

粒子探测器多通道读出 电子学

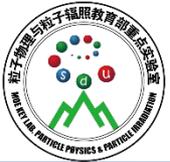
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联系邮箱：kun.hu@sdu.edu.cn



山东大学





引言

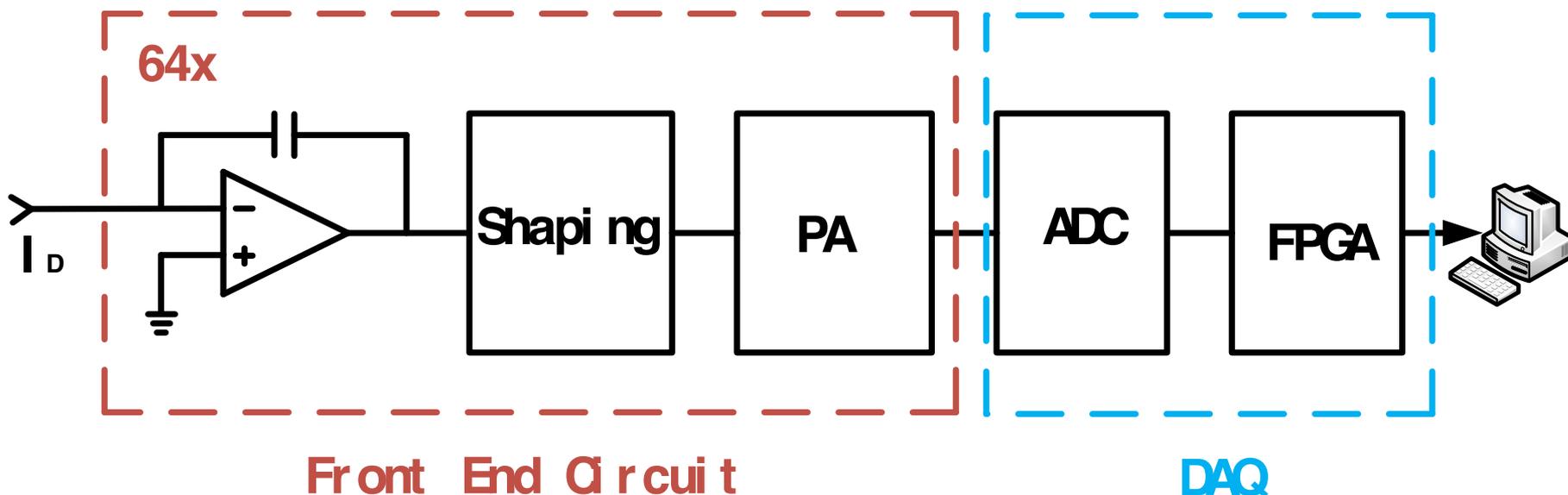


多通道高密度前端读出电子学的需求：

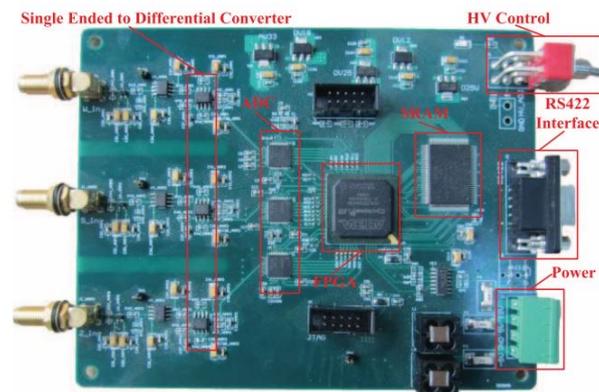
- ✓ 气体探测器：TGC, MWPC等；
- ✓ 半导体探测器：SiPM/MPPC, 硅像素探测器等；
- ✓ 光电倍增管：mult-pixel PMT；
- ✓ 新型高密度探测器的研发。

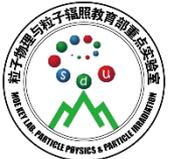
解决方案：

- ✓ 传统的积分成型器+ADC+FPGA等；
- ✓ **ASIC**: 功能强大，抗辐照，通道密度高，集成了高精度幅度测量+时间测量+事例缓存等；
- ✓ 其他办法？

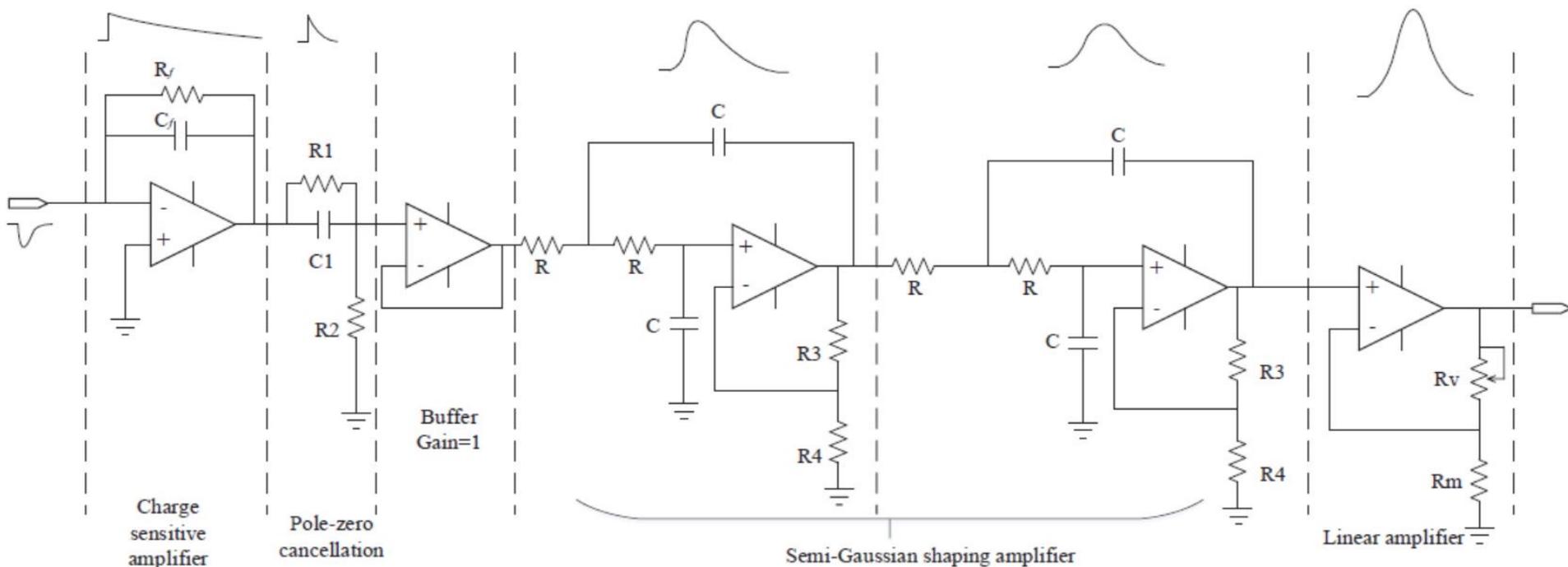


信号读出分为两个部分：前端板（FEE）和数据获取系统DAQ；前端板主要包含积分成形和增益调整；DAQ系统包含ADC+FPGA存储器。（右图是3路DAQ的模型）





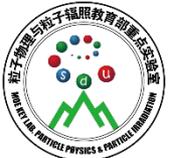
前放+主放



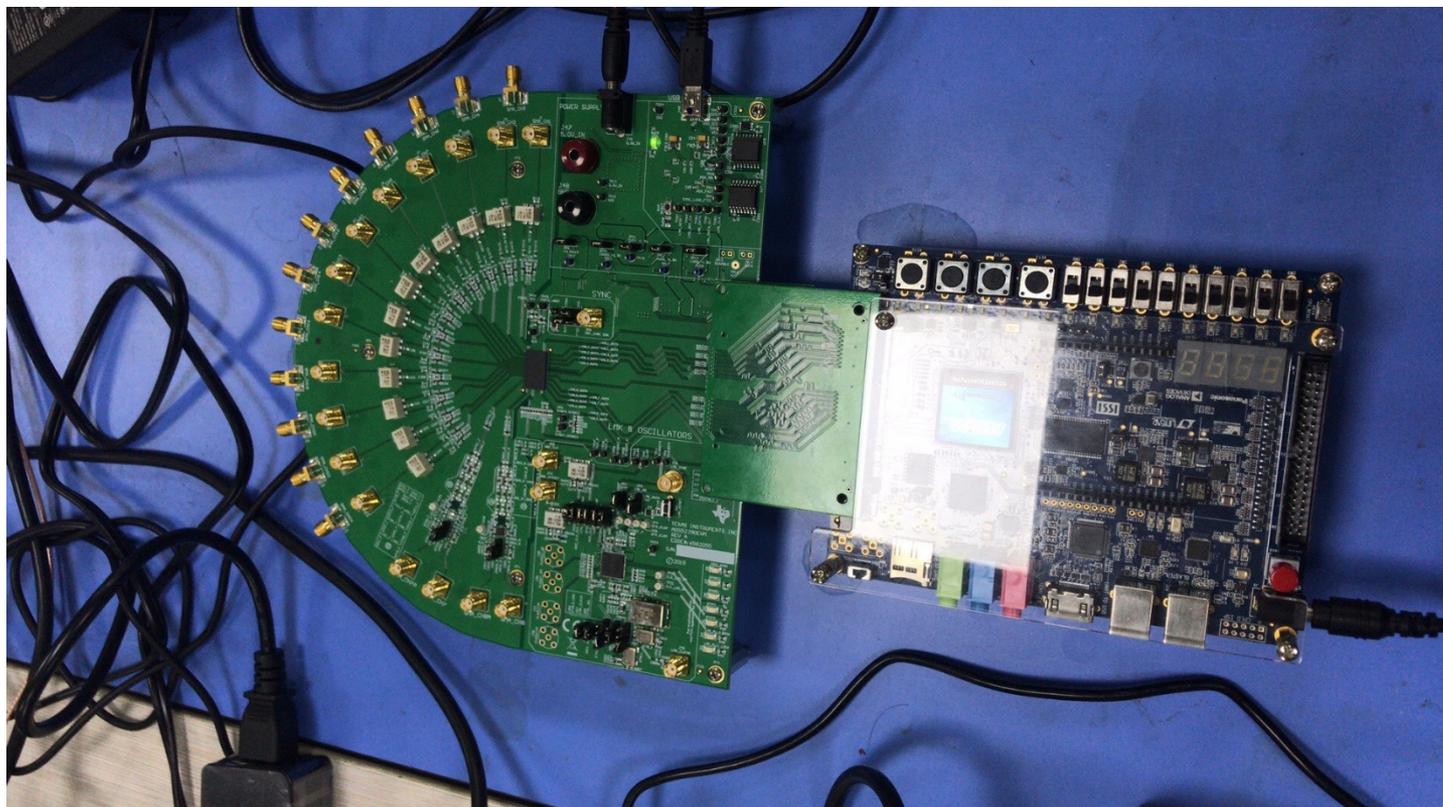
电荷灵敏放大器
极零相消器

准高斯成形电路

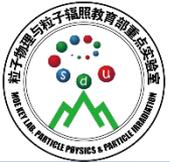
增益调整电路



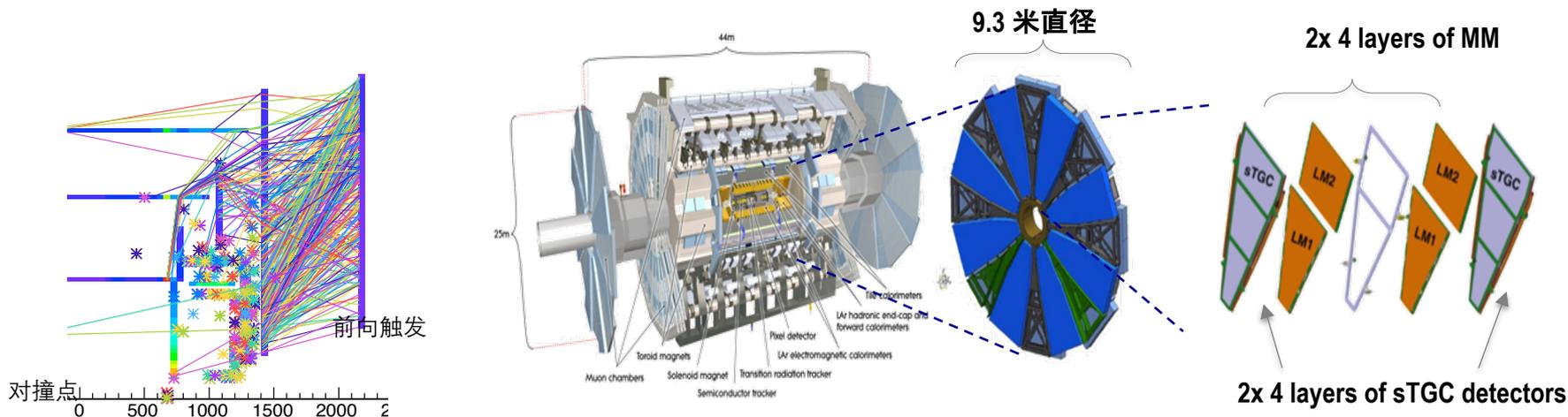
DAQ:ADC+FPGA



16-ch ADC + xGb DDR3 + PCIe



- ATLAS实验muon系统升级前端电子学
- PET读出电子学系统
- 锥束CT和放疗系统中的电子学

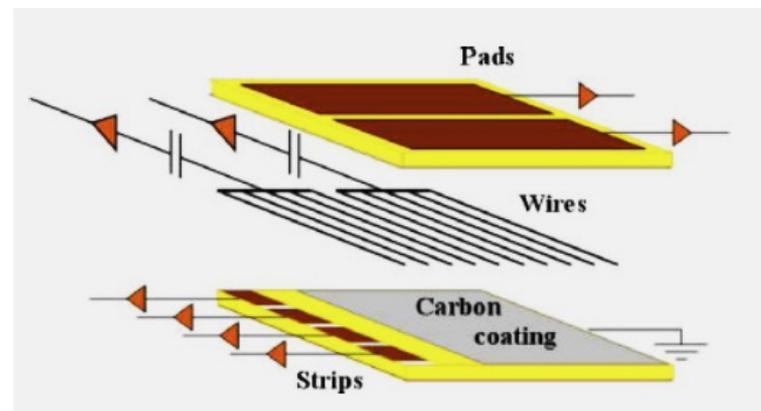
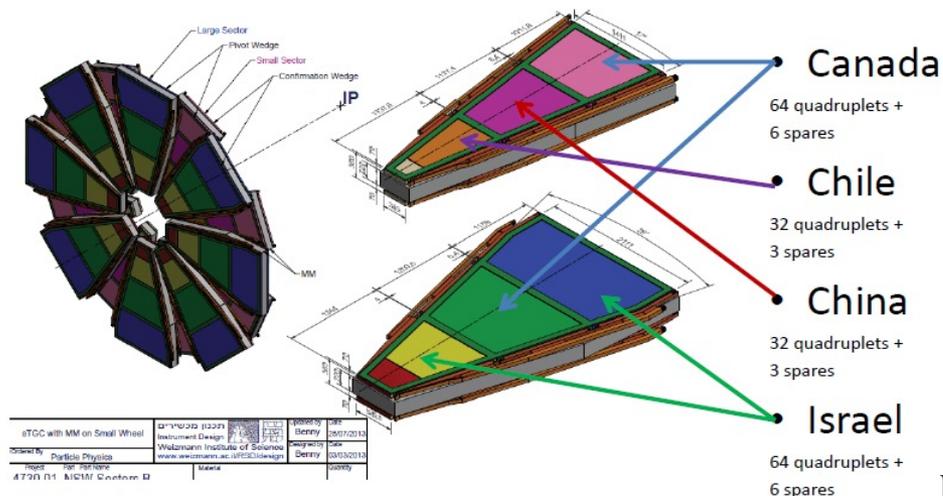


