



清华大学 工程物理系

Department of Engineering Physics, Tsinghua University

第三届全国辐射探测微电子学术交流会

时间投影室读出芯片及应用

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2023年10月 广西·南宁

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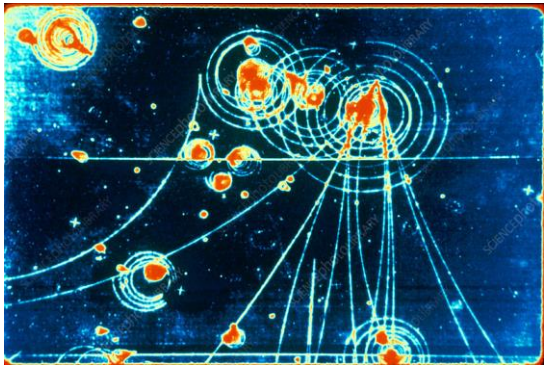
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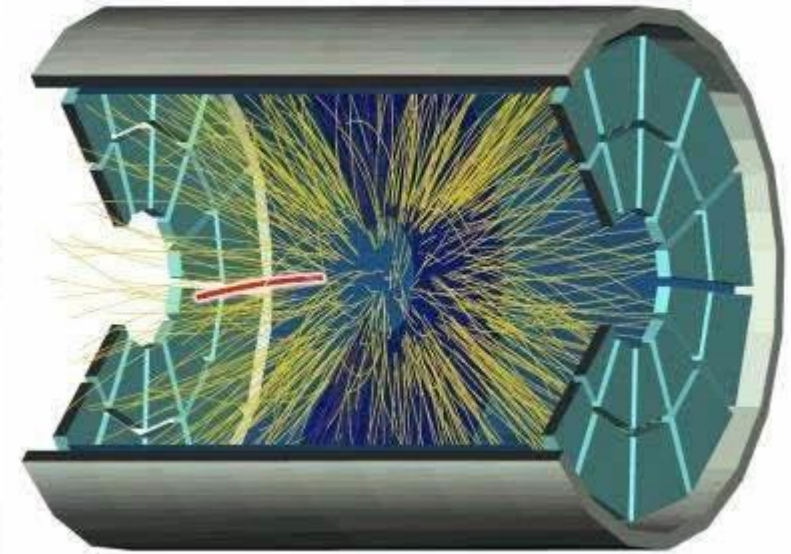
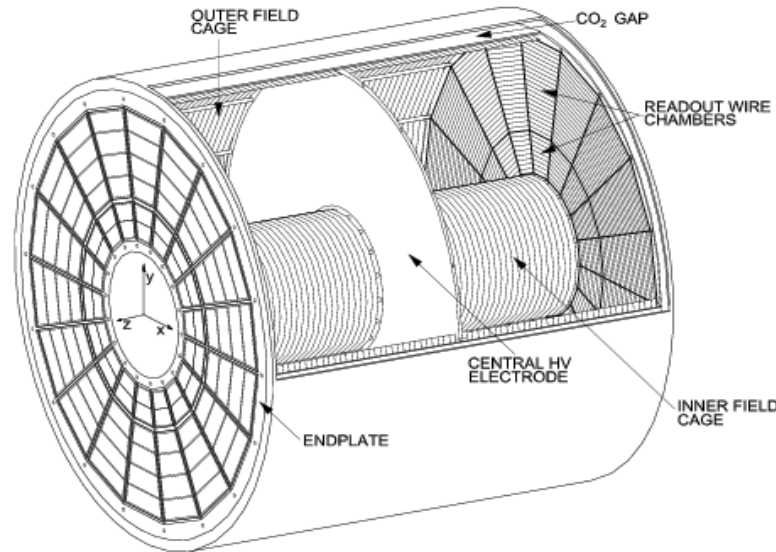
01

Time Projection Chamber and Readout Electronics
时间投影室及读出电子学

- 1970年代最早由LBL的David Nygren提出并建造，探测器灵敏体积由气体组成，中心为阴极平面，两端为阳极，高能粒子产生的初级电子从中心匀速漂移到两端
- 可以实现三维粒子径迹探测： xy -二维端面； z -漂移时间；同时还可以通过测量 dE/dx 实现粒子鉴别
- TPC灵敏体积可以较大，覆盖 4π 立体角，工作介质可以是气体或惰性液体
- 在 高能粒子与核物理实验、低本底稀有事例探测和天文观测等领域中有广泛应用

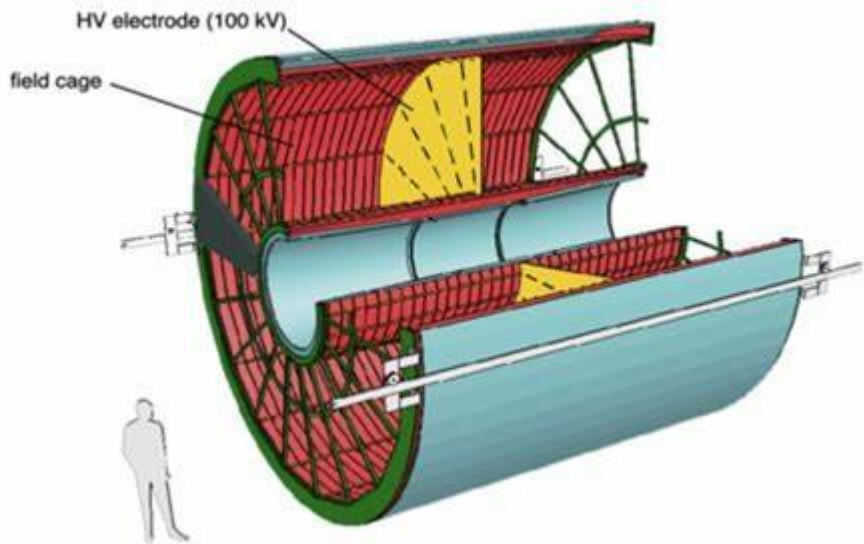


Bubble Chamber

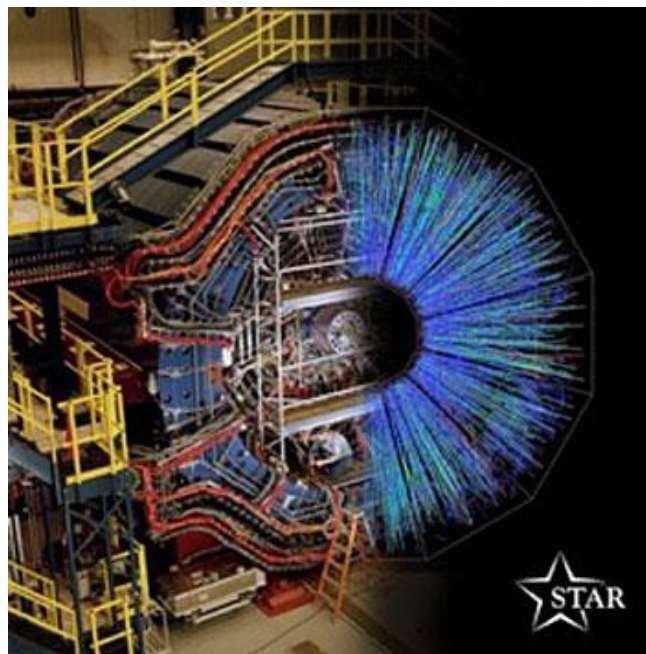


Time Projection Chamber

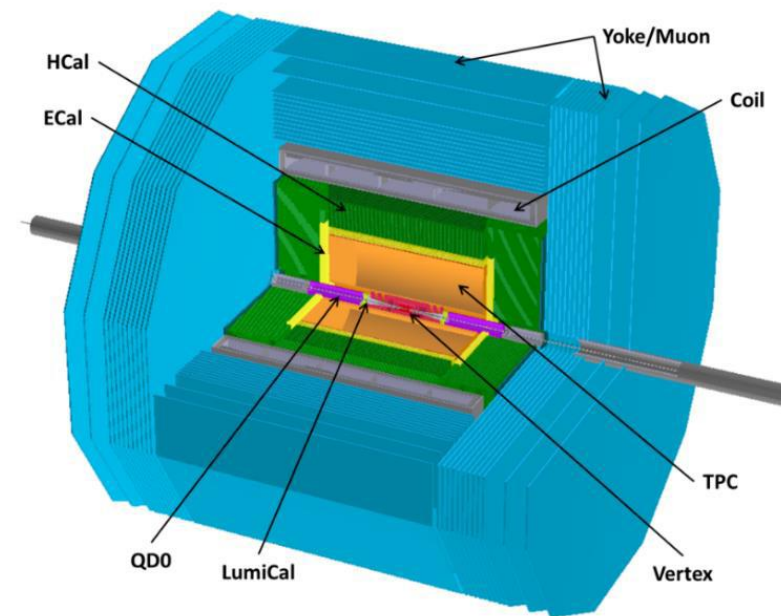
基于加速器的粒子与核物理实验



ALICE-TPC

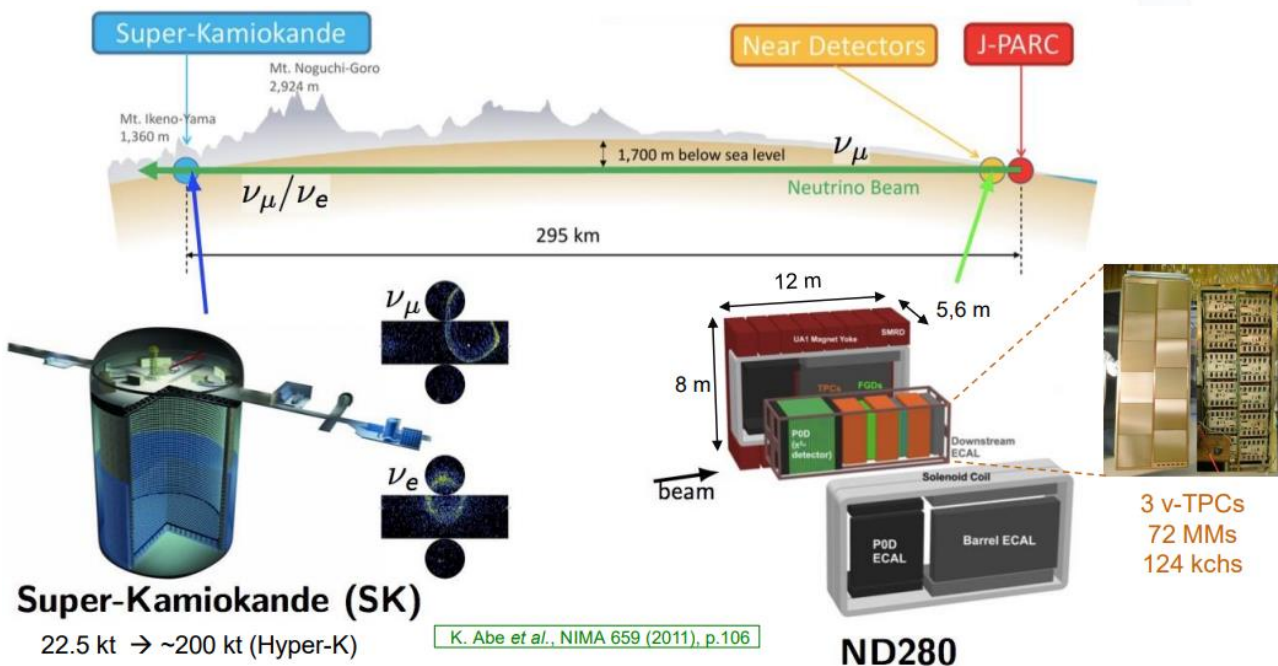


STAR-TPC

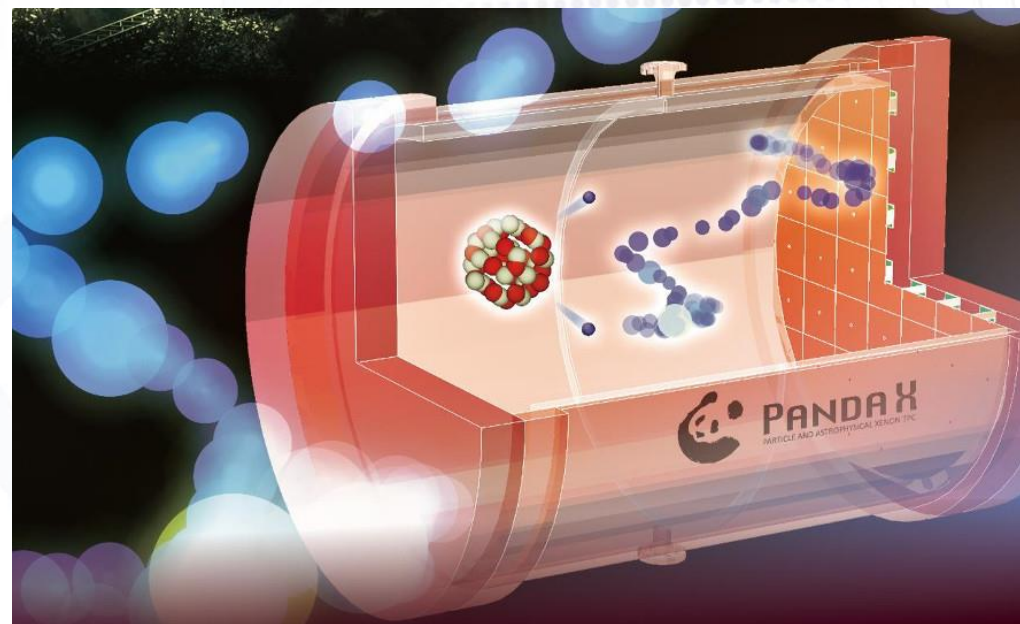


CEPC-TPC

► 低本底物理实验

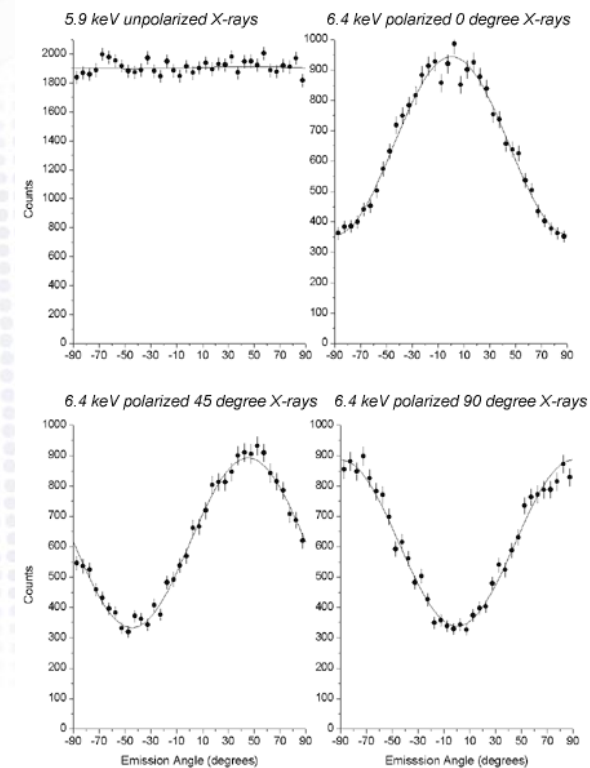
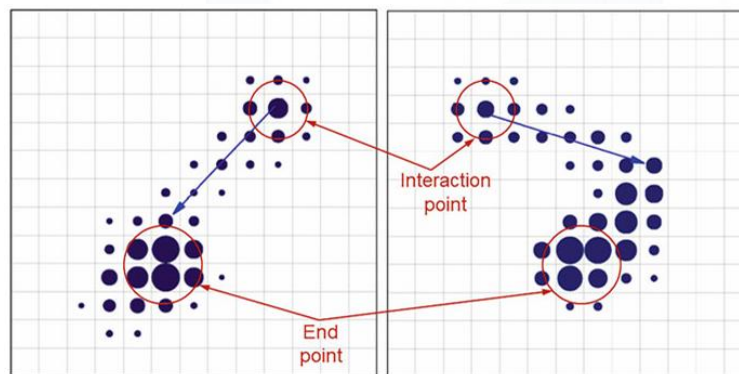
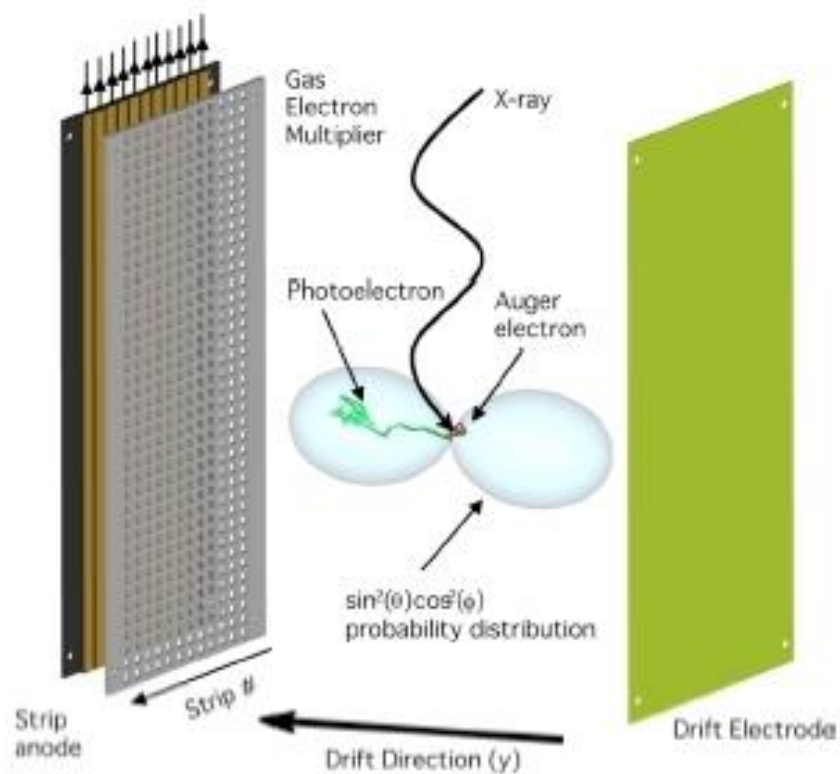


