新型辐射探测
对微电子技术的需求

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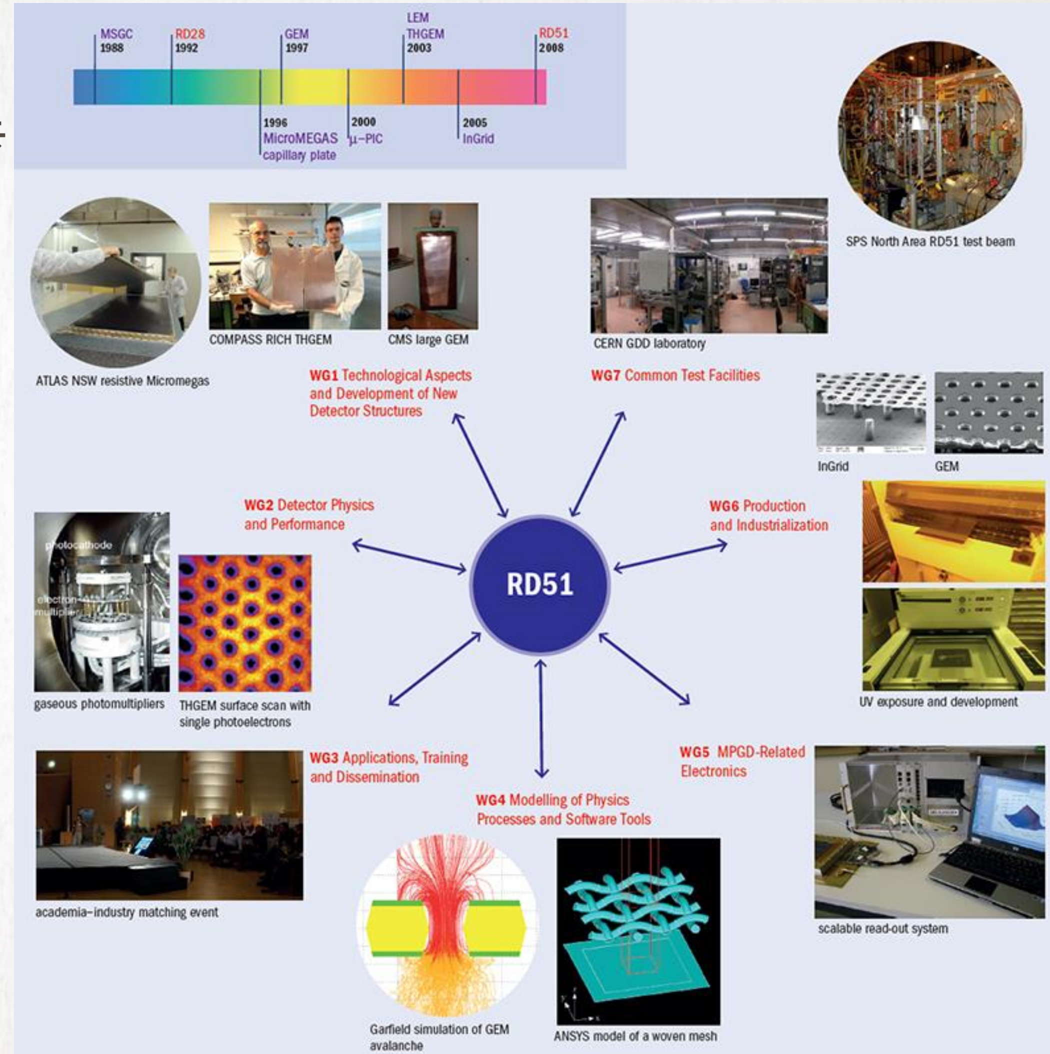
内容提纲

- 气体探测器的发展及其对微电子技术的需求
  - MPGD/TPC
- 闪烁探测器的发展及其对微电子学技术的需求
  - 基于SiPM的读出（PET）
  - 脉冲甄别技术（PSD）
- 半导体探测器的发展及其对微电子技术的需求
  - 硅探测器（略）
  - HPGe探测器（暗物质寻找）
  - CZT探测器（3D-CZT，能谱成像）

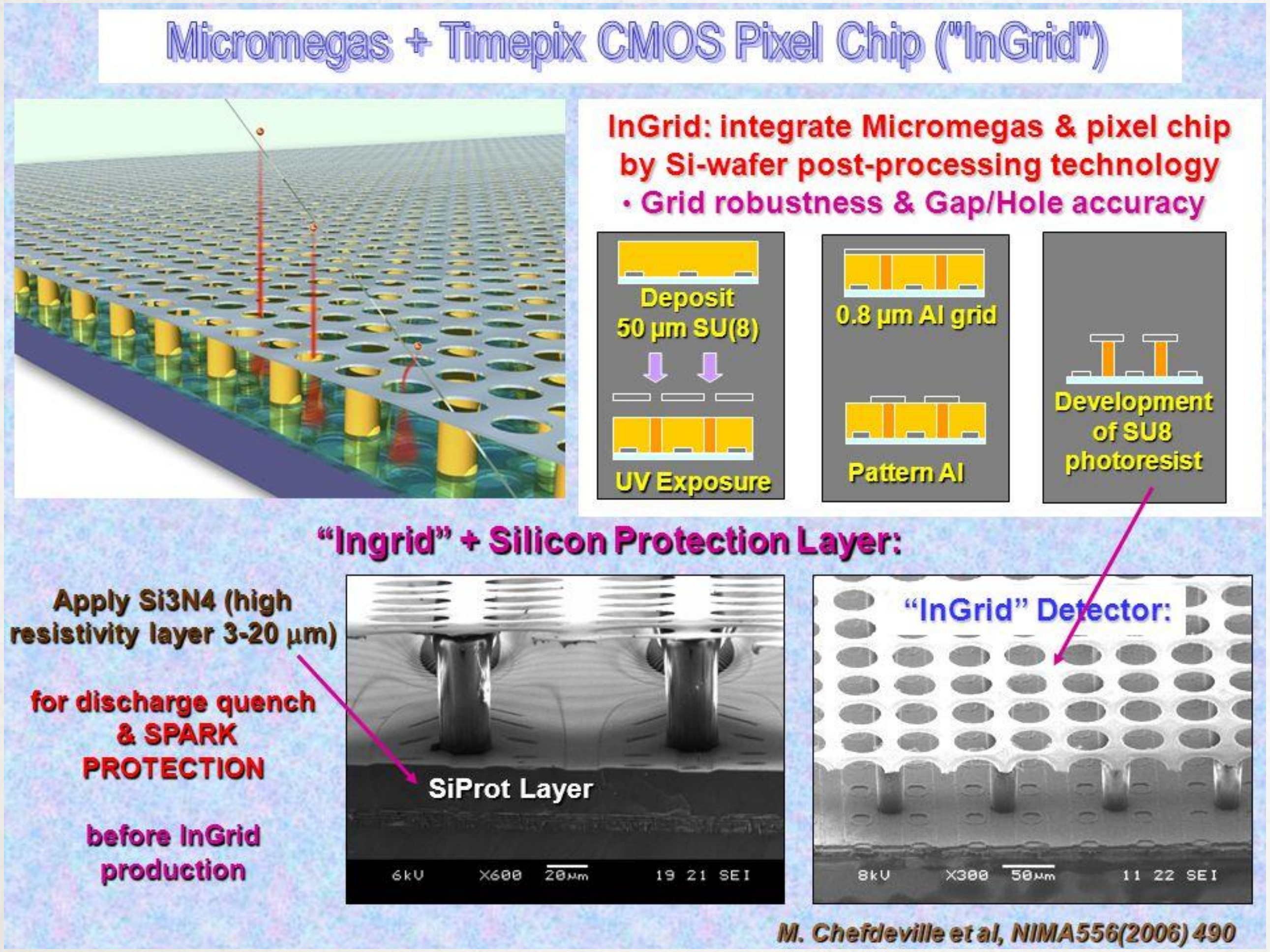
气体探测器的发展(1)

- 过去的二、三十年，光刻技术、微电子技术以及PCB技术的进步催生了微结构气体探测器的发展:
  - MPGD：Micro Pattern Gas Detector
  - pitch size: few hundred μm,
  - high-rate capability: > 1 MHz/mm2,
  - spatial resolution: ~ 30 μm,
  - time resolution for single photoelectrons: < 1 ns.



气体探测器的发展(2)

- 结合微电子技术以及先进的PCB技术，MPGD探测器实现了更小的单元尺寸；



- InGrid/GridPix:
  - GEM/Micromegas:
  - CMOS pixel ASIC:
    - MediPix;
    - TimPix.
- 接近了固体像素探测器的：
  - integration
  - compactness
  - resolving power
- 典型应用：TPC的读出

现代物理实验对TPC的要求

- ILC

Performance/Design Goals	
Momentum resolution[a] at B=3.5T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c TPC only
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05\,X_0$ including the outer field cage in r
	$< 0.25\,X_0$ for readout endcaps in z
Number of pads/timebuckets	$\simeq$ 1-2$\times 10^6$/1000 per endcap
Pad pitch/no.padrows	$\simeq 1\,\mathrm{mm}\times 4\text{-}10\,\mathrm{mm}/\simeq 200$
σ_{point} in $r\phi$	$< 100\mu$m (avg for straight-radial tracks)
σ_{point} in rz	$\simeq 0.4-1.4$ mm (for zero – full drift)
2-hit resolution in $r\phi$	$\simeq 2$ mm (for straight-radial tracks)
2-hit resolution in rz	$\simeq 6$ mm (for straight-radial tracks)
dE/dx resolution	$\simeq 5$ %
Performance	$> 97\%$ efficiency for TPC only ($p_t > 1$GeV/c)
	$> 99\%$ all tracking ($p_t > 1$GeV/c)
Background robustness	Full efficiency with 1% occupancy,
Background safety factor	Chamber prepared for 10–20% occupancy
	(at the linear collider start-up, for example)

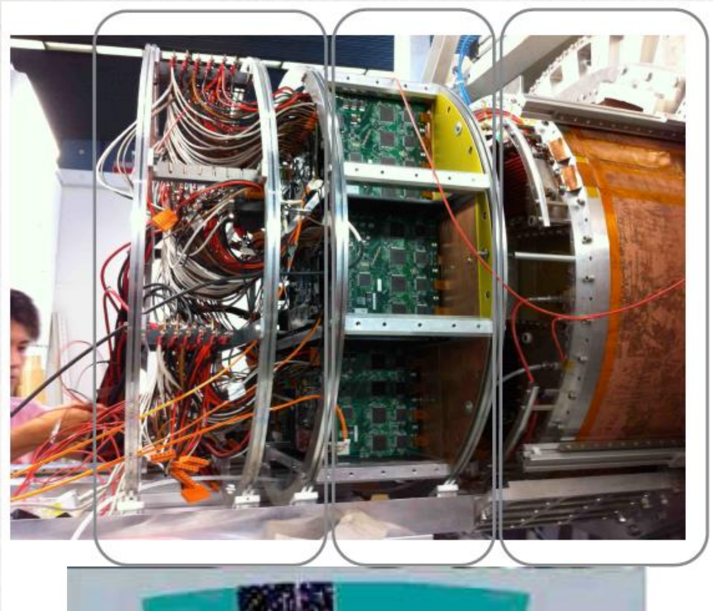
- 单侧读出电子学通道：10^6；

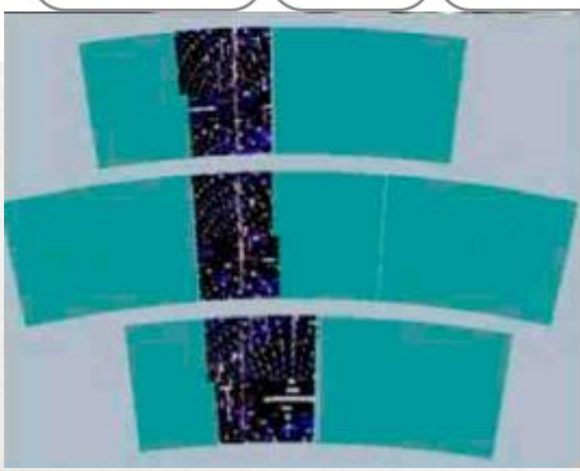
- ALICE TPC：
  - pad大小：$7\times4.5\ \mathrm{mm}^2$
  - 通道数：570132