ATLAS端盖量能器中的粒子泄露导致前向区域大量的fake muon触发(左图)，

新的探测器系统为直径9.3米探测器圆盘，包含800个大面积sTGC探测器，共30万个信号通道，信号的处理和数据获取是一项巨大的挑战。

新探测器系统将帮助去除占比95%的fake触发，解决数据采集的带宽限制，是ALIAS实验重新启动后，开展新物理研究的基本保障

带领几个研究生，我负责设计，建造，测试了批量sTGC前端电子学板，为该升级项目建设的重要组成部分。



pad (ϕ , L0 trigger) \oplus strip(R, L1trigger)

➤ 山东大学SDU :

+ 研发经验: 现行TGC探测器建造

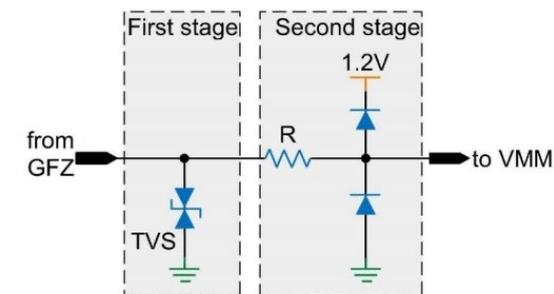
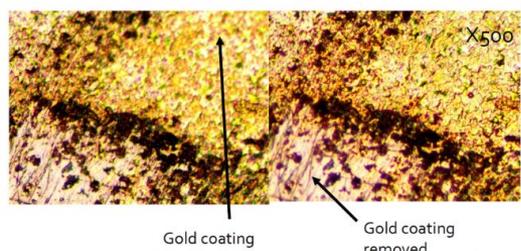
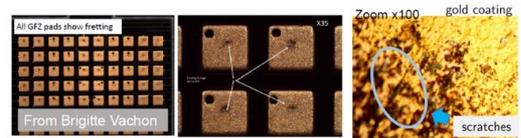
+ 升级计划: 1/6 sTGC探测器建造

➤ 中科大USTC :

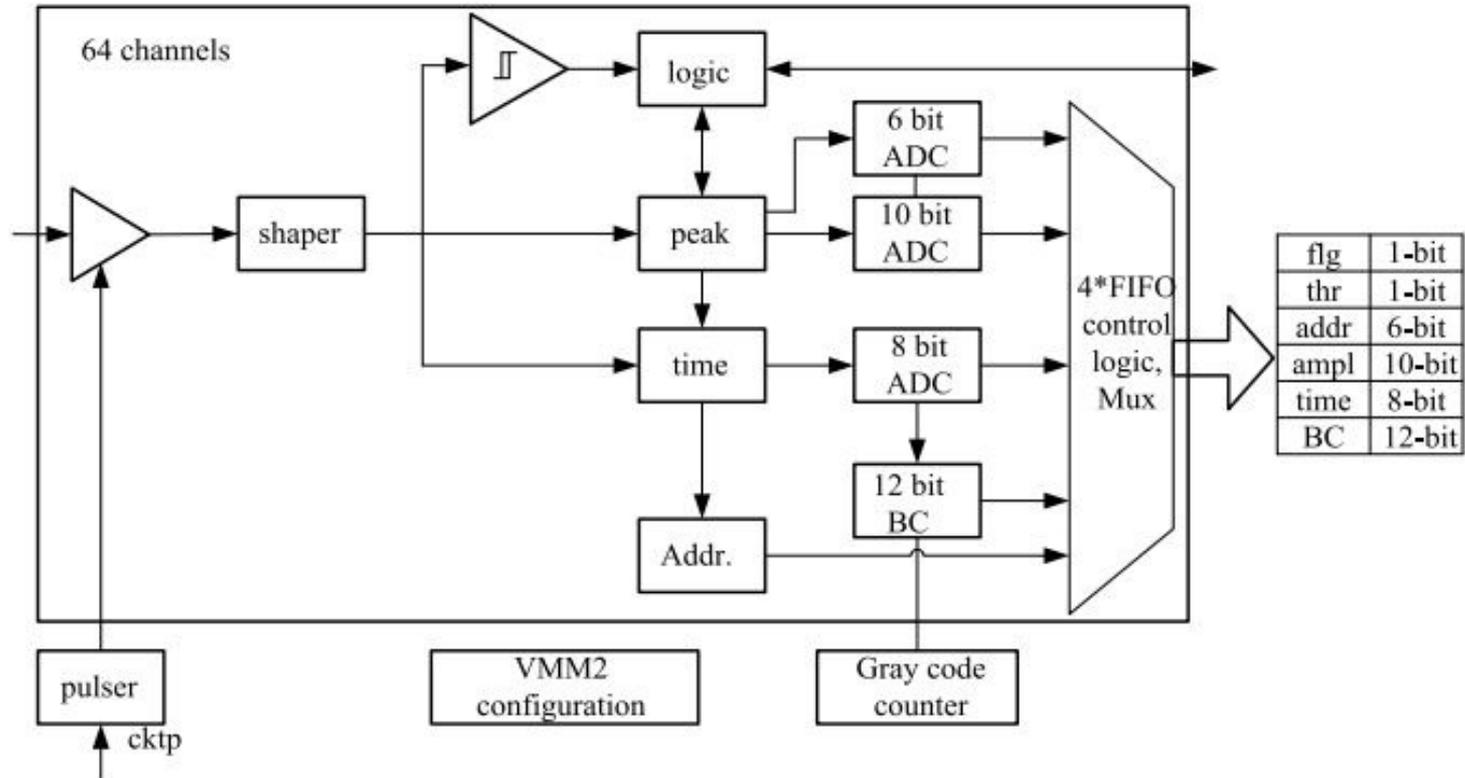
+ 研发经验 : 现行TGC电子学测试系统

+ 升级计划 : 100% sTGC前端电子学研制

● 电子学通道 : ~ # 30万通道



- **空间限制：**
 - 探测器替换空间狭窄，前端电子学板尺寸受限，设计难度加大。
- **抗辐照：**
 - ALTAS前向区辐射强度高，所有器件必须抗辐照
- **信号通道密度大：**
 - 例如27x6厘米的区域内需处理512个信号通道，每个通道包含完整的模拟信号处理，数字化，以及数据读出，信号道之间的干扰是重要的研究课题
- **信号干扰：**
 - 除了以上信号密度大带来的串扰，低压模块，模拟和数字部分的互相干扰，探测器地干扰都是重要的干扰源，为设计带来挑战。
- **探测器信号差异：**
 - sTGC探测器面积大，信号道形状，通道长度等都不相同，信号差异较大，为信号的处理带来难度
- **高压保护：**
 - sTGC工作在3000V高压下，瞬间放电对前端电子学损坏极大，每一路信号道需要单独的过压保护。



单通道读出电路原理图



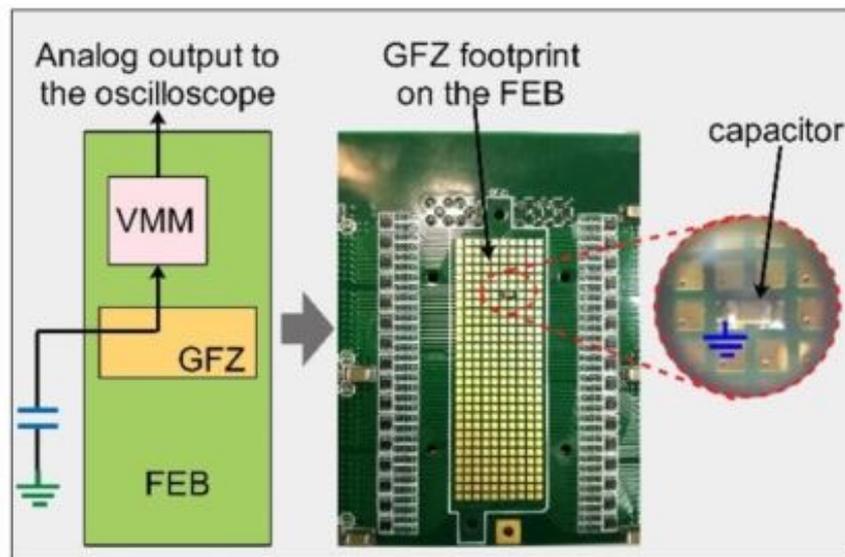
**高度集成 : 128 channels for pad trigger;
+ 尺寸 16 × 6 cm 128 channels for wire readout**



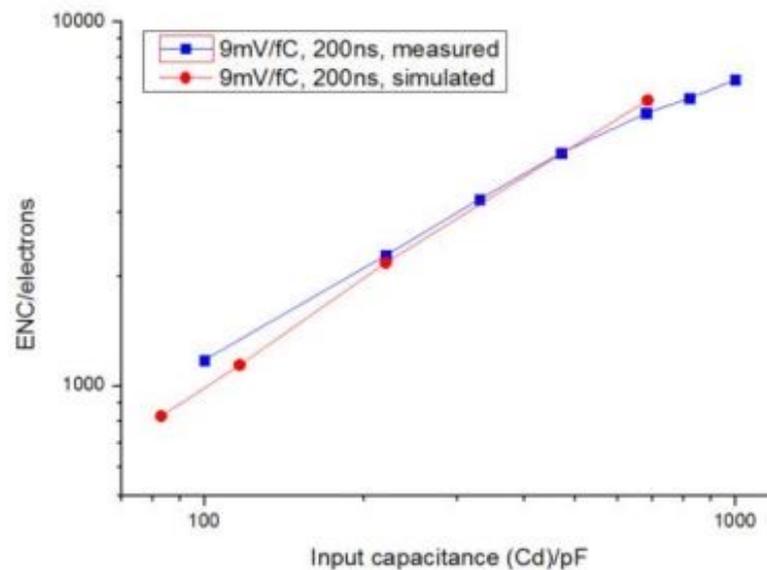
**高度集成 : 512 channels for strip readout
+ 尺寸 27 × 6 cm**



256通道TGC仿真信号源的研制

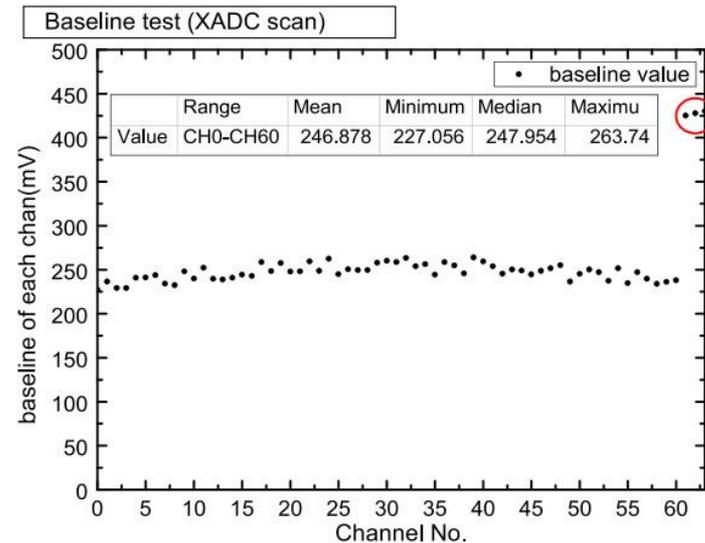
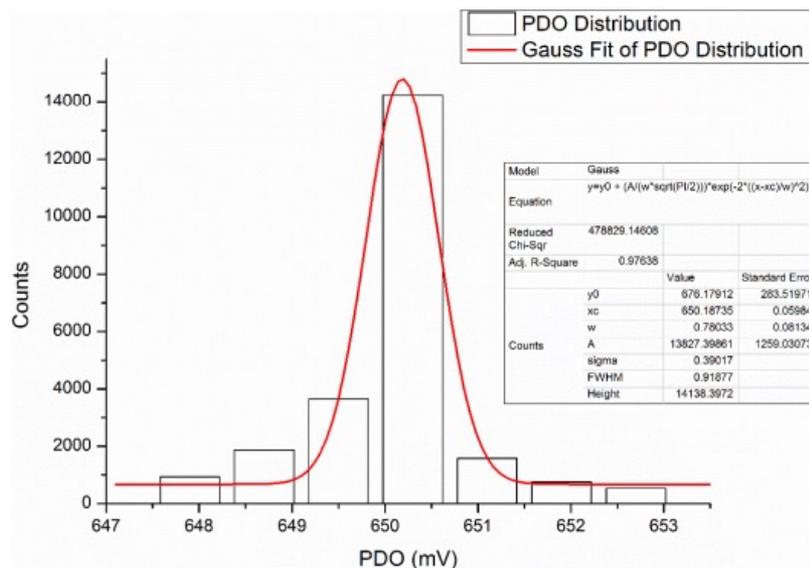


(a)



(b)

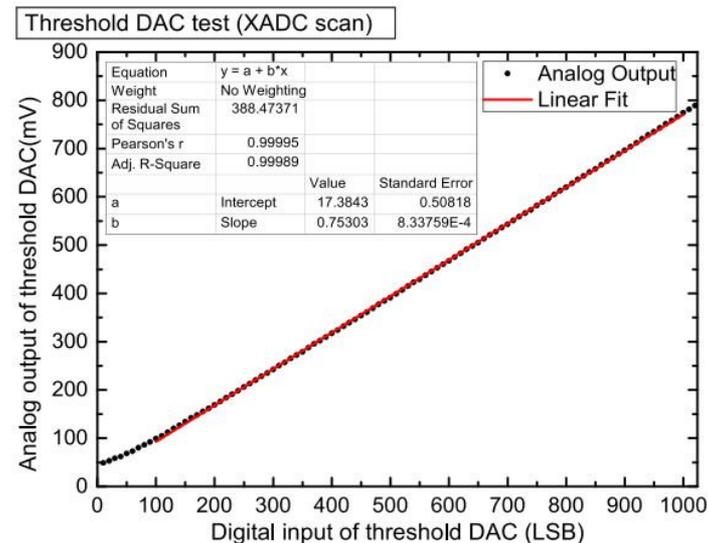
使用电容器模拟探测器电容，将测得的噪声与单通道的仿真值对比，符合还是很好的，说明我们已经把板级噪声影响降到理论值附近了

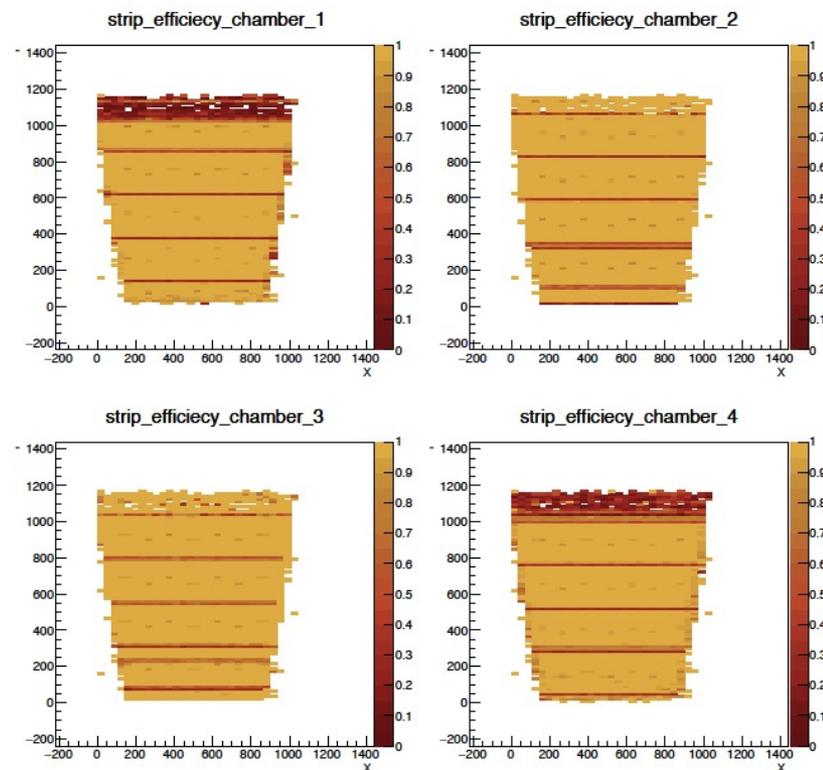
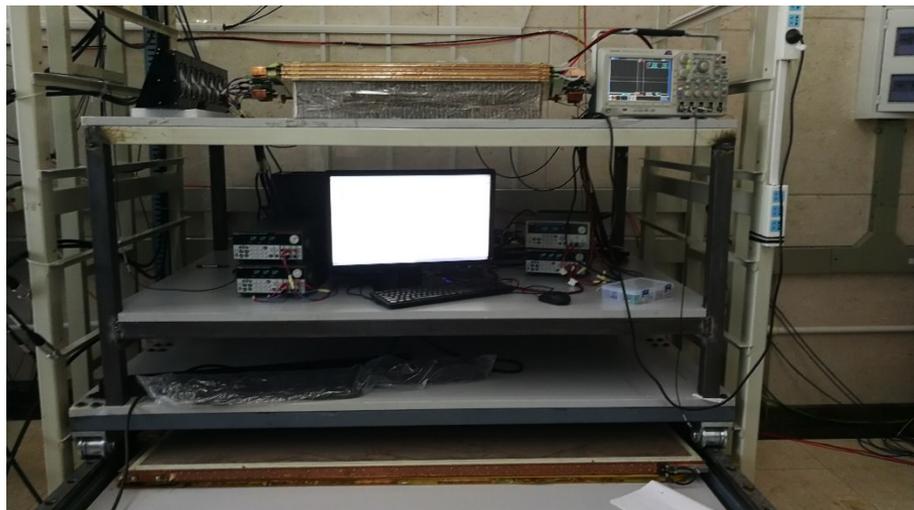