T2K-TPC

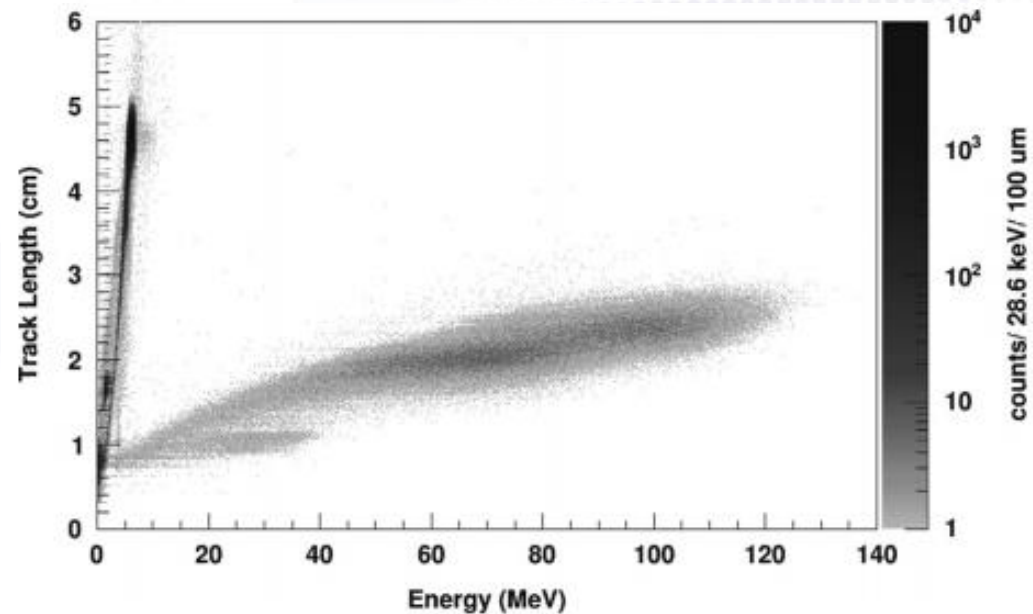
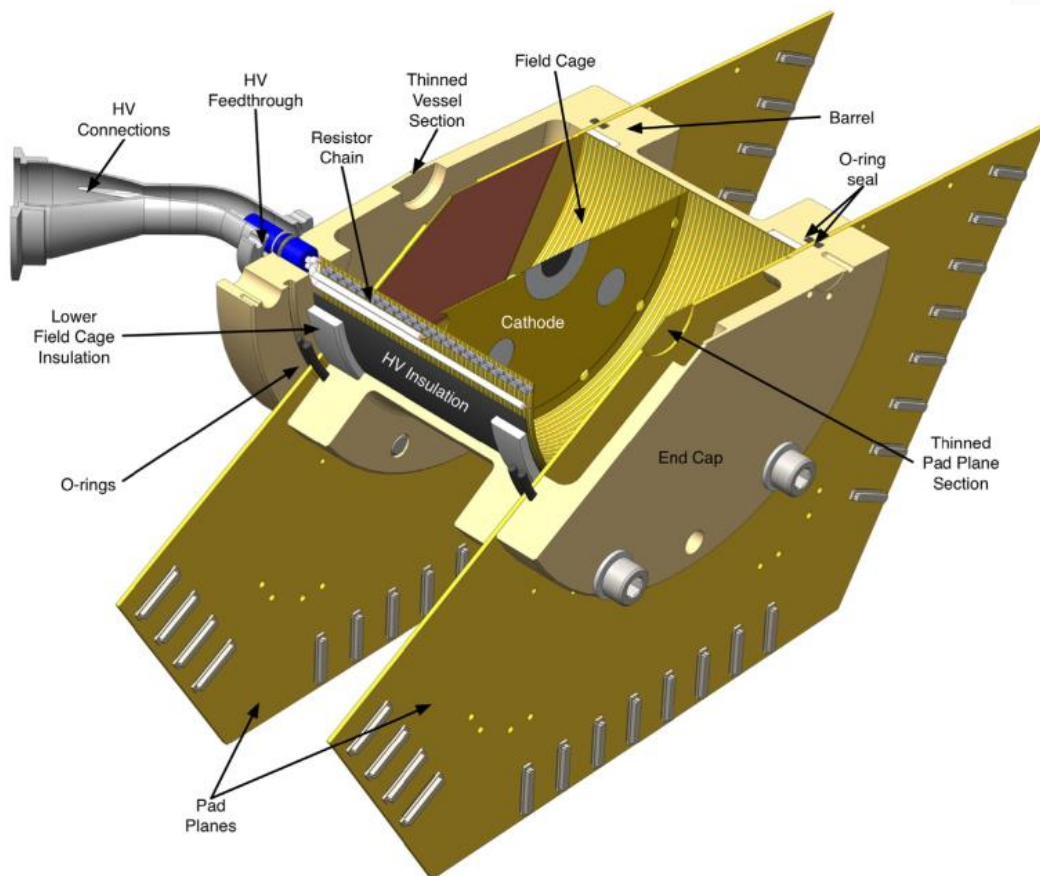


PandaX-TPC

► 天文探测：X射线偏振探测

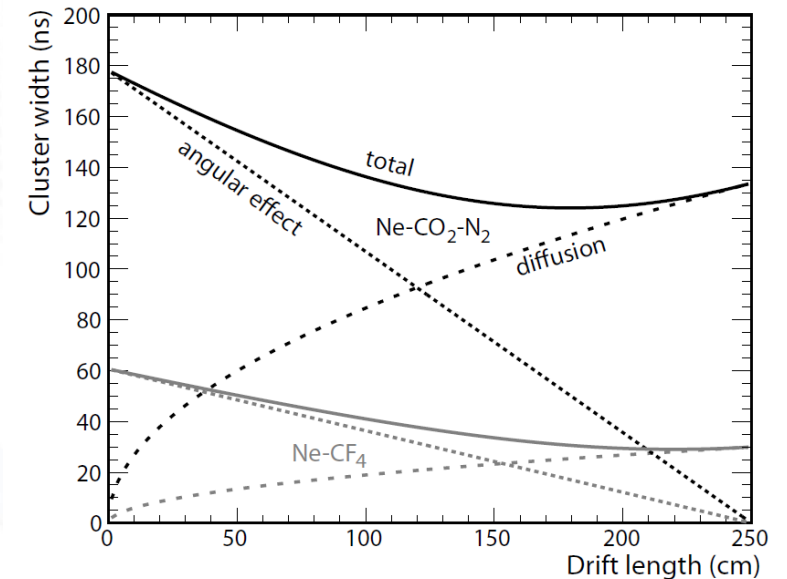
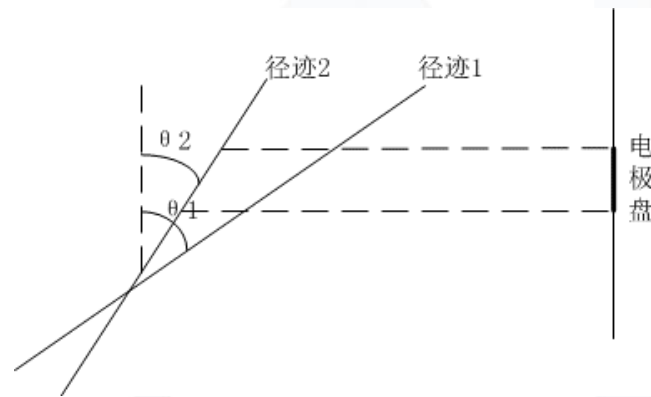
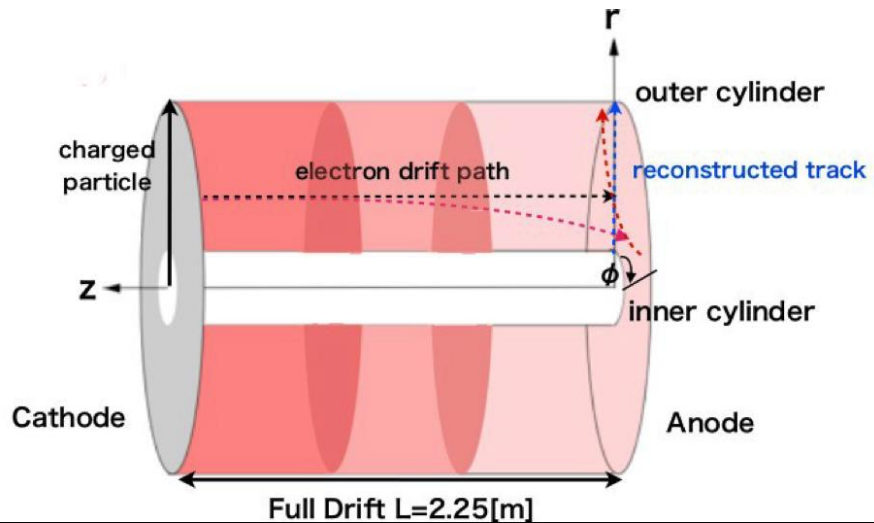


► 低能核物理实验：核裂变截面精确测量



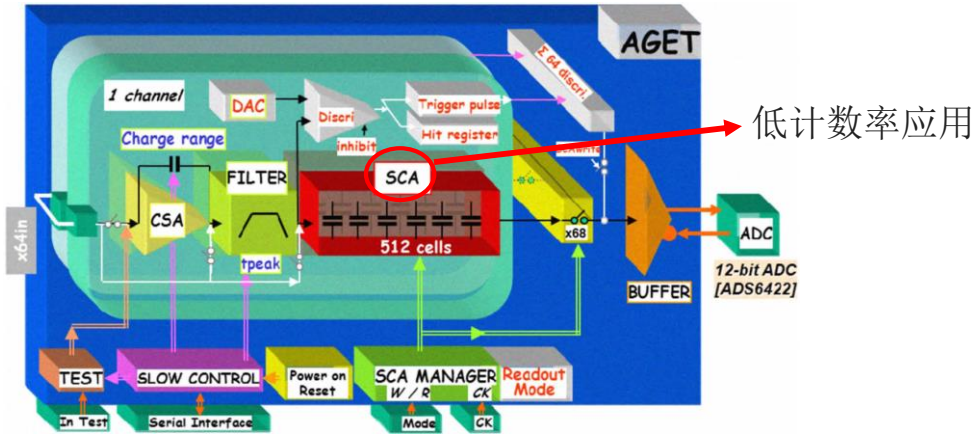
- 探测器电流的持续时间和初级电子径迹与收集平面的角度有关：
 - 径迹平行于收集平面时，持续时间短
 - 径迹垂直于收集平面时，持续时间长
- 弹道亏损 vs. 信号堆积
- 同时获取幅度和时间（重心）信息

波形采样



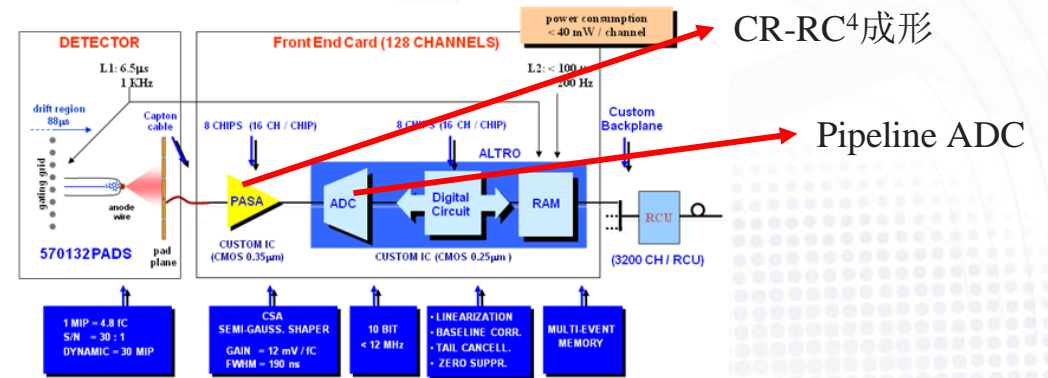
AGET (T2K)

Anvar S, et al. IEEE NSS, 2011



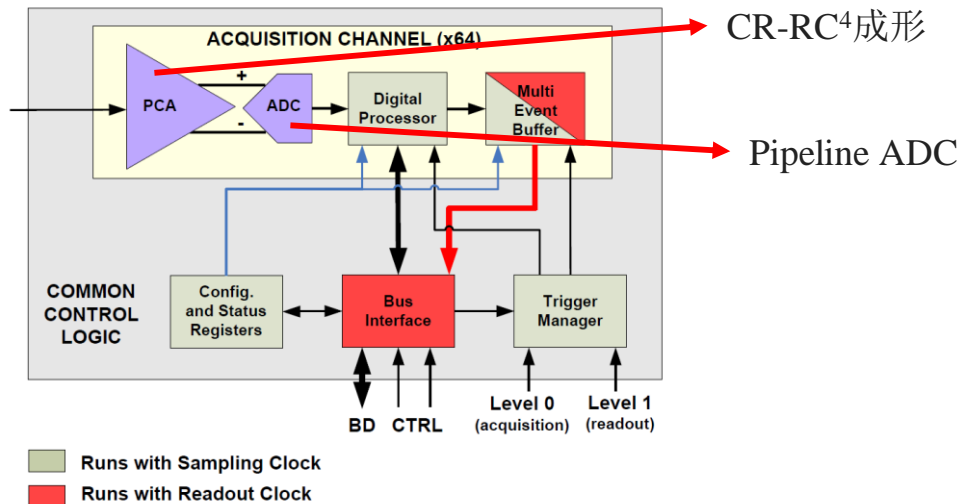
PASA+ALTRO (ALICE)

Musa L, et al. IEEE NSS, 2003



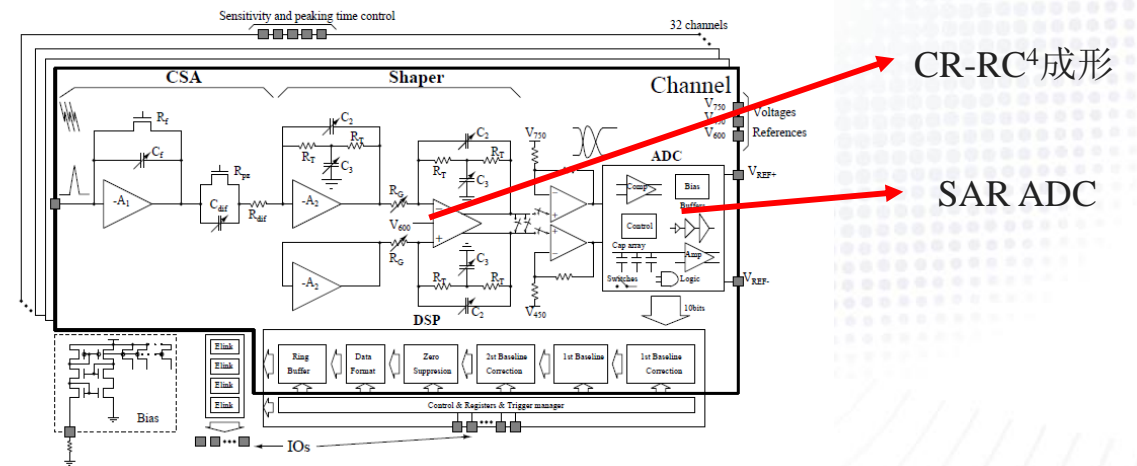
Super-ALTRO (ILC)