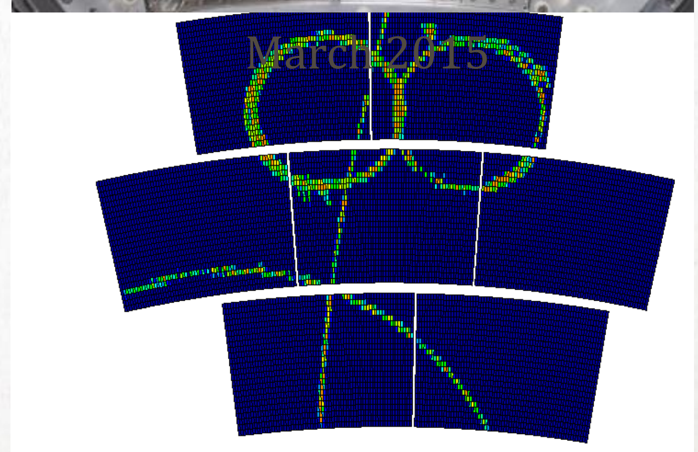
ILC-TPC LP1 STUDY

GEMs

Micromegas





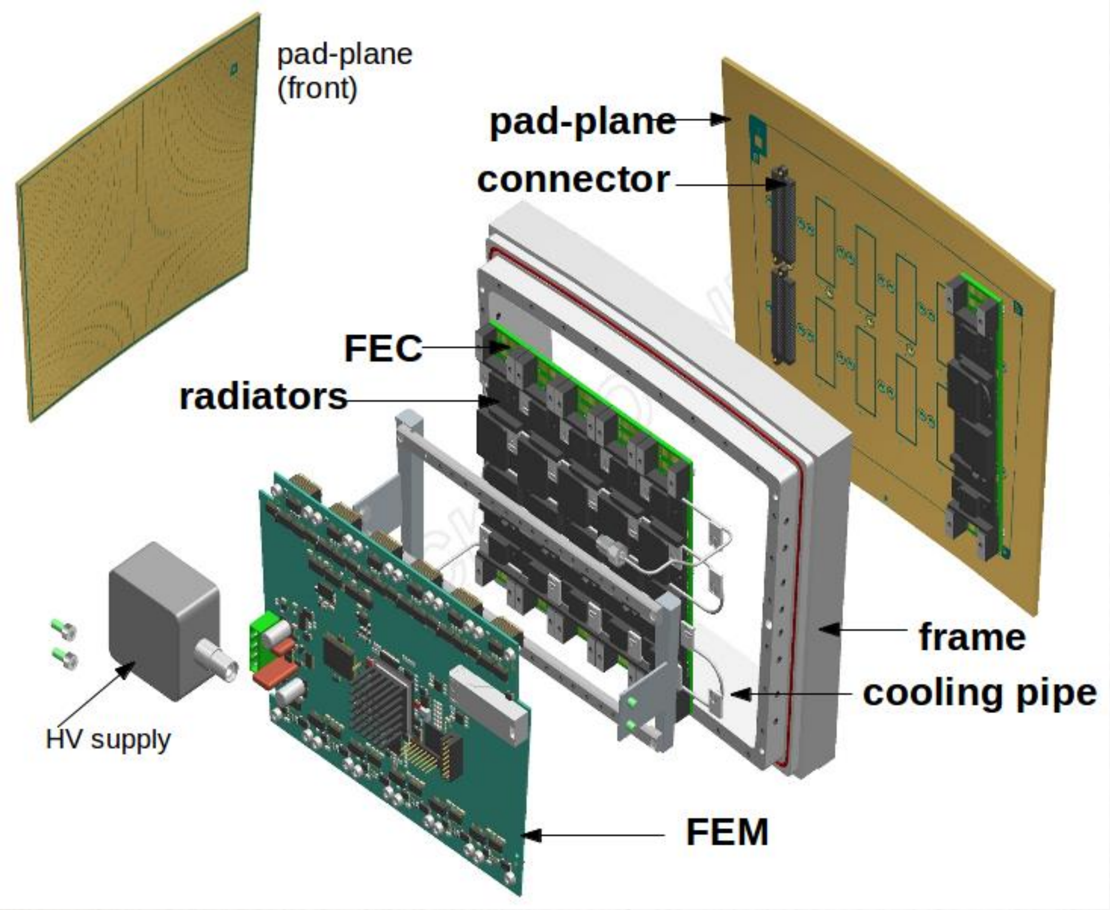


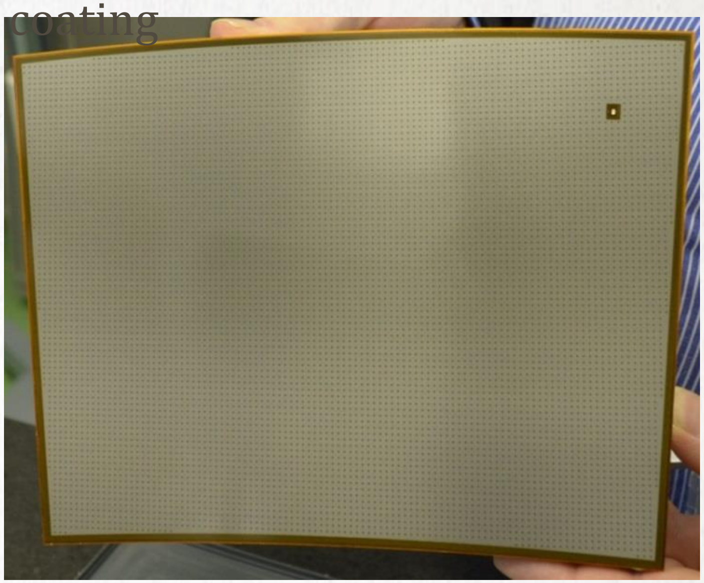
Pad: ~1×6 mm^2, ~5000ch/Module

Pad: ~1×6 mm^2, 1728ch/Module

ILC-TPC LP1Micromegas module

Bulk process for MM manufacture
Carbon-loaded kapton or Diamond-like carbon as resistive coating





Module size: 22 cm × 17 cm

Readout: 1726 Pads

24 rows

Pad size: ~ 3 mm × 7 mm

Chips on board (wire bonding) – The resistive foil suffices to protect against sparks – 0.25 X° thick

LP1-TPC readout using GridPix

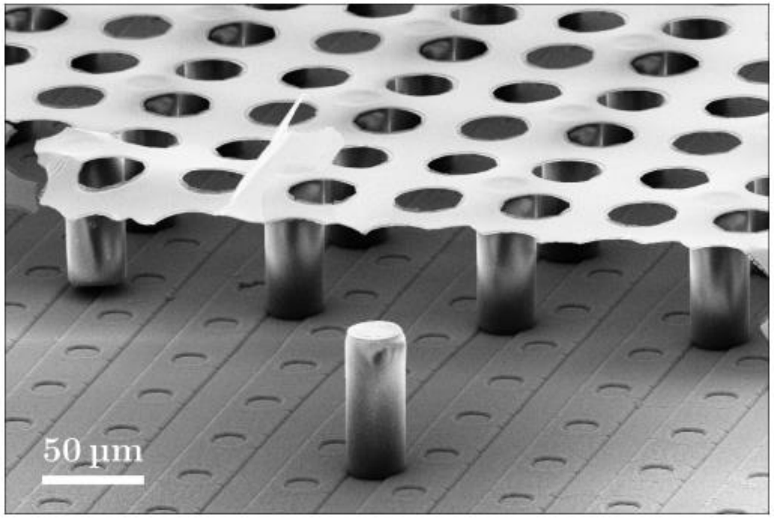
What is GridPix?

- GridPix is a type of micro-pattern gaseous detector (MPGD)
- Other well known types of MPGDs use GEM foils and Micromegas

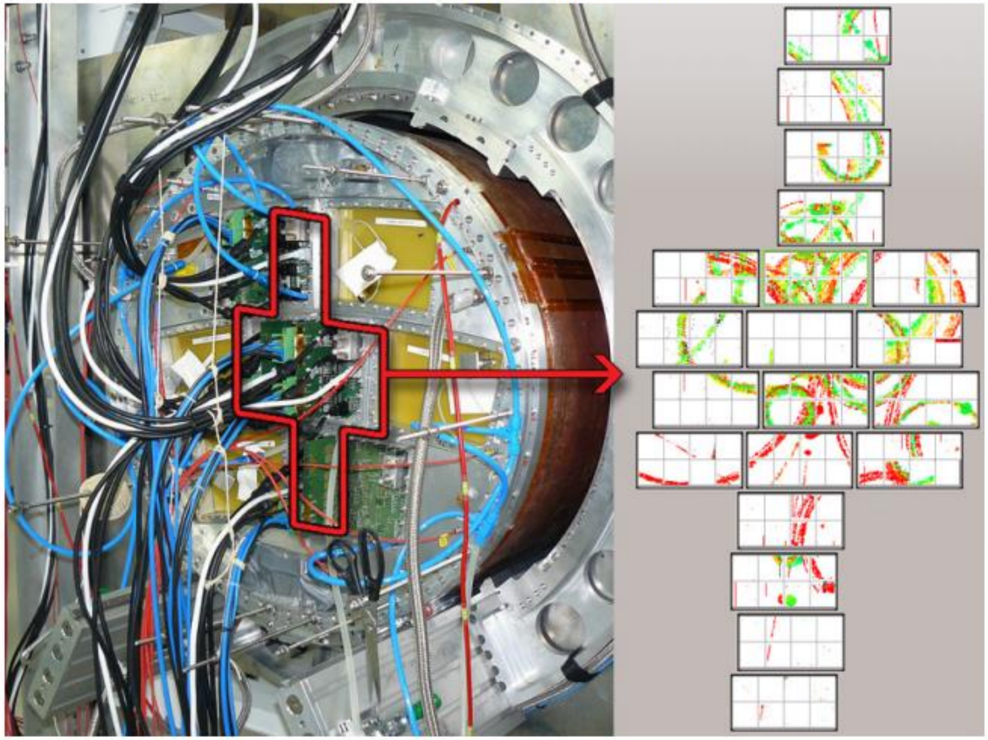
What sets GridPix apart from the others?