我们设计了通用的高度电子学板测试系统，测试系统模拟高密度的sTGC探测器的输出信号，并将处理后的数字信号读出

右图（上）为其中64个信号道（来自同一个芯片）的基值分布，具有很好的一致性，为大批量数据的采集提供了基础

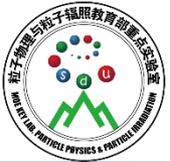
右图（下）为一个信号道输入和输出的线性关系图，为高精度记录探测器的信号强度的保障





我们研发了针对sTGC module, 1740个通道的宇宙线测试系统, 并和山大所建造的sTGC探测器进行了联合宇宙线测试

测试系统给出一个探测器module中四个探测器的效率扫描图, 其中清晰可见探测器内部的支撑条结构, 探测器的位置分辨率为~170微米, 达到了设计要求(<300微米)



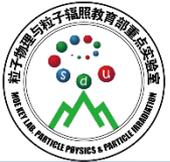
ASIC :

- ✓ 优势明显 ;
- ✓ 缺点也明显 : 周期长, 在ATLAS升级中的VMM芯片

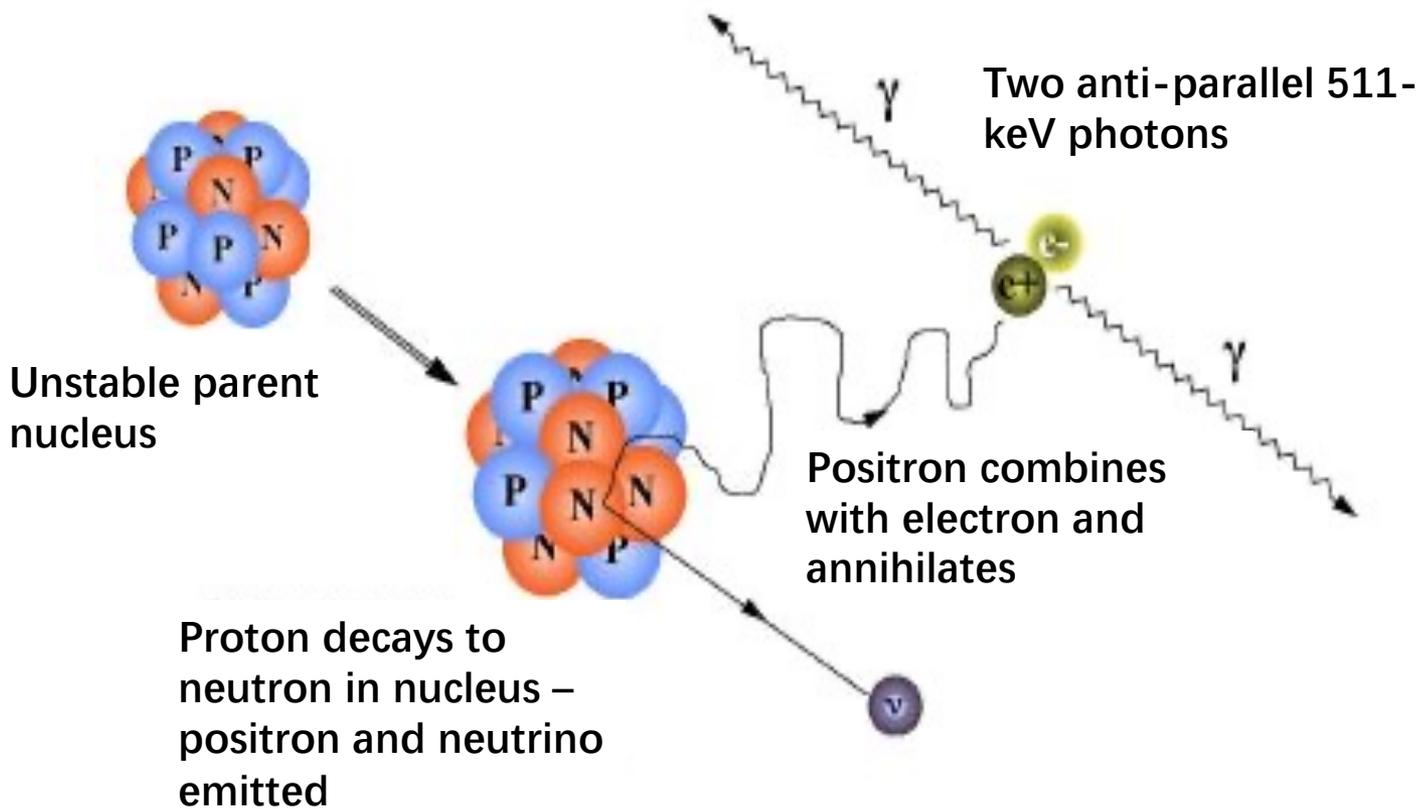
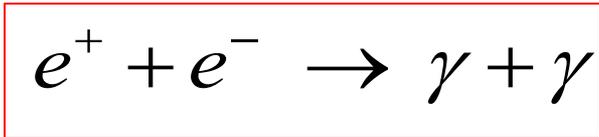
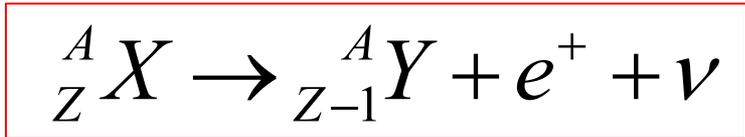
VMM1  VMM2  VMM3a

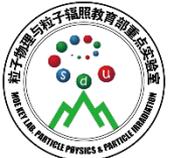
在实验室里, 无需抗辐照, 有没有折中的方法, 快速设计出多通道的前端读出电子学系统?

PET系统读出电子学

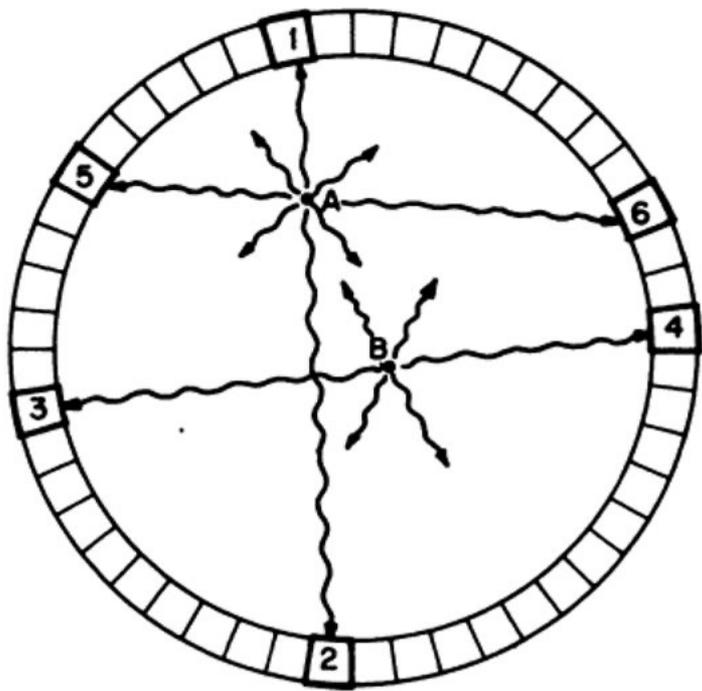


PET物理原理



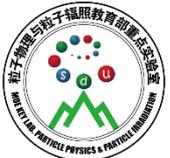


PET物理原理

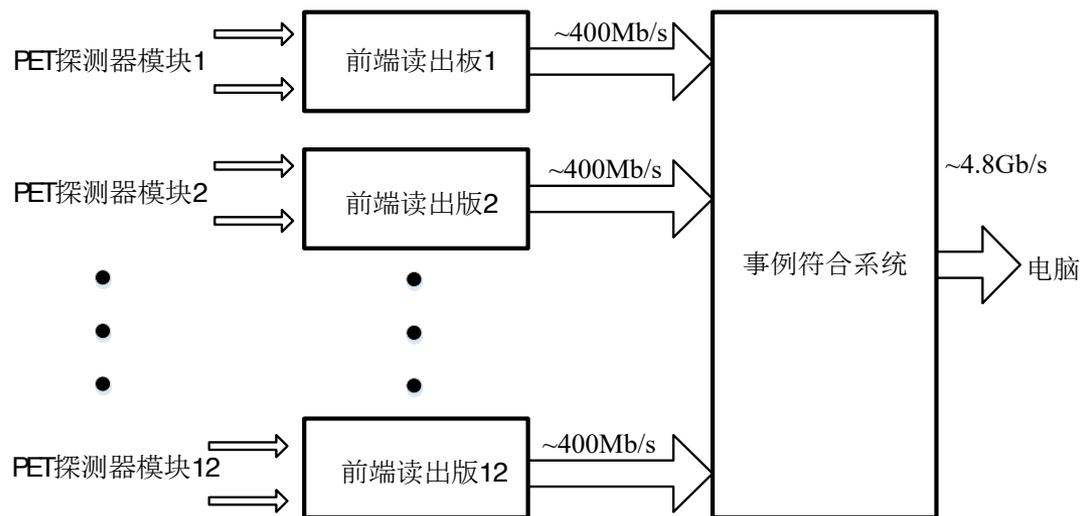
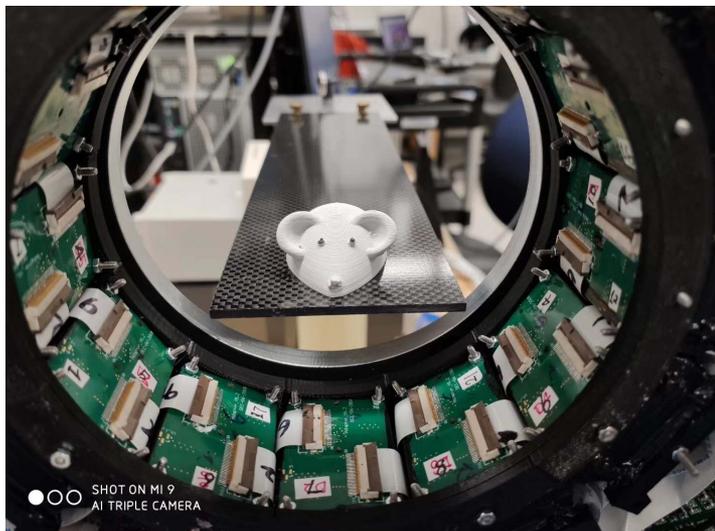


放射性示踪剂： ^{18}F -FDG (110min)

商用PET系统

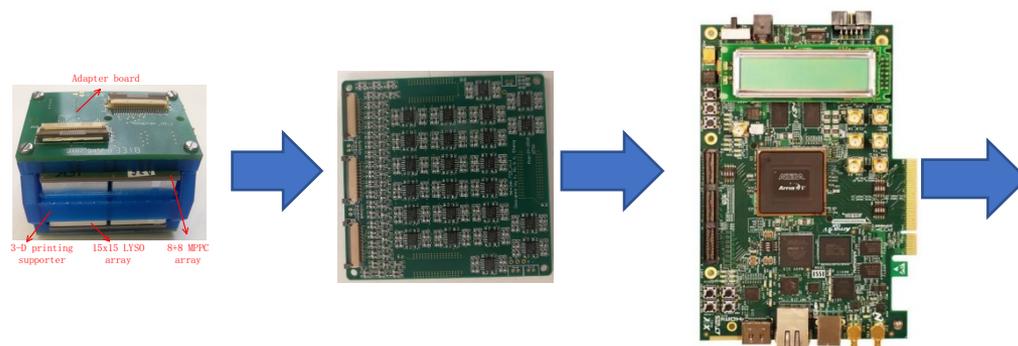


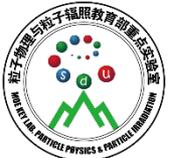
读出电子学系统



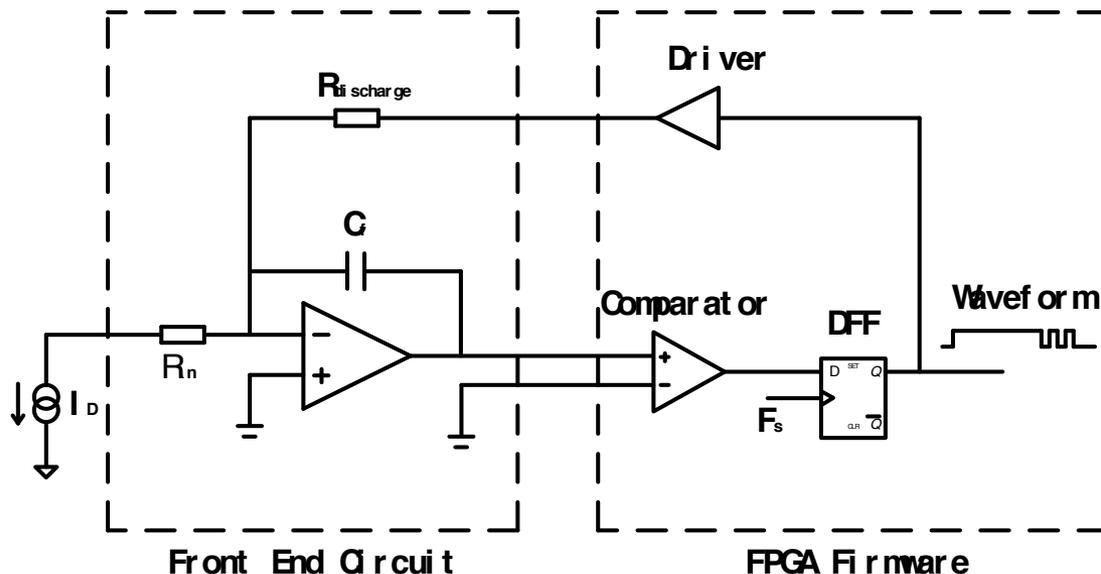
PET电子学读出系统:

- (1) 高密度多通道读出电路 (>1000通道);
- (2) 数据同步技术, 高精度时钟分发网络 (时钟晃动 < 60 ps);
- (3) 高速输出传输技术 (>10Gb/s)。