Aspell P, et al. TNS, 2013



SAMPA (ALICE Upgrade)

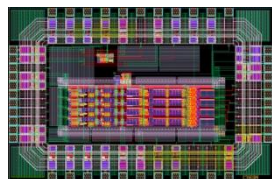
Barboza, et al. JINST, 2016



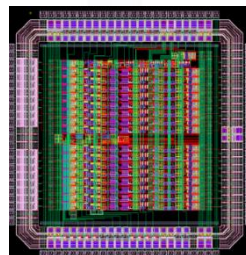
02

Development of Readout ASIC for TPC @ Tsinghua's Group
TPC读出芯片的研制@清华

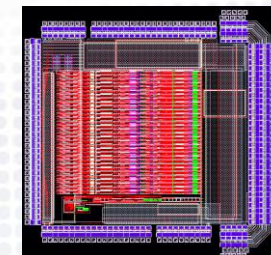
- 从2006年开始，主要针对TPC探测器读出
- 分为前端模拟（CASA）、SCA和ADC波形采样三类



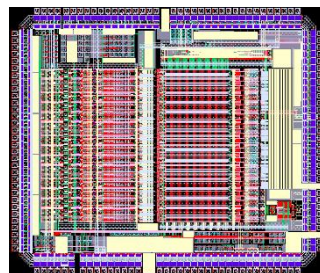
CASA: 4ch CSA+Shaper



CASAGEM: 16ch CSA+Shaper



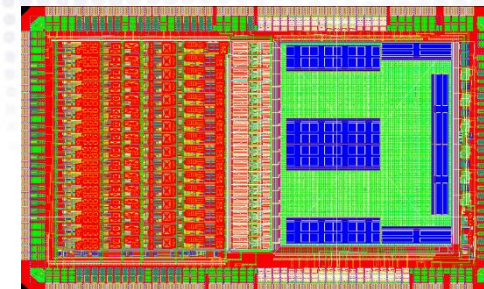
CASA32: 32ch CSA+Shaper



CASCA: 32ch CSA+Shaper+SCA

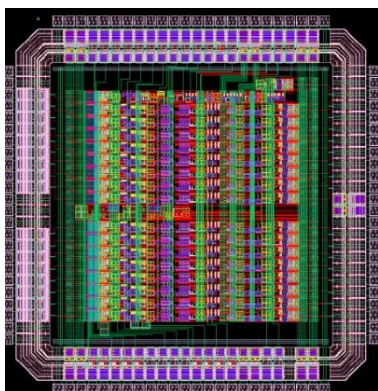
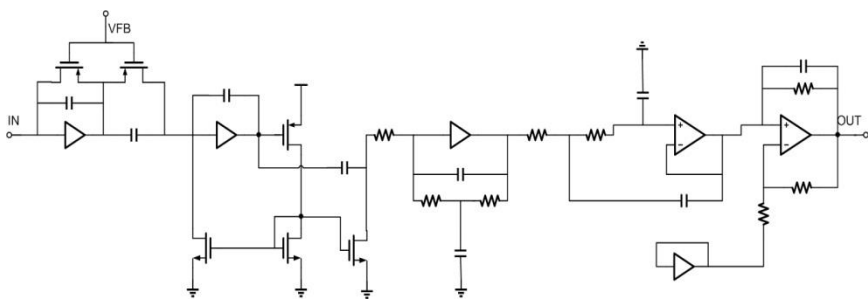


GERO: 16ch SCA

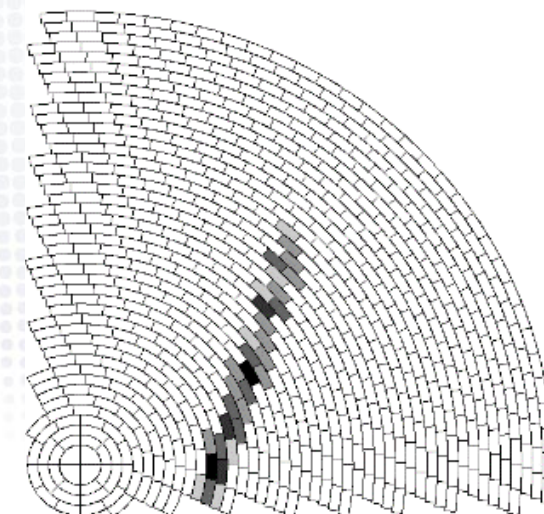
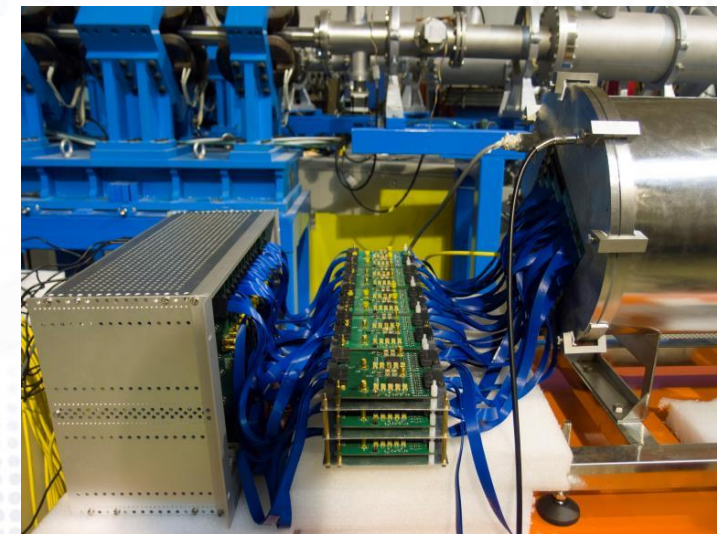


WASA: 16ch AFE+ADC+DSP

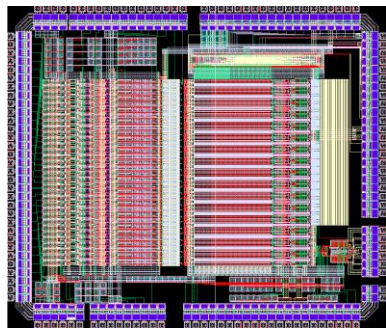
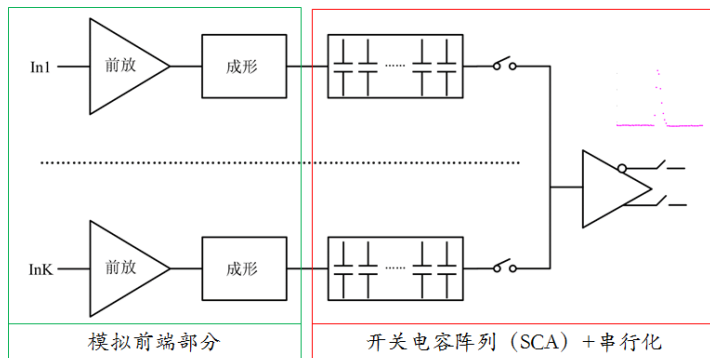
➤ CASA系列



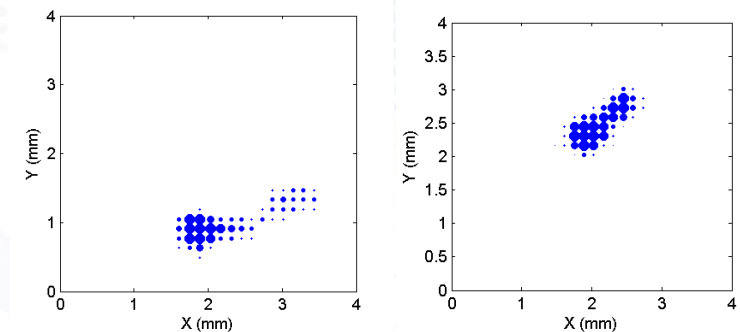
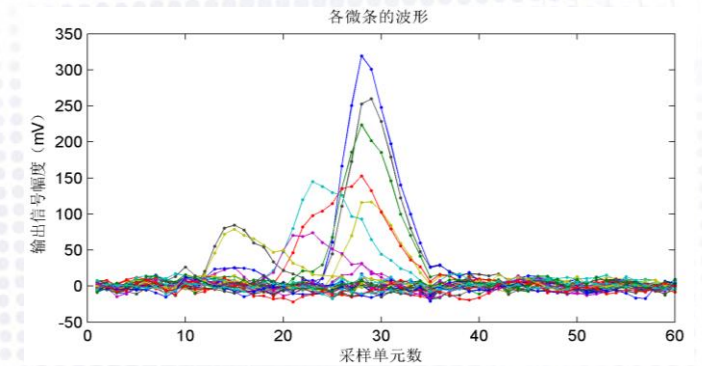
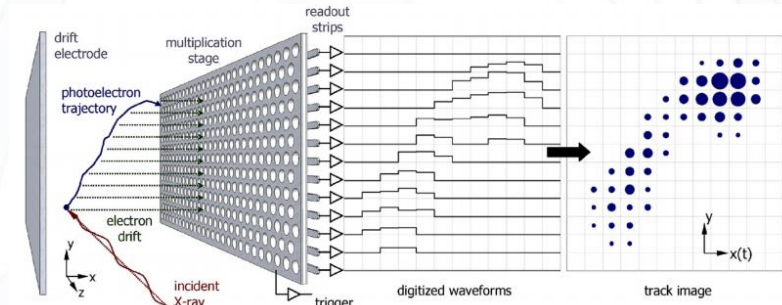
参数	指标
增益	2-40mV/fC
成形电路	CR-(RC) ⁵
达峰时间	100-400ns
噪声	<2000e @ 10pF
积分非线性	<1%
串扰	<1%
通道数	16+1



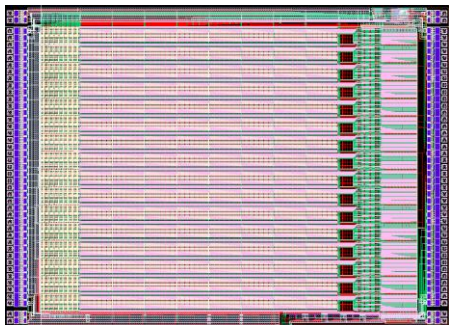
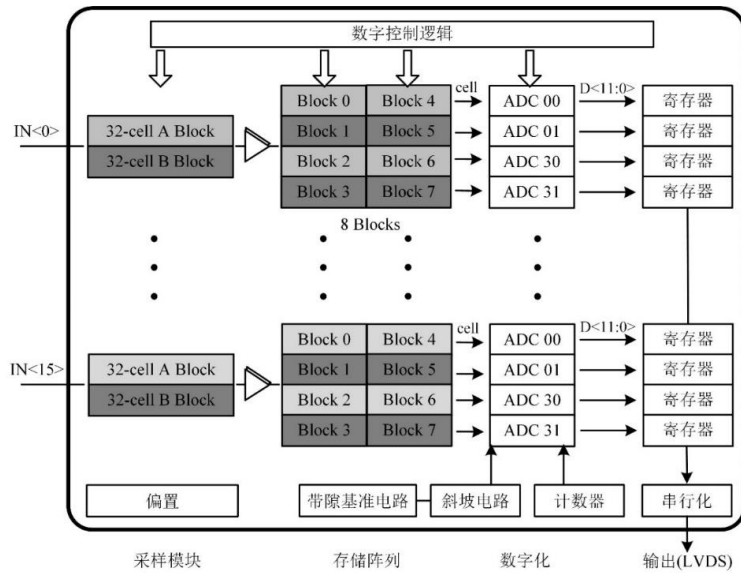
➤ SCA系列: CASCA



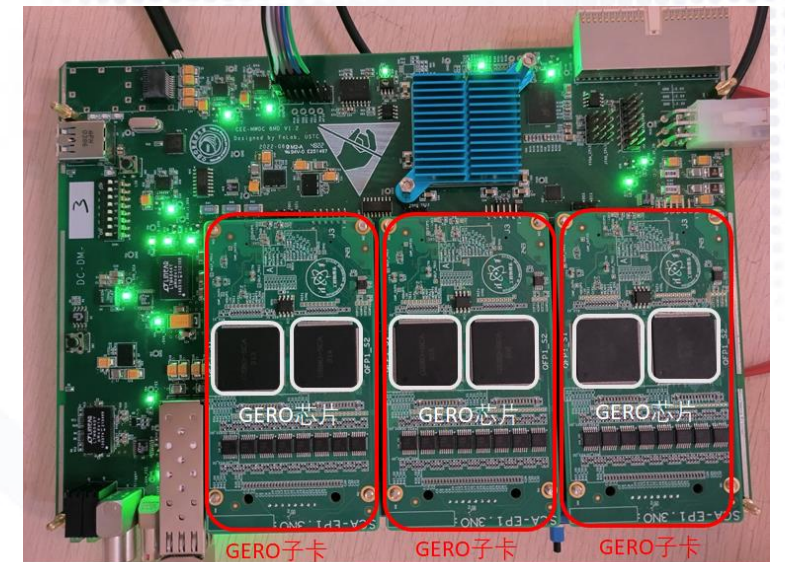
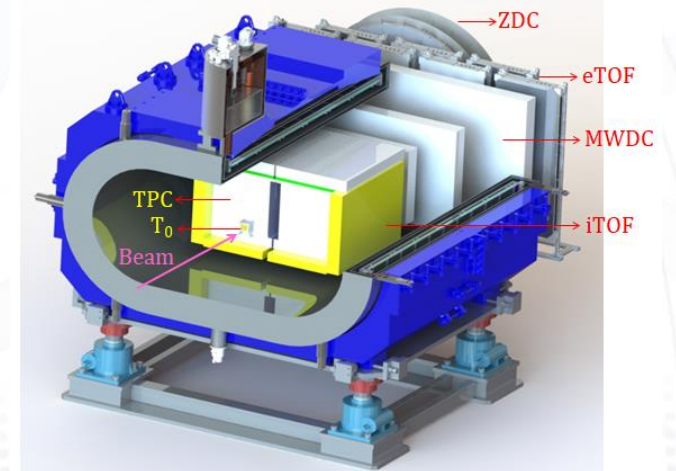
参数	指标
通道数	32
输入电荷范围	0-40fC
增益	25mV/fC
成形电路	CR-RC
达峰时间	50ns
ENC	68.3e/pF+7.2e
采样率	50MSPS
采样有效分辨率	~9bit
采样深度	64 points
读出时钟频率	16MHz
功耗	2.8 mW/ch
工艺	0.18 μ m



➤ SCA系列: GERO

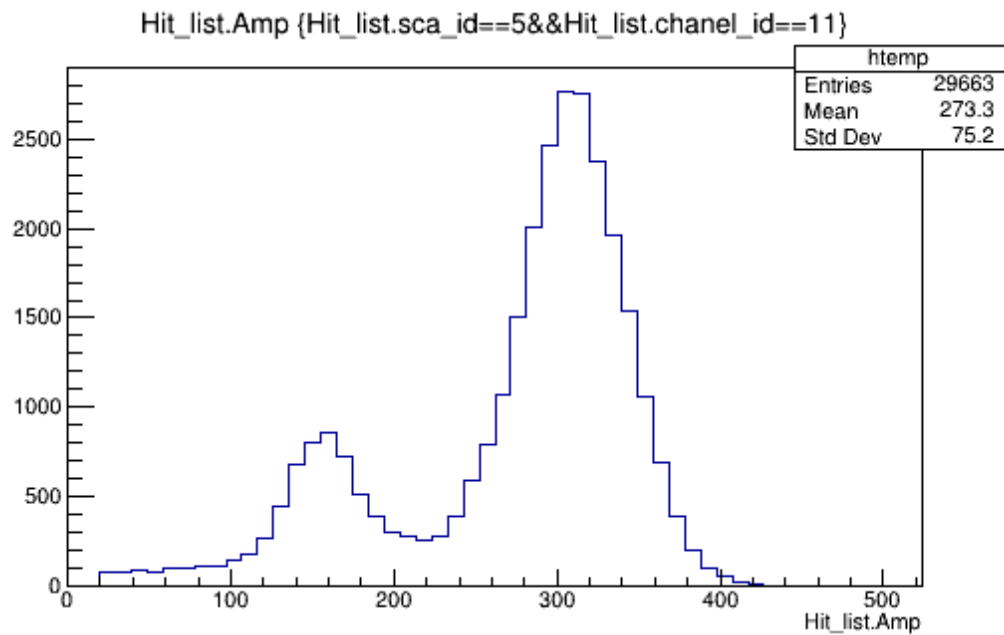


参数	指标
工作电压	1.8 V, 2.5 V
输入动态范围	0.3V - 1.3 V
采样频率	100 MS/s
采样精度	> 10 bits
采样深度	256
ADC时钟频率	100 MHz
ADC计数器	12 bits
ADC转换时间	42 μ s
最大死时间	336 μ s
核心功耗	2.3 mW/ch
工艺	0.18 μ m



