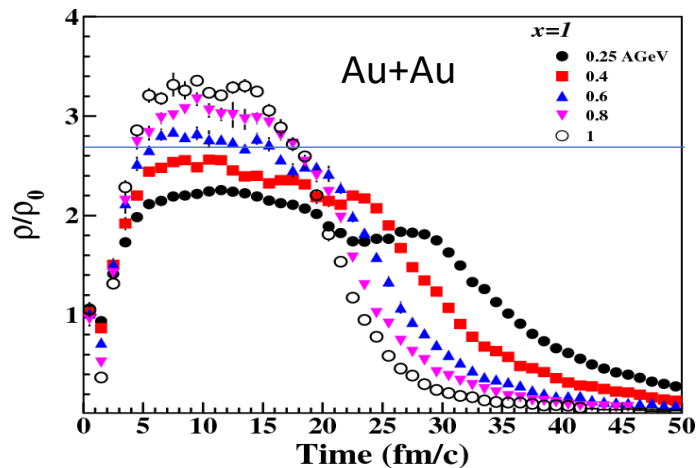
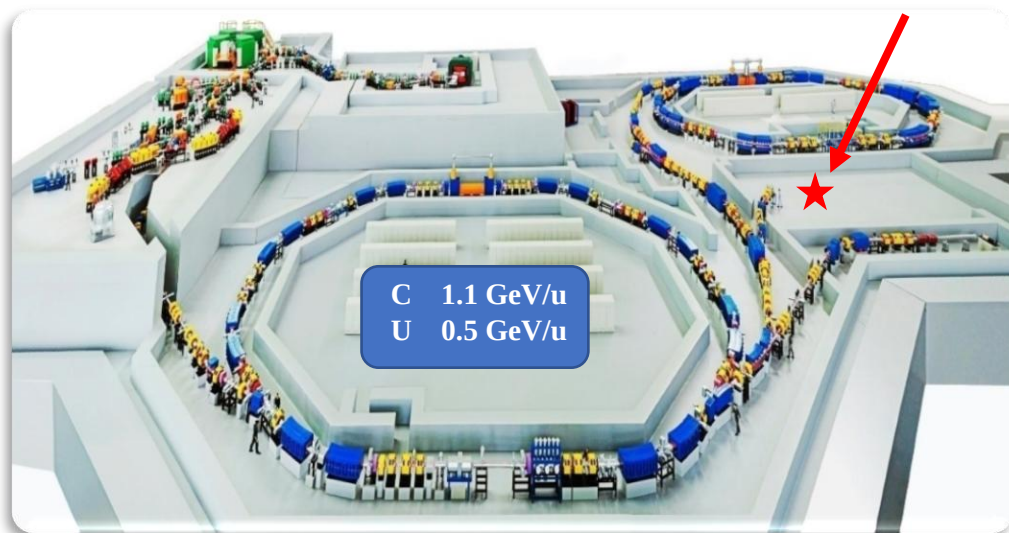
内容

- 物理动机
- CEE谱仪探测系统研制进展
- CEE谱仪软件系统介绍
- CEE谱仪物理实验进展
- 总结

兰州重离子加速器-冷却储存环(HIRFL-CSR)

HIRFL-CSR装置

CEE



M. Zhang, ZGX et al., PRC 80 (2009) 034616

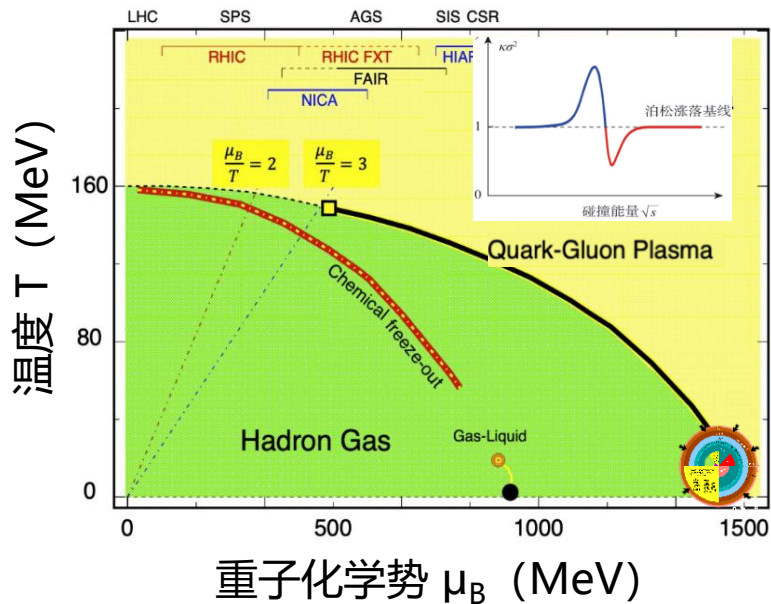
F. Fu ZGX et al, PLB 666 (2008) 359

低温高密区寻找QCD相变
临界点和相边界
核物质液气相变?

研究 $\rho > 2\rho_0$ 的核物质状态
方程
=> 致密星体内部结构

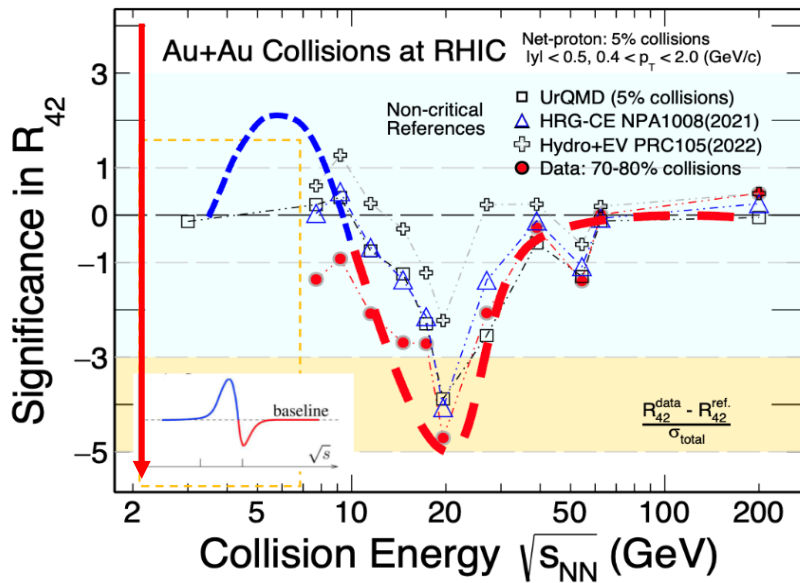
超核物理、三体力
短程关联、介质效应
.....

QCD相结构



HIRFL-CSR

STAR: PRL 135, 142301 (2025)



核物质状态方程 (EoS)

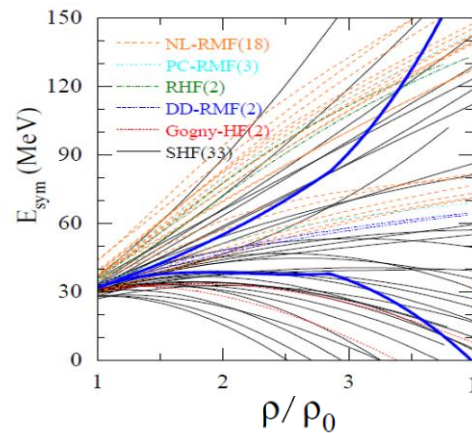
原子核束缚能:
$$B(Z, A) = B_v + B_s + B_c + B_a + B_p$$
$$= a_v A - a_s A^{2/3} - a_c Z^2 A^{-1/3} - a_a (N - Z)^2 A^{-1} + a_v \delta A^{-1}$$

核物质状态方程:

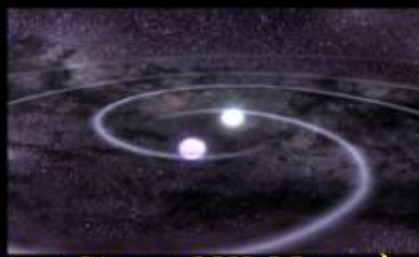
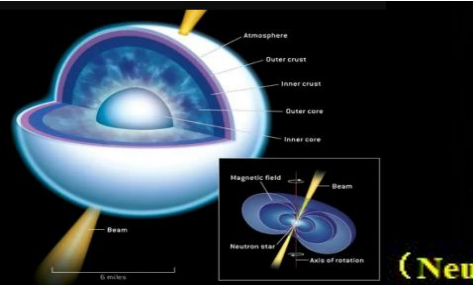
$$E(\rho, \delta) = E_0(\rho) + \delta^2 E_{\text{sym}}(\rho)$$

$$\delta = \frac{N - P}{N + P}$$

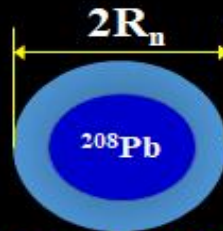
$$E_{\text{sym}}(\rho) = L \frac{\rho - \rho_0}{3\rho_0} + \frac{K_{\text{sym}}}{2} \left(\frac{\rho - \rho_0}{3\rho_0} \right)^2 + \frac{J_{\text{sym}}}{6} \left(\frac{\rho - \rho_0}{3\rho_0} \right)^3$$