- The grid is produced directly on top of ASIC
- Good alignment of grid holes and pixels
- Primary electron counting instead of charge integration improves the energy resolution

GridPix



Linear Collider TPC with 160 GridPixes
Test e-beam at DESY



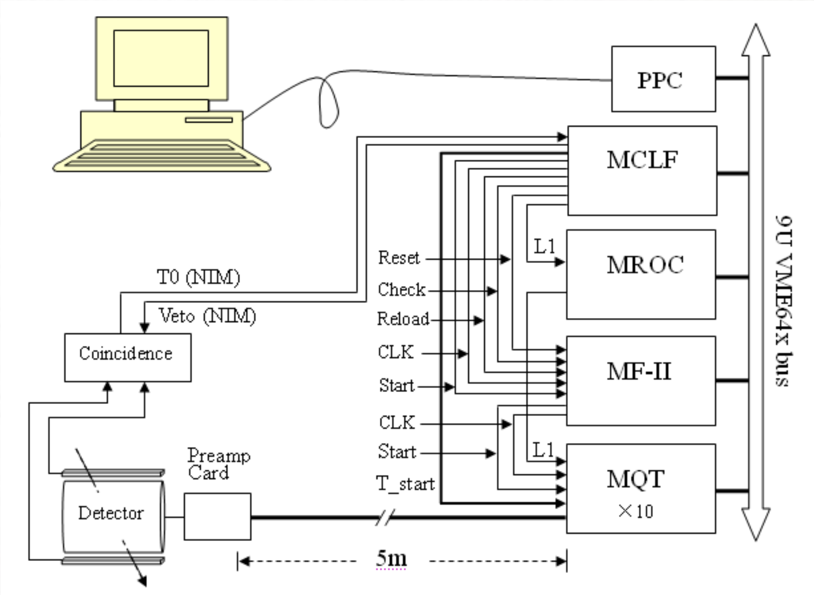
国际上现有的TPC读出ASIC芯片

	PASA/ALTRO	AFTER	Super-ALTRO	Timpix
TPC	ALICE	T2K	ILC	ILC
Pad size	$4 \times 7.5mm^2$	$6.9 \times 9.7mm^2$	$1 \times 6mm^2$	$55 \times \mu m^2$
Pad channels	5.7×10^5	1.25×10^5	$1 - 2 \times 10^6$	10^6
Max drift time	$92\mu s$	$20\mu s$	$46\mu s$	$46\mu s$
Readout Chamber	MWPC	MicroMegas	GEM/MicroMegas	GEM/MicroMegas
Front-end				
Gain	12mV/fC	18mV/fC	12-27mV/fC	2.64mV/fC
Shaper	$CR-(RC)^4$	$CR-(RC)^2$	$CR-(RC)^4$	None
Peaking time	200ns	100ns	30-120ns	90-180 ns
ENC	385e	1000e	520e	100e
Front-end				
Method	ADC	SCA	ADC	TOT
Method	ADC	SCA	ADC	TOT
Sampling frequency	10MSPS	25MSPS	40MSPS	
Dynamic range	10bit	10bit	10bit	
Buffer depth	1k	511	1k	
Data reduction	Yes	No	Yes	Low data amount
Power consumption	32mW/ch	6.2 7.5mW/ch	1.76mW/ch*	14ïĄŋW/ch
Radiation tolerance	160krad	No		200krad
CMOS Process	250nm	350nm	130nm	250 nm
Status	Installed	Installed	In study	In study
* with 0.5% duty cycle of power pulsing				

国内TPC读出电子学系统(1)

- TU-TPC@2007年

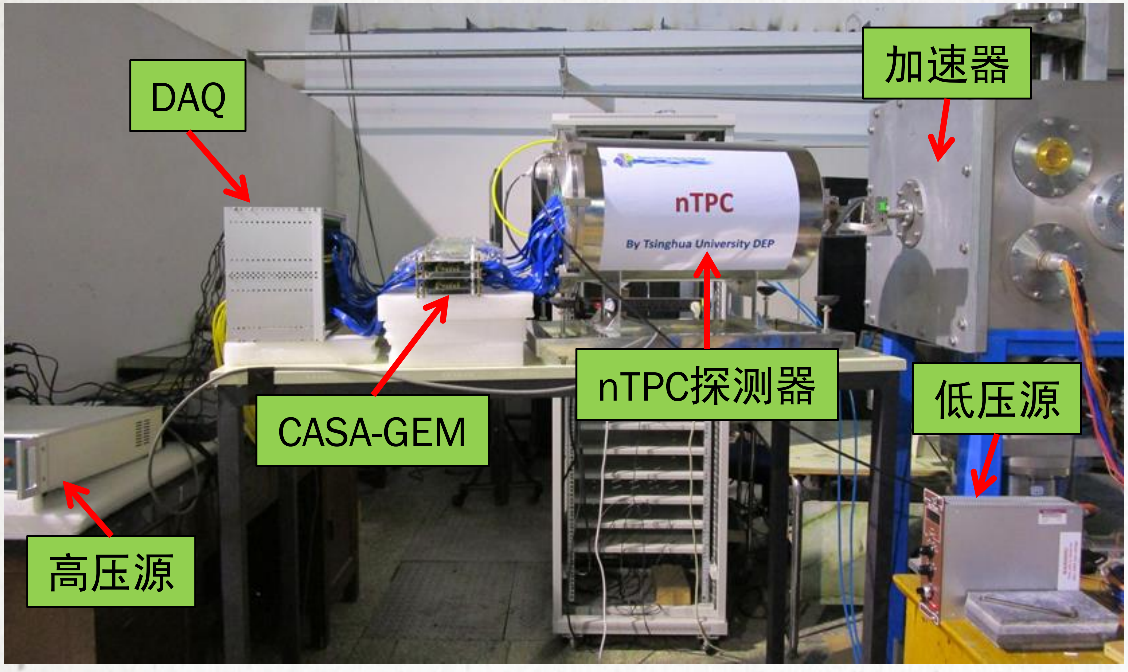
- 基于BESIII-MDC电子学系统
- 320个通道；
- 基于分列器件的前放
- 读出面积：10cm×10cm



TPC/MRPC prototype electronics block diagram

国内TPC读出电子学系统(2)

- Neutron-TPC@2014年



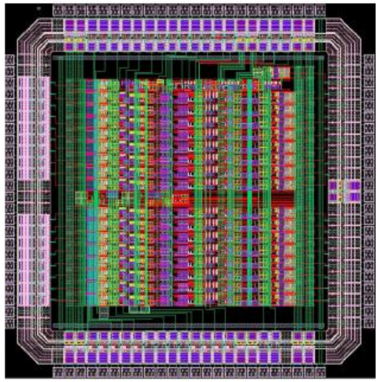


Fig. 4. The layout of CASAGEM.

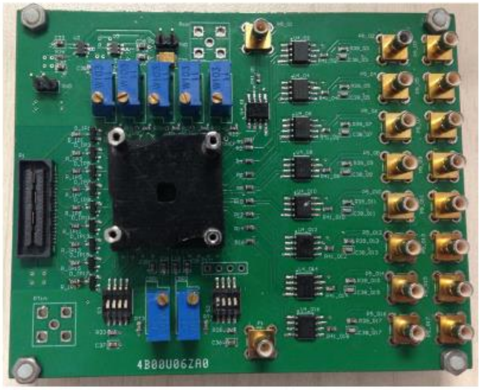


Fig. 5. The testboard of CASAGEM.

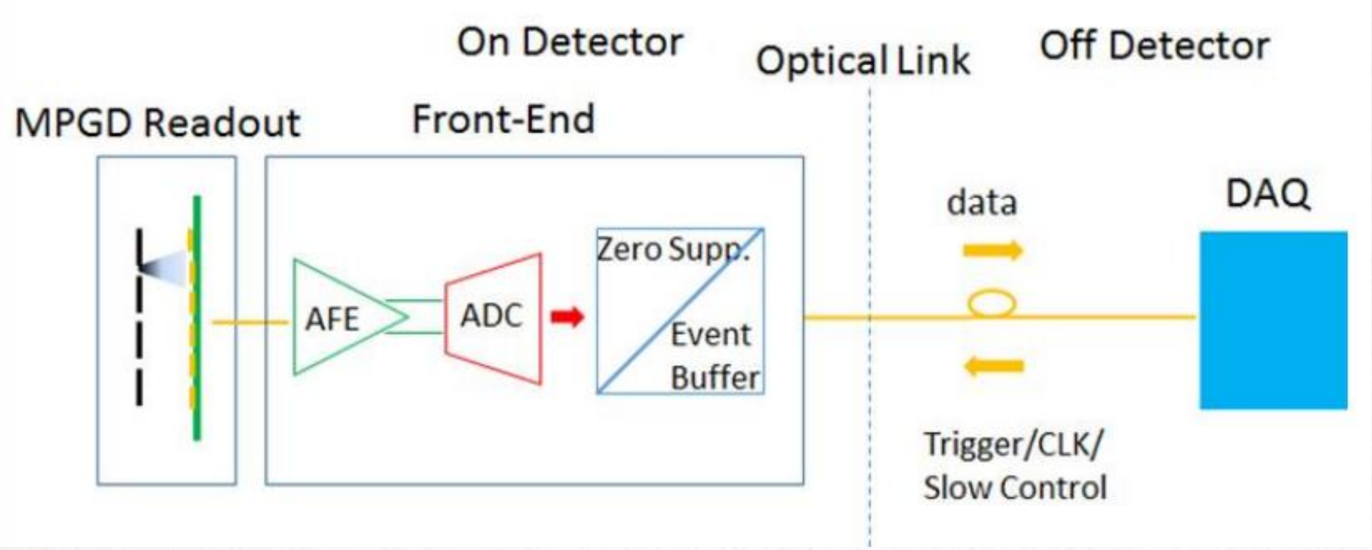
- 基于自行研制的ASIC:CASAGEM
- 320个通道；
- 读出面积：10cm×10cm

Table 1. The specifications of CASAGEM.

element	value	unit	note
gain	2, 4, 20, 40	mV/fC	
dynamic range	0–1000	fC	
shaping time	20,40,60,80	ns	
integrated linearity	<1%		
power consumption	<10	mW/ch	
ENC	<2000	electron	input cap:50pF

国内MPGD-TPC读出电子学规划

- CEPC：Pre-CDR



- AFE: preamplifier + shaper
- ADC: waveform sampling ADC
- 同时立项研究：基于开关电容阵列的波形采样技术

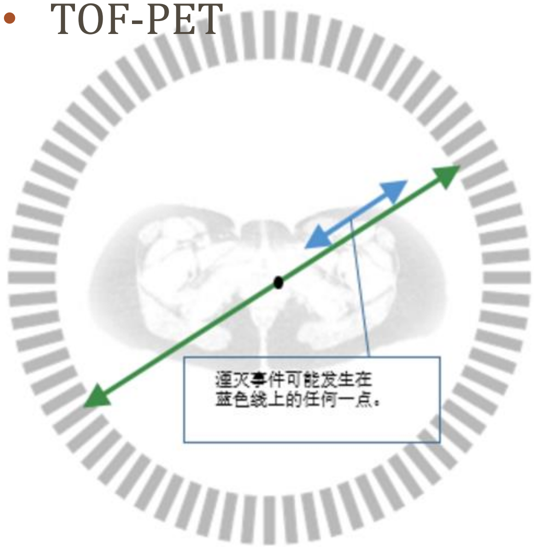
Total number of channels	1 2 Million
AFE/ENC	500e
AFE/Gain	10-30 mV/fC, programmable
AFE/Peaking time	30-120 ns, programmable
ADC/Sampling rate	40 MSPS
ADC/Resolution	10 bit
Buffer latency	50μs
Data readout rate	20-40 Gb per event w.o. zero suppression
Power consumption	<10 mW per channel
Area	$< 6mm^2$ per channel, incl. cooling
Process	CMOS 65nm

闪烁探测器的发展及其对微电子学技术的需求

- 闪烁晶体：多发光，发好光，快发光
- 读出：SiPM
- 举例：
  - PET
  - CLYC

PET探测器的发展

- TOF-PET



- 非TOF-PET

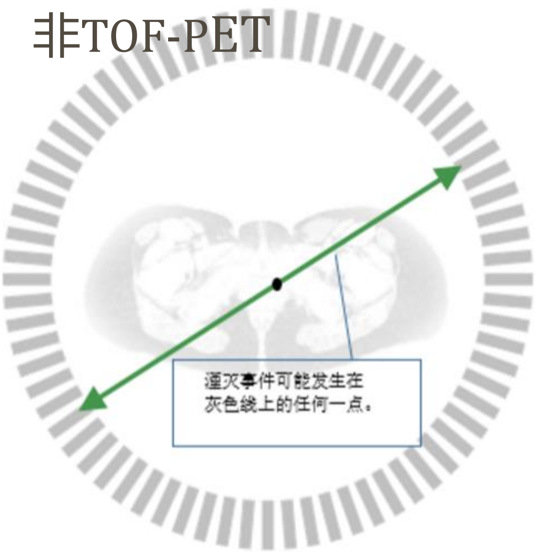


表 1　PET 的 TOF 时间分辨率提高 PET 图像质量和临床应用比较

TOF 时间分辨率	淹没作用位置范围	增益（Gain）	临床应用
550ps 第一代 TOF 技术	8.25cm	2.42~4.85	①对于胸腹部、大脏器图像对比度有提高；②对于脑无改进；
450ps 第二代 TOF 技术	6.75cm	2.97~5.93	①对于脑、小脏器图像对比度均有显著提高，同时对 PET 图像分辨率有改进；②对脏器生理运动所致伪影不能消除；
350ps 第三代 TOF 技术	5.25cm	3.81~7.62	①覆盖全身所有脏器。对 PET 图像对比度、分辨率均有显著提高，而且能够消除运动脏器伪影和提高衰减校正精准度；②部分替代呼吸门控技术；
250ps 第四代 TOF 技术	3.75cm	5.33~10.67	出提高 PET 图像质量外，有可能替代呼吸门控技术；