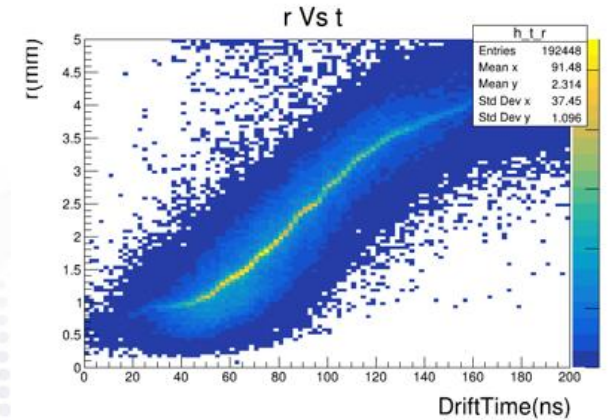
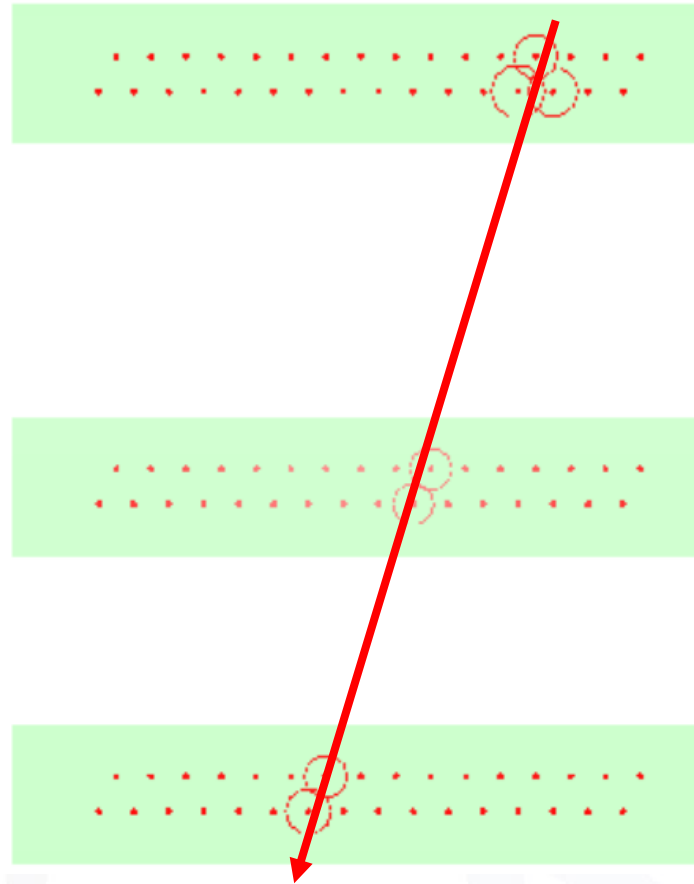
➤ SCA系列: GERO

Fe-55能谱

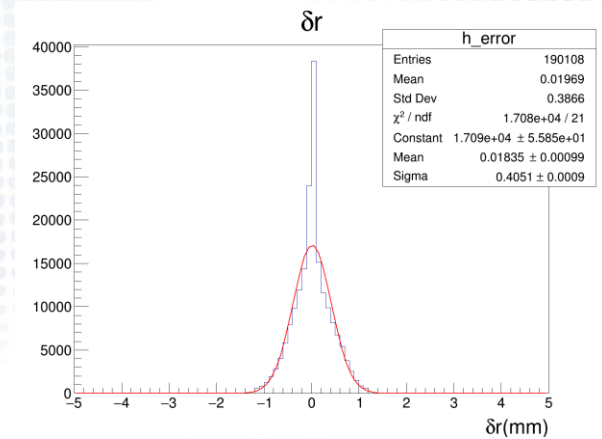


- 工作气体Ar+CO₂(80:20)
- 能量分辨率~25%(FWHM)

宇宙射线径迹



R - T曲线



径迹重建残差

03

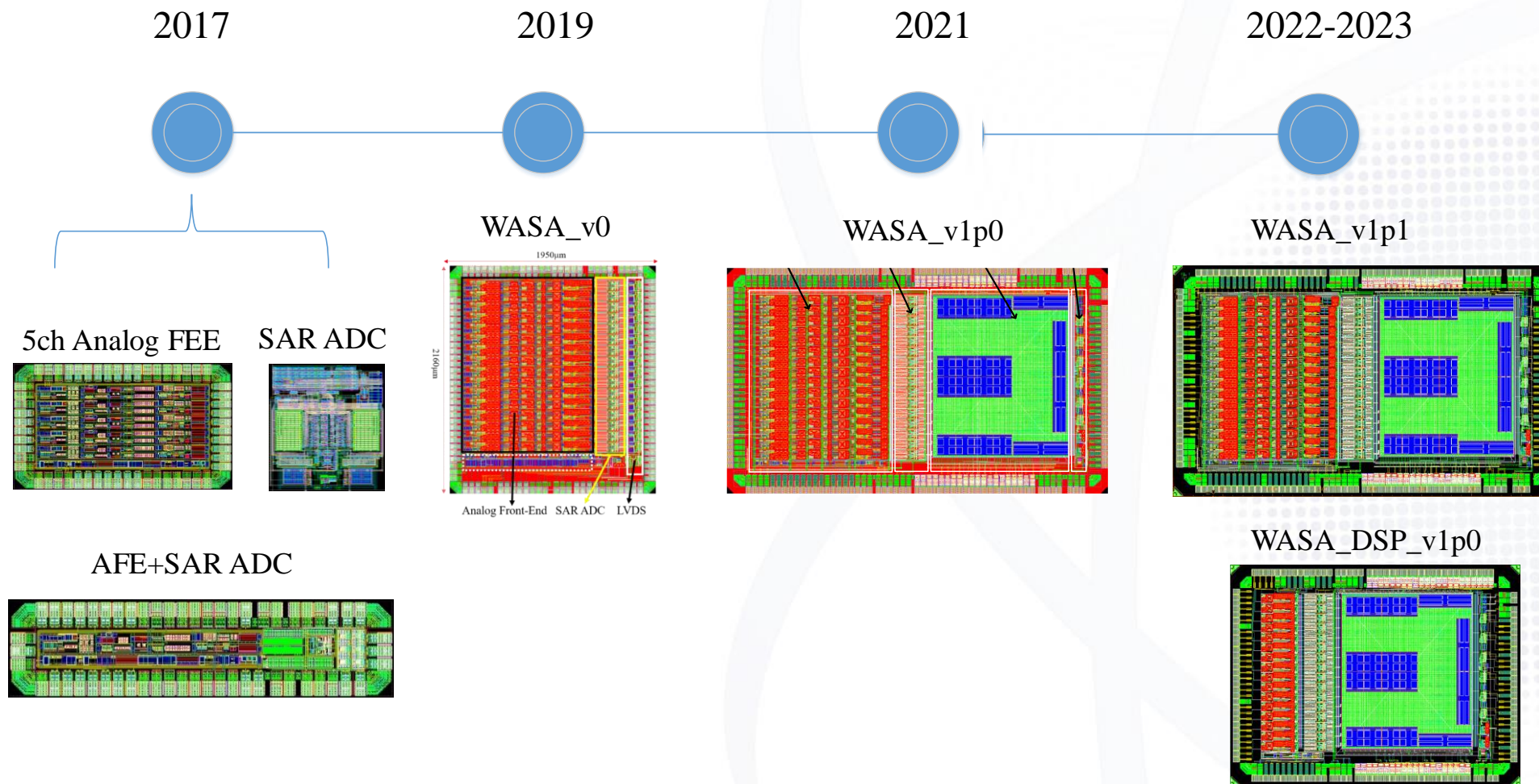
Progress on WASA chip
WASA芯片进展



WASA芯片: Waveform Sampling ASIC

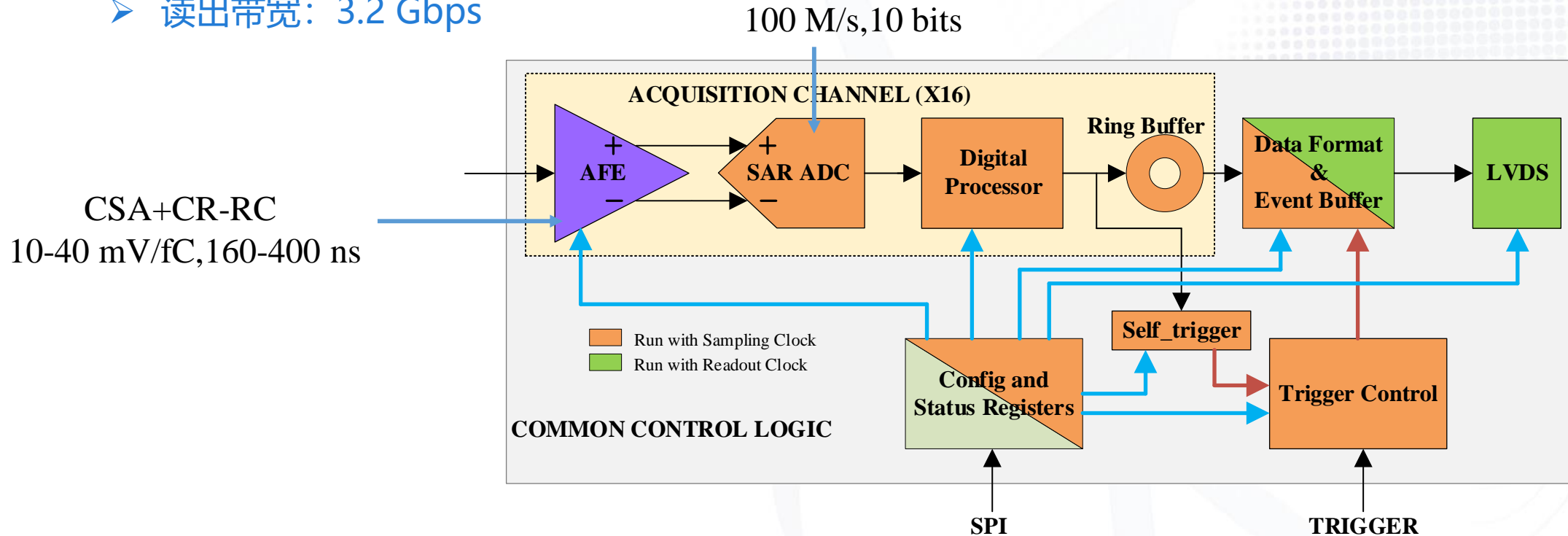


➤ 用于CEPC-TPC读出的低功耗、高集成度前端芯片



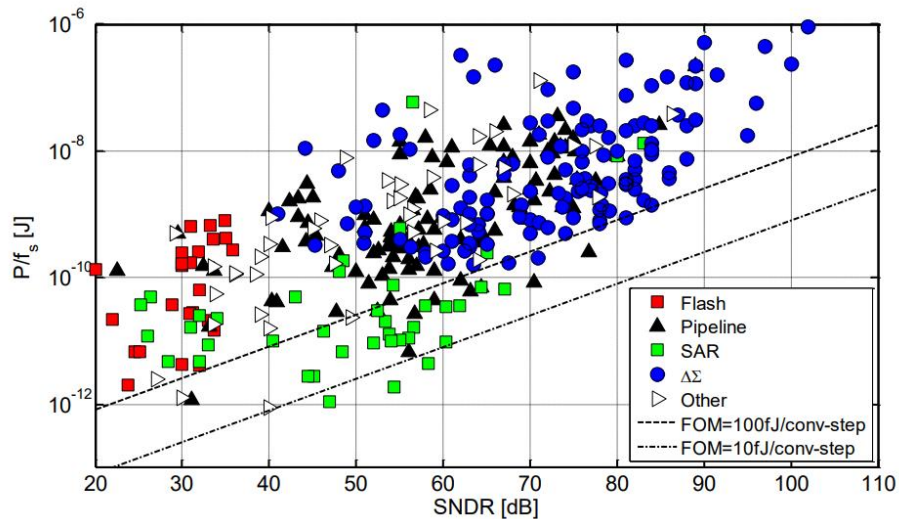
➤ 原理框图

- 模拟CR-RC成形+数字滤波器：基线恢复+数字梯形
- 触发模式：自触发、外触发、外触发加窗
- 二级缓存：Ring buffer+去随机事例缓存器
- 触发延迟：25.6 μ s @ 40 MHz（1024采样点），事例缓存深度：4
- 事例大小：1-256采样点
- 读出带宽：3.2 Gbps

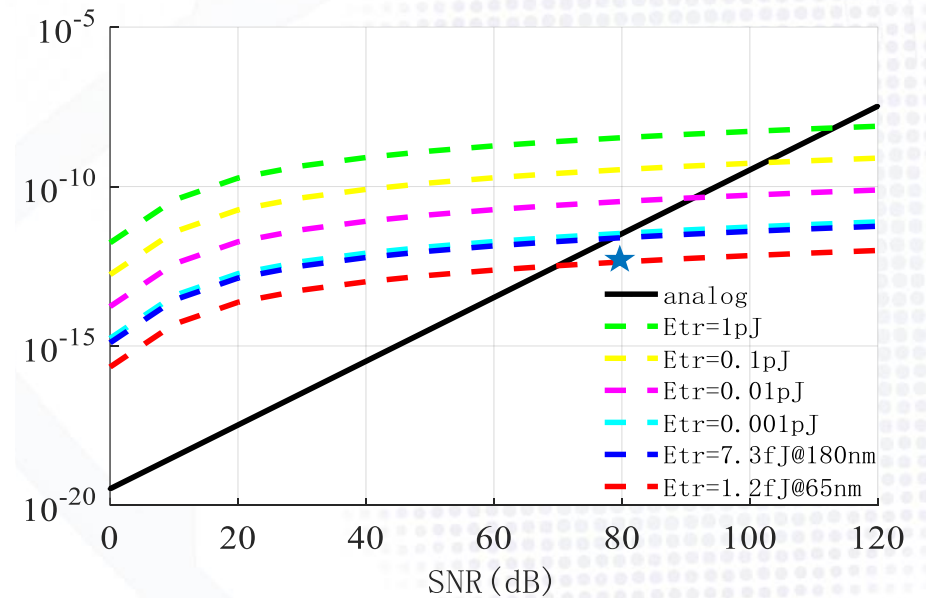


- 功耗!!!
 - Pipeline ADC vs. SAR ADC
 - 模拟滤波 vs. 数字滤波

Energy by Architecture



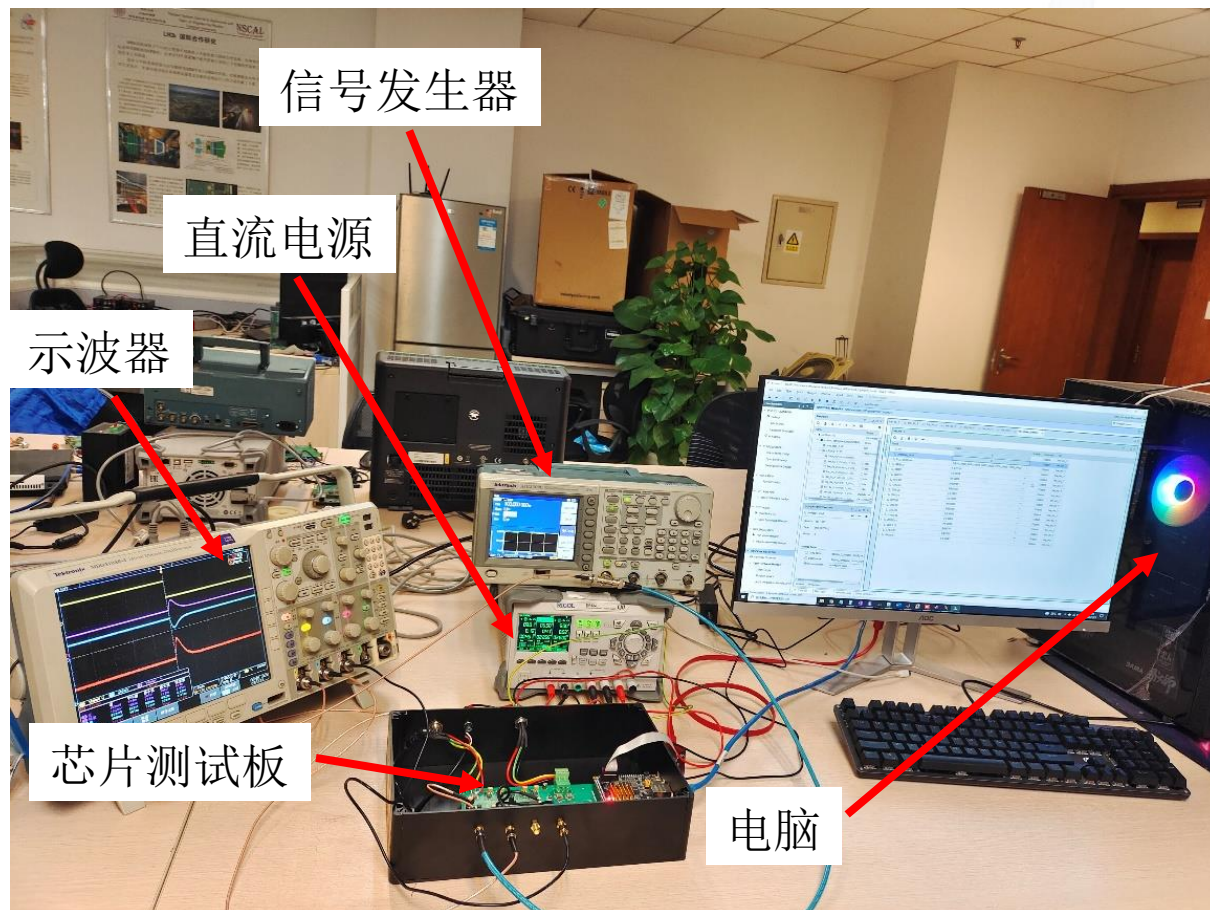
Energy needed for a single-pole low-pass filter (J)