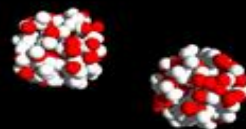
B.A Li et al. Universe, 7, 182(2021)



(Neutron Star and NS Merge)



(Static Properties of Nuclei)

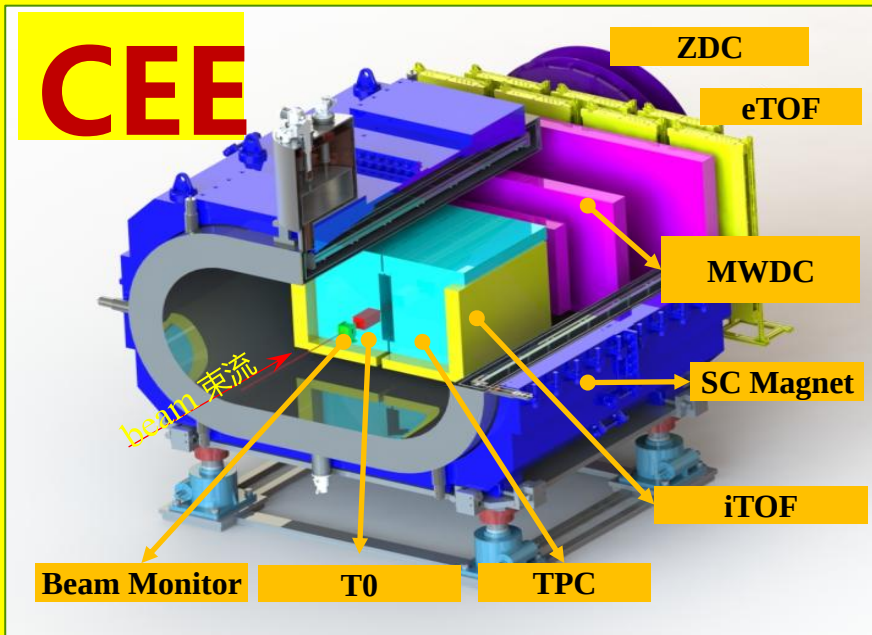


(Heavy Ion Collisions)

CEE谱仪探测系统

CEE 谱仪:

- 1) 超导二极磁铁
- 2) 微像素束流定位探测器 (BM)
- 3) 时间投影室 (TPC)
- 4) T0/内飞行时间探测器 (iTOF)
- 5) 外飞行时间探测器 (eTOF)
- 6) 多丝漂移室阵列 (MWDC)
- 7) 零度角探测器 (ZDC)
- 8) 数据获取系统 (DAQ)
- 9) 触发系统 (Trigger)
- 10) 时钟系统 (Clock)
- 11) 技术支持系统
- 12) 慢控系统 (SC)
- 13) 科学应用系统 (模拟和分析软件)



- $\Delta p/p: \leq 5\%$, $\Delta t/t: \leq 80\text{ps}$
- 反应率: 10 KHz
- 带电粒子接受度: $> 80\%$

基金委重大仪器项目和中科院B类“先导”专项支持

CEE合作组

中国:

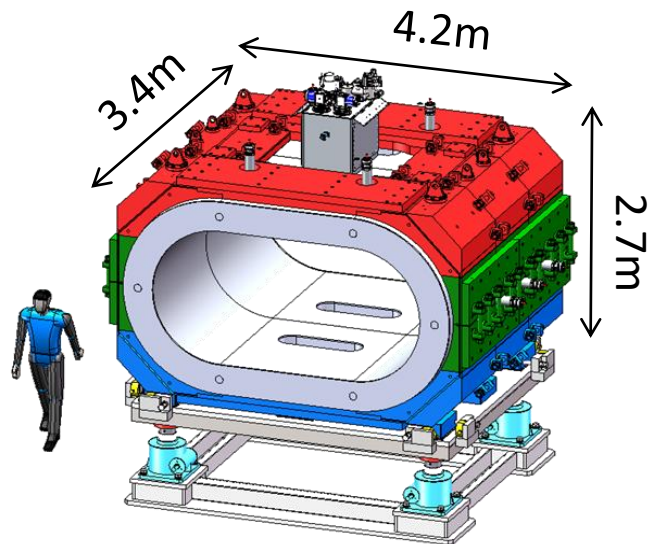
- 华中师范大学(CCNU)
- 复旦大学 (FDU)
- 哈尔滨工业大学(HIT)
- 中科院近代物理研究所 (IMP)
- 清华大学(THU)
- 中国科学技术大学 (USTC)

日本:

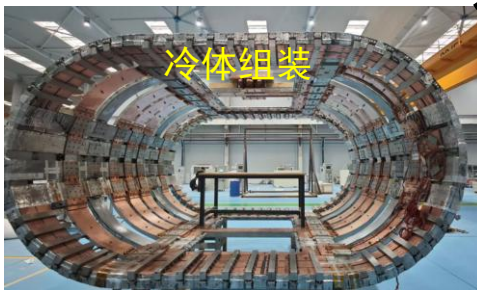
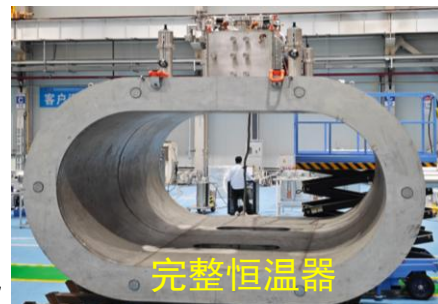
- 筑波大学 (Tsukuba University)

超导二极磁铁

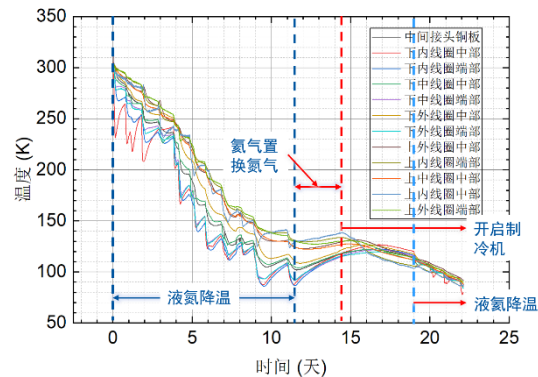
Quantity	Performance
Central Field	0.5 T
Uniform range	$1200 \times 800 \times 900 \text{ mm}^3$
Uniformity	$\pm 2.5\%$
Current in operation	231 A



- ◆ 完成铁芯的加工与组装，并安装于终端；
- ◆ 完成冷体装配（线圈、氦槽），以及与低温恒温器的集成装配；
- ◆ 低温恒温器正在进行降温实验。



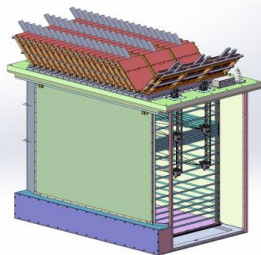
六个线圈安装在氦槽框架内



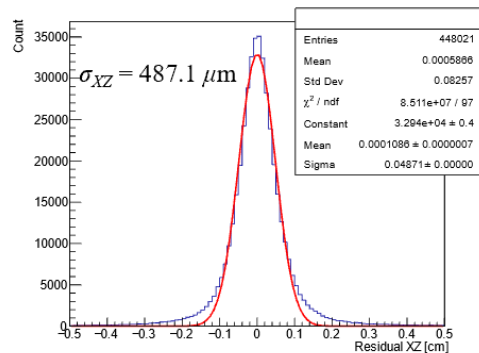
时间投影室 (TPC) - 中心径迹探测器

Quantity	Design index
Channels	15000
Volume	$2 \times 45 \times 80 \times 90 \text{ cm}^3$
σ_{xz}	500 μm
2-track separation	3 cm
Momentum resolution	5%

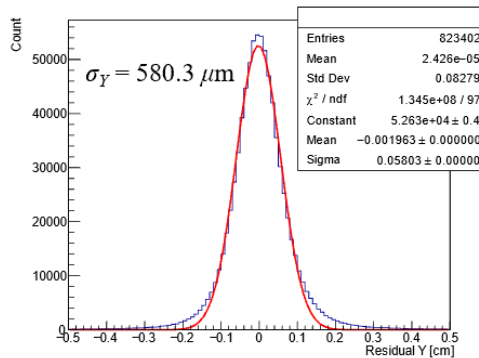
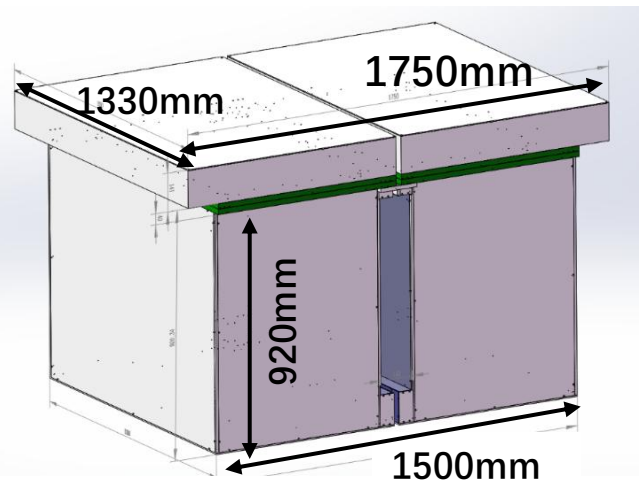
SAMPA-based readout