*增益计算按照 40 和 20cm 两个直径计算，获得结果是范围。

“得益于飞行时间**TOF**技术，从而实现了更快的扫描，更低的注射药量，更高的信噪比，和更好的图像分辨率。”——核医学之父瓦格纳教授

而TOF技术的进步则得益于：

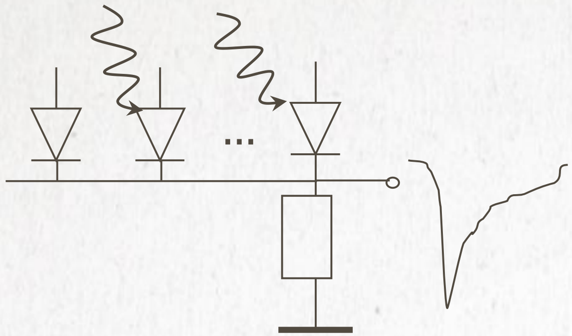
- 晶体：LSO/LYSO
- 光电读出器件：SiPM
- 微电子学：ASIC

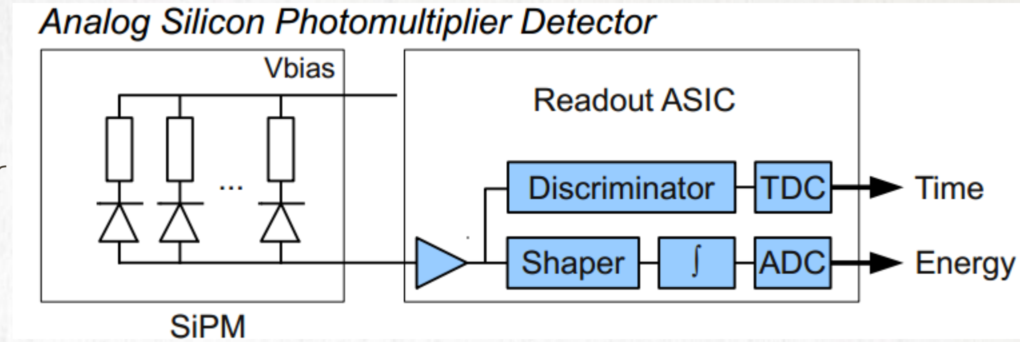
PET中常（曾）使用的闪烁晶体性能

Property	NaI(Tl)	BGO	LSO	YSO	GSO	BaF2
Density (g/cm3)	3.67	7.13	7.4	4.53	6.71	4.89
Effective Z	50.6	74.2	65.5	34.2	58.6	52.2
Attenuation length	2.88	1.05	1.16	2.58	1.43	2.2
Decay constant (ns)	230	300	40	70	60	0.6
Light output (photons/keV)	38	6	29	46	10	2
Relative light output	100%	15%	75%	118%	25%	5%
Wavelength ^(nm)	410	480	420	420	440	220
Intrinsic AE/E (%)	5.8	3.1	9.1	7.5	4.6	4.3
AE/E (%)	6.6	10.2	10	12.5	8.5	11.4
Index of refraction	1.85	2.15	1.82	1.8	1.91	1.56
Hygroscopic?	Yes	No	No	No	No	No
Rugged?	No	Yes	Yes	Yes	No	Yes