➤ 主要性能指标

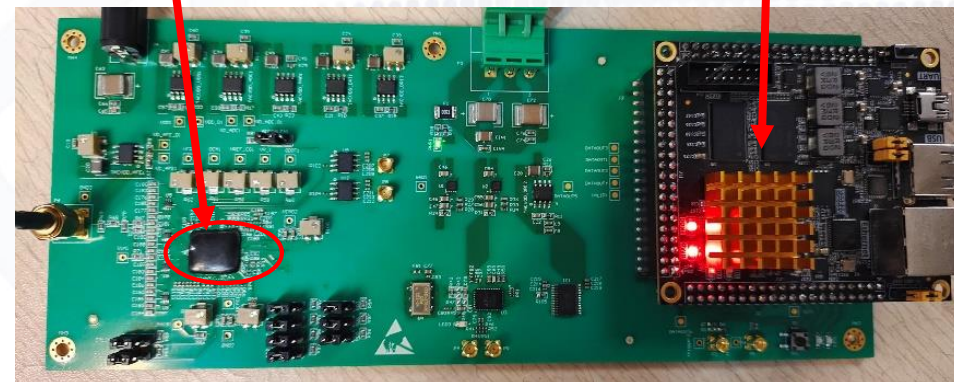
	PASA+ALTRO	Super-ALTRO	SAMPA	WASA
TPC	ALICE	ILC	ALICE upgrade	CEPC
Pad尺寸	4x7.5 mm ²	1x6 mm ²	4x7.5 mm ²	1x6 mm ²
通道数	5.7 × 10 ⁵	1-2 × 10 ⁶	5.7 × 10 ⁵	2 × 10 ⁶
读出结构	MWPC	GEM/MicroMegas	GEM	GEM/MicroMegas
增益	12 mV/fC	12-27 mV/fC	20/30 mV/fC	10-40 mV/fC
成形方式	CR-(RC) ⁴	CR-(RC) ⁴	CR-(RC) ⁴	CR-RC
达峰时间	200 ns	30-120 ns	80/160 ns	160-400 ns
ENC	370+14.6 e/pF	520 e	246+36 e/pF	569+14.8 e/pF
波形采样方式	Pipeline ADC	Pipeline ADC	SAR ADC	SAR ADC
采样率	10 MHz	40 MHz	10 MHz	10-100 MHz
精度	10 bit	10 bit	10 bit	10 bit
模拟前端功耗	11.7 mW/ch	10.3 mW/ch	9 mW/ch	1.4 mW/ch
ADC功耗	12.5 mW/ch	33 mW/ch	1.5 mW/ch	0.8 mW/ch@40 MHz
数字部分功耗	7.5 mW/ch	4.0 mW/ch	6.5 mW/ch	2.7 mW/ch@40 MHz
总功耗	31.7 mW/ch@10MHz	47.3 mW/ch@40 MHz	17 mW/ch@10 MHz	4.9 mW/ch@40 MHz
CMOS工艺	250 nm	130 nm	130 nm	65 nm

测试系统



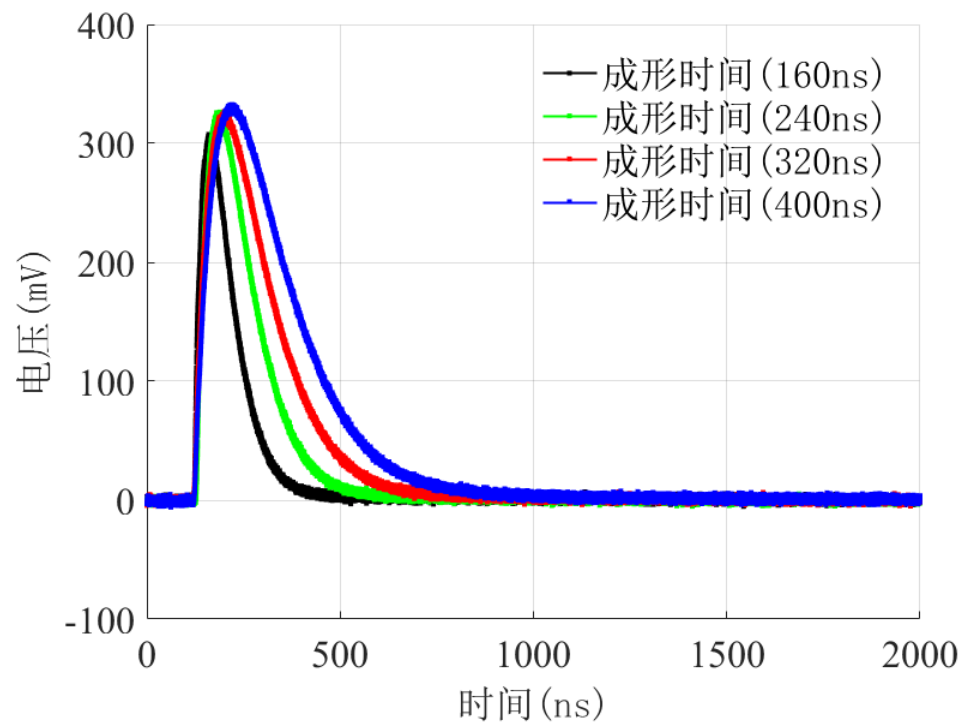
TPC前端读出原型芯片

ZYNQ核心板

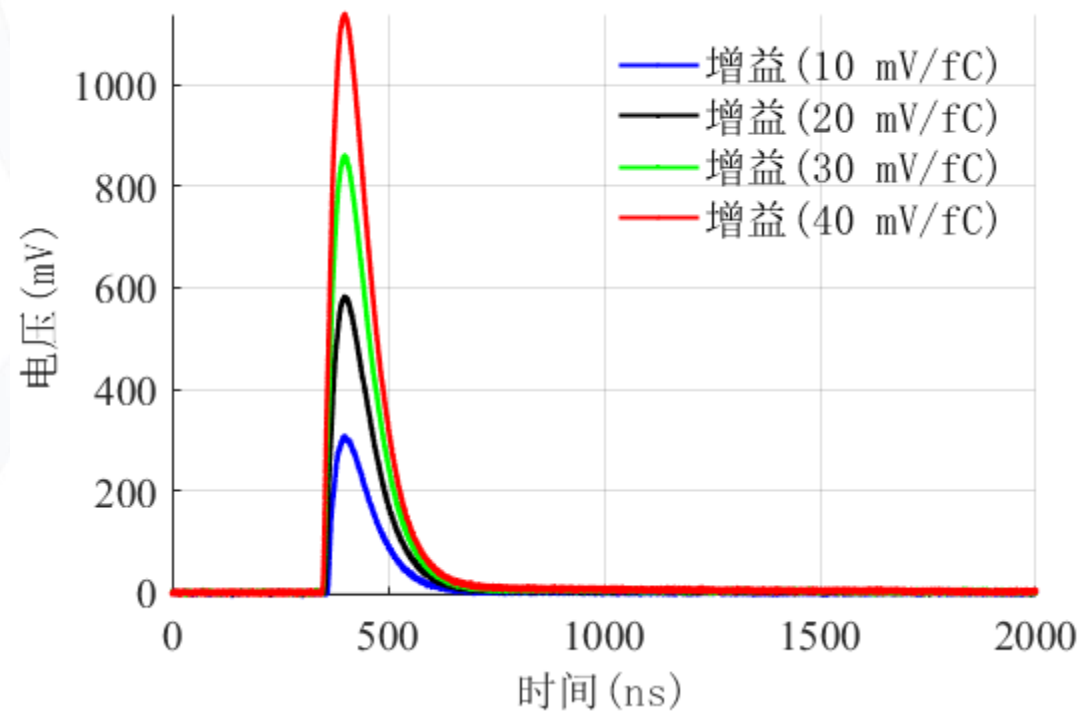


瞬态响应：模拟部分

模拟前端瞬态输出随成形时间的变化

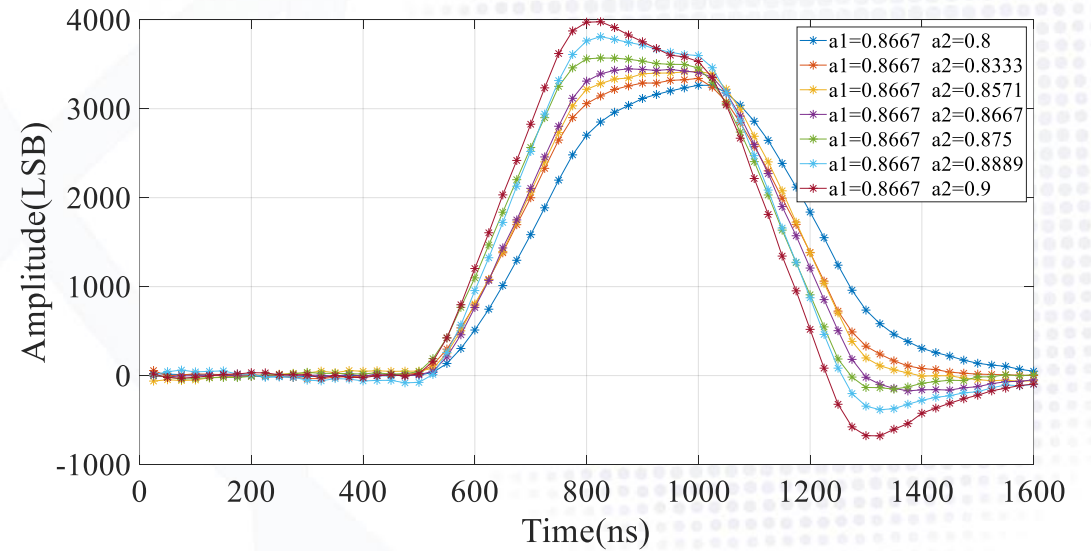
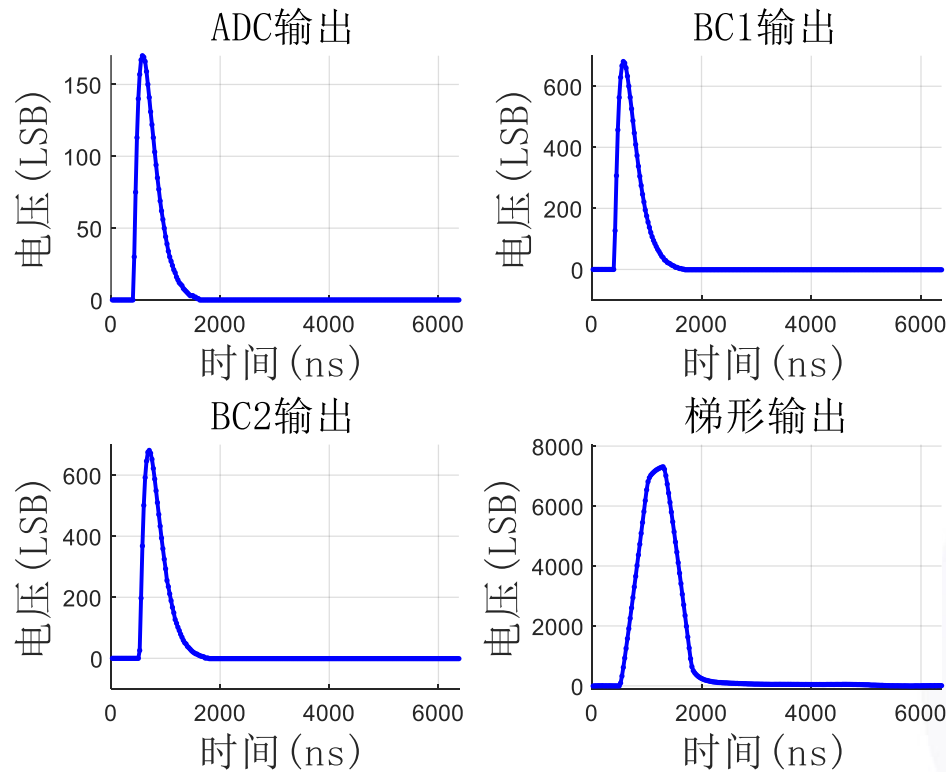


模拟前端的瞬态输出随增益的变化

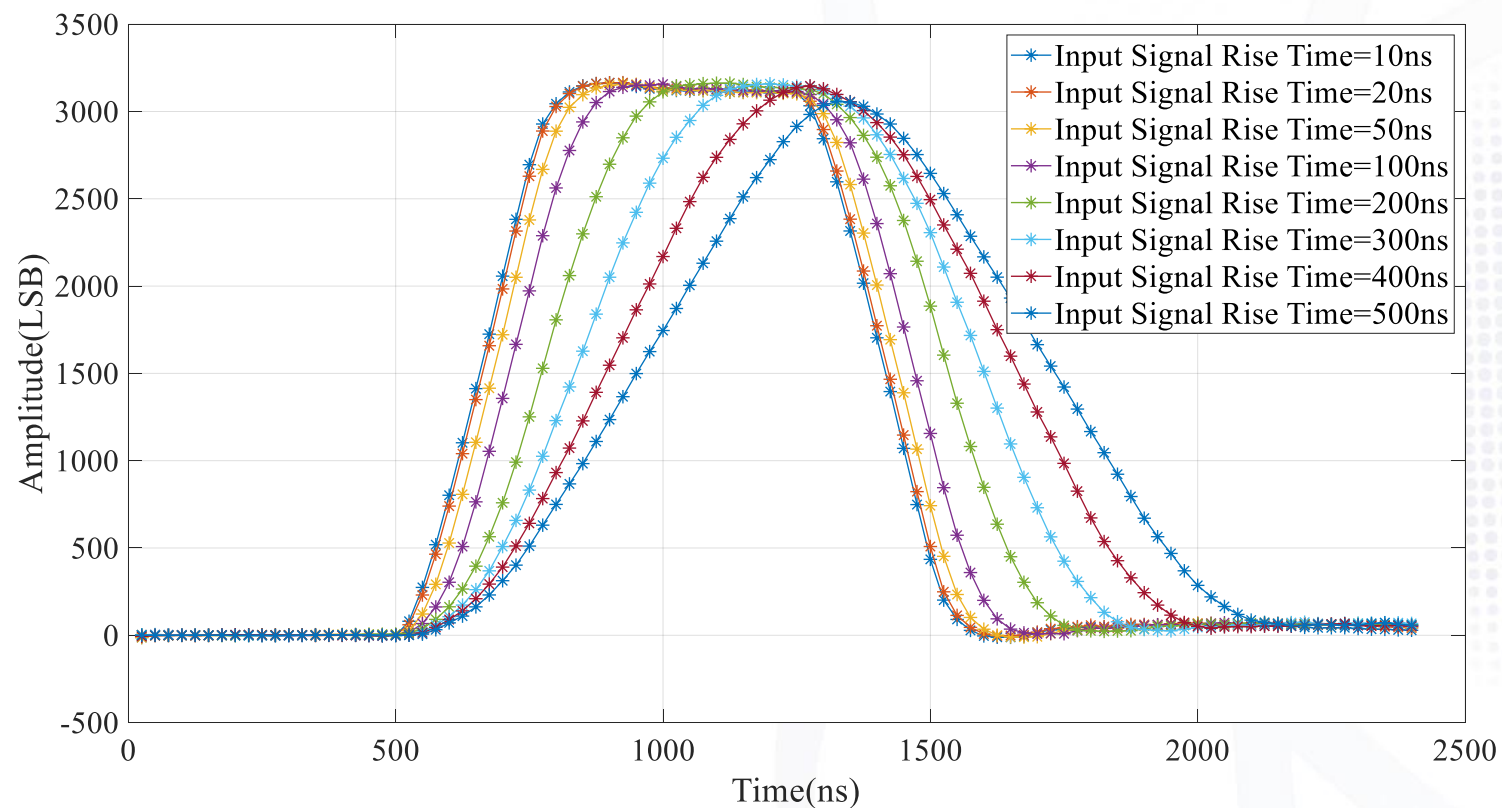


➤ 数字滤波器响应:

- 模拟前端: 增益10 mV/fC, 成形时间 160 ns, $Q_{in}=120$ fC
- ADC采样率: 40 MHz
- 梯形: 上升时间 600 ns, 平顶时间 200 ns

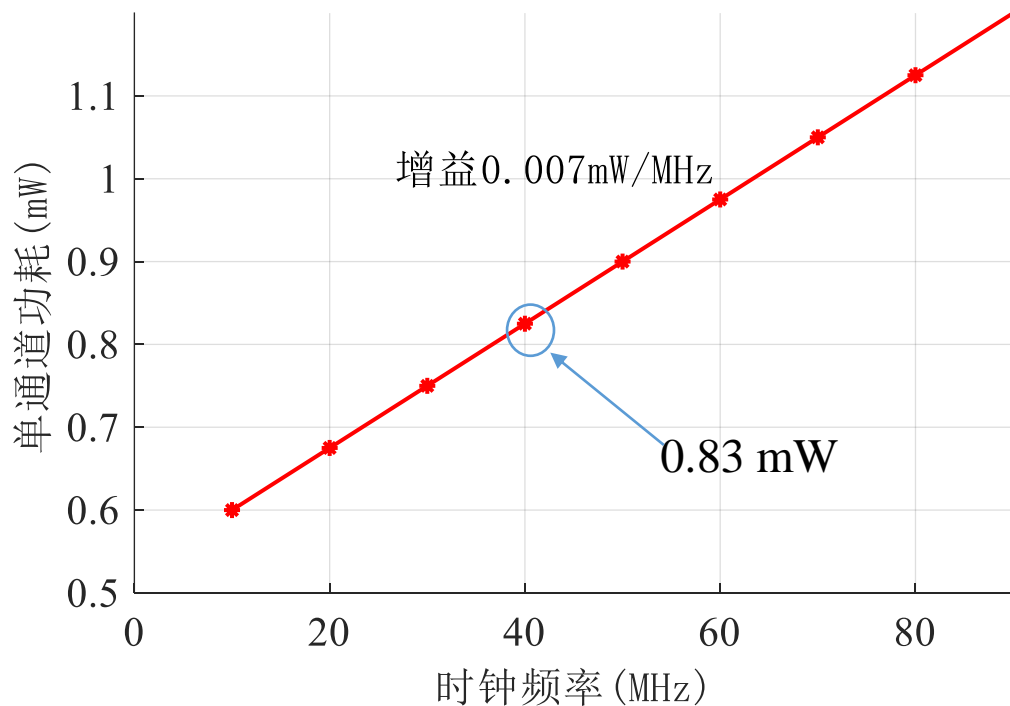


➤ 数字滤波器响应：弹道亏损

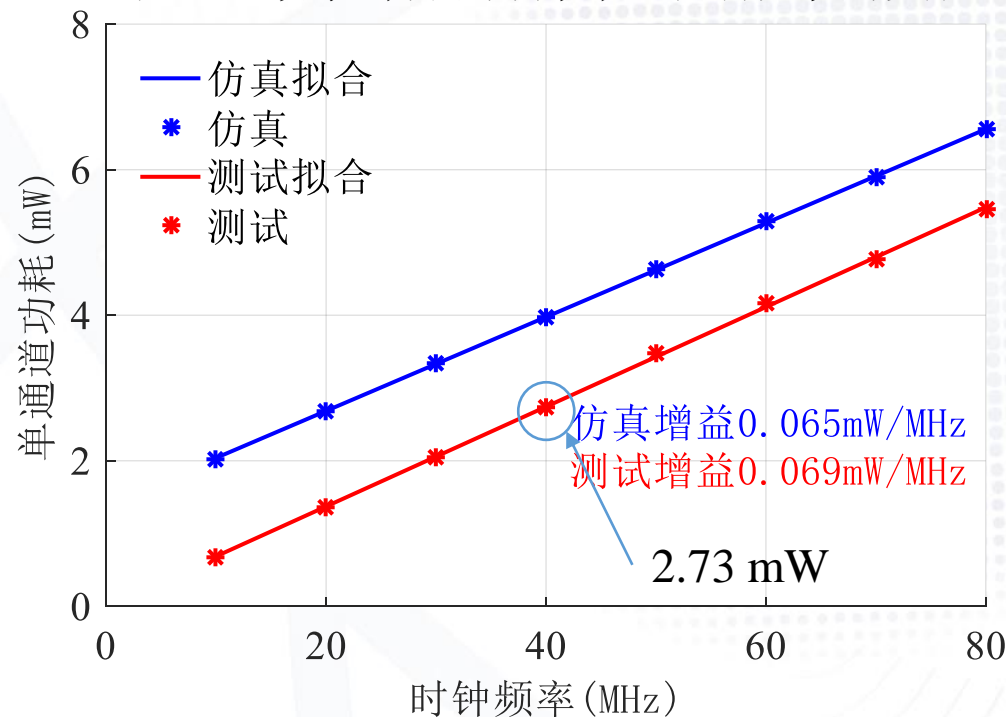


- 功耗: 4.94 mW/ch@40 MHz
 - 模拟前端功耗: 1.38 mW/ch
 - ADC功耗: 0.83 mW/ch
 - 数字电路功耗: 2.73 mW/ch

单通道ADC的功耗随时钟频率的变化

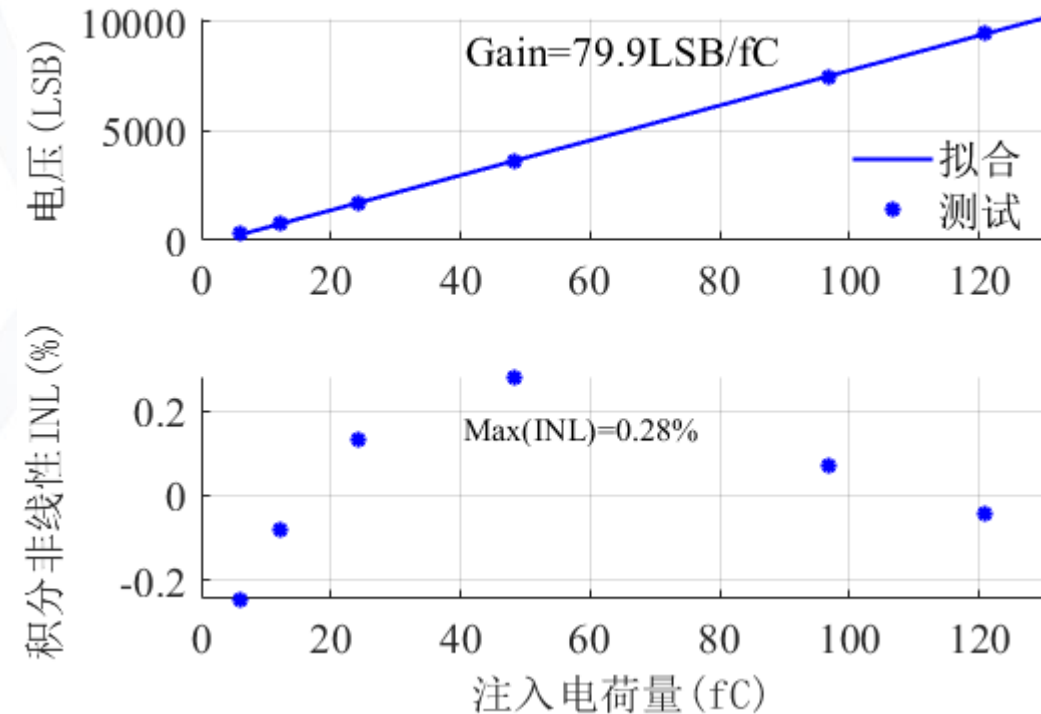
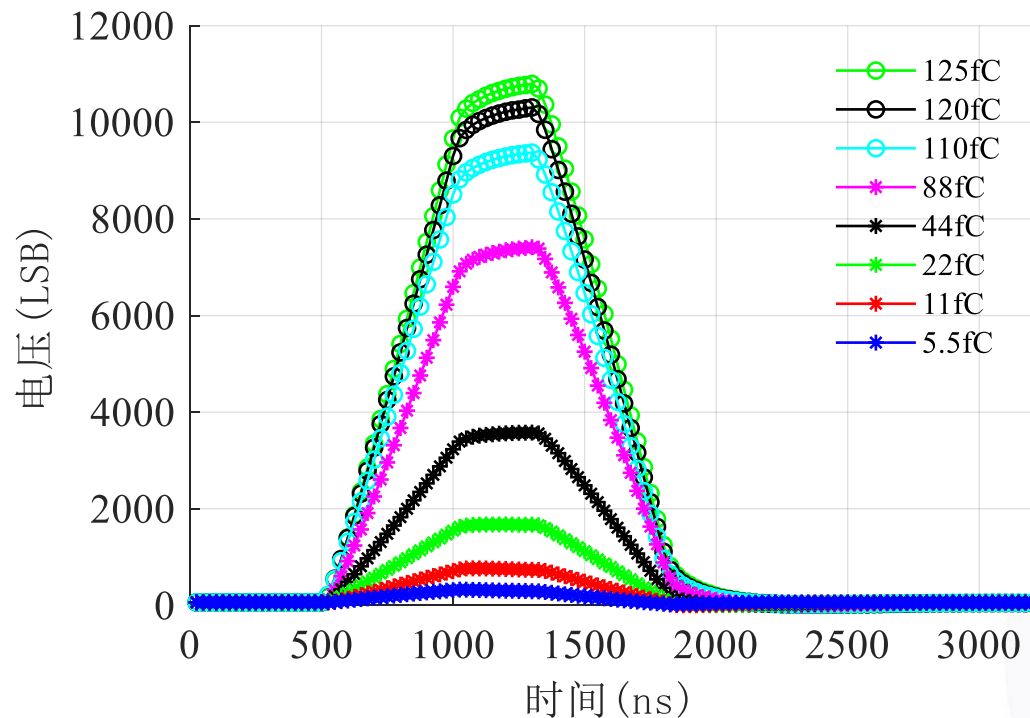


单通道数字部分的功耗随时钟频率的变化



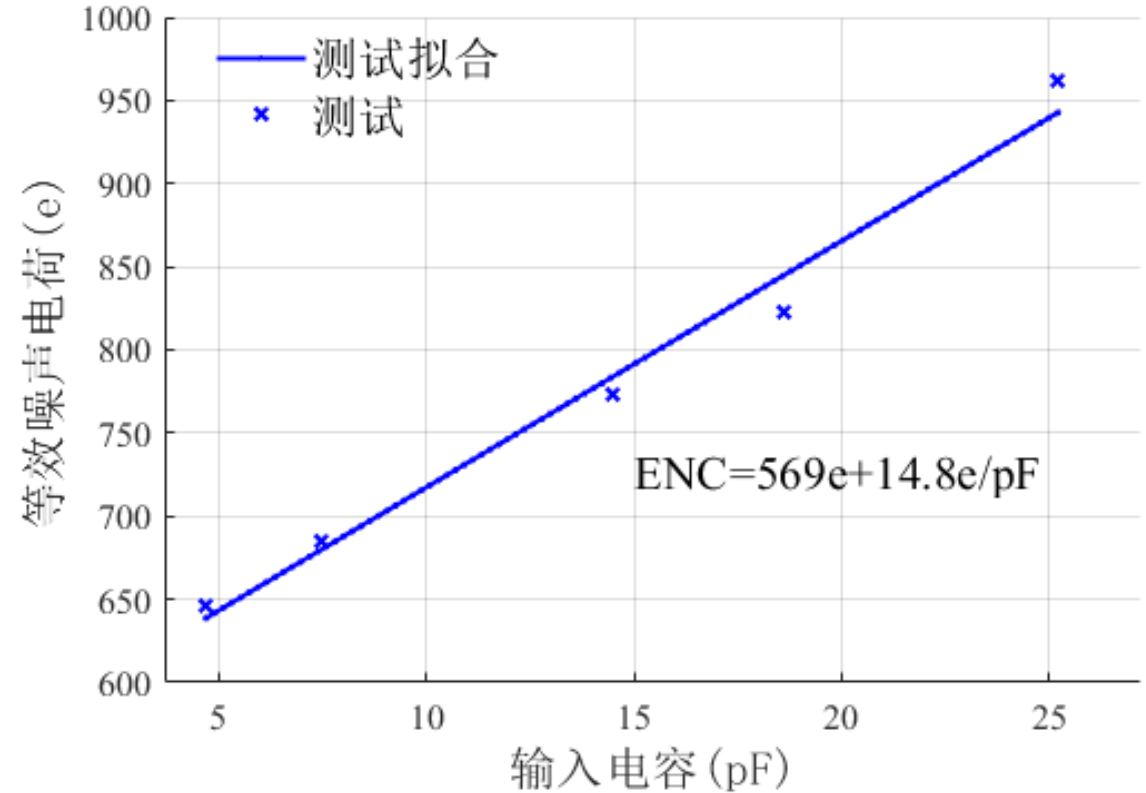
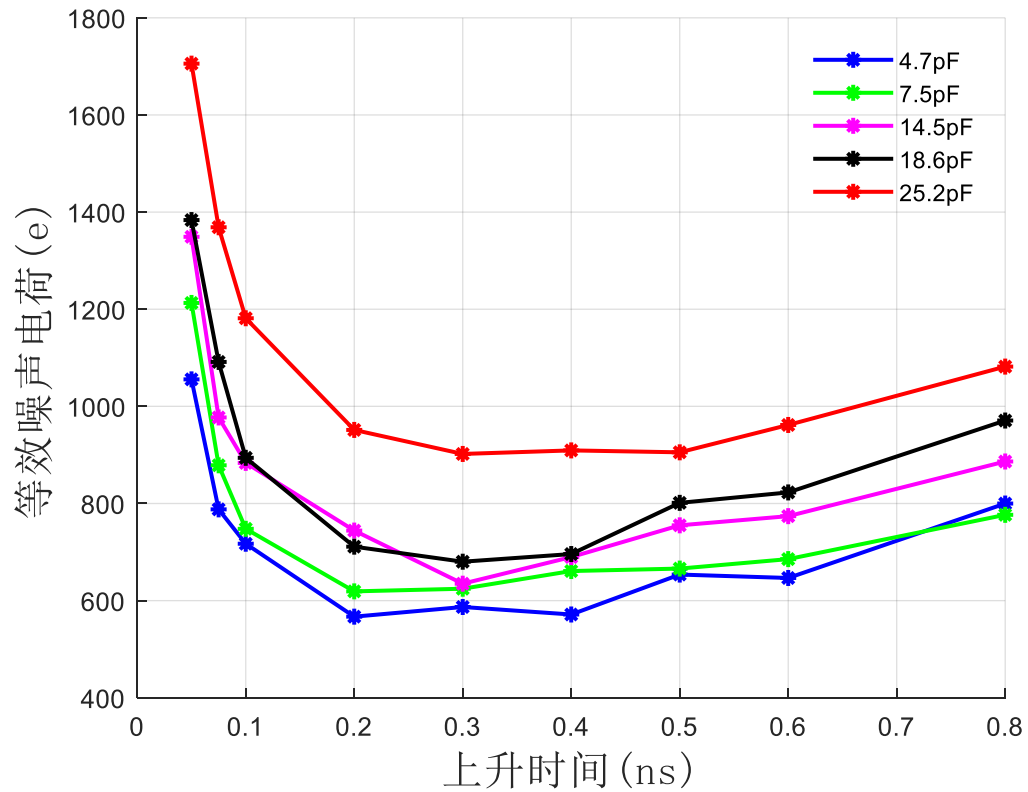
➤ 线性