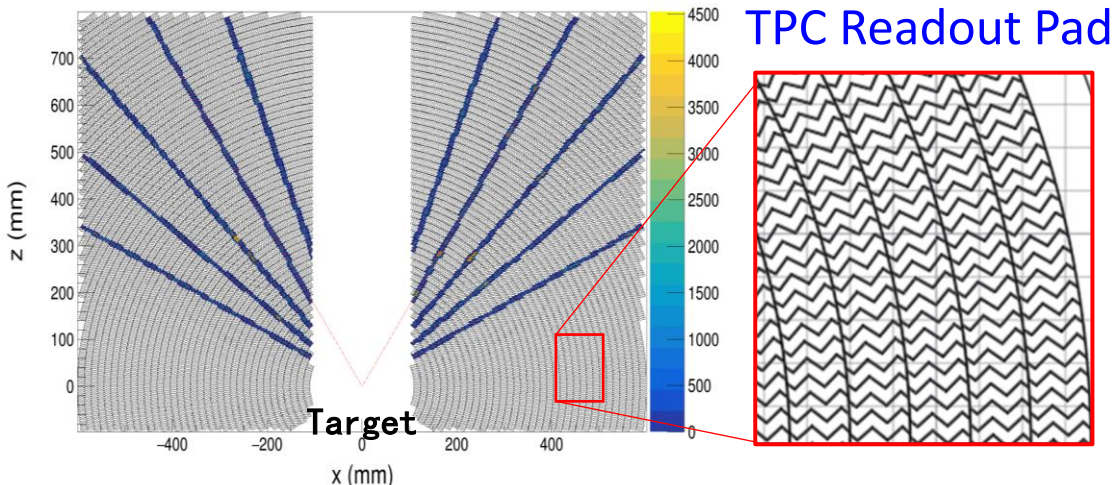
TPC径迹残差



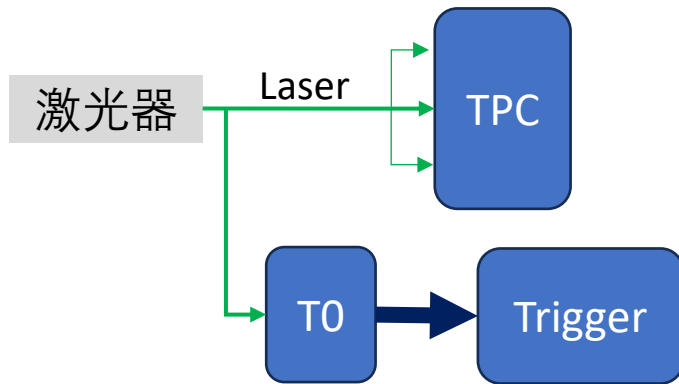
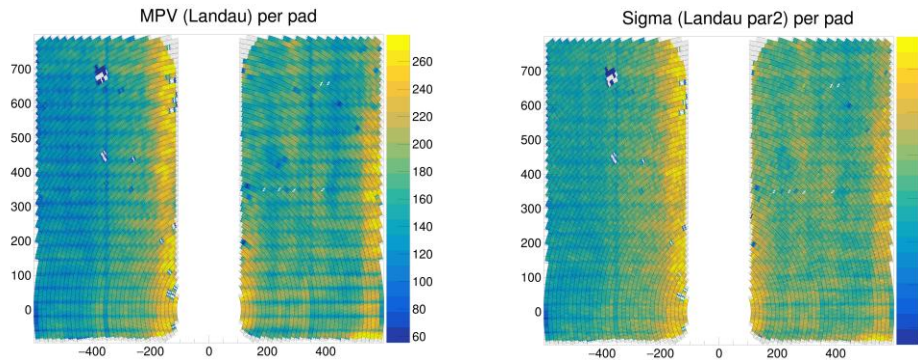
TPC探测器



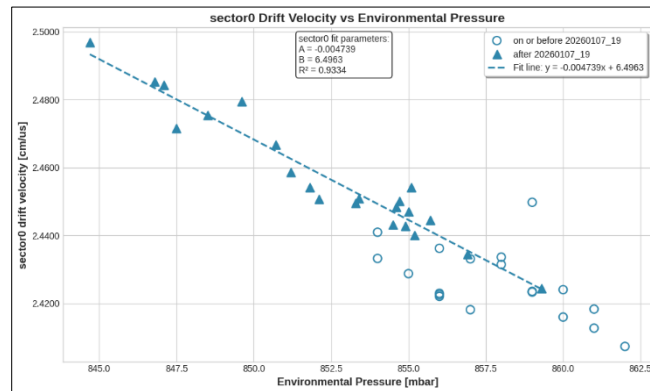
TPC探测器刻度



基于宇宙线数据的增益刻度

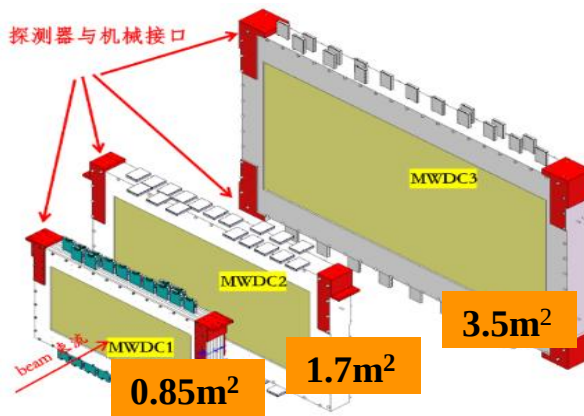


TPC漂移速度vs气压

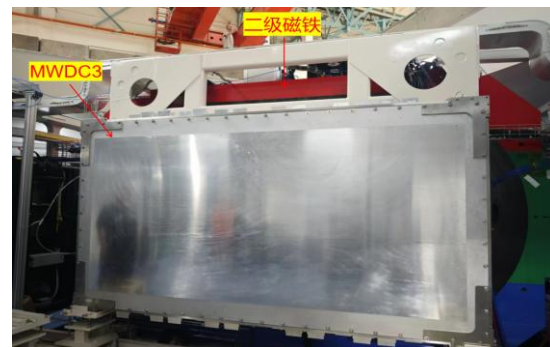


多丝漂移室阵列 (MWDC)

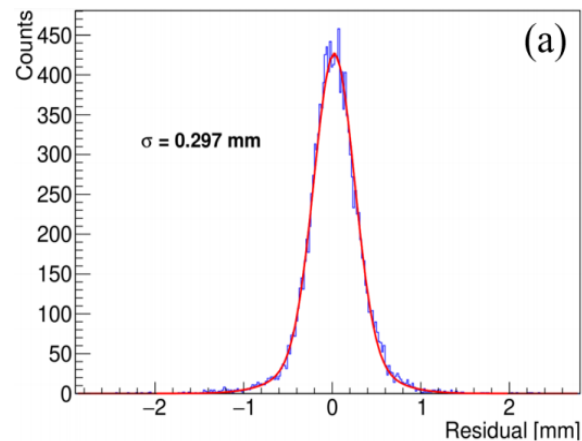
Quantity	Design index
Channels	~3200
Wire layer per module	X、X'、U、U'、V、V'
σ_{xz}	300 μm
Energy resolution	> 22%
Detection efficiency	> 98%
Momentum resolution	< 5%