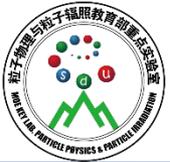
基于离散器件的放电电路



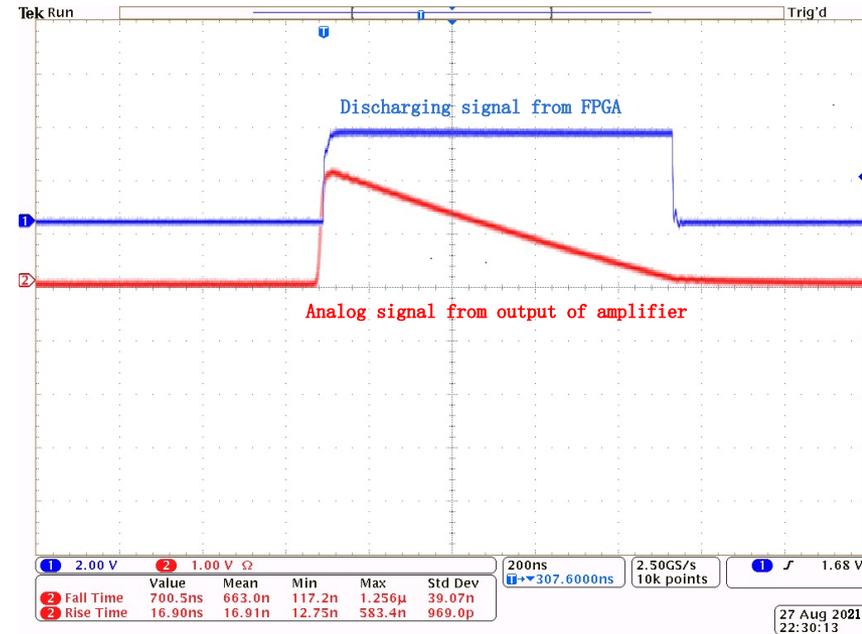
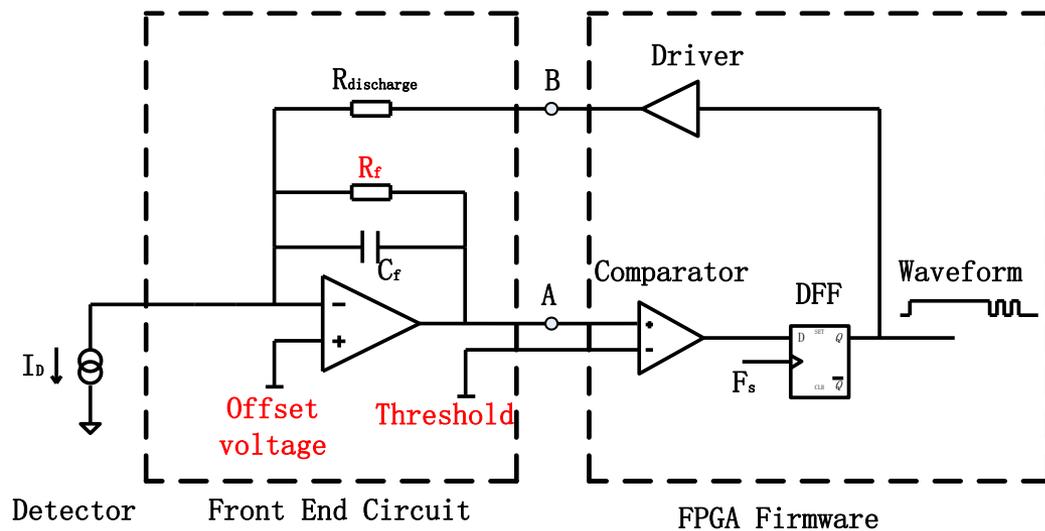
模拟部分：电容电阻+放大器；

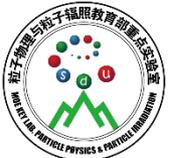
数字部分：LVDS等效为比较器，IO电压与外部泄放电阻形成恒流源。

$$Q = \Delta Q \cdot N = (I_{\text{dis}} \cdot T_{\text{clk}}) \cdot N = V_{\text{IO}} / R_{\text{dis}} \cdot T_{\text{clk}} \cdot N$$

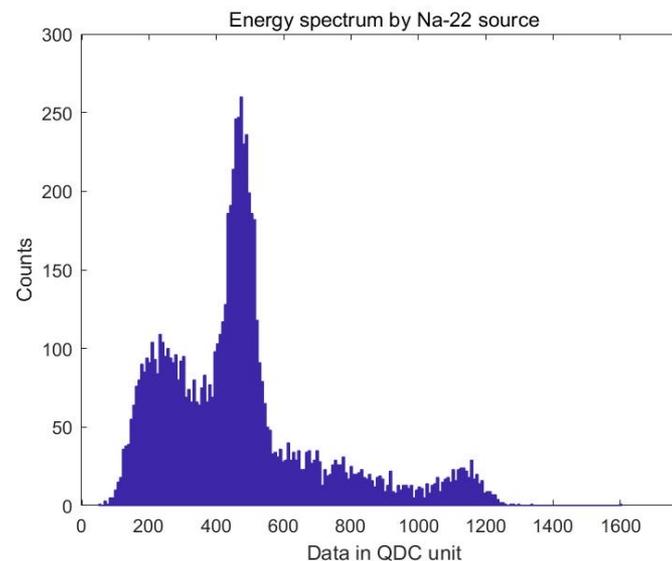
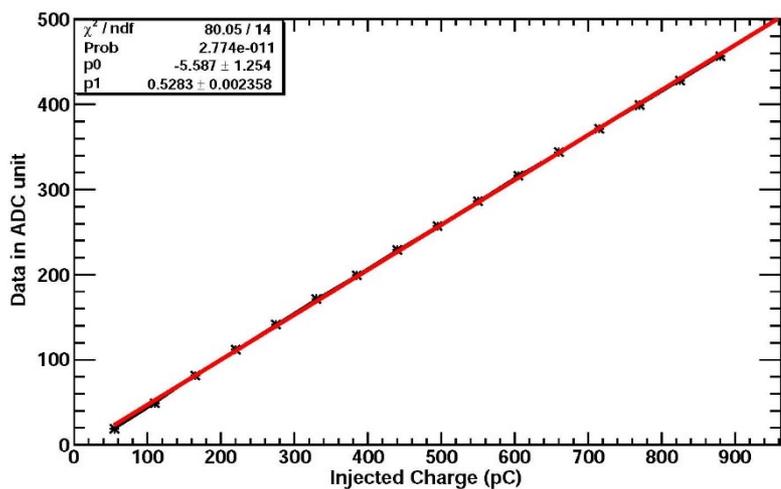
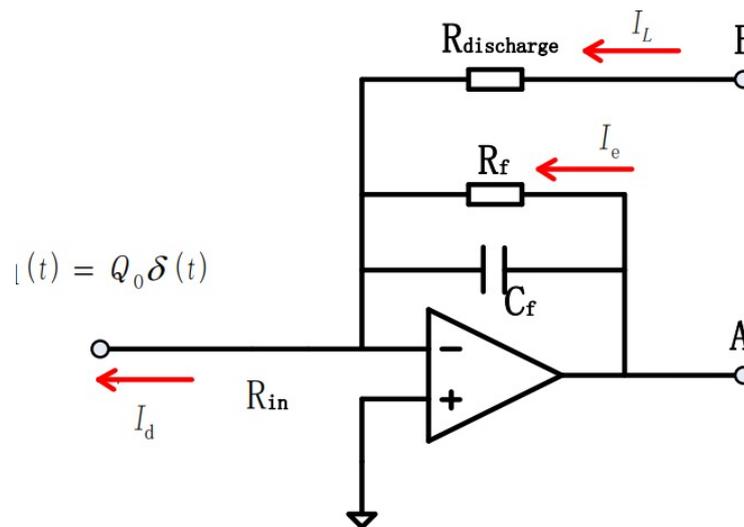
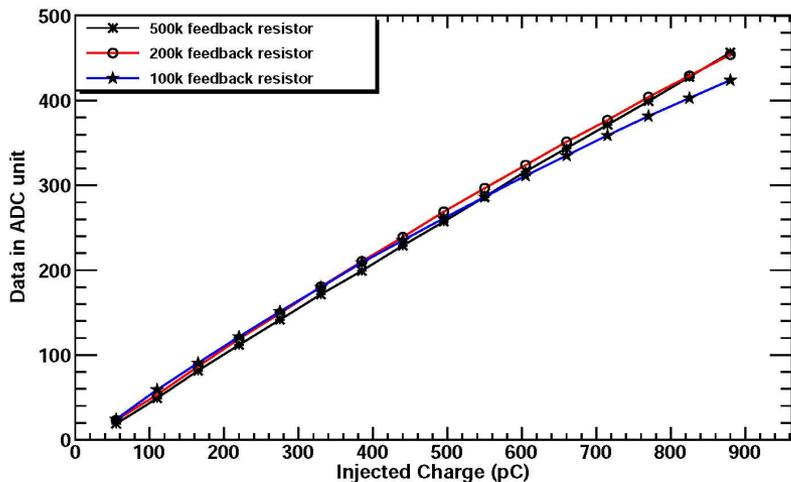


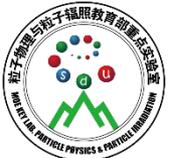
放电电路-改版1





放电电路-改版1



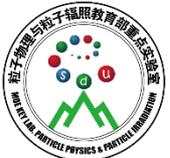


优点：

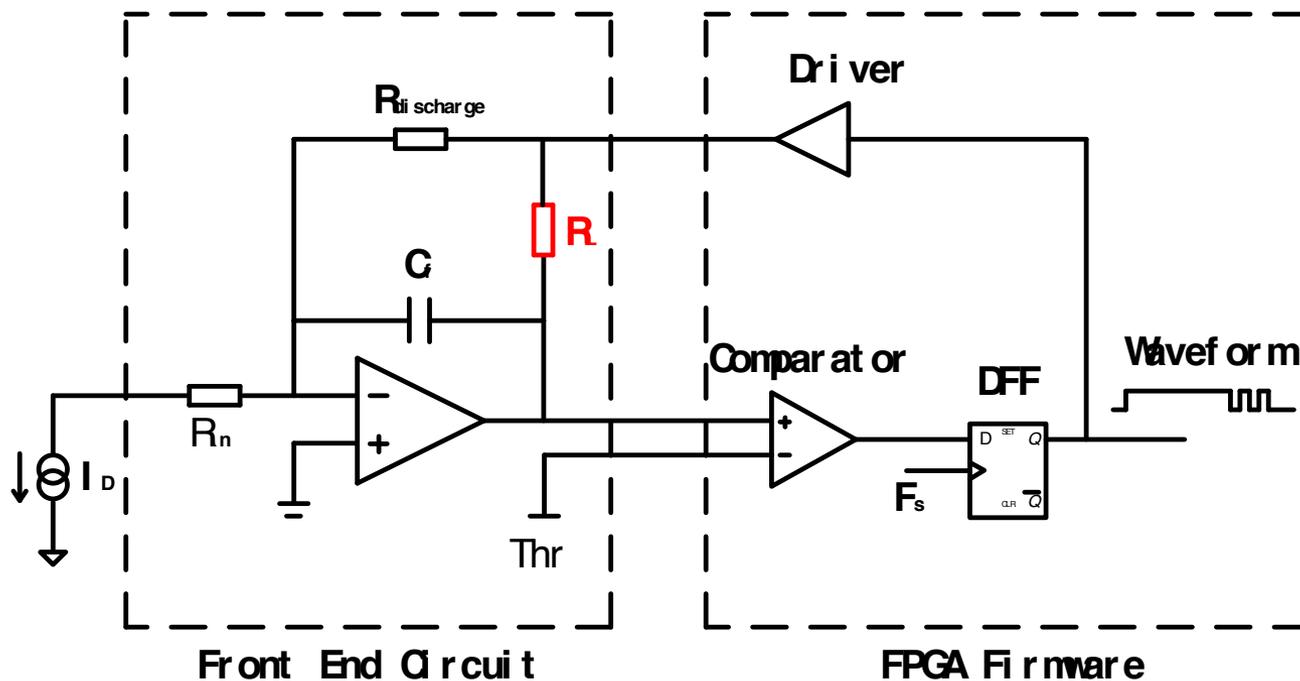
- ✓ 放大器有稳定的输出基线；
- ✓ 阈值可调节，便于剔除电子学噪声信号；

缺点：

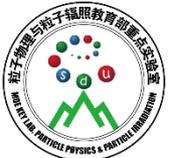
- ✓ 引入了指数放电，需要大的反馈电阻；
- ✓ 在探测器有大暗噪声的情况下，如半导体探测器，输出基线涨落较大；



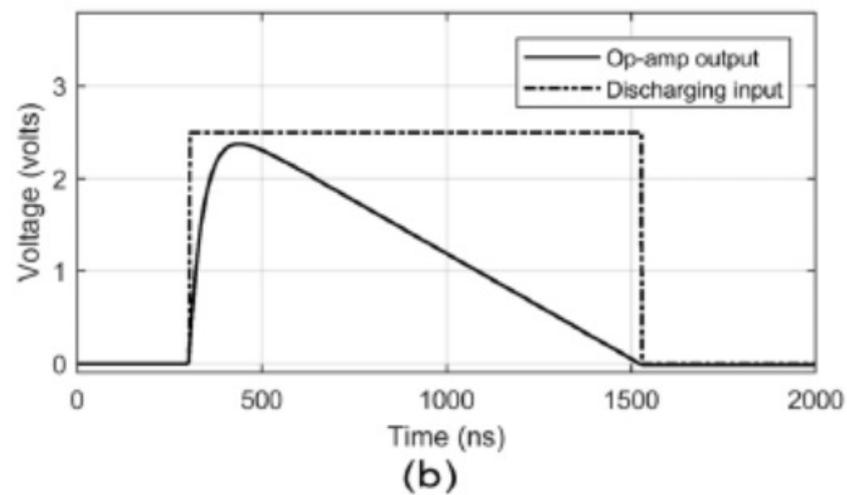
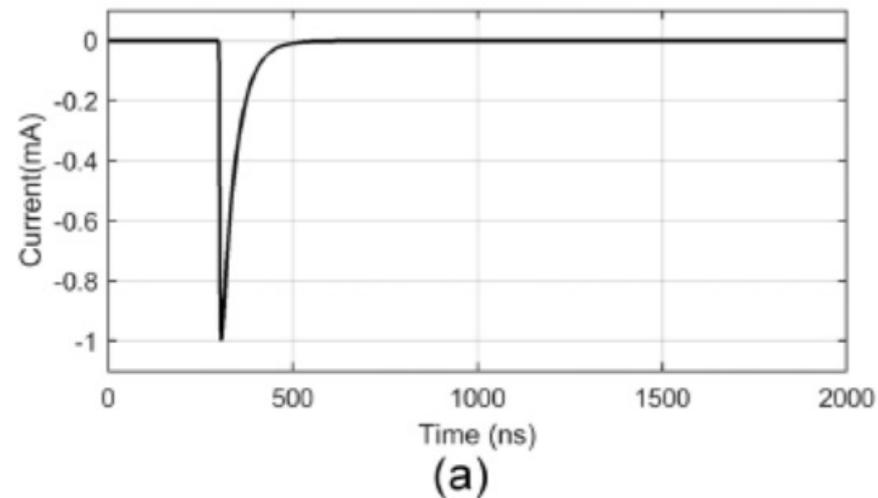
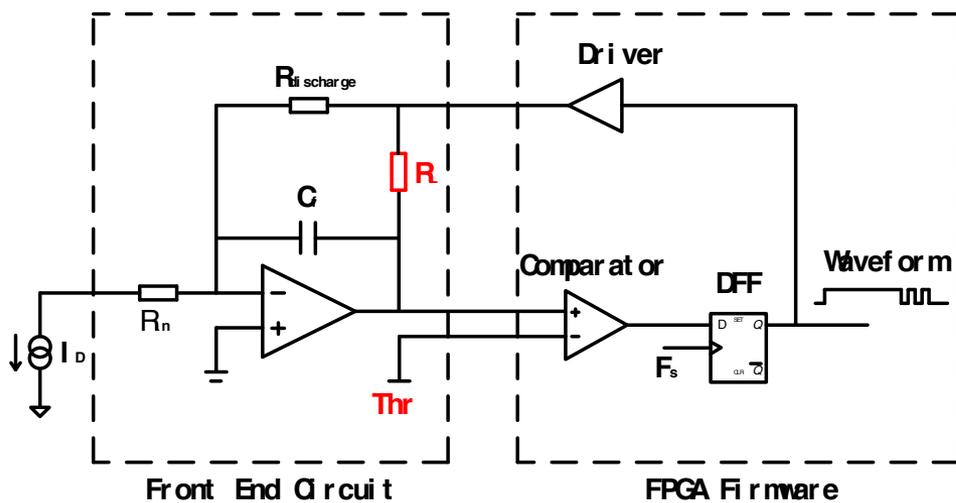
放电电路-改版2