- 模拟前端：增益10 mV/fC，成形时间 160 ns
- ADC采样率：40 MHz
- 梯形：上升时间 600 ns，平顶时间 200 ns



➤ 噪声

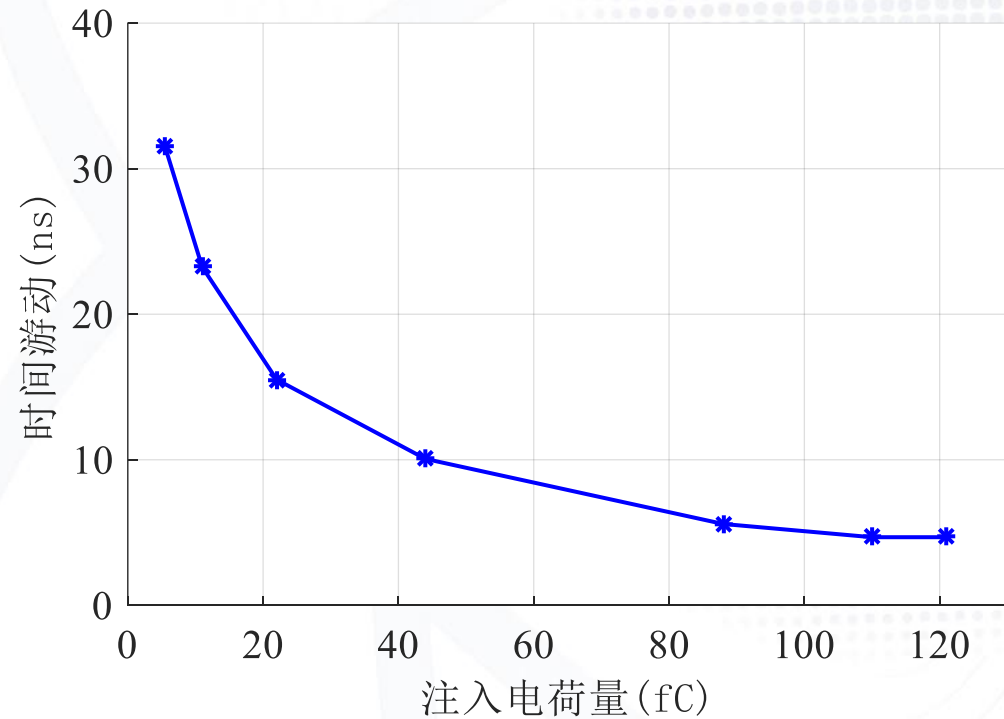
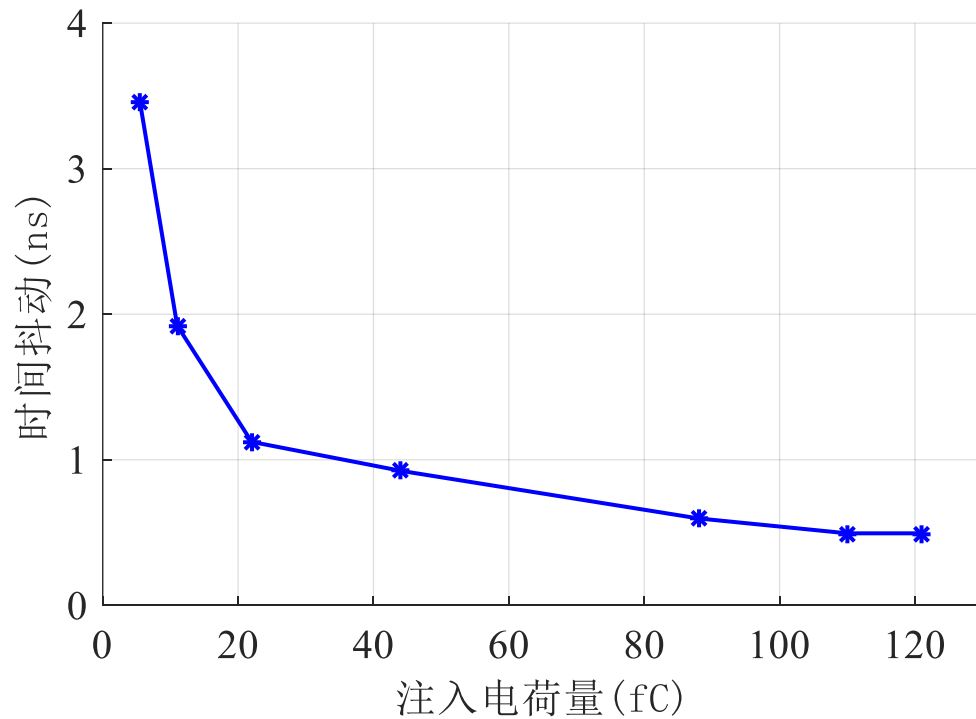
- 模拟前端：增益10 mV/fC，成形时间 160 ns
- ADC采样率：40 MHz
- 梯形平顶时间：200 ns



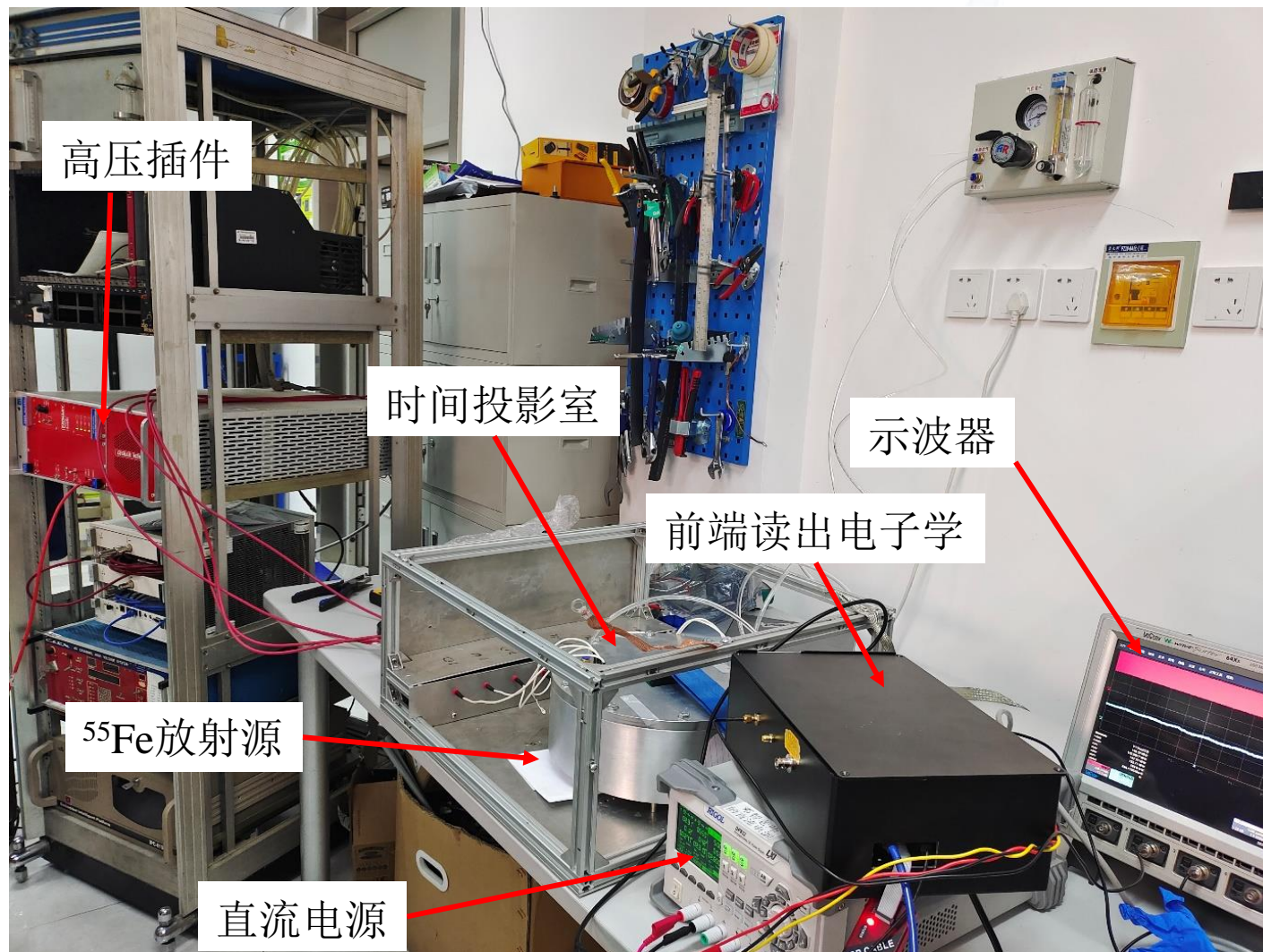
➤ 定时性能

- 模拟前端：增益10 mV/fC，成形时间 160 ns
- ADC采样率：40 MHz
- 梯形：上升时间 600 ns，平顶时间 200 ns
- 定时算法：时间重心

$$\text{时间重心: } t = \frac{\sum t_i \times f(t_i)}{\sum f(t_i)}$$



➤ 探测器测试: Fe-55



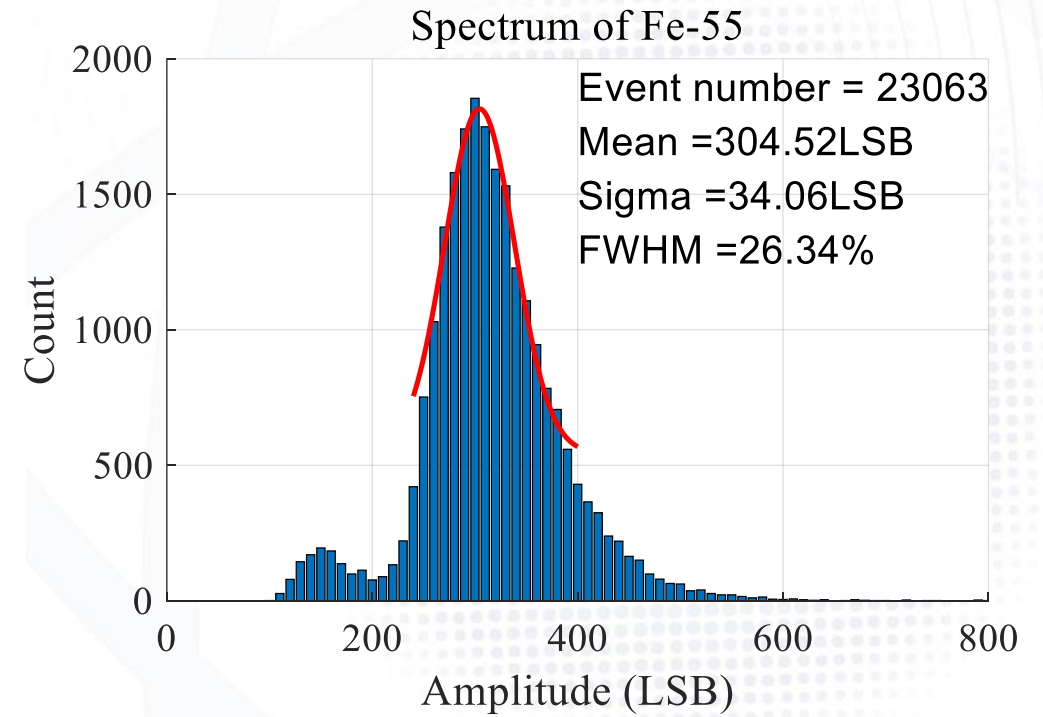
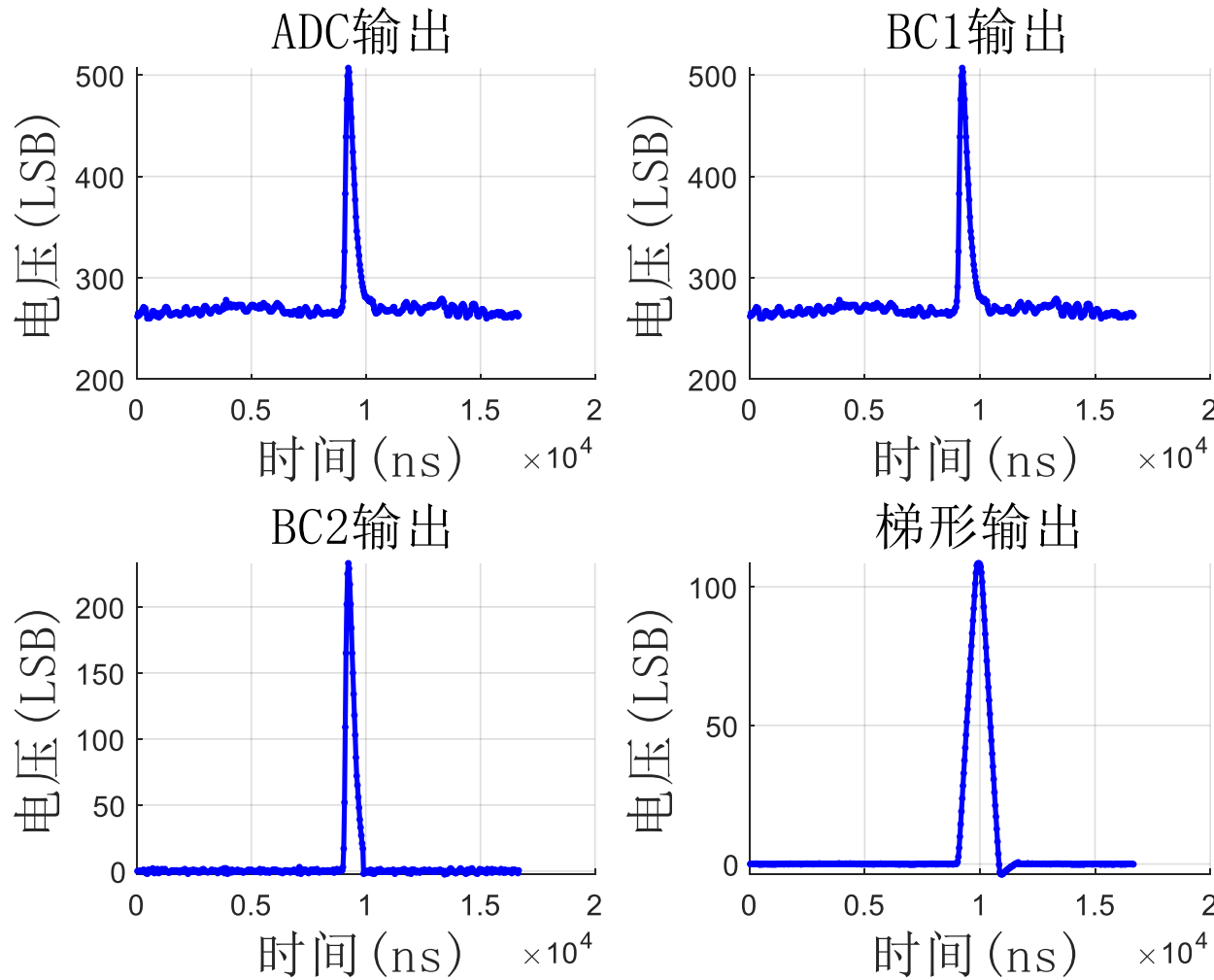
TPC的工作条件:

- GEM电压: 310 V
- 漂移电场: 3.23×10^4 V/m
- 气体: T2K (Ar/CF₄/iC₄H₁₀ 95/3/2)