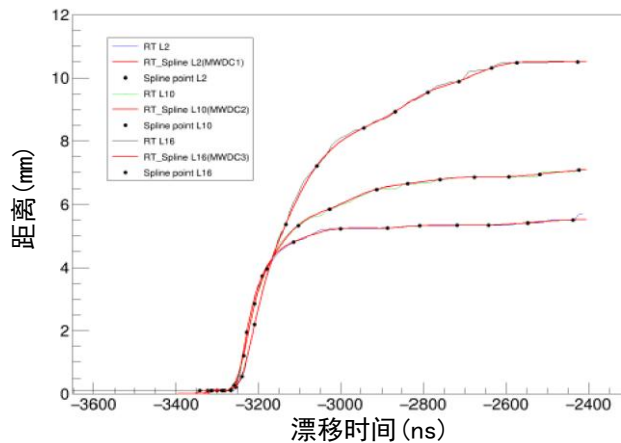
MWDC3的安装



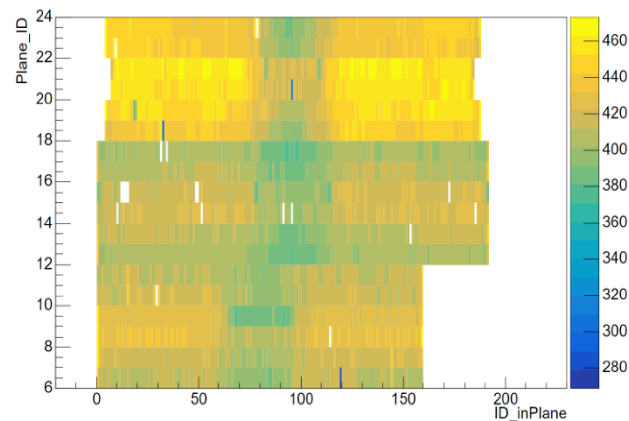
径迹残差 < 300 μm



漂移时间-距离 刻度



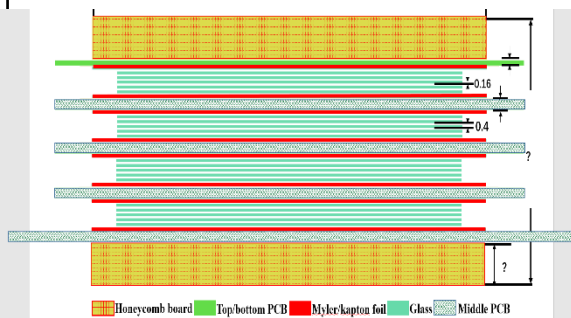
增益均匀性刻度



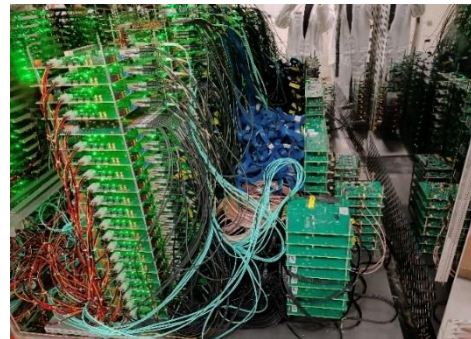
T0/内飞行时间探测器(iTOF)

Quantity	Design index T0/iTOF
σ_T	50ps / 50 ps
Efficiency	>99% / >95%
Rate	1MHz / 10kHz

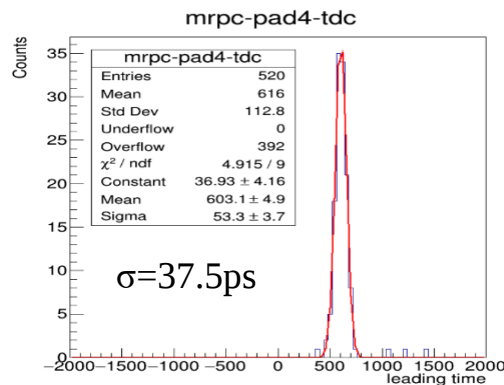
iTOF based MRPC Design



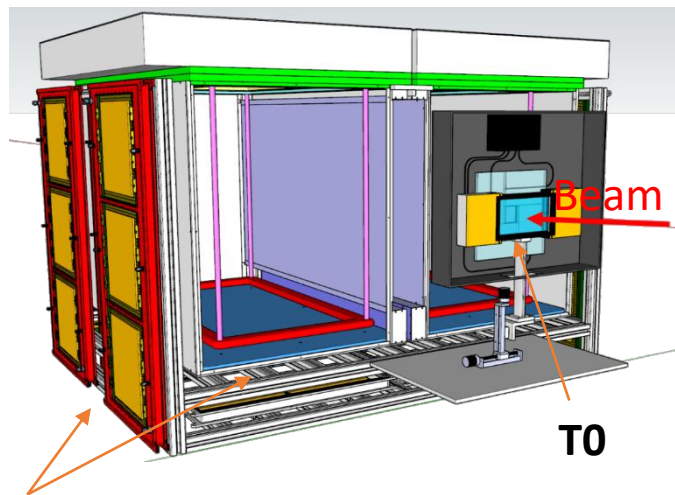
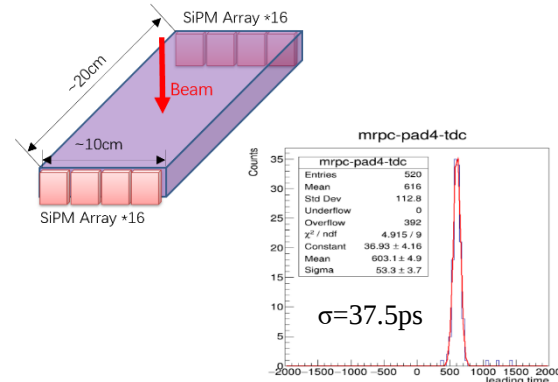
Electronics Stability Test



Beam test results



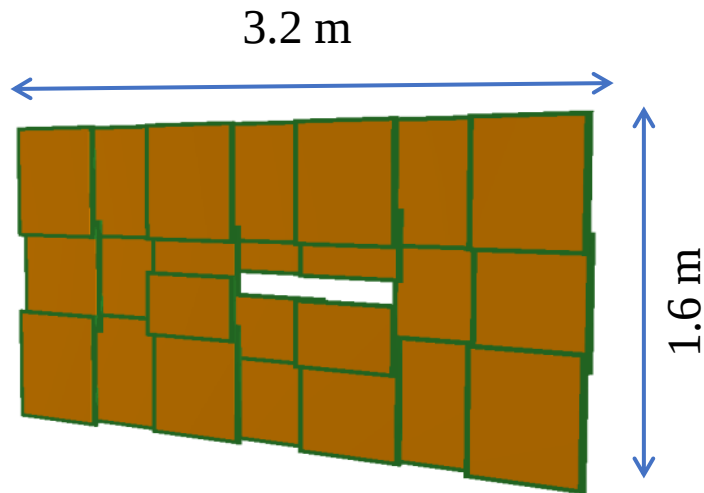
T0: Scintillator + SiPM



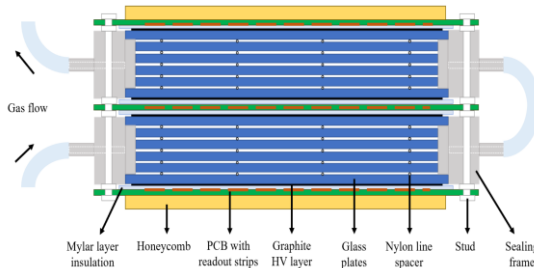
iTOF: covers 3 side of TPC

外飞行时间探测器(eTOF)

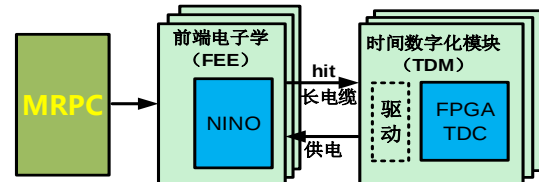
Quantity	Design index
σ_T	60 ps
Efficiency	>95%
Rate	>10kHz



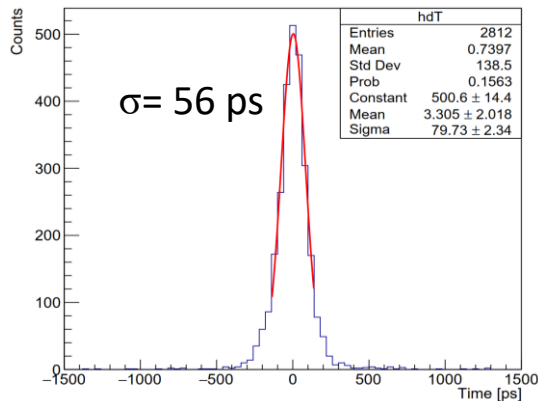
eTOF MRPC configuration



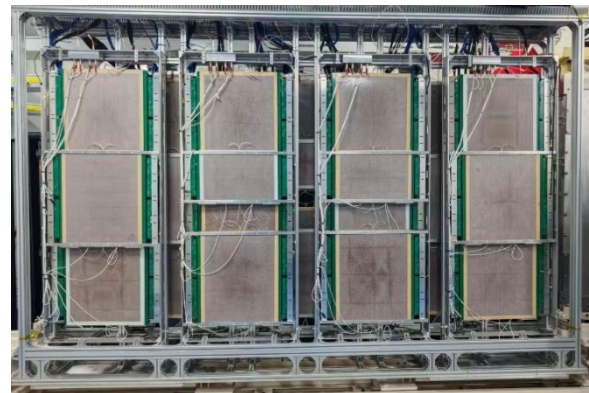
MRPC readout



Prototype time resolution

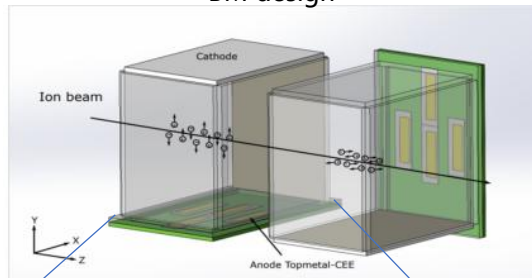


Module Installation

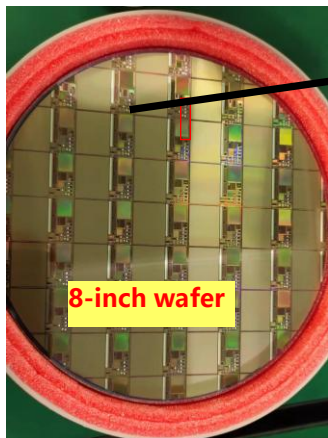


微像素束流定位探测器 (BM)