模拟SiPM和数字SiPM

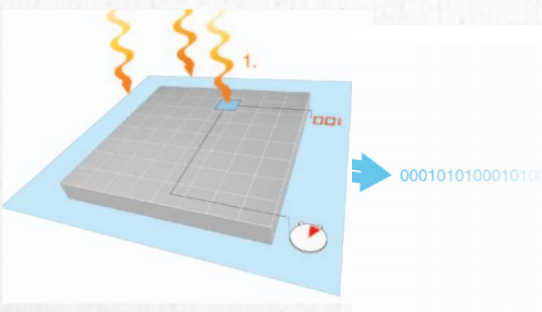
模拟
SiPM

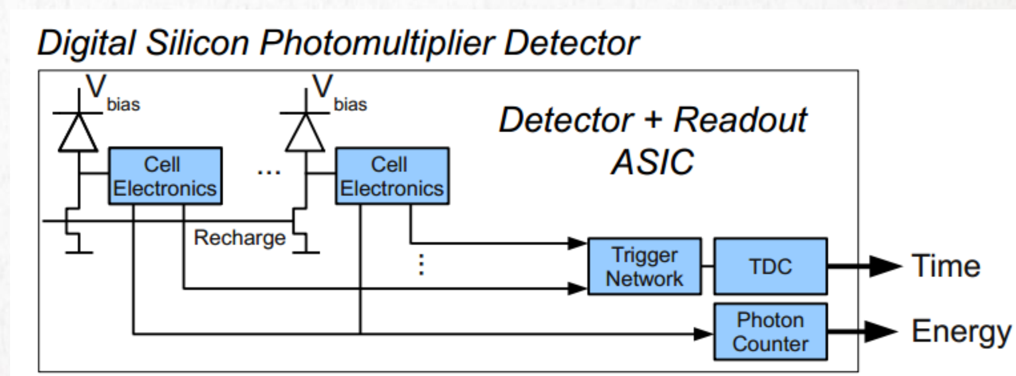




Analog SiPM 输出模拟信号（电流脉冲）

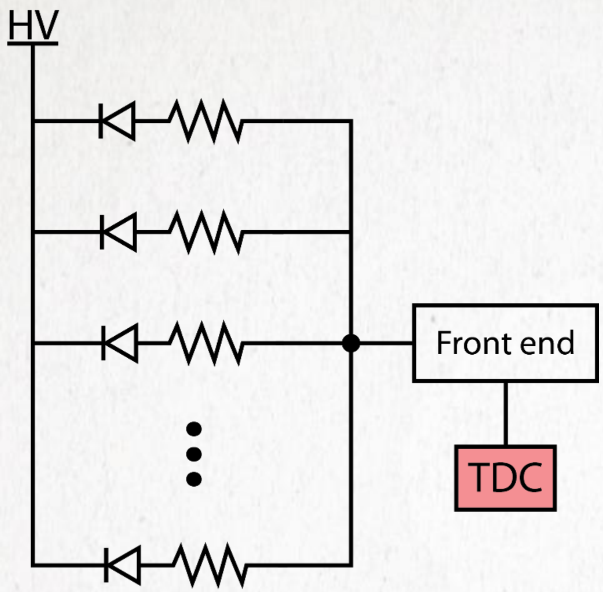
数字
SiPM



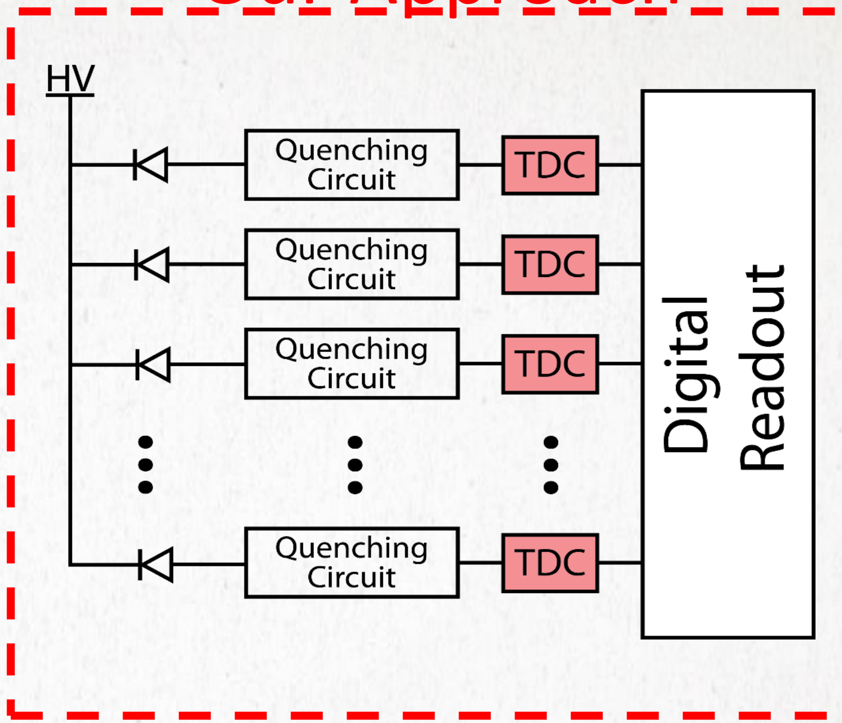


Digital SiPM 输出数字信号（光子计数和到达时间）

如何实现ps级的时间分辨率



Our Approach



Analog SiPM

- High output capacitance
- Skew between channels

Not suitable for ps timing resolution

Digital SiPM

- ~~High output capacitance~~
- ~~Skew between channels~~

☹ Photosensitive area

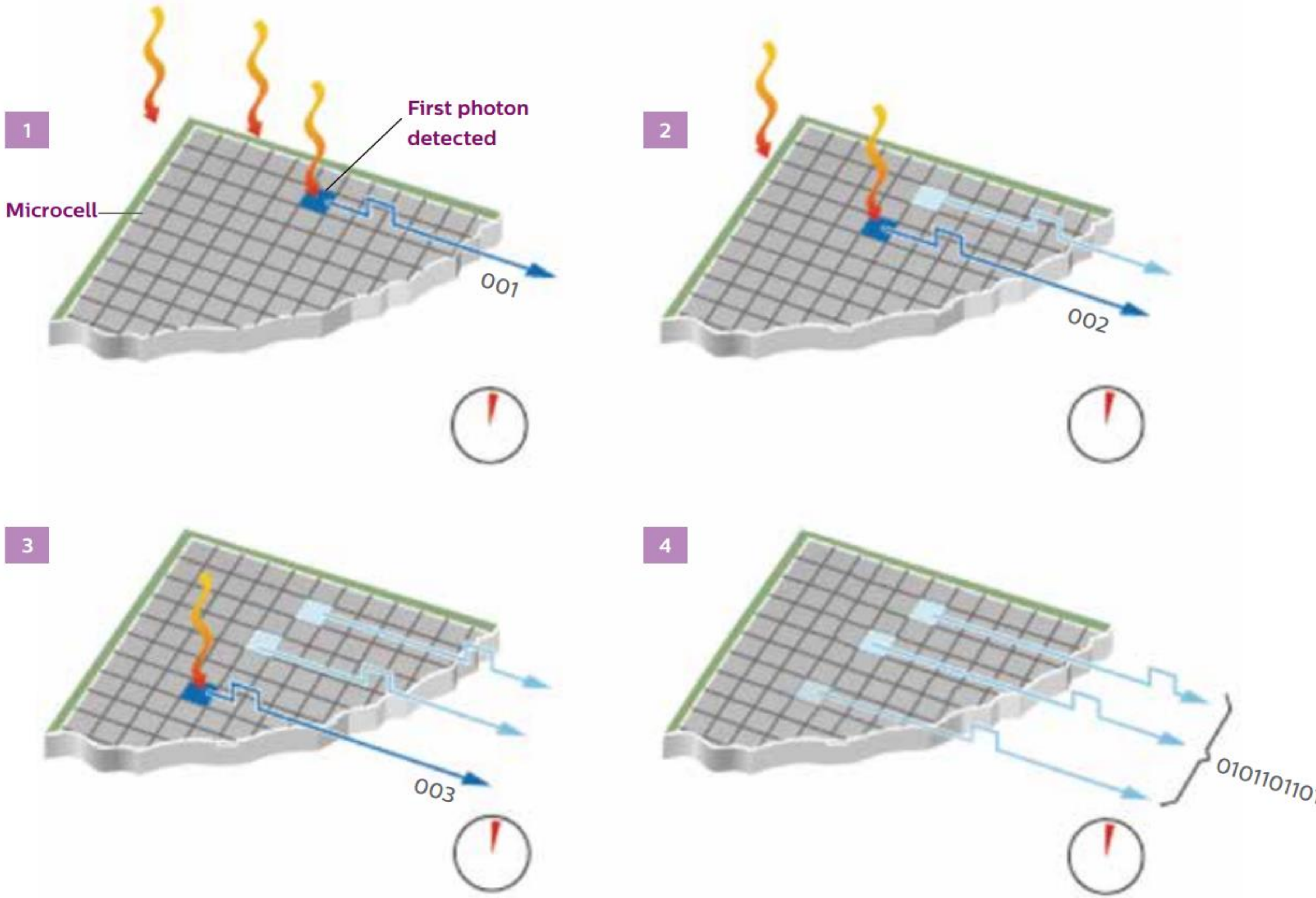
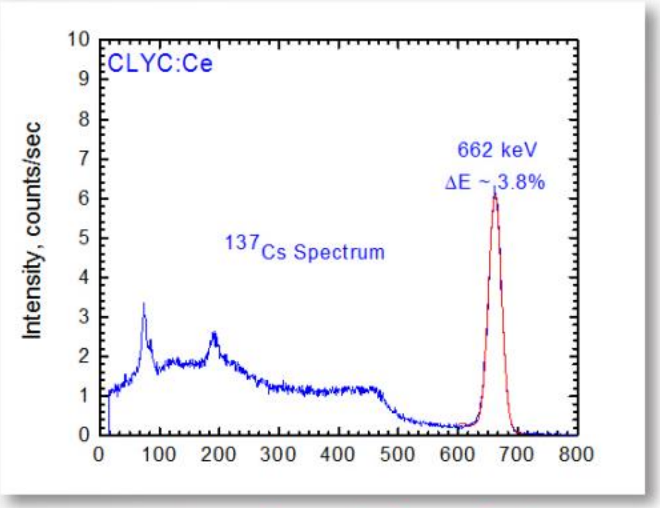


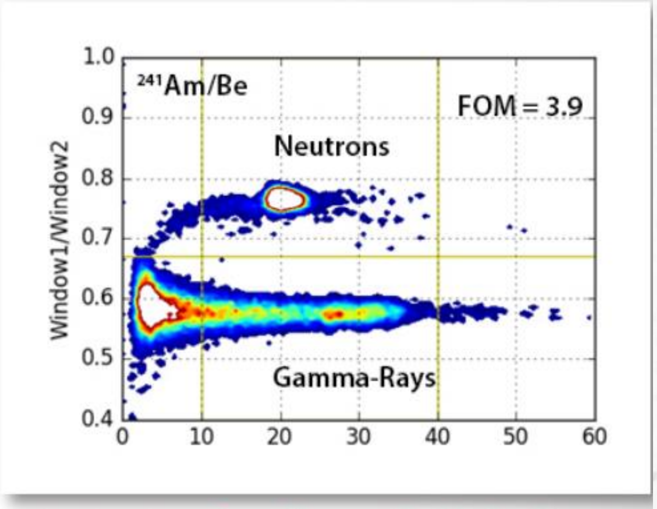
Figure 3 Digital photon counting in practice, showing the arrival and detection of individual photons, and timing measurements.

CLYC: CS_2LIYCL_6:CE

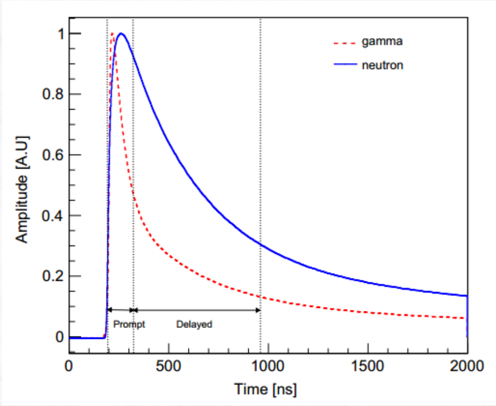
Material	Cs_2LiYCl_6:Ce	Peak Scintillation Wavelength	370 nm
Melting Point	640°C	Decay Constants (CVL, Ce3+, Ce-STE)	1 ns, 50 ns, 1000 ns
Density	3.31 g/cm^3	Scintillation Light Yield	20,000 ph/MeV
Crystal Structure	Cubic	GEE for Thermal Neutrons	3.2 MeV
Cleavage planes	None	X-ray Absorption Coef. at 100 KeV	3.97 cm^{-1}
Water Solubility	Hygroscopic	X-ray Absorption Coef. at 662 KeV	0.251 cm^{-1}
Refractive index	1.81 ± 0.037 @ 405 nm	Radiation Length	3.42 cm
Coefficient of Thermal Expansion	34.34x10^{-6}/°C @ 30°C	Heat Capacity	0.379 J/(g*K)
Emission Spectral Range	275 – 450 nm	Thermal Conductivity	0.0067 W/(cm*K) at 50°C



2" CLYC - Pulse Height Analysis



2" CLYC - Pulse Shape Discrimination



- 第一种可以实用的同时代替中等能量分辨率的γ探测器和He-3中子管的晶体；
- 但晶体目前体积还做不大，且很贵；
- 在手持设备中应用潜力很大：PRD、SPRD、RID

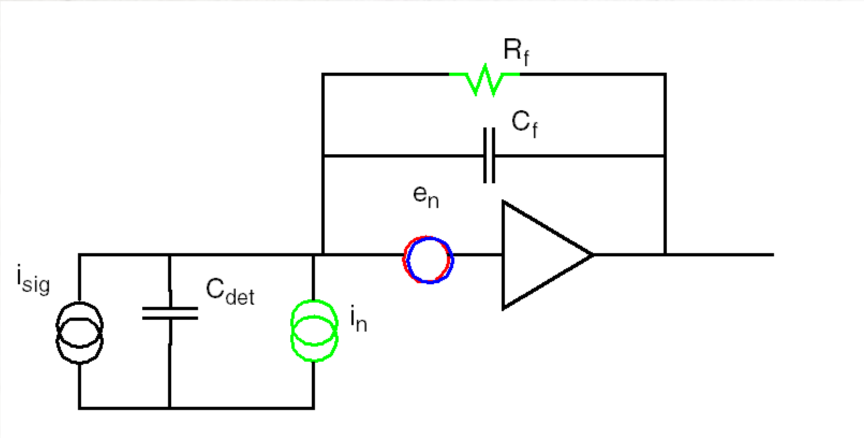
- 要求电子学：
  - 紧凑
  - 低功耗
  - 具有FADC、PSD功能
- ASIC

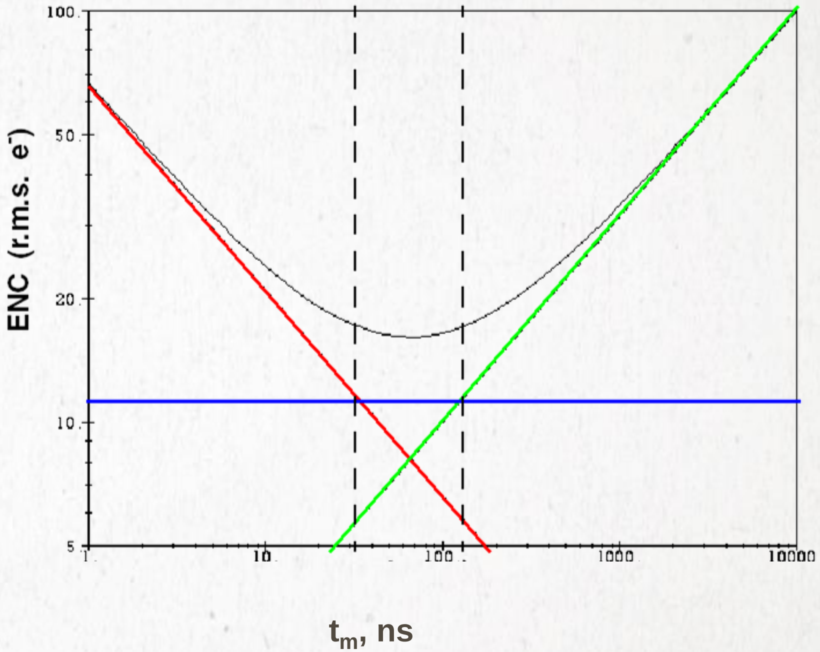
半导体探测器的发展及其对微电子技术的需求

- 硅探测器（略）
- HPGe探测器
- CZT探测器

高纯锗探测器：基于J-FET的电荷灵敏前放

- 电荷灵敏前放的噪声





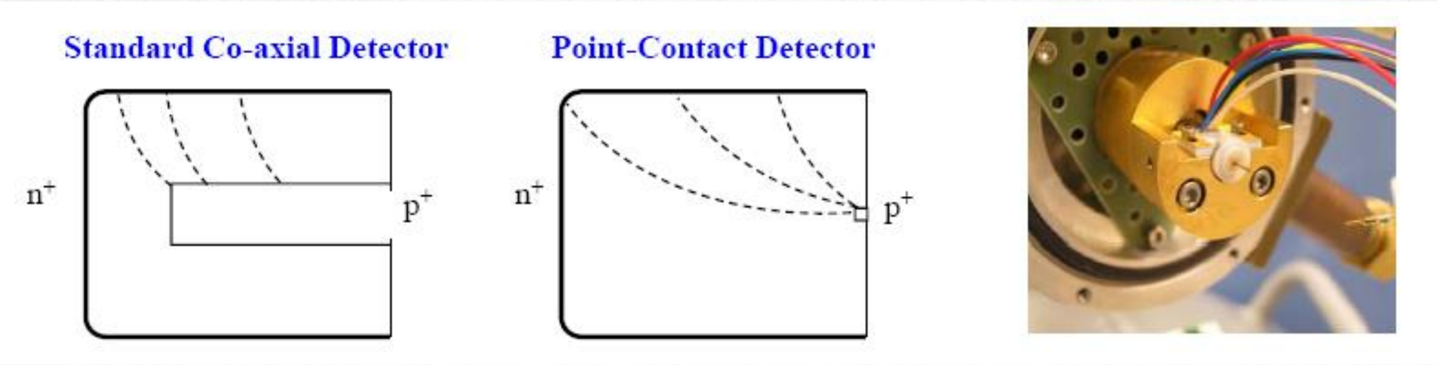
$$C_{tot} = C_{det} + C_{in}$$

$$ENC^2 = \boxed{\frac{a_1 e_{nw}^2 C_{tot}^2}{\tau}} + \boxed{a_2 K_F C_{tot}^2} + \boxed{a_3 i_n^2 \tau}$$

对于~10pF量级的平面电极HPGe探测器，总噪声以1/f噪声贡献为主，而JFET管的1/f噪声系数K_F比CMOS管要小1-2个数量级

新型点电极高纯锗探测器

- 点电极的出现使得大体积而小电容的探测器成为可能，但也需要新的JFET管或前放来优化噪声



随着探测器电容的降低，1/f噪声降低到原来的~1/10，即几个电子的水平；而1pA漏电流在6μs成形时间的噪声贡献为9e (~72eV FWHM)