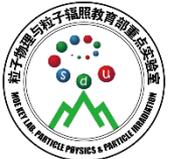


没信号：IO输出高阻 'Z'
态；
有信号：IO输出放电 '1'
态

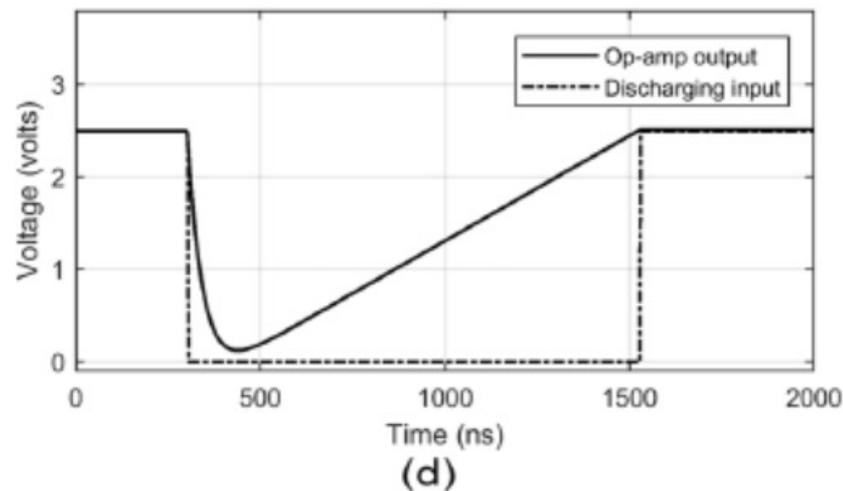
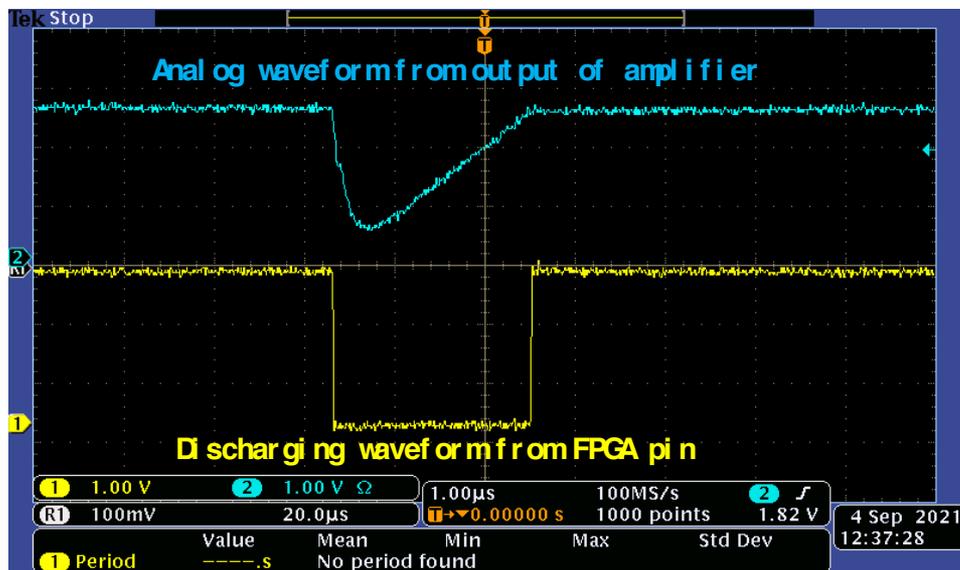
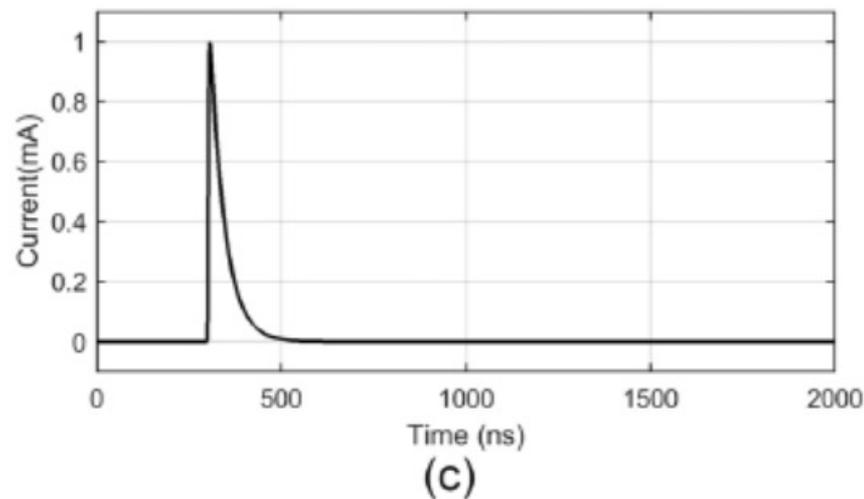
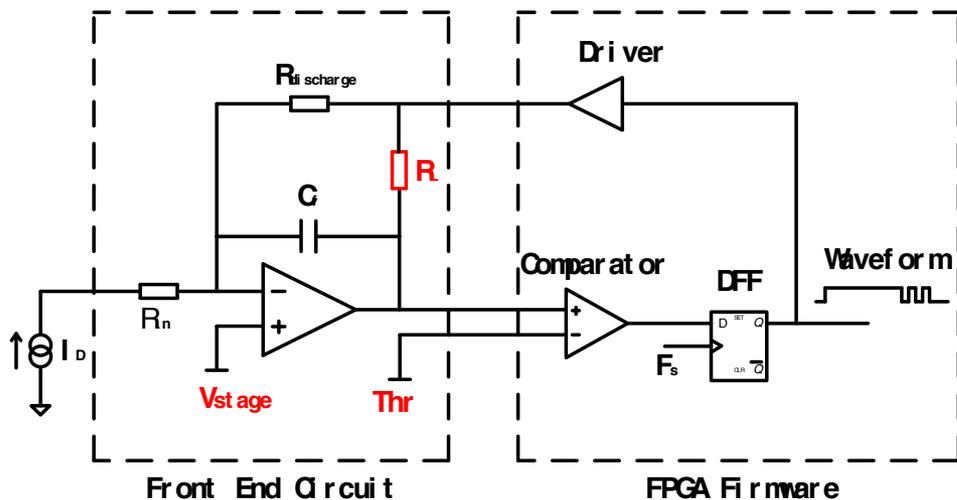


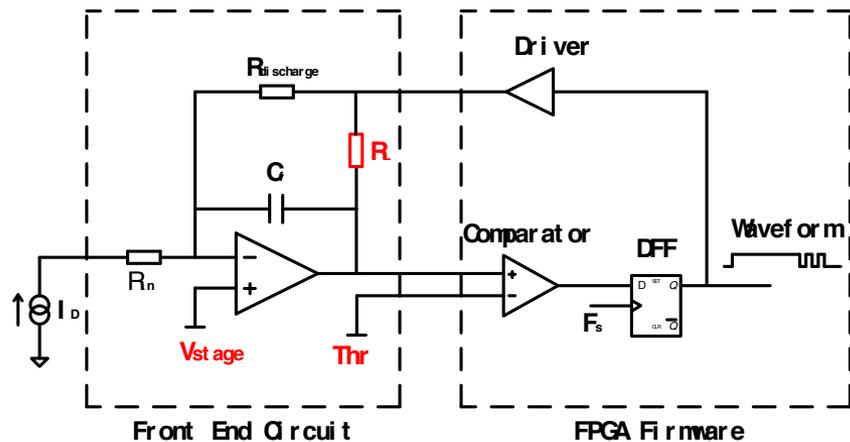
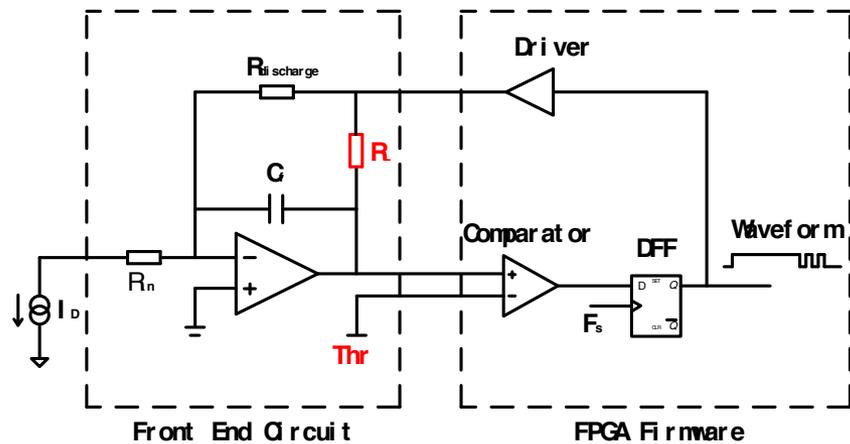
放电电路-改版2





放电电路-改版2





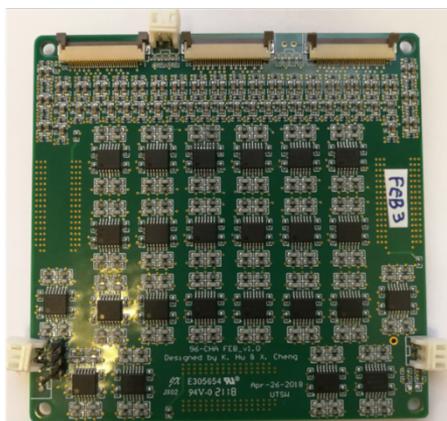
(a)



(b)



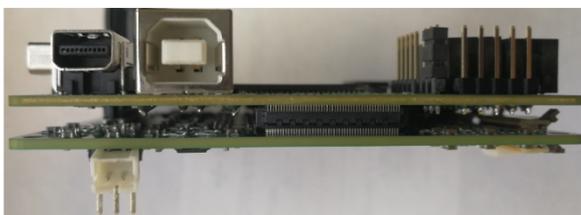
(c)



(a)

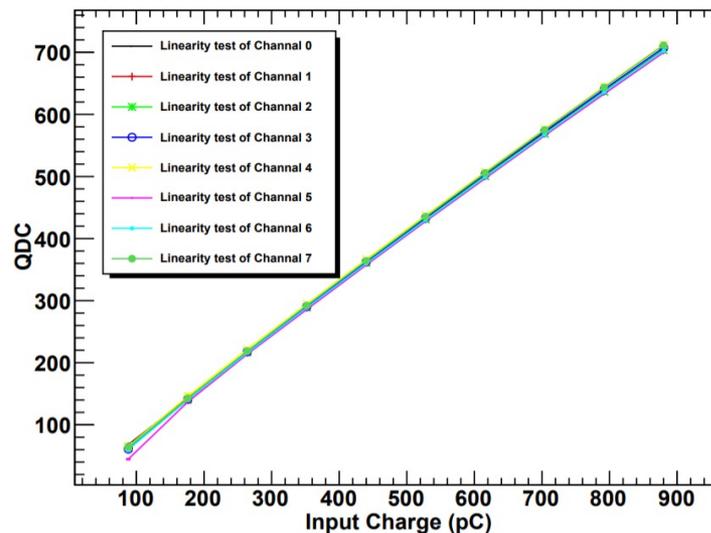
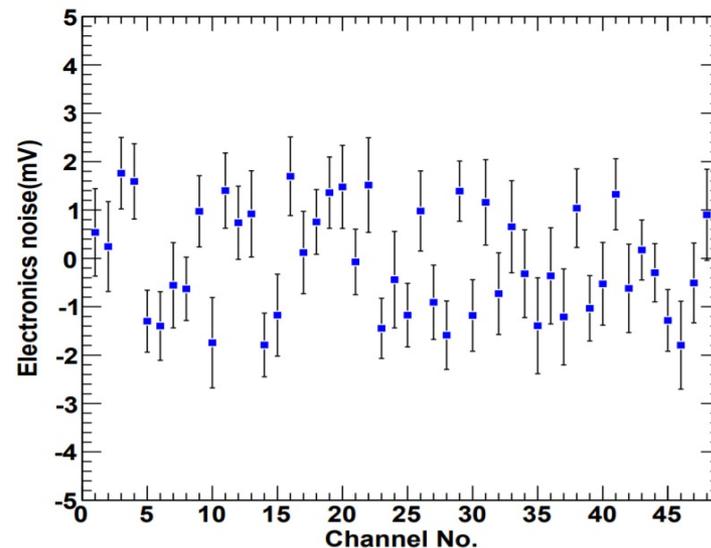


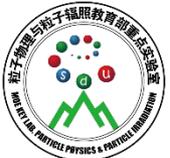
(b)



(c)

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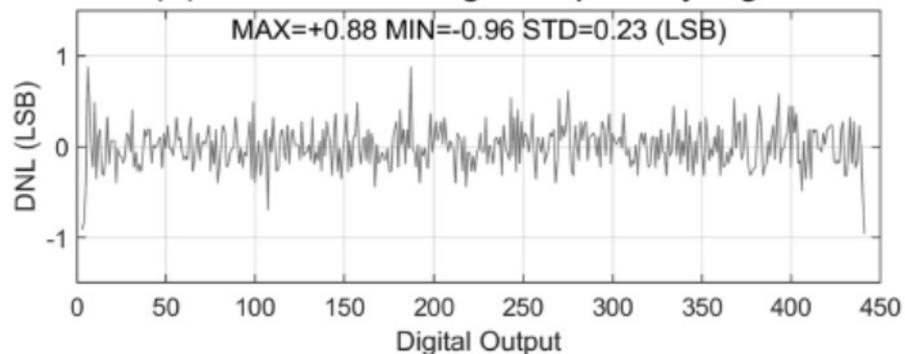




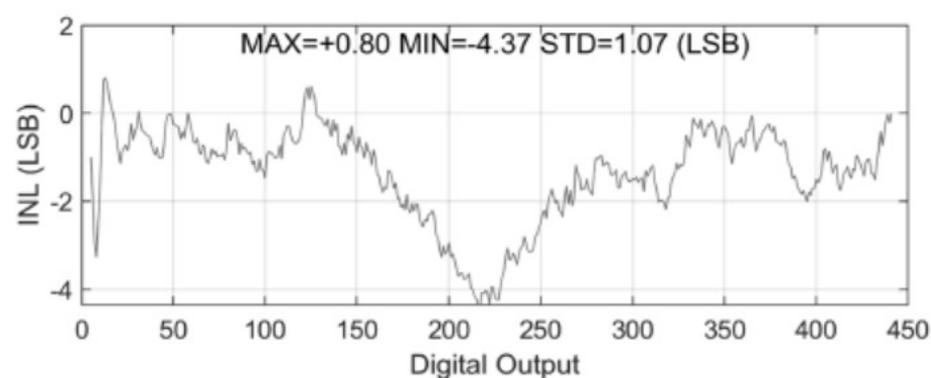
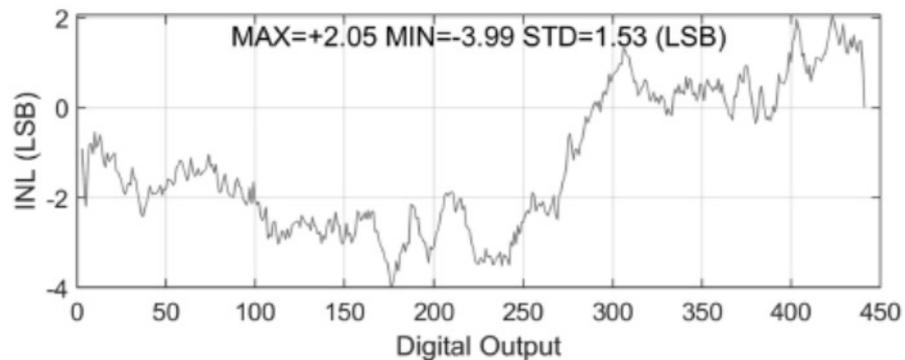
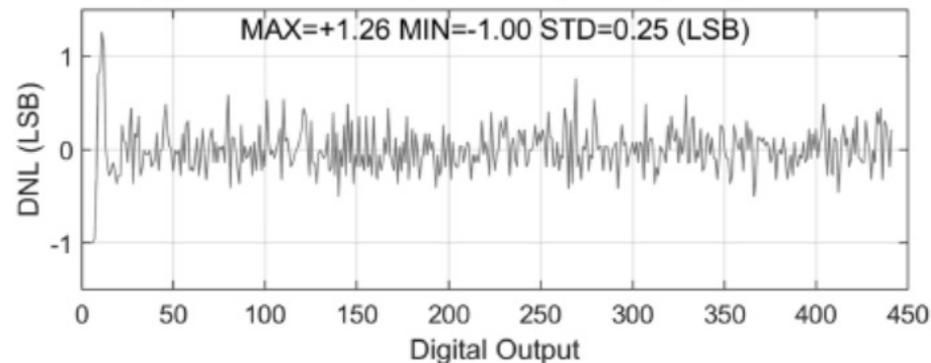
放电电路-改版2