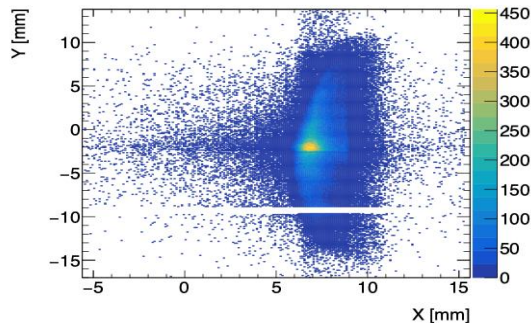
BM design



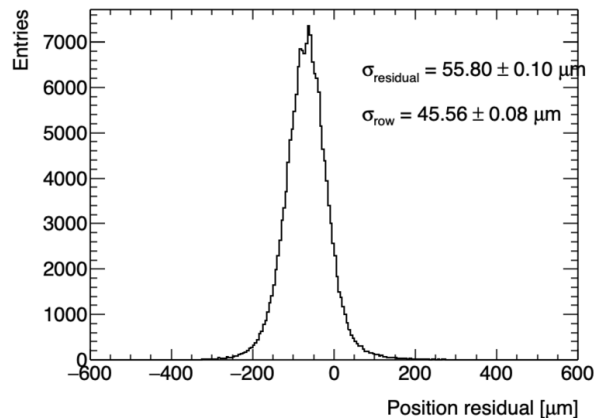
Topmetal-CEE chip



1.1 GeV/u的C束斑



X 方向位置分辨

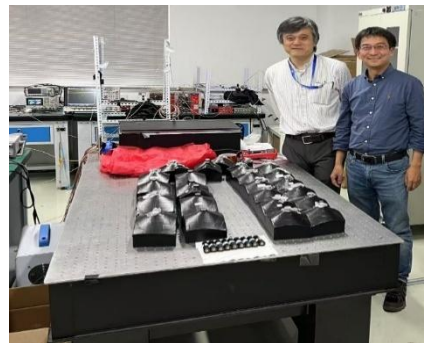


零度角探测器(ZDC)

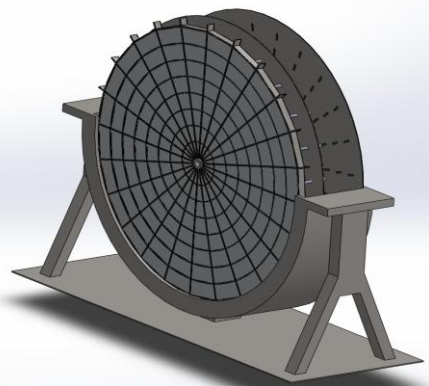
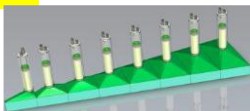
ZDC Parameters	Design index
Charge resolution	$\sim 15\% / Z=1-15$
Area	$5 < R < 100 \text{ cm}^2$

主要功能:

- 重建反应平面
- 确定碰撞中心度

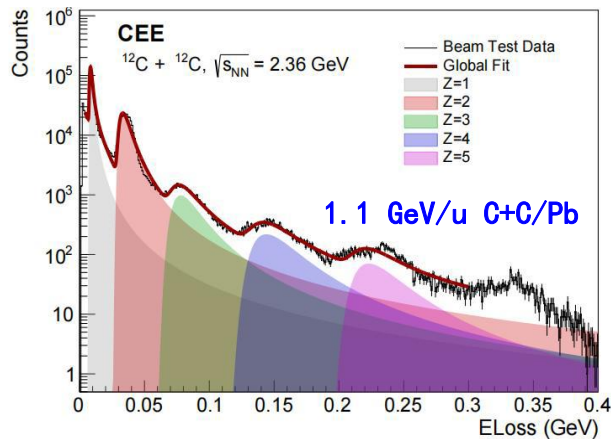


ZDC设计

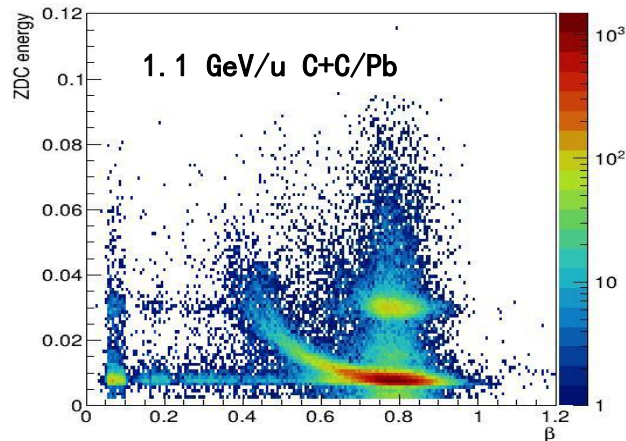


24 Sectors $\times$ 8 Rings

ZDC电荷测量谱

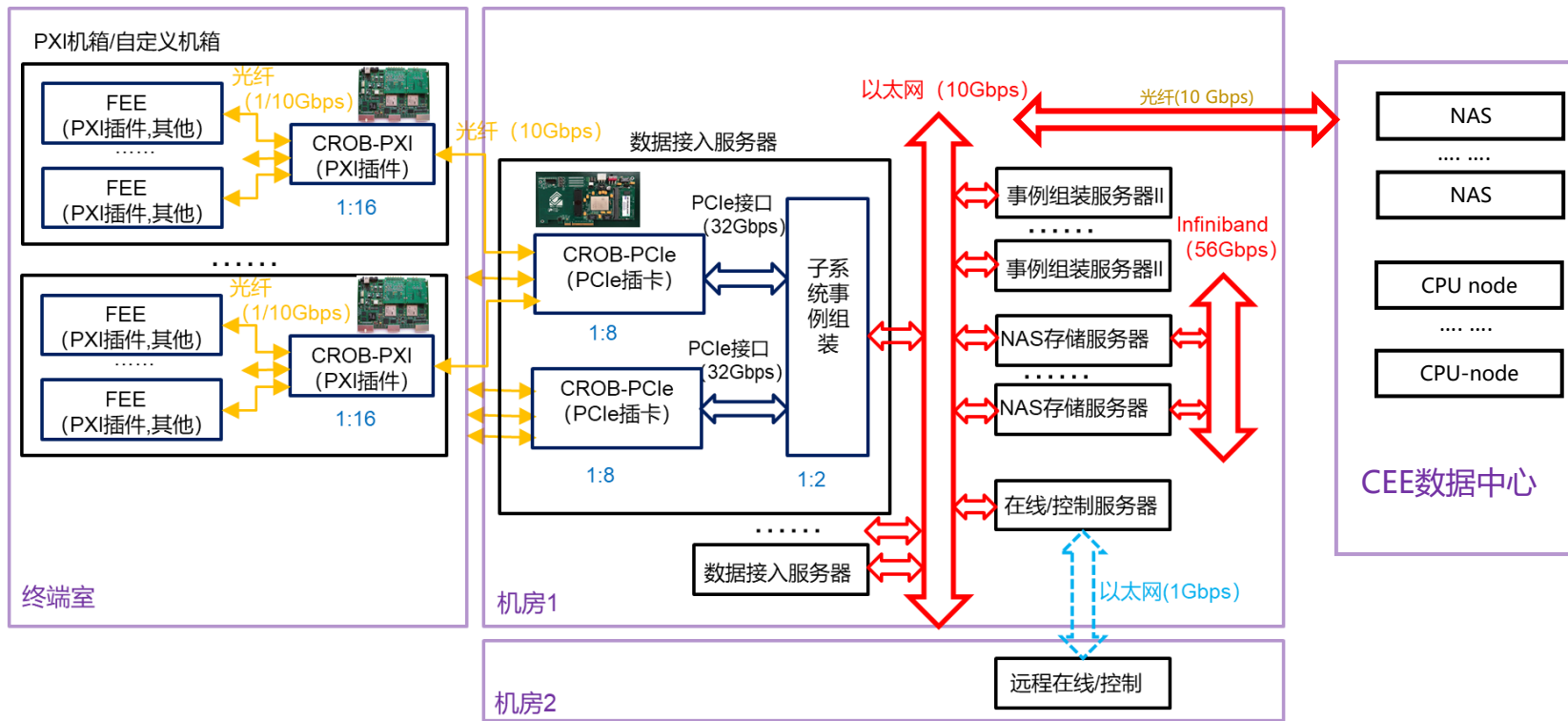


ZDC dE/dx Vs eTOF



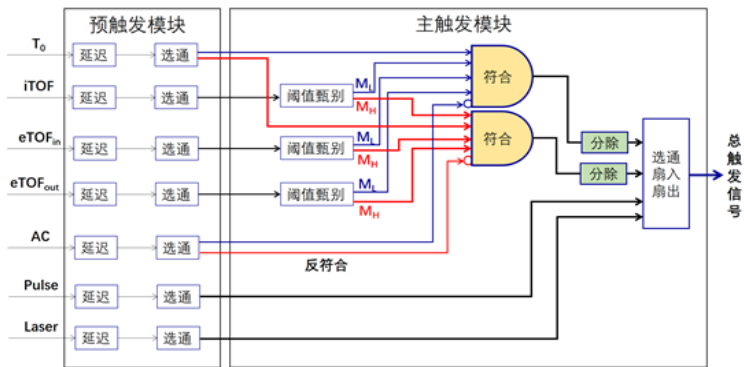
数据获取系统 (DAQ)