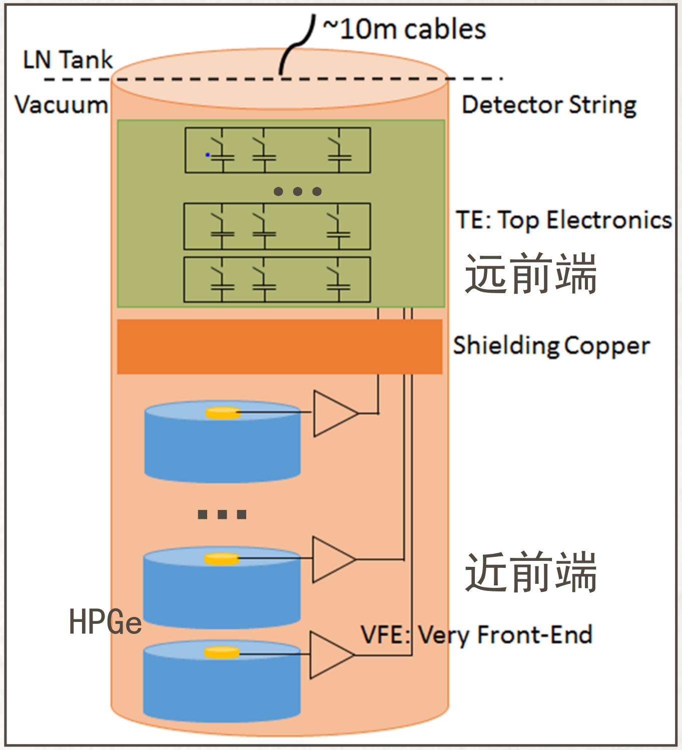
CDEX关键技术之一：低温低噪声低本底前端电子学

必要性

- 高纯锗探测器无自增益fC量级电离信号读出

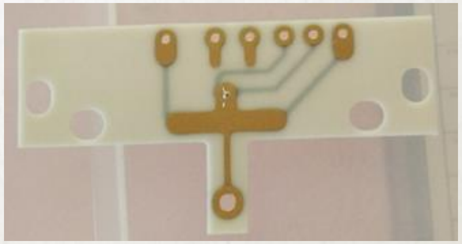
难点

- 液氮温区芯片级低噪声前端电子学技术
- 多通道弱信号长距离传输技术
- 电子学低本底材料控制技术

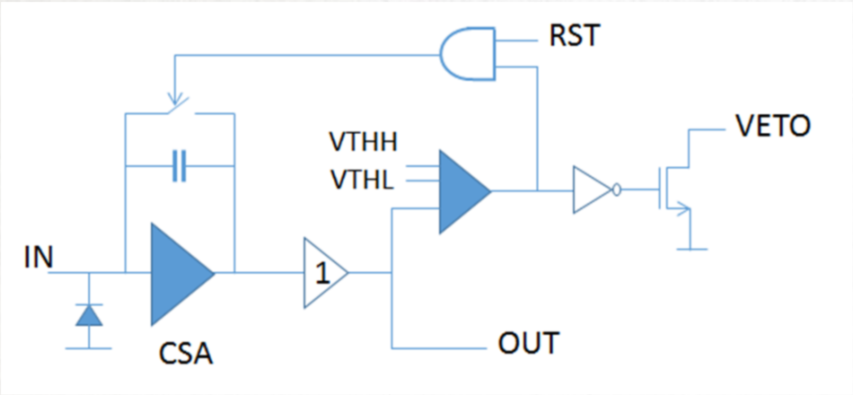


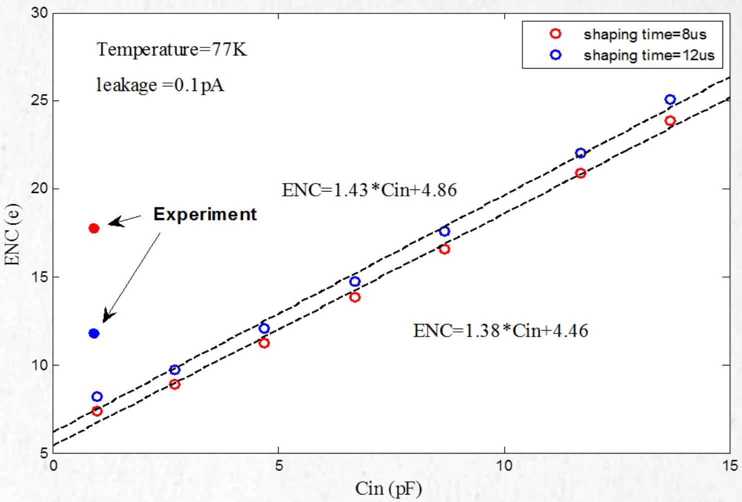
创新点

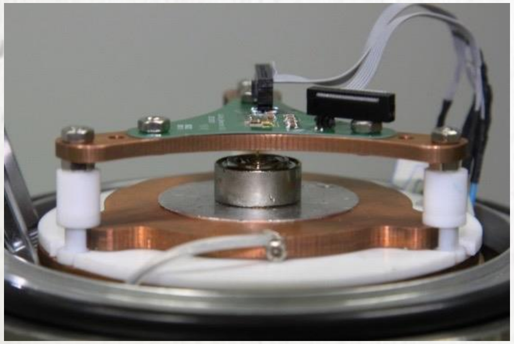
- 自主研发CMOS专用集成芯片
  - 近前端：单颗集成的脉冲反馈式电荷灵敏前放
  - 远前端：大驱动缓冲放大器或电容开关阵列
- 采用低介电损失低本底基材
  - 高纯硅或高纯聚四氟

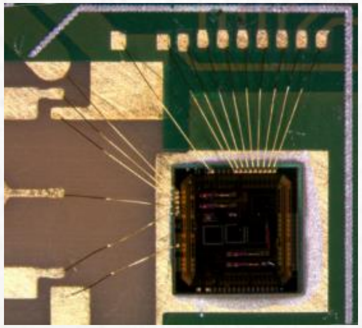


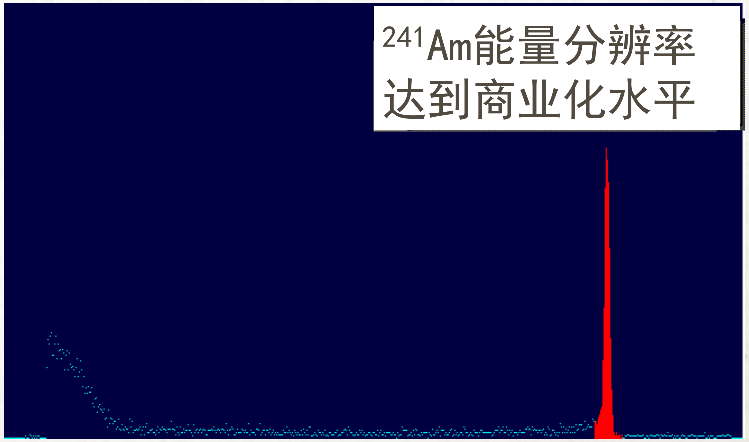
CMOS ASIC 电荷灵敏前放



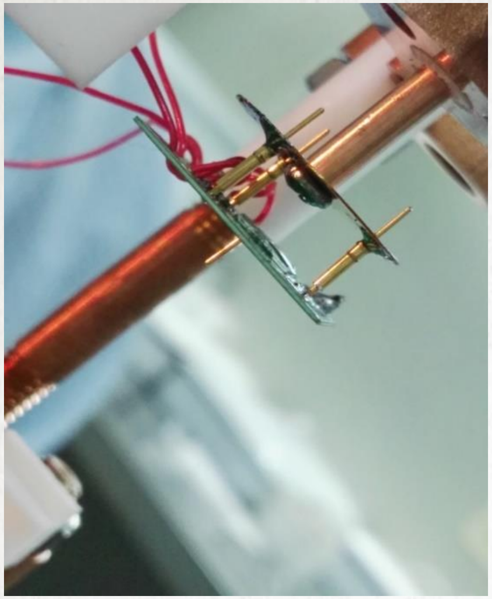


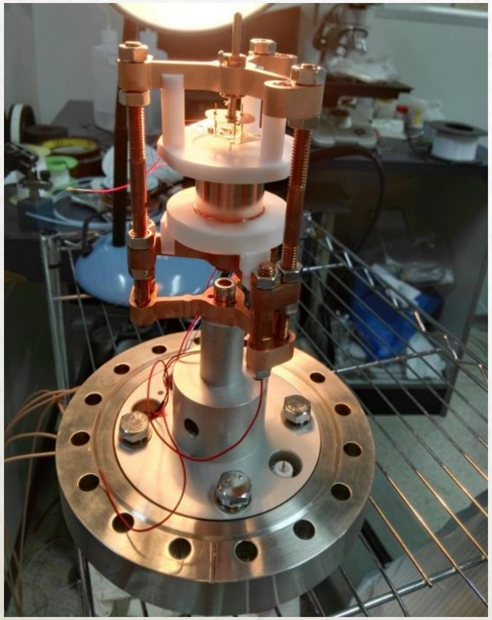


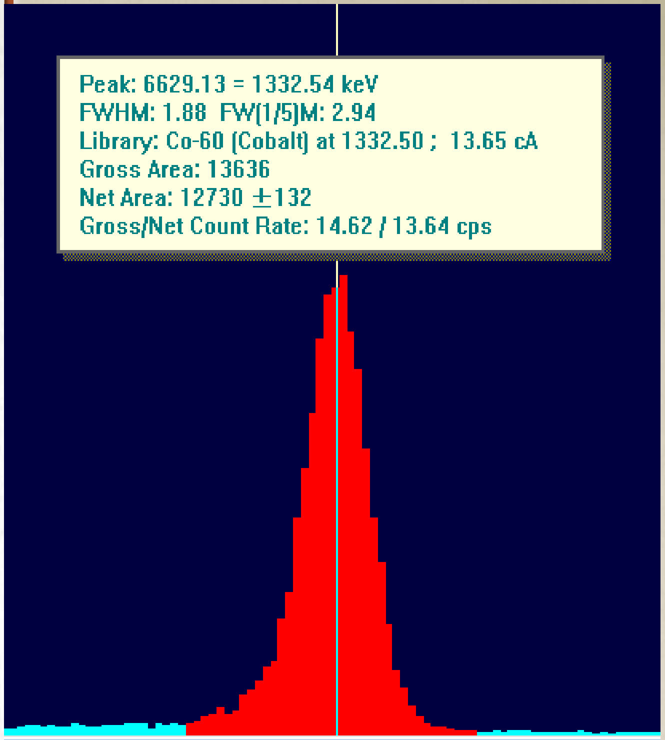




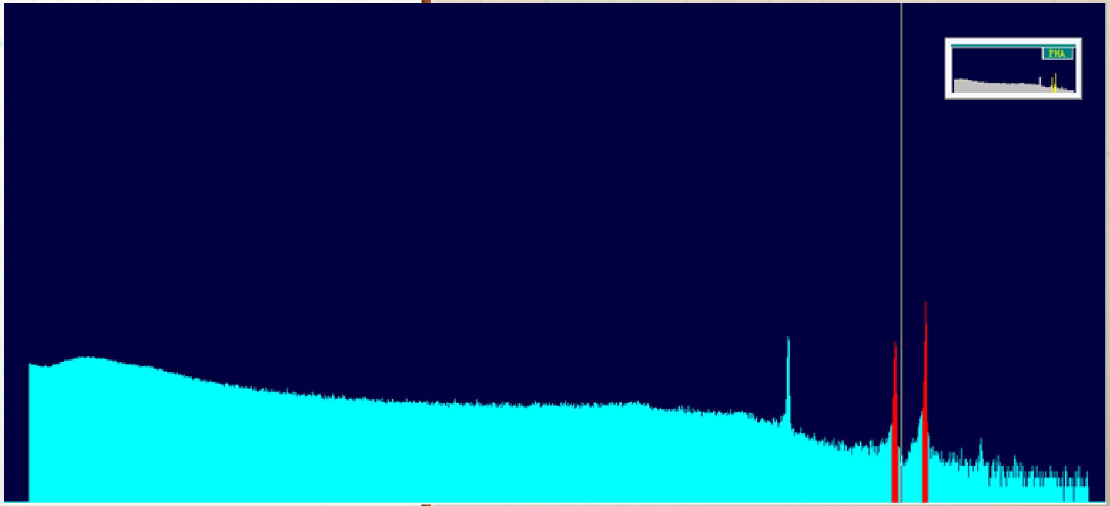
CDEX-10X







FWHM=1.88keV@Co-60



具有内部放大机制的高纯锗探测器

- 目标：实现低于100eV的探测阈值；
- Silicon APD：
  - 增益：100-10000；
  - 灵敏体积：~mm^3
- HPGe 平面探测器：
  - 灵敏体积：~100 cm^3；
  - $K = 2^{h/l}$，（h：雪崩区的高度，0.5 μm；l：电子自由程，5μm）
  - 增益K可以达到1000；
  - 阈值：12 eV