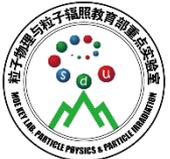


(a) Result from negative polarity signals

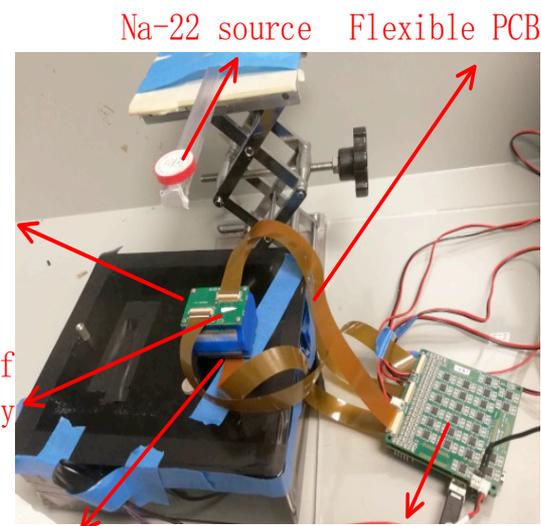
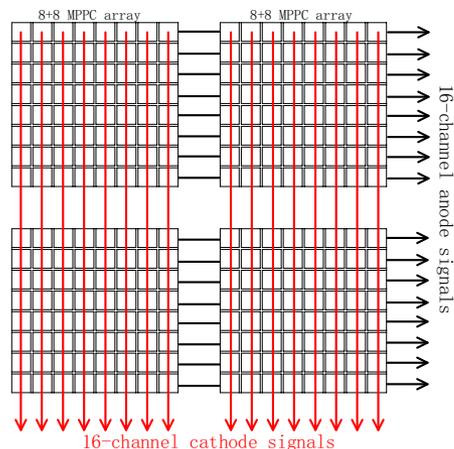
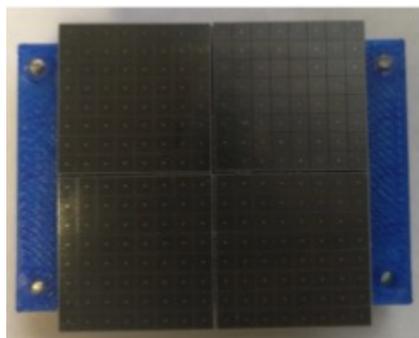


(b) Result from positive polarity signals





SiPM探测器应用

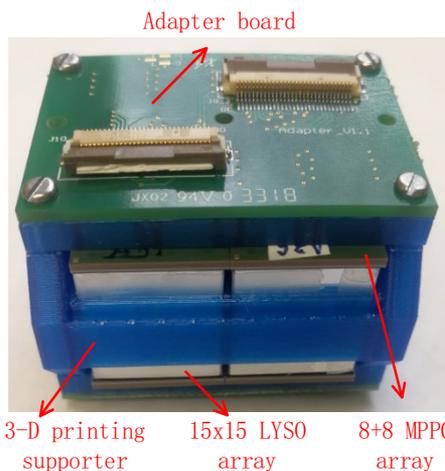
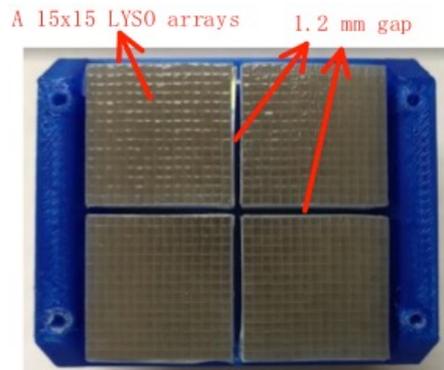


A PET detector module

One end of LYSO array (A side)

Other end of LYSO array (B side)

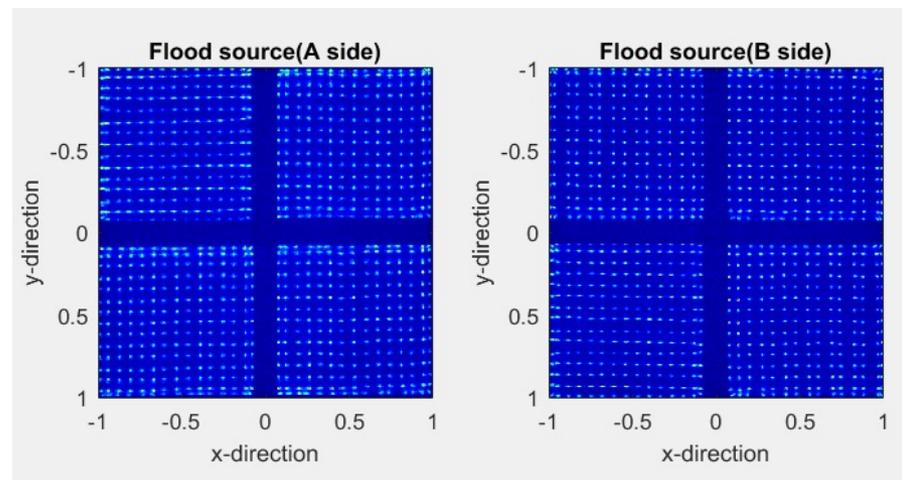
96-ch readout electronics

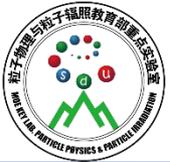


3-D printing supporter

15x15 LYSO array

8x8 MPPC array

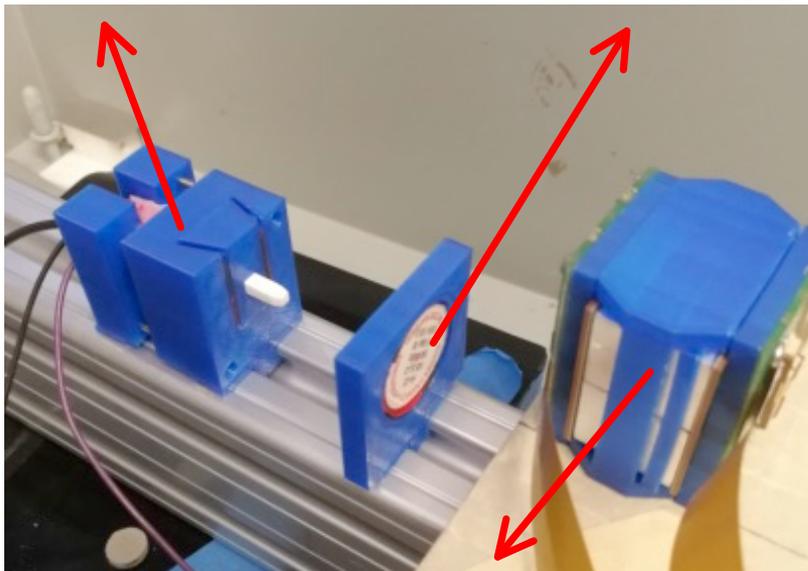




时间性能

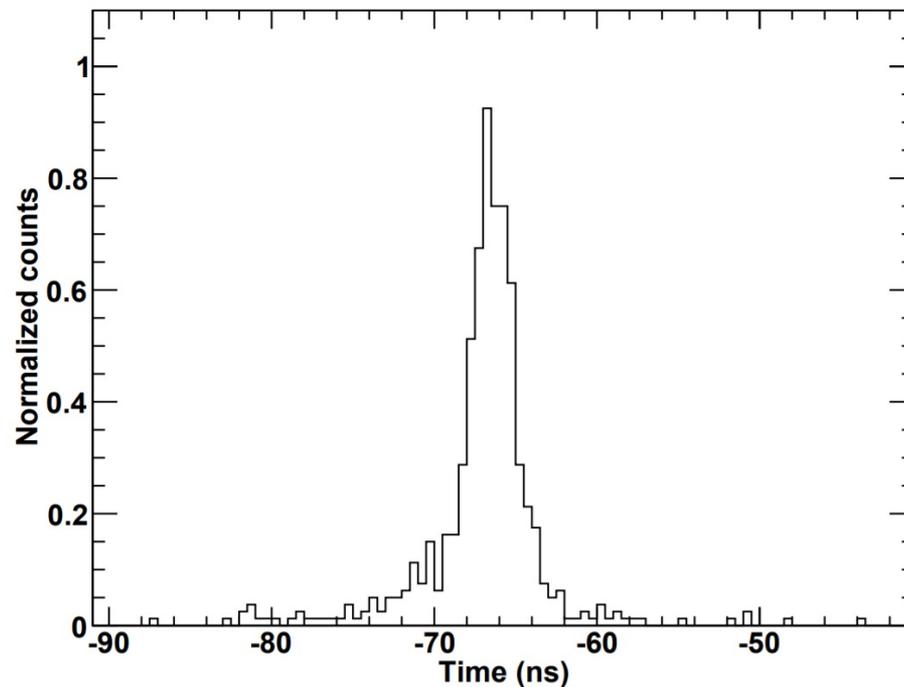


PMT Na-22 source

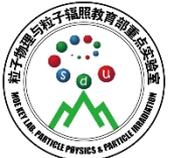


A PET detector module

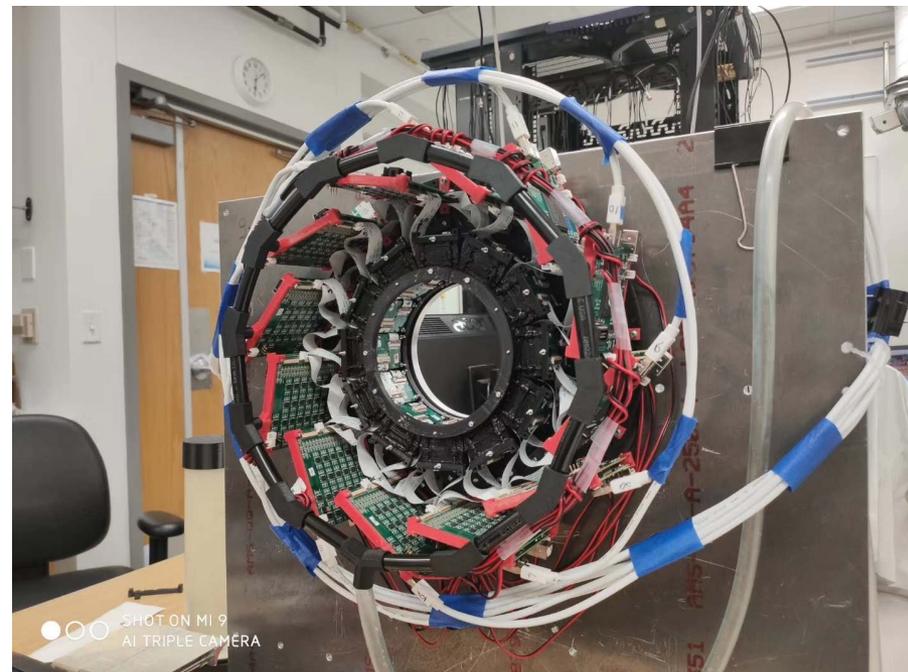
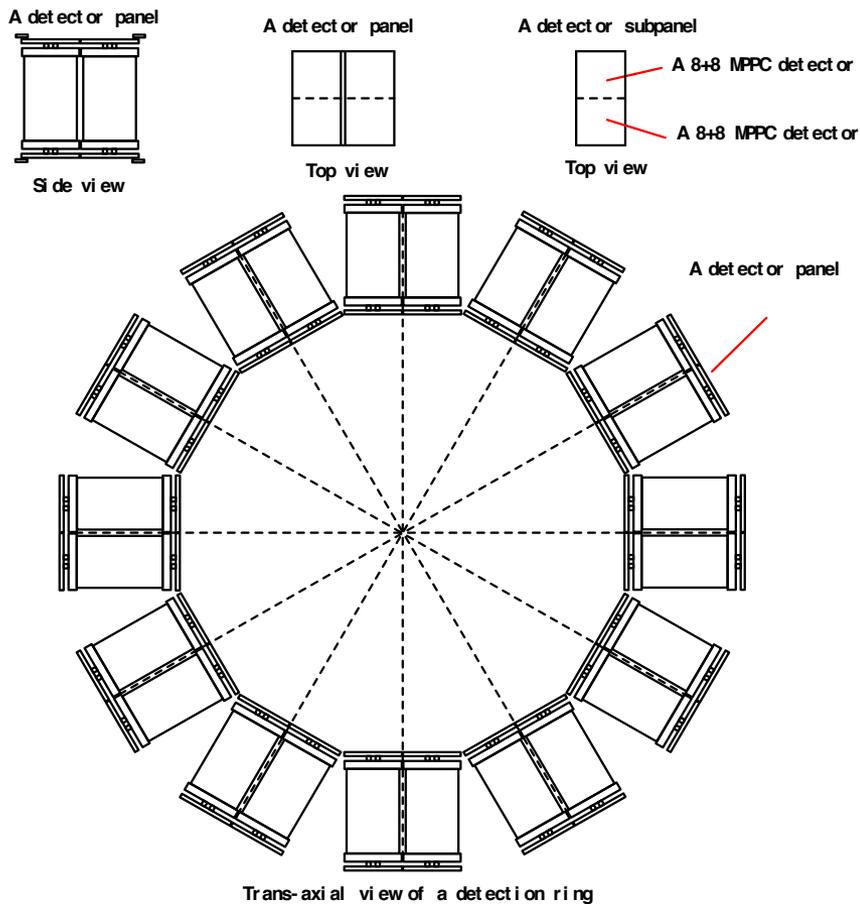
PET探测器符合测试系统。



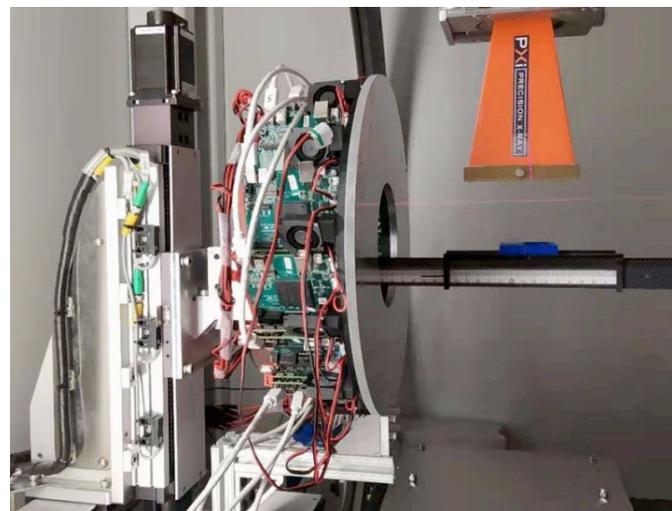
符合时间谱。



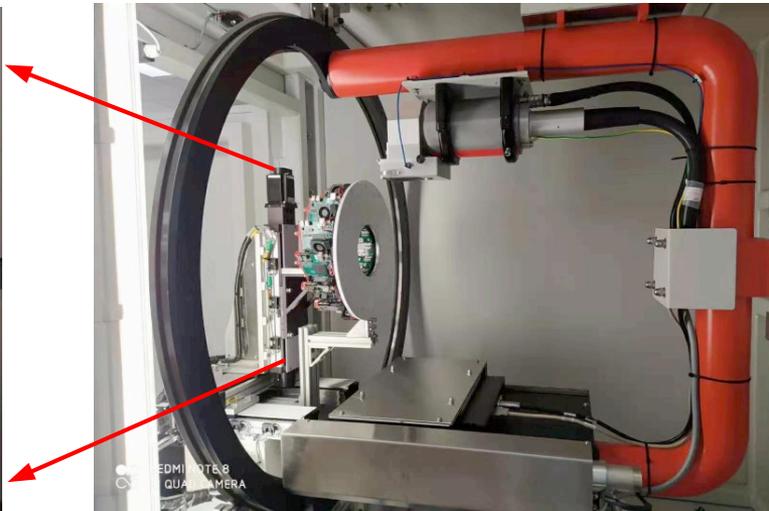
Small animal PET Scanner



- 小动物PET (1) 视场 (FOV) : 70 mm;
- (2) 空间分辨率: <1 mm;
- (3) 时间分辨率: <3 ns

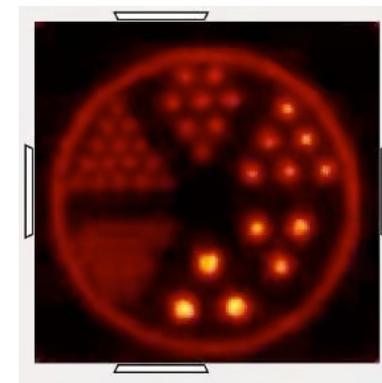


PET Ring



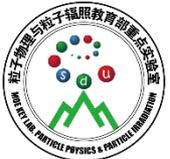
PET/CT/RT

(a)