最大数据率（零压缩）：~4.5 GB/s

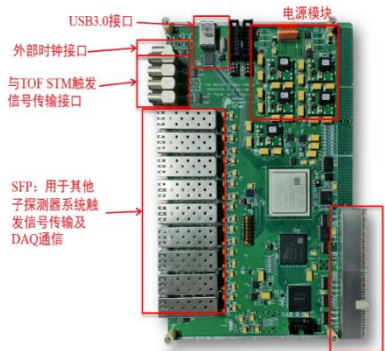


触发、时钟、慢控系统

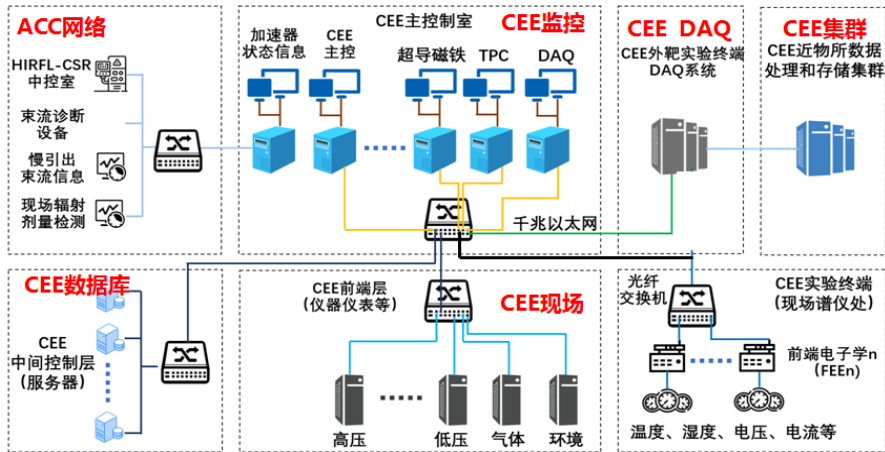
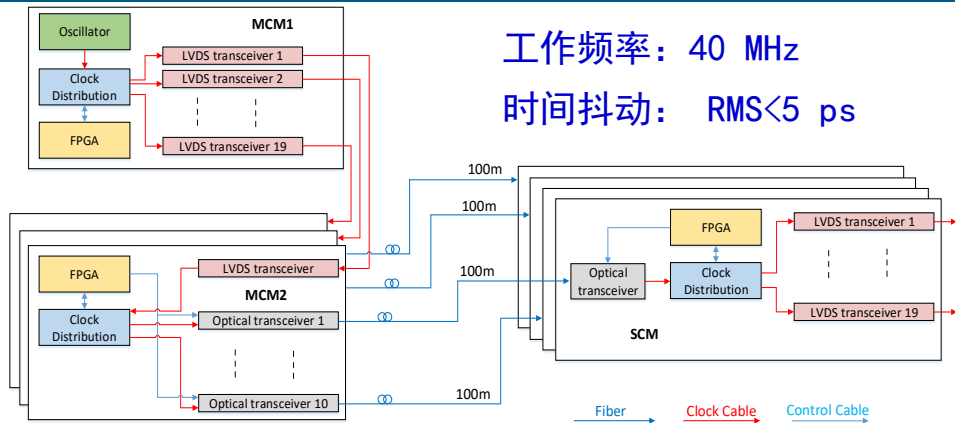
触发逻辑



触发板

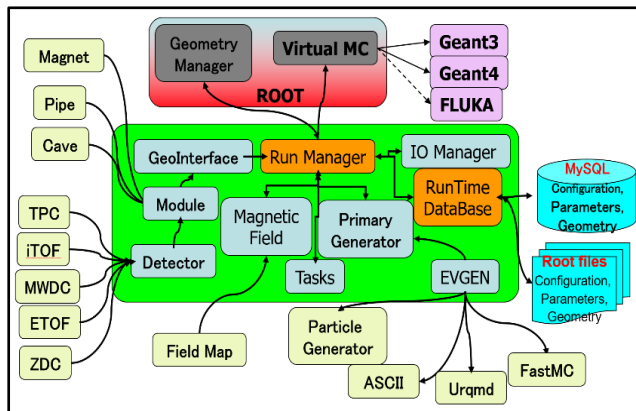


时钟板老练



CEE实验模拟和分析软件: CeeROOT

CeeROOT: 基于FairROOT平台开发



FairROOT:

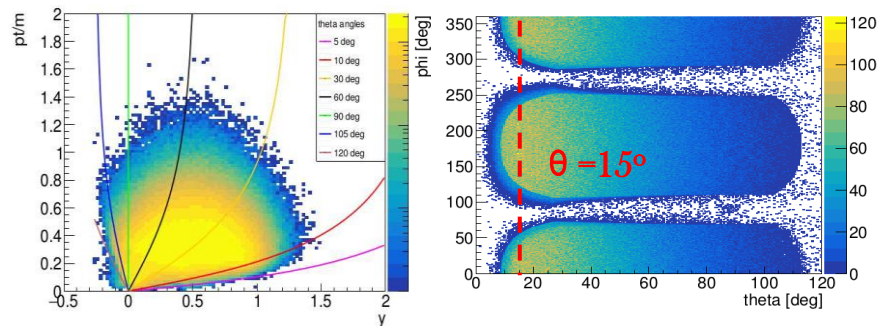
<https://fairroot.gsi.de>

CeeROOT
Home page:

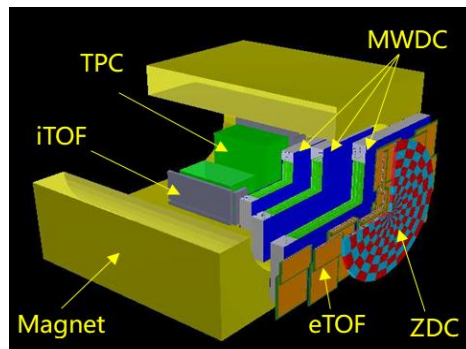
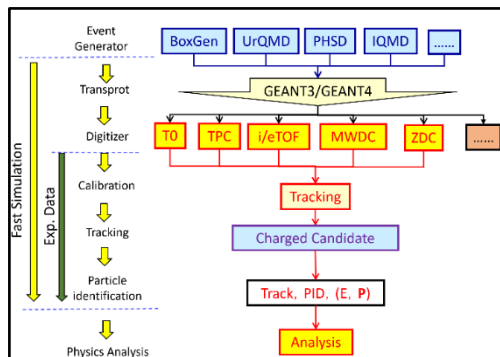
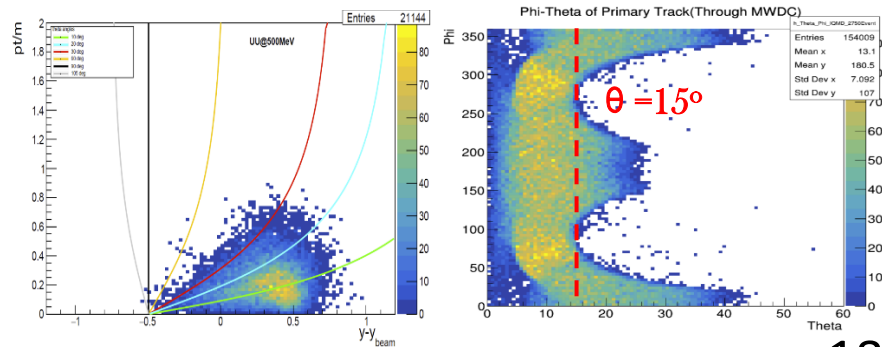
[https://gitee.com/
CEESM/CeeRoot](https://gitee.com/CEESM/CeeRoot)

(开源软件)