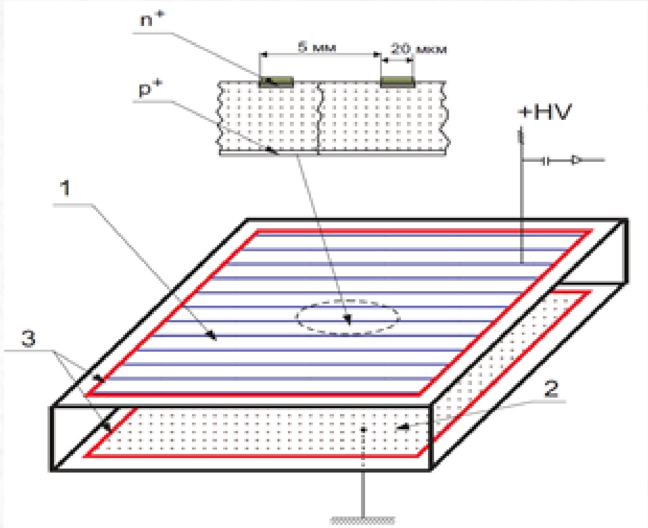


Fig. 5: Ge detector with internal amplification [64]. Shown in the upper part are: 1 – anode strips, 2 – cathode, 3 – guard electrodes, the scheme of n+ and p+ - layers.

理论设计模型

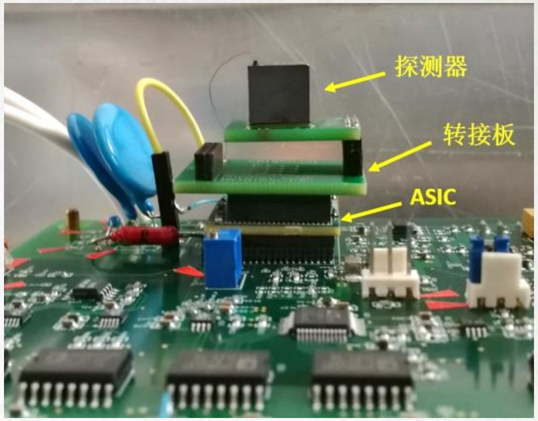
CZT探测器—三维位置灵敏

Pixel 像素

- “小像素效应”，电子学复杂
- Michigan 近二十年的研究
- 20×20×15 mm³ ,121 像素
- 三维位置灵敏与校正，**3D CZT**
- ~1.1% @662 keV （或者<0.8%）
- 可用于康普顿成像

- ASIC是必需的；
- BNL & Michigan
- Ideas公司
- Harvard大学
- 。。。

清华大学基于Ideas ASIC的探测器模块



- 高密度；
- 低噪声：~200e
- 低功耗：~2 mW/ch

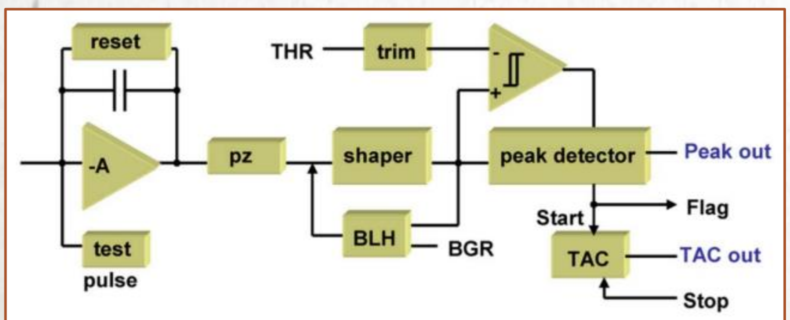


Fig. 3. Block diagram of the anode channel.

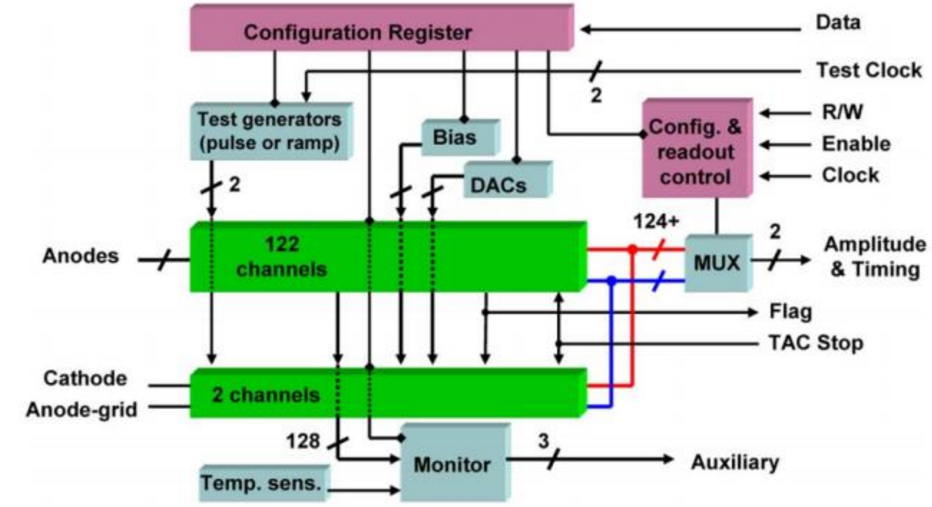


Fig. 2. Block diagram of the ASIC.

3D CZT的应用

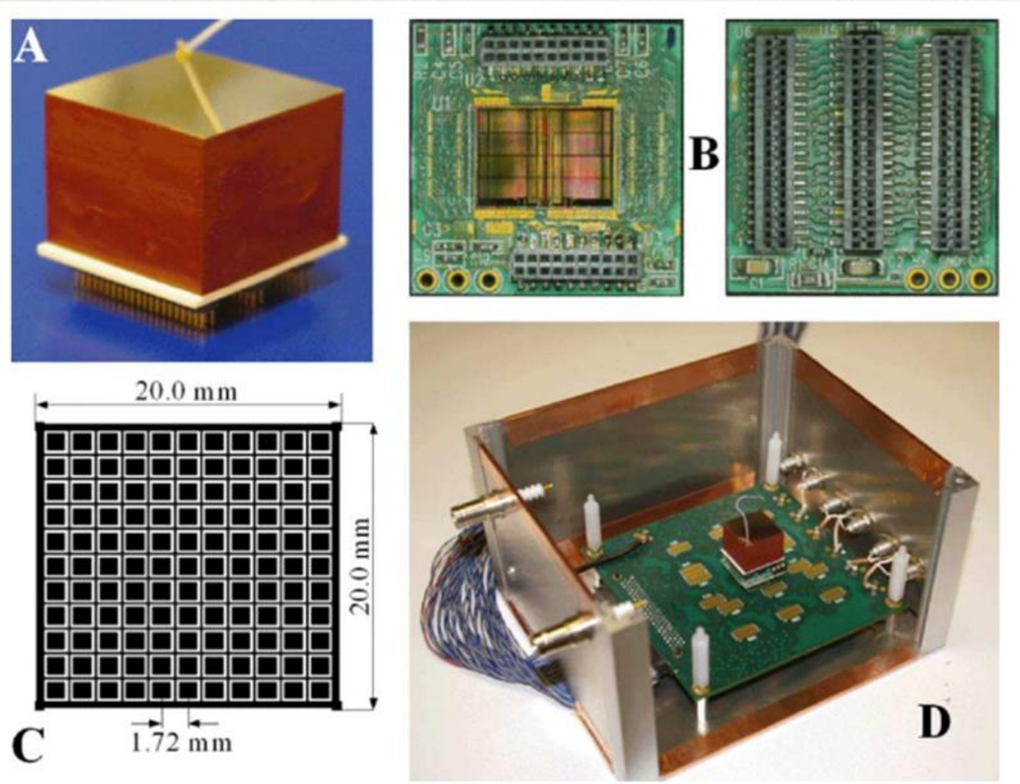
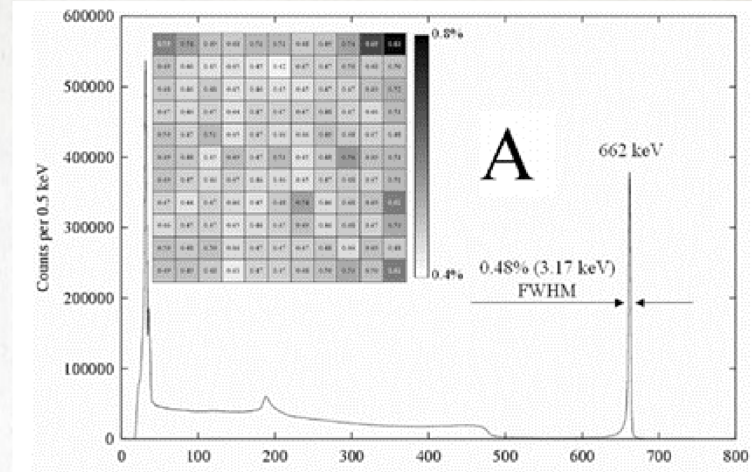


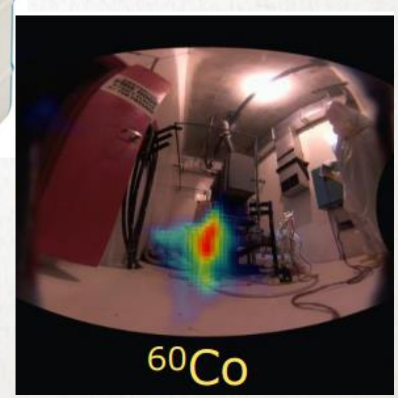
Fig. 1. (A): A 20 mm × 20 mm × 15 mm CdZnTe detector made by eV-Products. (B): The top and bottom views of H3D ASIC front-end board designed by Brookhaven National Laboratory. (C): The common-grid pixelated anode pattern. (D): One assembled detector module mounted on the motherboard.