PMMA Phantom

(b)



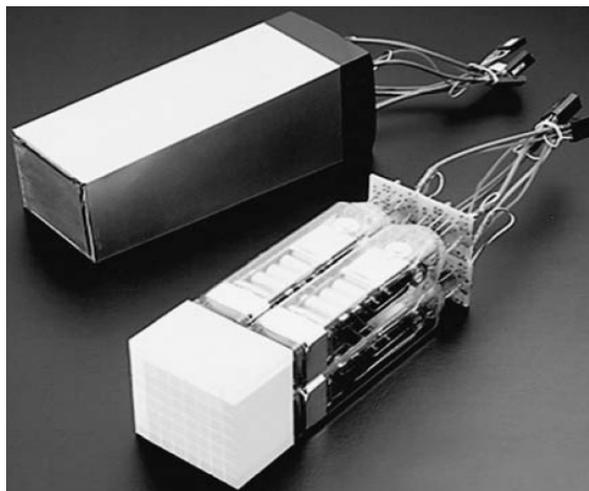
PET的研究方向



PET探测器:

闪烁体+PMT;
闪烁体+SiPM;
半导体:

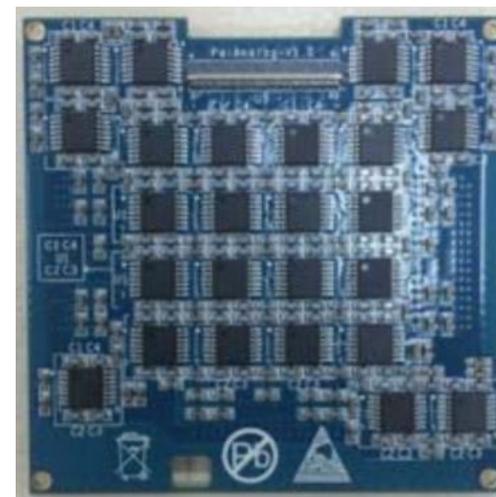
○ ○ ○



PET读出电子学:

多通道;
小型化;
ASIC;

○ ○ ○

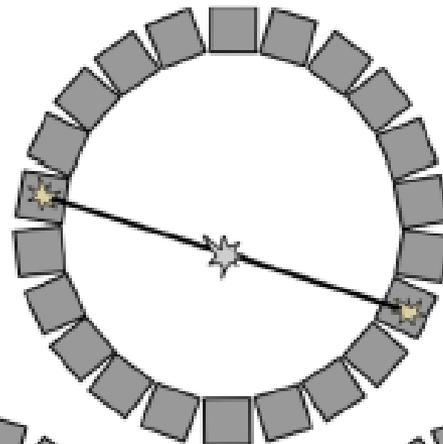


TOF PET:

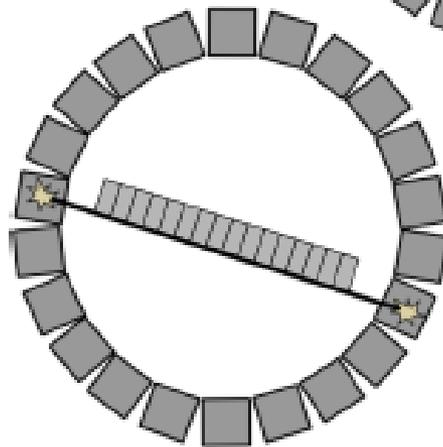
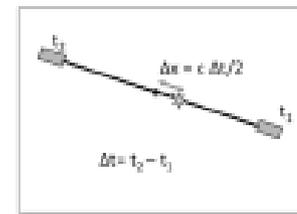
Time difference
of annihilation = Δx (2 × speed of light)
photon detections

300 picoseconds \Rightarrow 4.5 cm FWHM

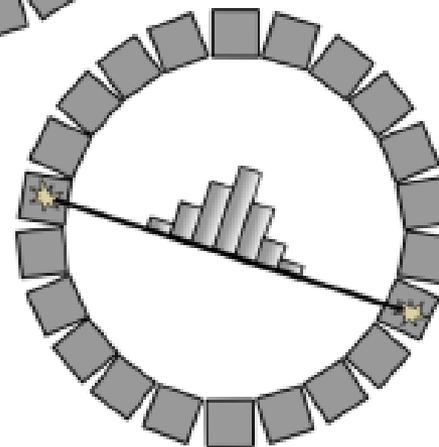
Real annihilation event



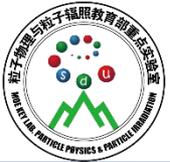
TOF principle



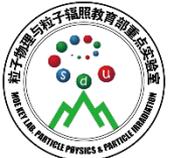
Conventional PET



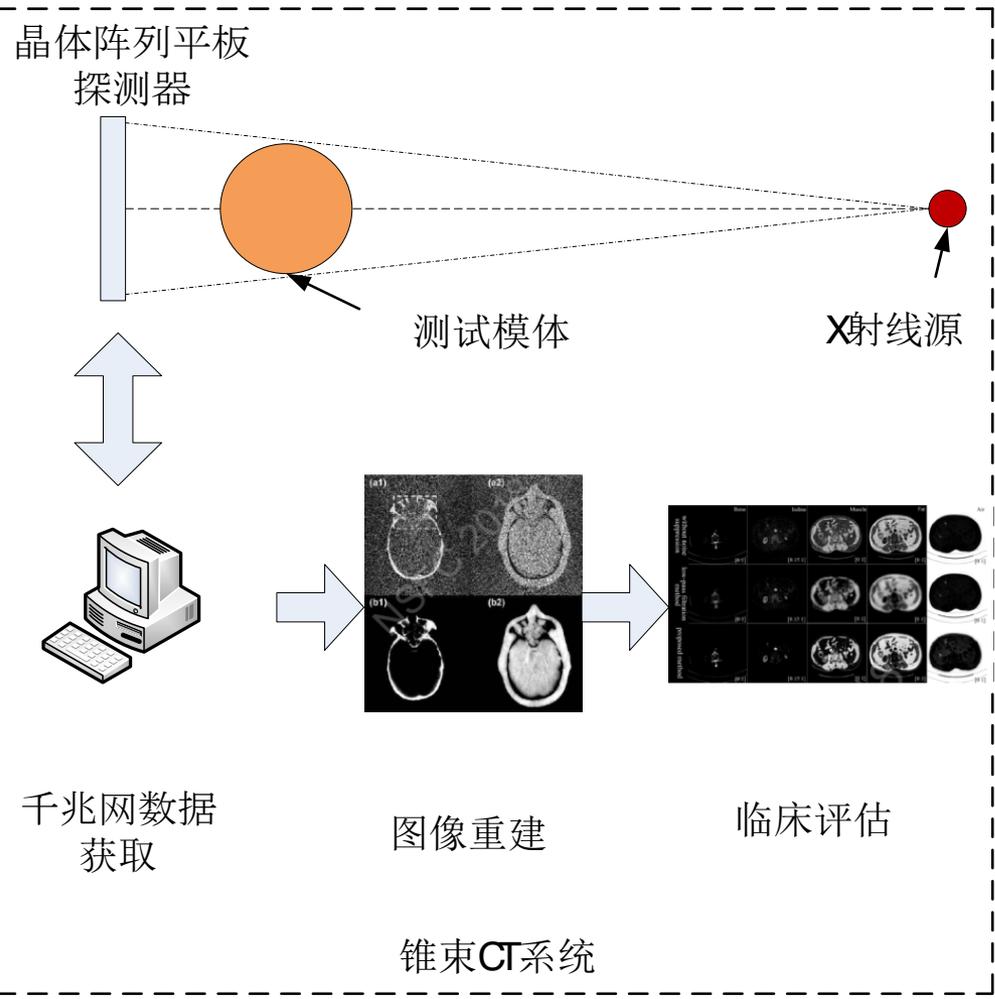
Time-Of-Flight PET



锥束CT与放疗系统



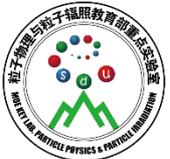
锥束CT系统



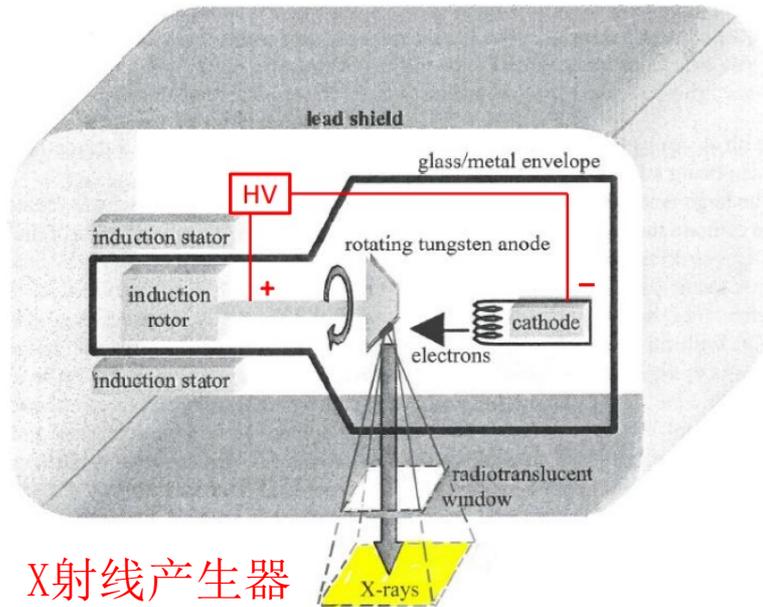
锥束CT系统:

- (1) 探测器采用CsI晶体阵列平板探测器;
- (2) 球管发射能谱X射线 (非单能);
- (3) 电机控制 (步进电机、伺服电机) 和探测器触发控制。

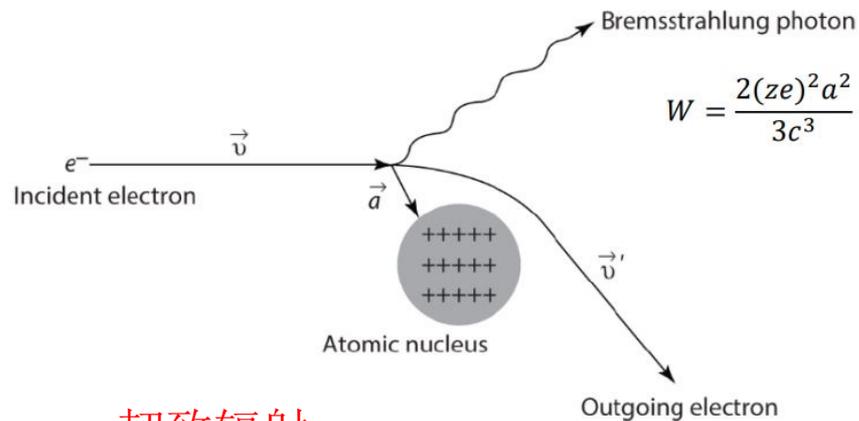
$$I(x) = I_0 * \exp(-ux)$$



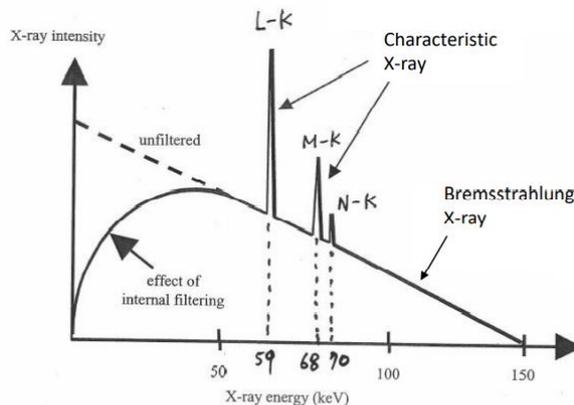
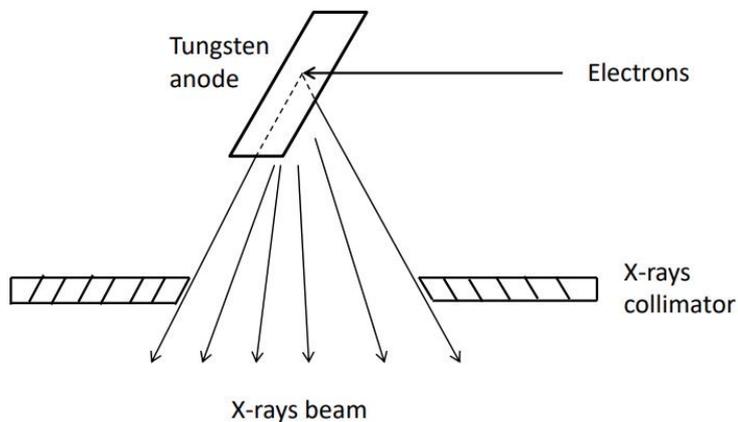
球管



X射线产生器



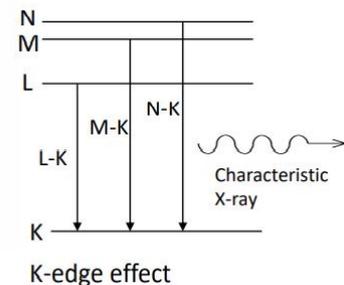
韧致辐射

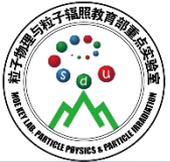


能谱

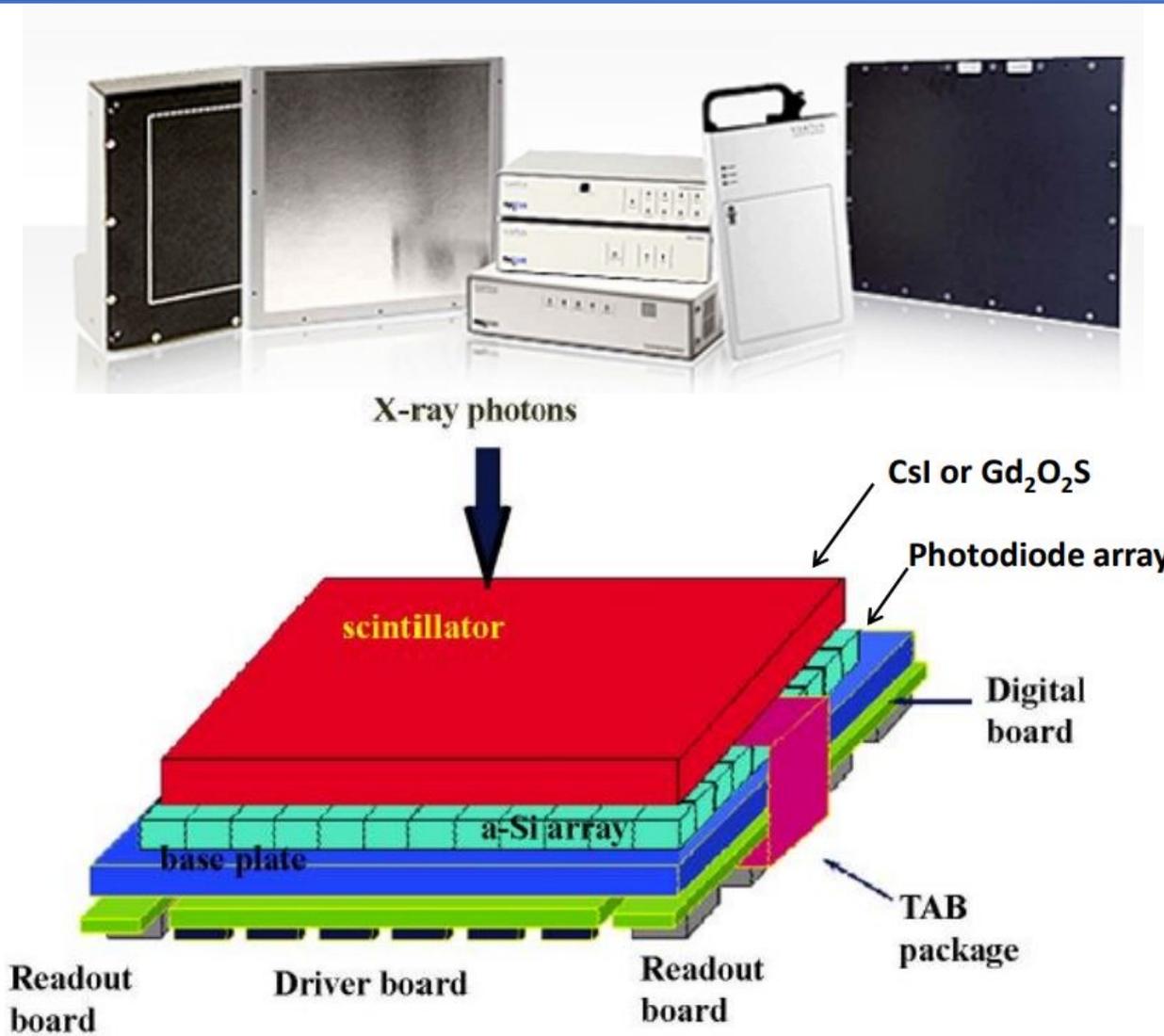
Electron binding energies for tungsten

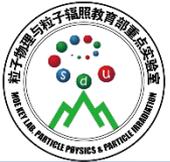
- K shell: 70 keV
- L shell: 11 keV
- M shell: 2 keV
- N shell: ~0