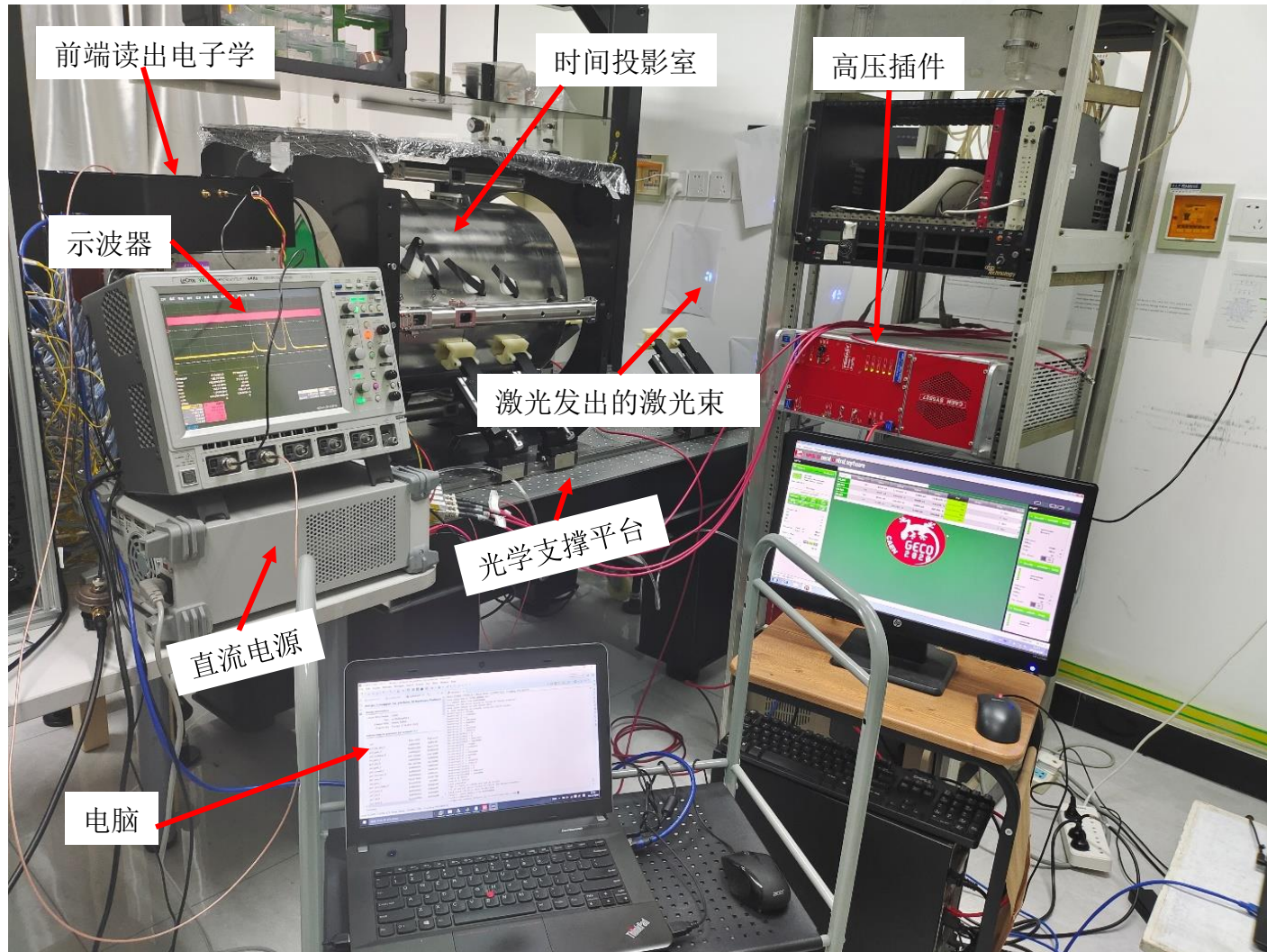
电子学工作条件:

- 增益: 20 mV/fC
- 采样率: 30 MHz
- 自触发模式

➤ 探测器信号的瞬态波形和能谱



➤ 探测器测试：激光径迹



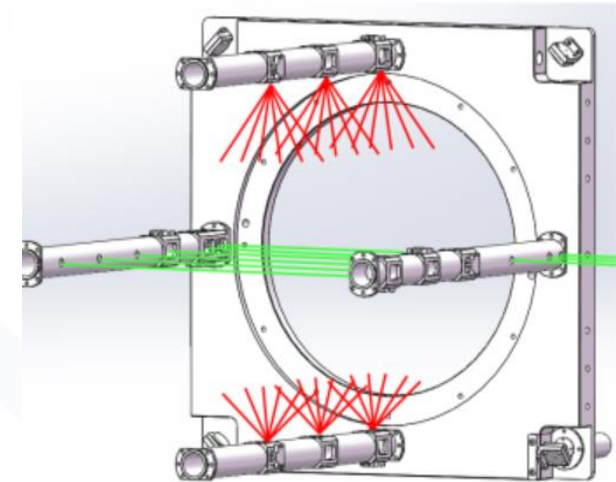
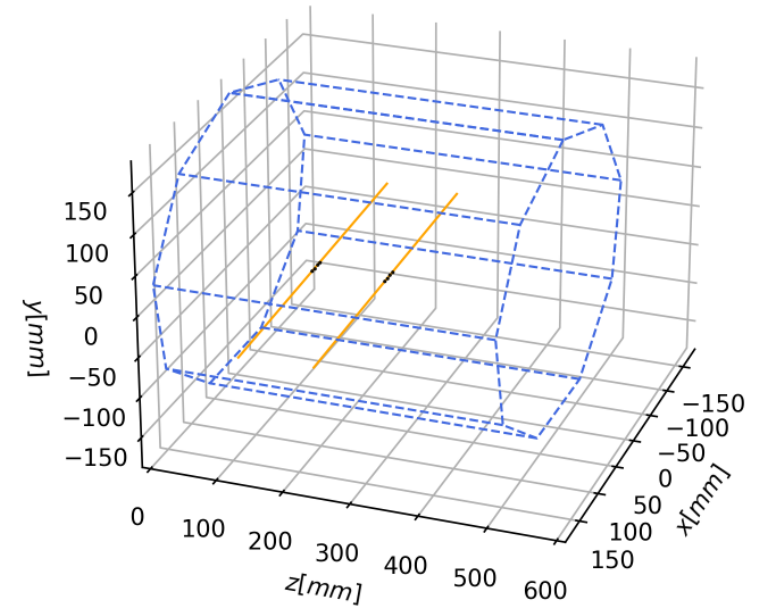
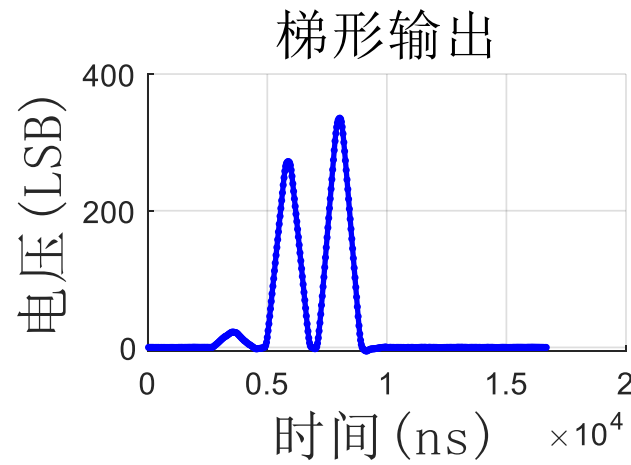
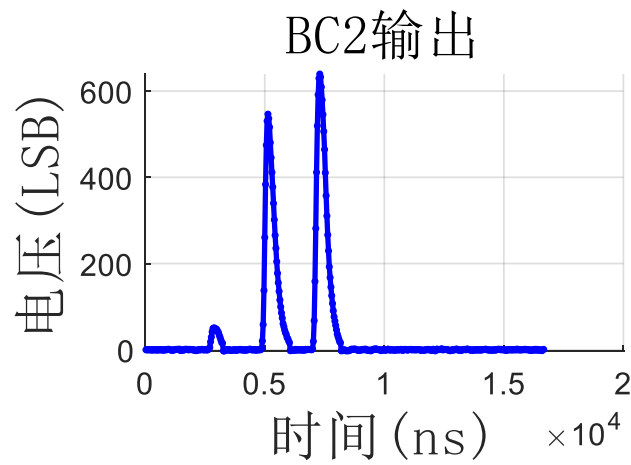
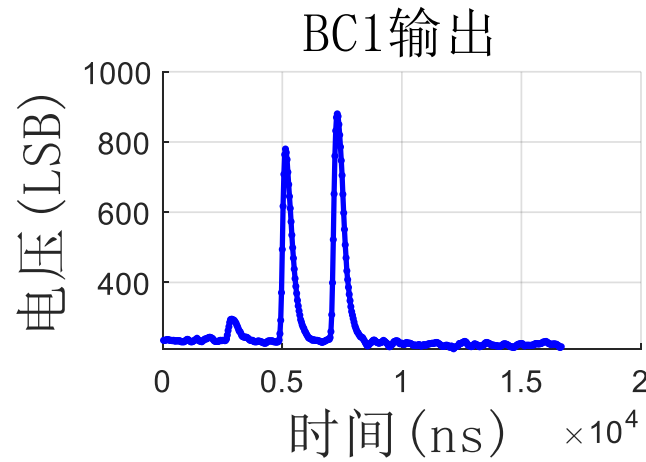
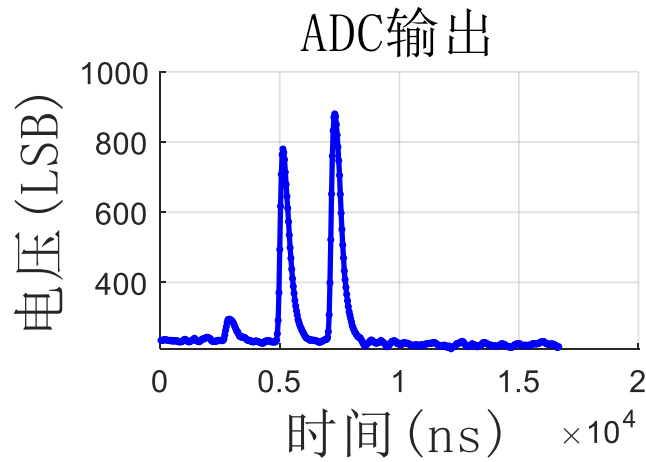
TPC的工作条件:

- GEM: 280 V
- 漂移电场: $9000 \text{ V}/50 \text{ cm} = 180 \text{ V}/\text{cm}$
- 气体: T2K (Ar/CF₄/iC₄H₁₀ 95/3/2)
- 激光器: 7.2 mJ @20 Hz

电子学工作条件:

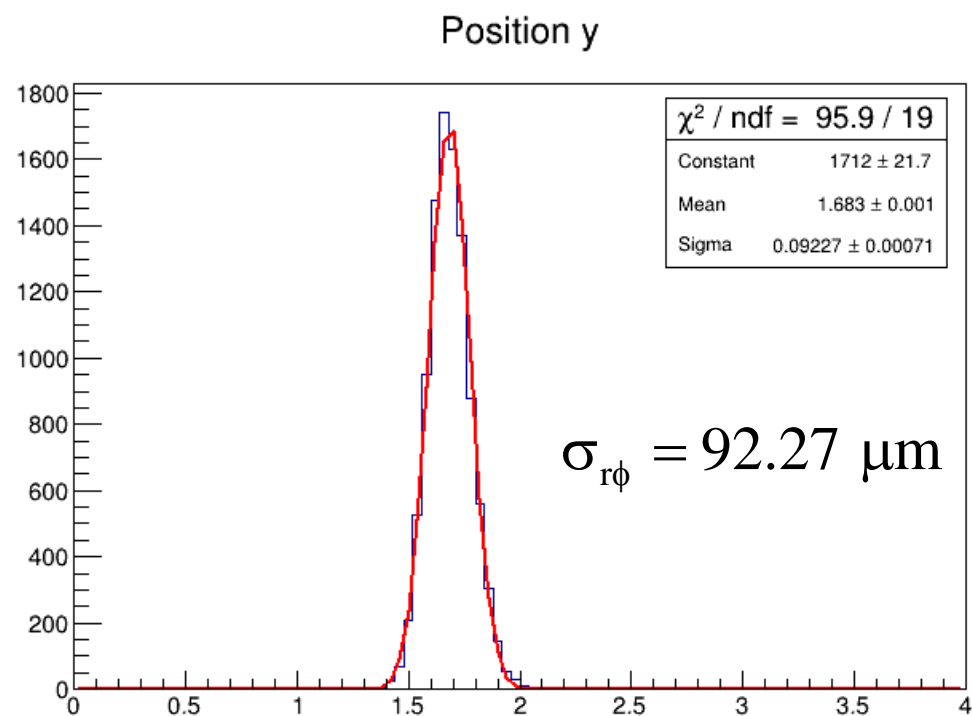
- 增益: 20 mV/fC
- 采样率: 30 MHz
- 外触发模式
- 触发延时: $2500 \times 8 \text{ ns} = 20 \mu\text{s}$

激光径迹

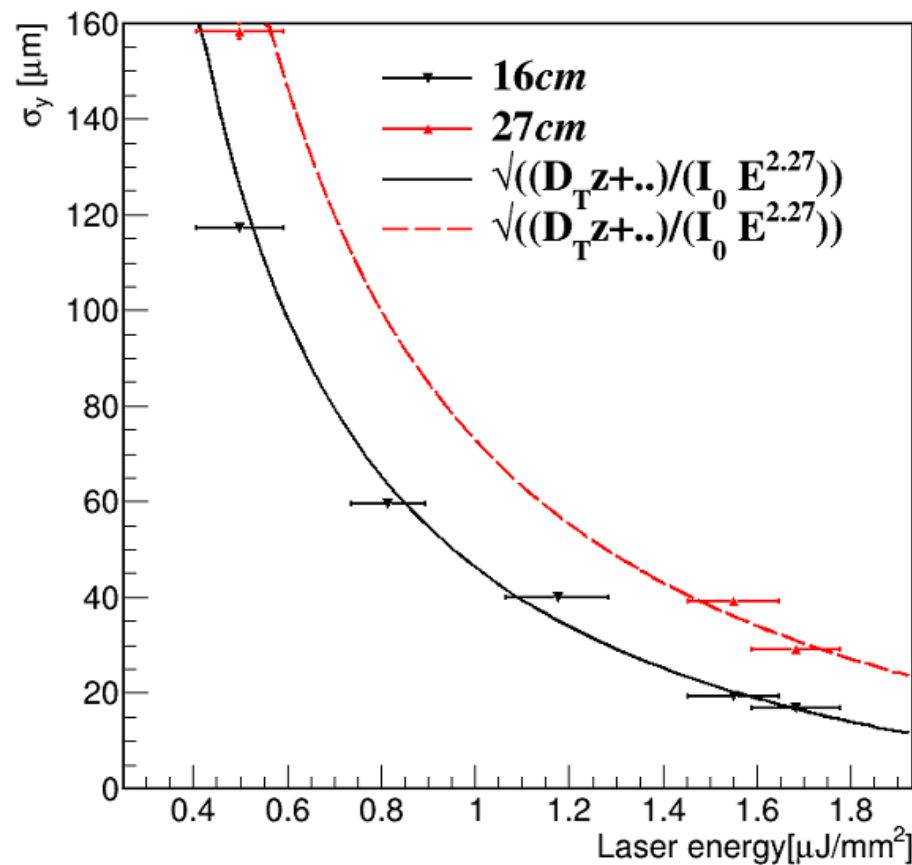


径迹分辨

rφ方向的位置分辨



位置分辨随激光能量的变化



04

Summary

小结与展望



➤ 小结

- TPC可以实现大体积、 4π 立体角覆盖的三维粒子径迹探测，在基础物理实验、天文观测和核能开发等领域中有广泛的应用前景
- 在过去的十多年中，我们针对TPC读出开展了多款波形采样前端芯片的研制，朝着更数字化、更集成化和更智能化的方向发展
- 相关的技术也可以应用在半导体探测器的读出中

➤ 展望

- 进一步提高模拟前端的动态范围，涵盖重核粒子的探测
- 开展低温工作的可行性研究，用于惰性液体TPC探测器的读出

- 感谢清华大学李玉兰、冯骅课题组、高能所李金、祁辉荣和山东大学祝成光在TPC探测器方面的技术交流和支持
- 感谢清华大学肖志刚课题组、近代物理所干奕、孔洁、科大赵雷、曹喆推动和帮助SCA (GERO) 芯片用于CEE-MWDC探测器的读出
- 感谢清华大学李福乐课题组完成ADC的设计
- 特别感谢参与芯片研制的研究生：何力、章红燕、赵馨远、刘丰、刘伟、刘灿文 (在读)



谢谢聆听