TPC接受度

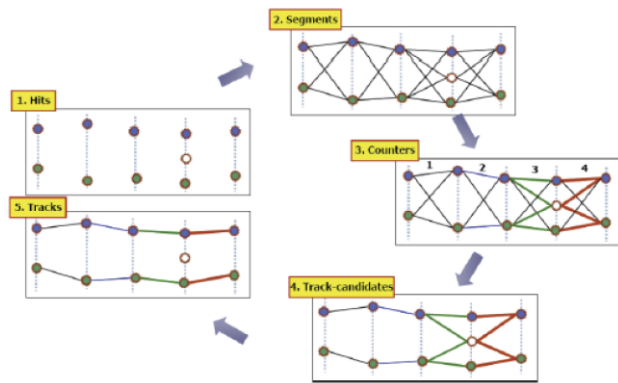


MWDC接受度

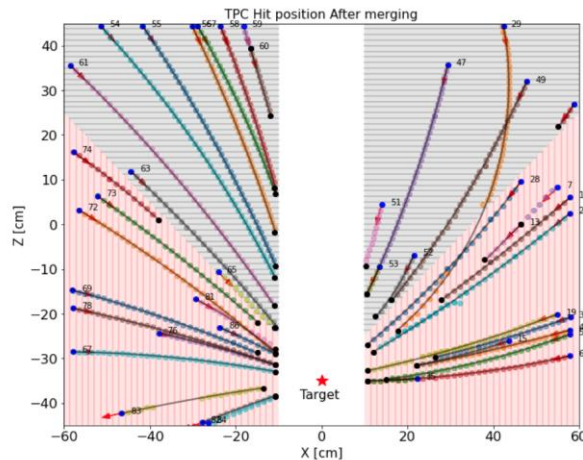
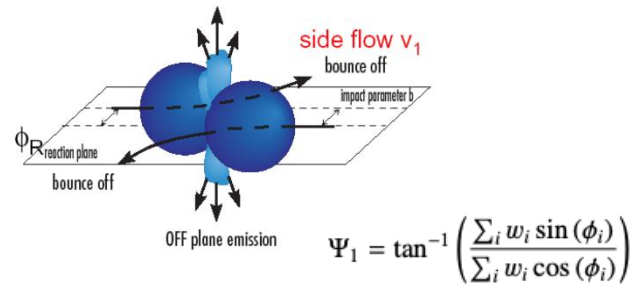
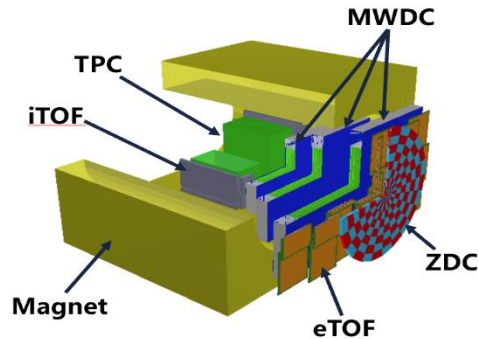


径迹重建和反应平面重建

- 径迹查找
元胞自动机 (CA)
- 径迹拟合
Kalman滤波算法

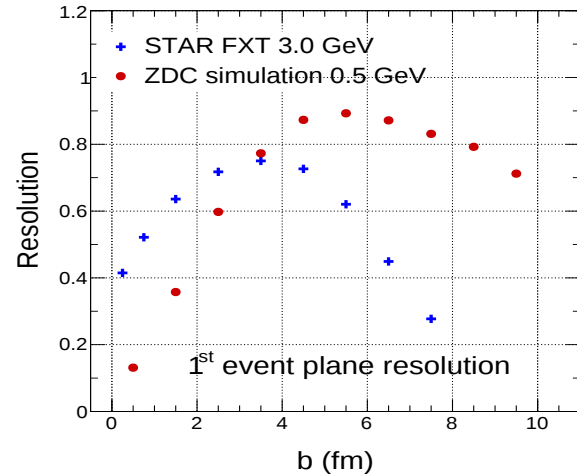


元胞自动机径迹查找示意图



径迹查找示意图

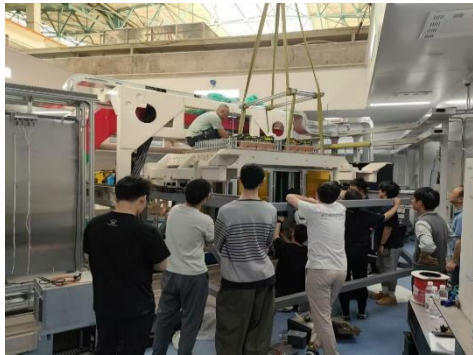
ZDC重建反应平面分辨率



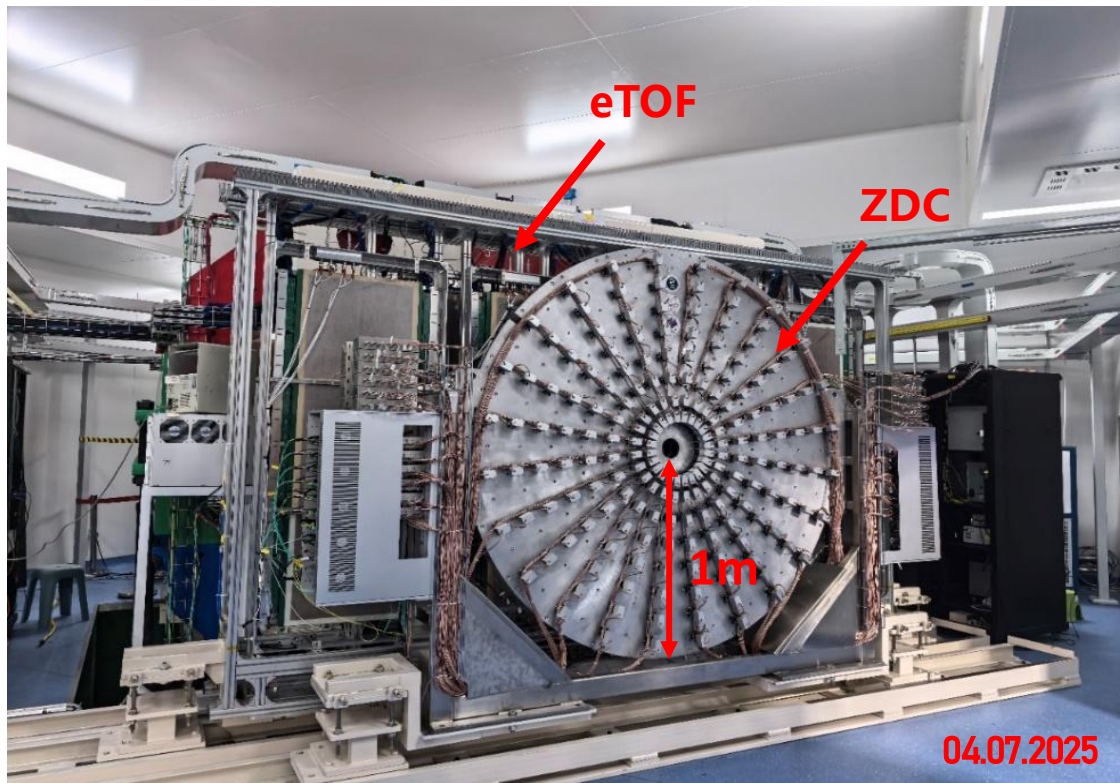
CEE谱仪探测系统整合

2025年7月完成CEE谱仪探测器系统集成和安装

TPC吊装



ZDC吊装

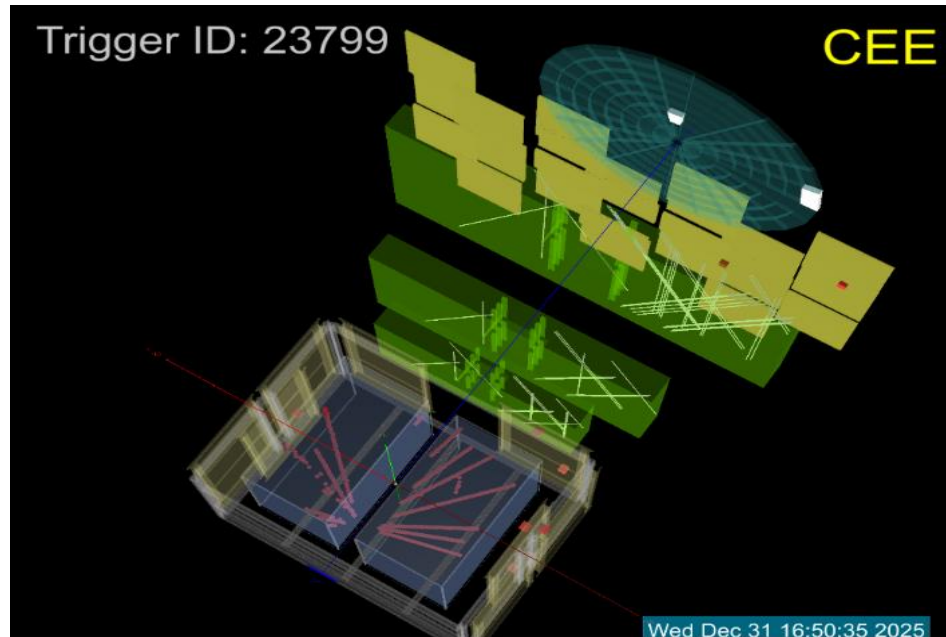
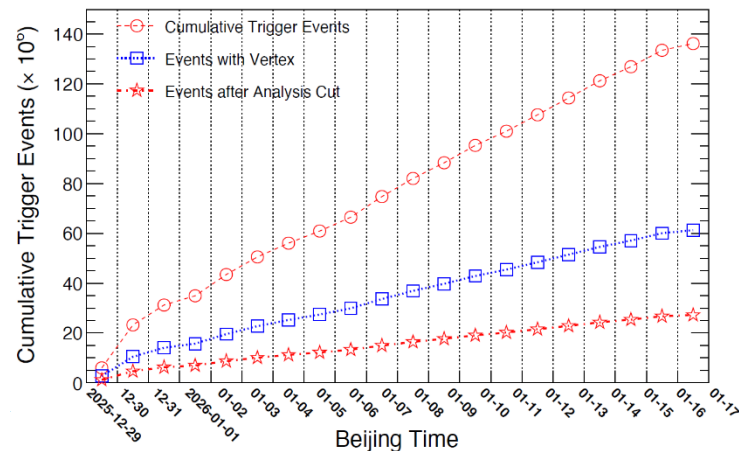
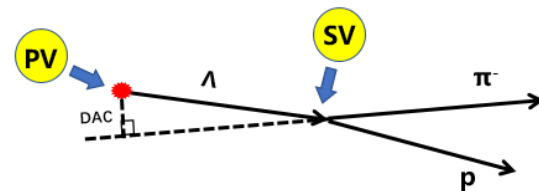