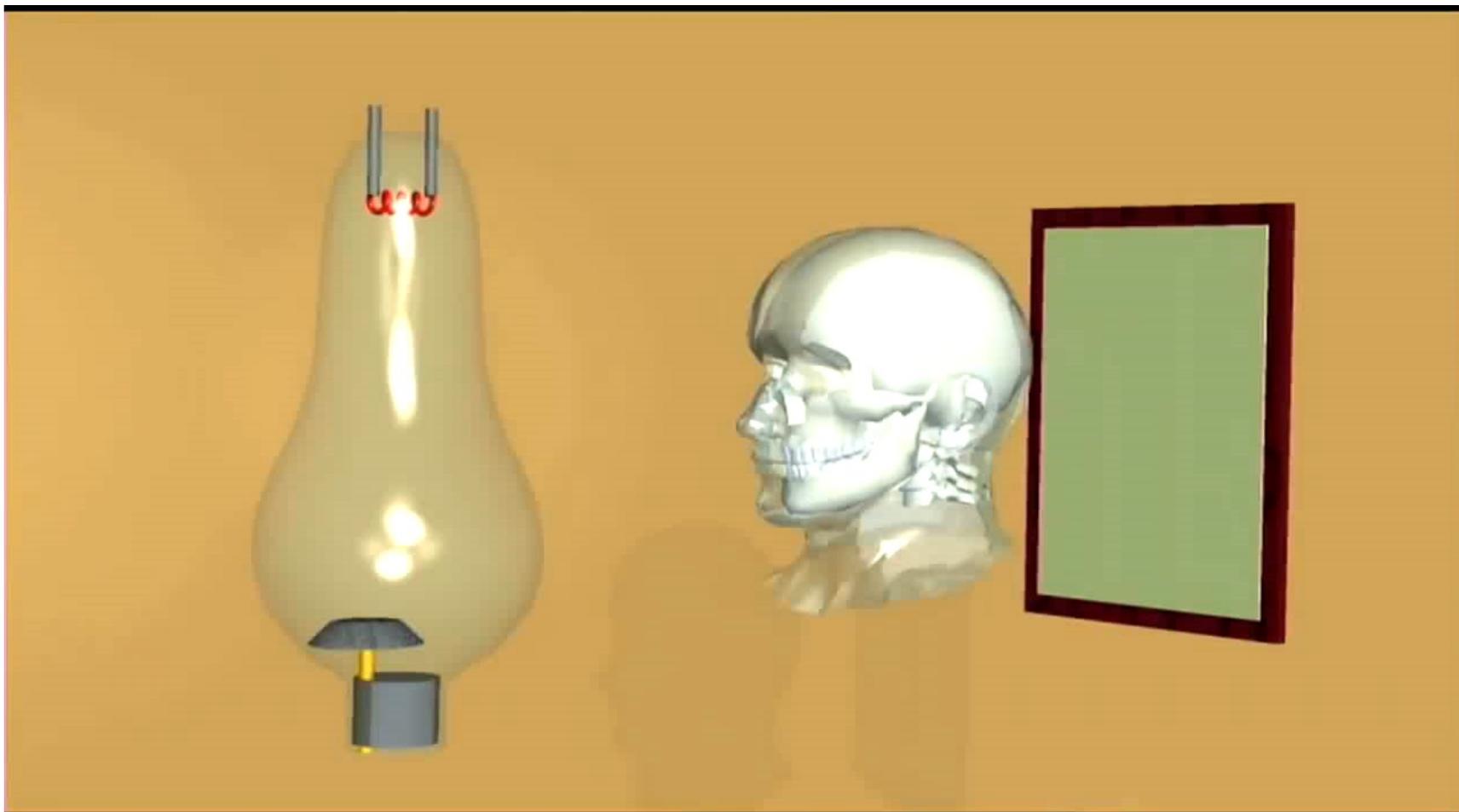


平板探测器



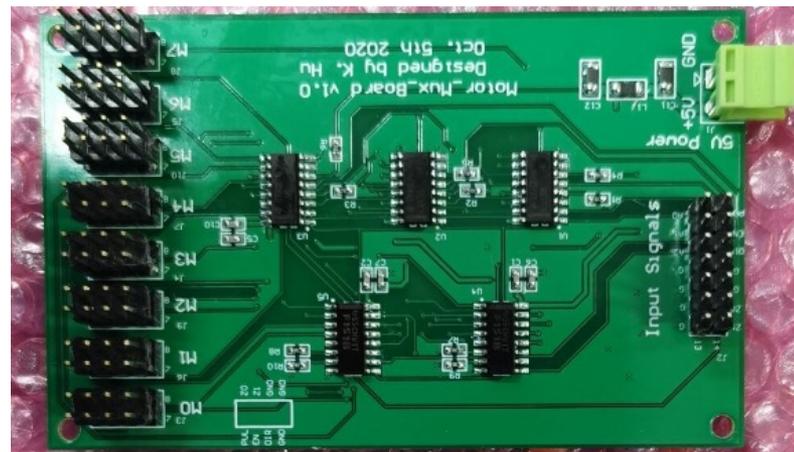


CT视频





单片机核心板



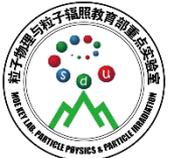
电机多路板



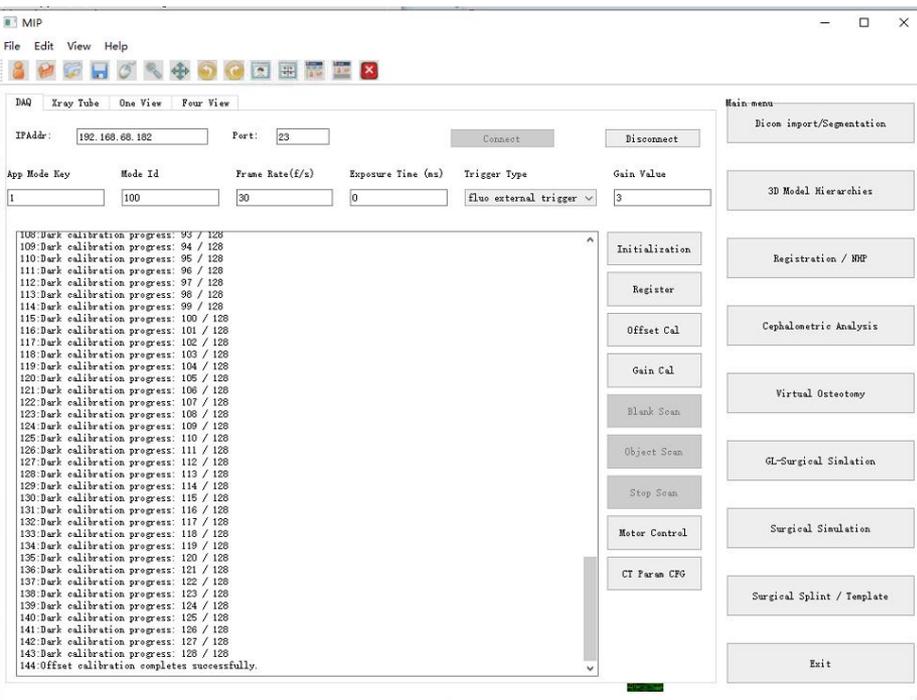
RS232串口多路板



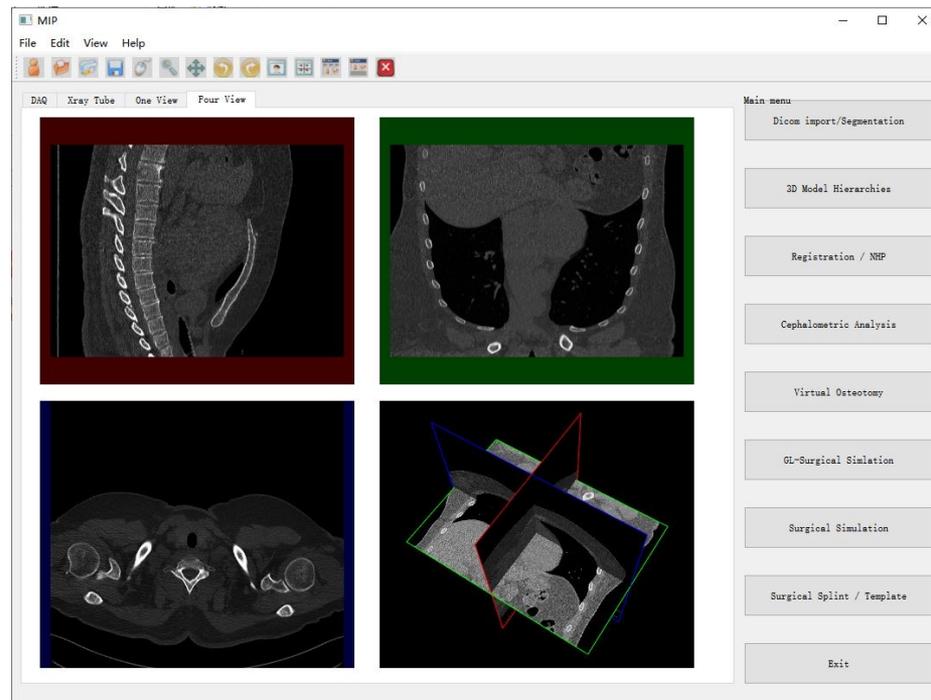
步进电机多路板



基于VS+QT+VTK的GUI界面



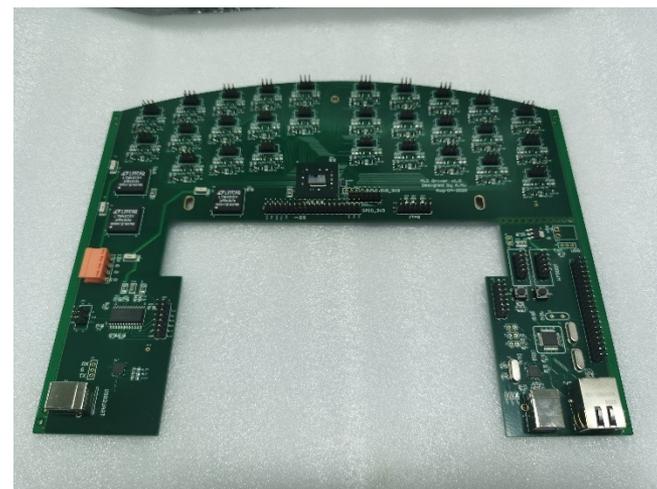
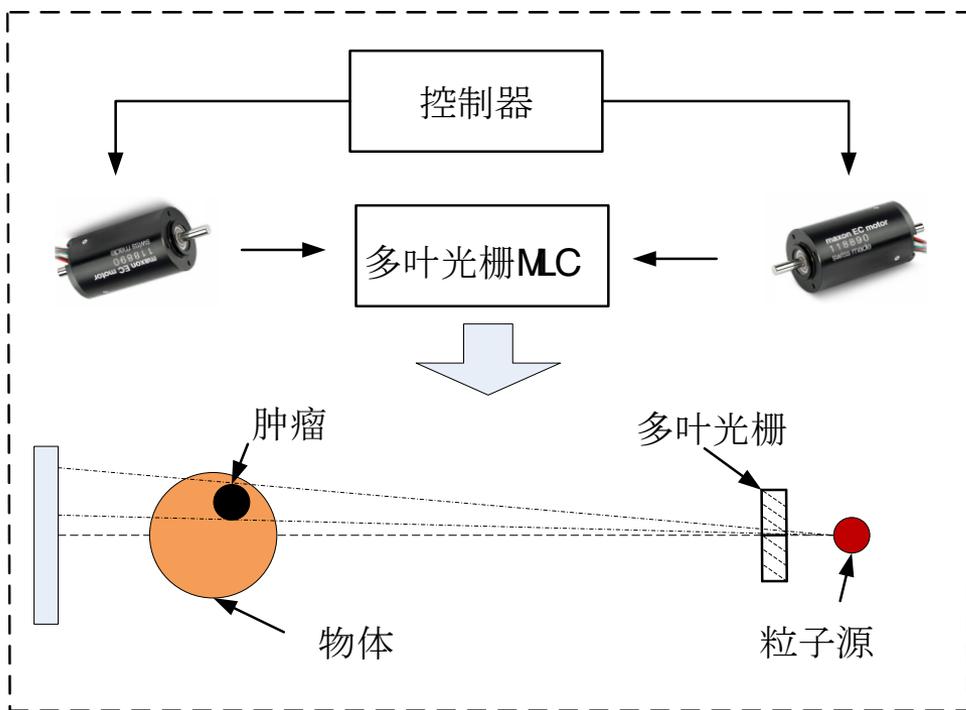
探测器数据获取界面



图像处理界面

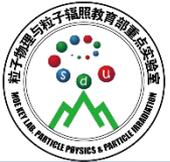


基于多叶光栅 (MLC) 的放疗系统



多叶光栅控制系统的挑战:

- (1) 小尺寸;
- (2) 根据治疗图像进行可编程控制;
- (3) 100多个伺服电机同时控制;
- (4) 高速运转, 精确定位。

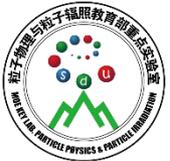


1. 算法:

- (1) 滤波反投影FBP (filtered backprojection) :
- (2) FDK算法: 近似的三维FBP;
- (3) 迭代算法 (如何找到一个迭代次数少, 收敛快, 噪声低的算法)
 - (a) 完全角度重建 (完备数据) :
 - (b) 不完全角度重建 (不完备数据, 方程组高度欠定),
例如 ASD-POCS算法, ABOCS算法, RRD算法, ADTVM算法;

2. 硬件 (下一代光子计数型CT)

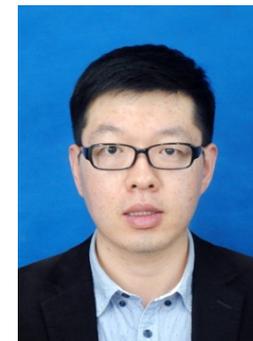
- (1) 探测器 (GE: 深Si, 西门子: 碲化镭):
- (2) 高计数率多通道读出电子学 (计数率 $>1\text{Mhz}$)



胡坤 研究员
前端电子学系统，
高速数据获取系统。
ATLAS实验



任祥祥 副教授
高速AD采样，
高速数据获取系统。
PandaX实验、阿里天文



张亮 副教授
ASIC设计，
硅像素探测器读出
电子学。
HERD、CEPC

专业技术人员与工程师：董家宁、李长裕、李玉英、王安庆。