1.1 GeV/u C+C/Pb实验 (无磁)

项目	描述
束流 (CSRm)	1.1 GeV/u $^{12}\text{C}^{6+}$
引出模式	慢引出
靶	C-Pb-C-Pb靶 (间隔1cm)
实验时间	2025/12/29-2026/01/17
获取事件数	1.36亿 (136M)

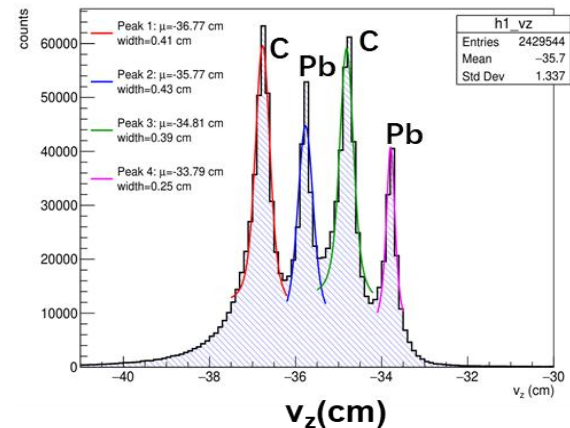
实验目的:

- 探测器全系统联测
- Λ 超子阈下产额

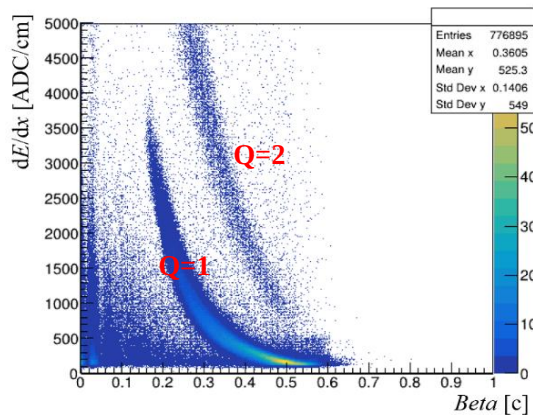


数据同步检查 and 数据分析进展

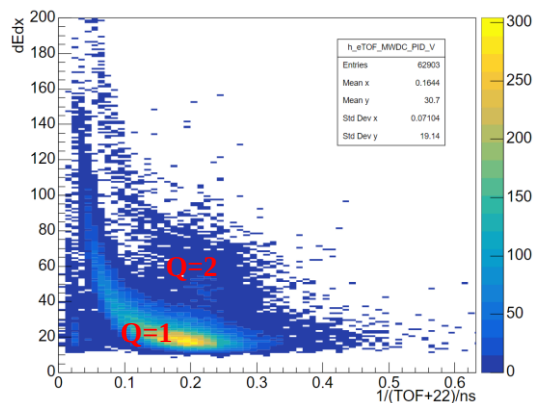
碰撞顶点重建



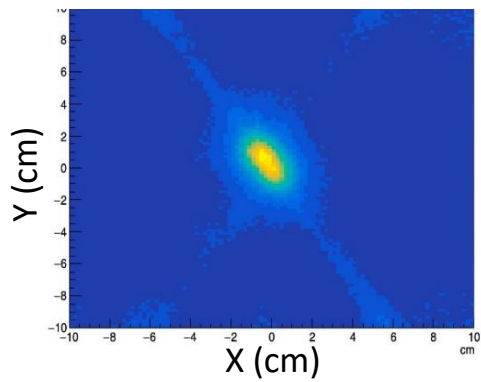
TPC dE/dx Vs iTOF



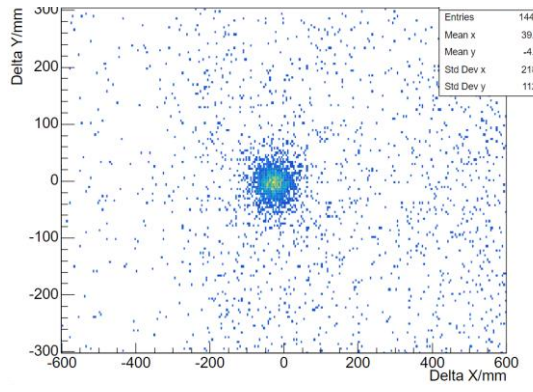
MWDC dE/dx Vs eTOF



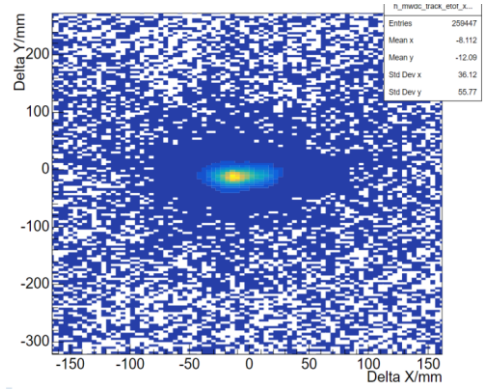
TPC径迹与MWDC径迹匹配



TPC径迹与eTOF Hit匹配



MWDC径迹与eTOF Hit匹配

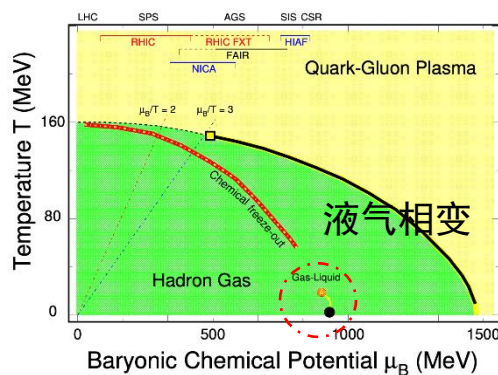
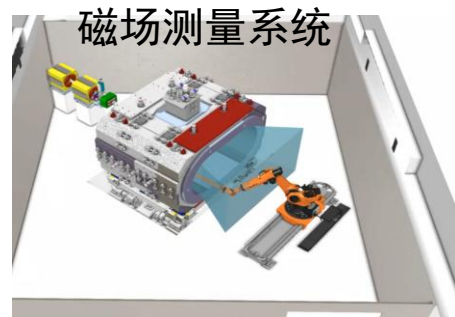


CEE谱仪上的实验计划

	Collision	Measurement	Physics
I	1.1 GeV/u C+C/Pb	Pion ratios (rapidity, Pt, Centrality)	EoS
		Collectivity: p, d, t, ^3He , ^4He , Λ , K^0	EoS
		Rapidity Distribution: p, d, t, ^3He , ^4He , Λ , K^0	EoS
		Correlations: pion HBT; p-p, p-d, p-t, d-d	FSI
		Hyper-Nuclei Production: $^3_{\Lambda}\text{H}$, $^4_{\Lambda}\text{H}$	EoS & YN
		High moments of proton	相结构
II	0.3-0.5 GeV/u U+U/Au+Au	Pion ratios (rapidity, Pt, Centrality)	EoS
		Collectivity: p, d, t, ^3He , ^4He	EoS
		Rapidity Distribution: p, d, t, ^3He , ^4He	EoS
		Correlations: pion HBT; p-p, p-d, p-t, d-d	FSI
		High moments of proton	相结构

总结

- CEE谱仪探测器系统完成组装，符合设计要求
- CEE谱仪的超导磁铁装配完成并开始降温，预计2026年10-12月完成降温实验、磁场测量、全谱仪整合
- 完成第一轮1.1 GeV/u C+ C/Pb碰撞，获取1.36亿个碰撞事件，数据刻度和数据分析进行中
- 2027-：利用HIRFL-CSR提供的束流开展核物质相结构、EoS、奇异强子阈值产生、超核、强子极化、短程关联、原子核集团结构等前沿课题实验研究



感谢各位老师对CEE项目的支持，希望感兴趣的单位
加入CEE合作组开展实验研究。