Michigan大学基于BNL的ASIC所研发的探测器系统

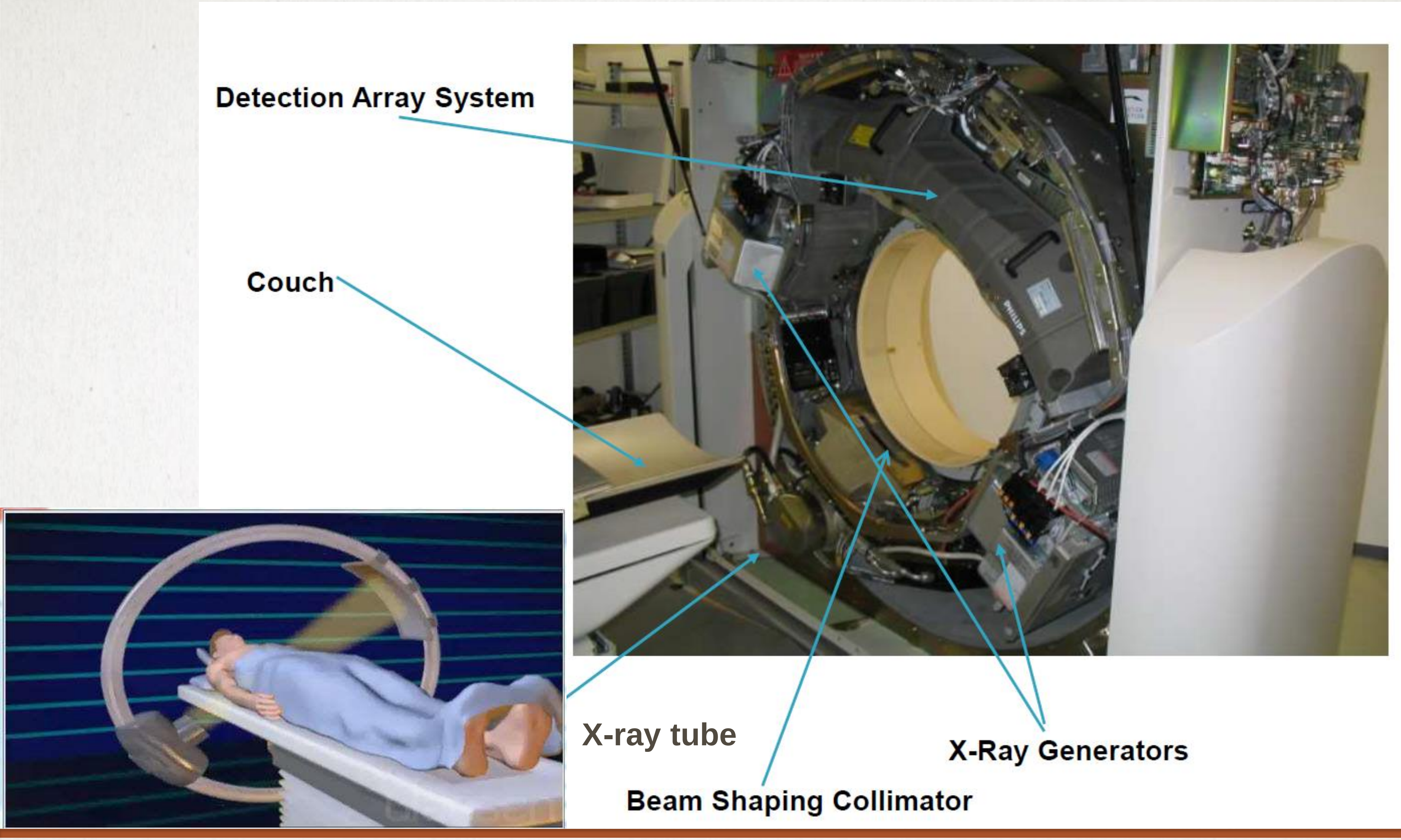
- 能谱测量



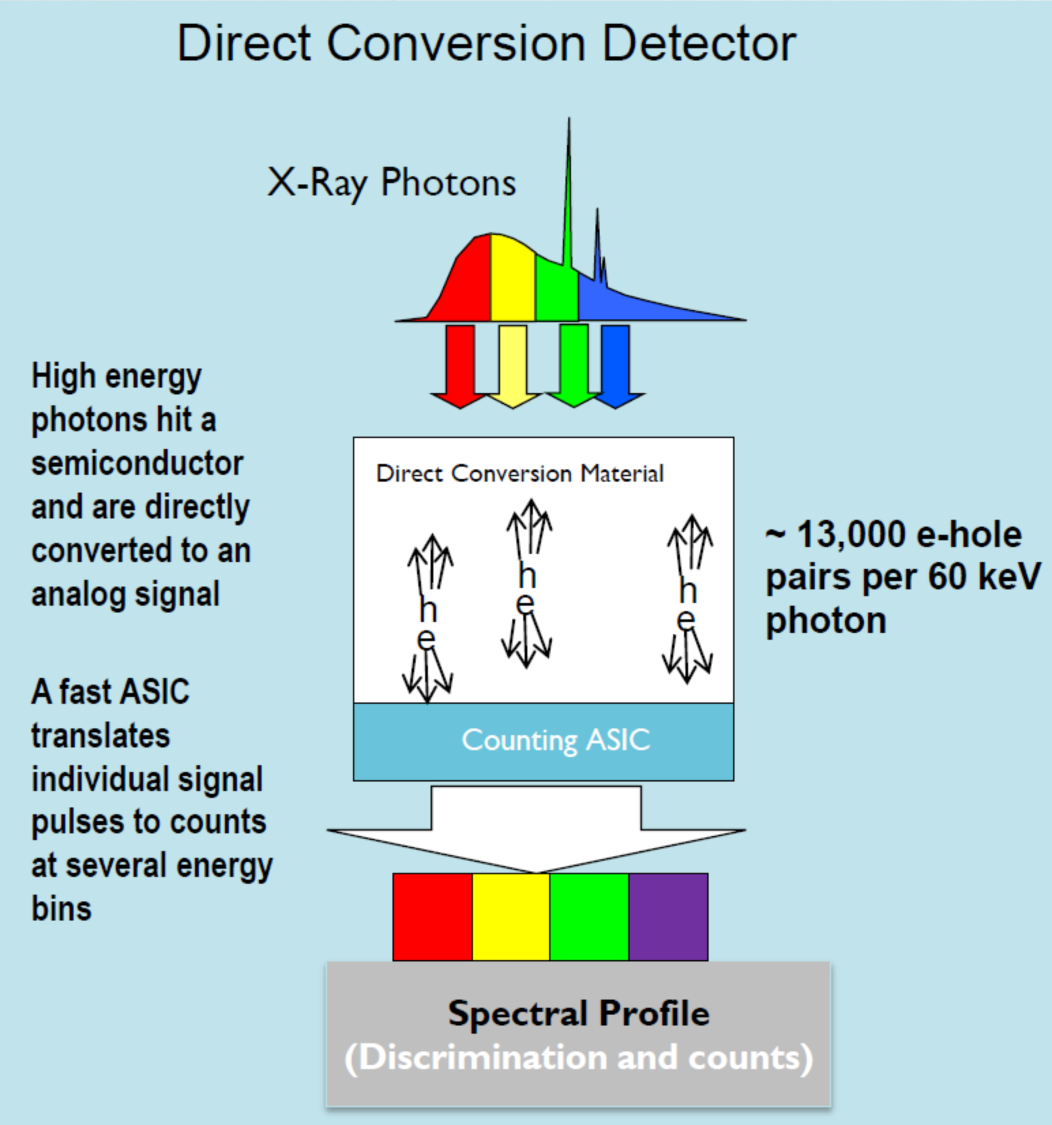
- Compton成像

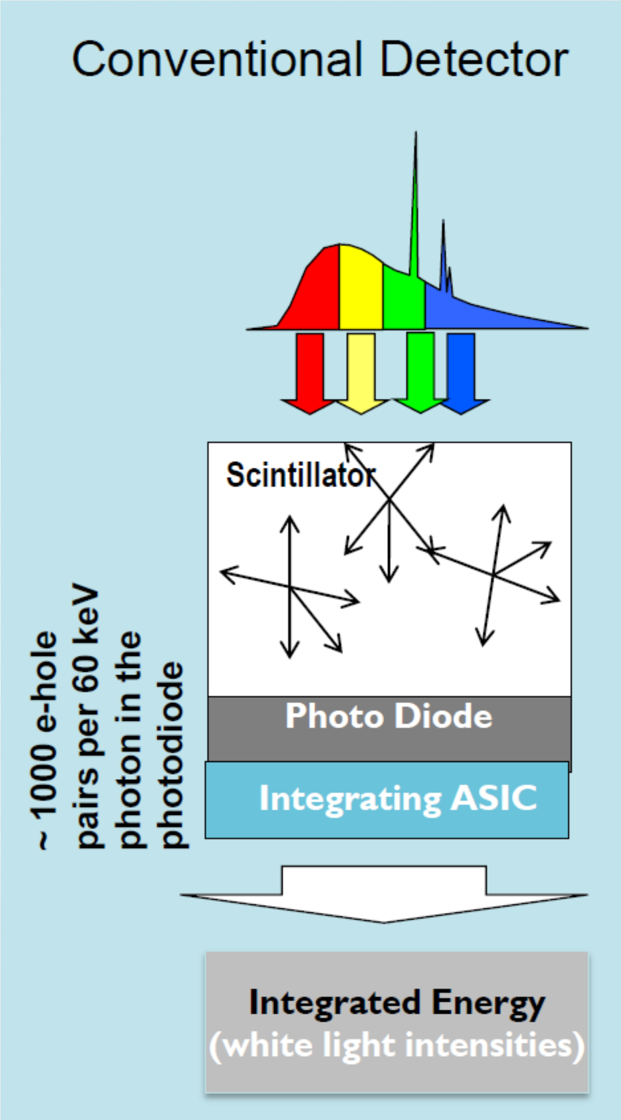


CT系统


Detection Array System
Couch
X-ray tube
X-Ray Generators
Beam Shaping Collimator

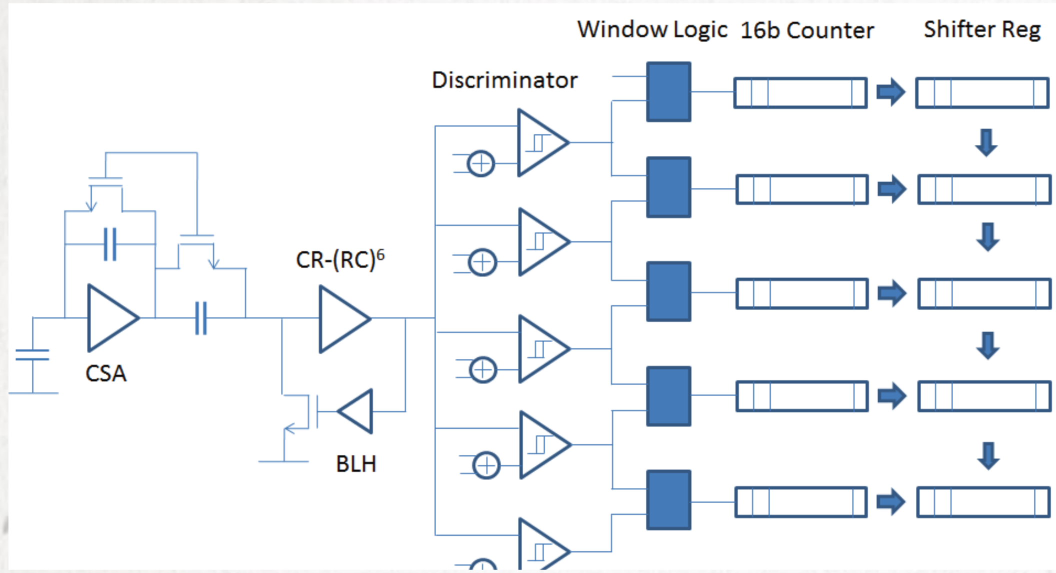
计数式（能谱成像）CT与传统CT





计数式成像-CZT探测器-ASIC

- 积分式成像ASIC已很成熟，并已商业化；
- 技术式成像探测器的关键技术：CZT探测器、ASIC
- 国内外多家单位都在开发：清华、西北工业大学、威视、。。。



清华核电子学
group

Parameters	Value
Gain	150 mV/fC
Peak time	100 ns
Shaper	CR-$(RC)^6$
Dynamic range	8 fC (250 keV @ CZT)
ENC	<500 e @ 2pF
Power consumption	<4 mW/ch
Channel no.	32
Process	0.18 μm CMOS

- **总结：**
  - 无论基础研究还是核技术应用都对探测器系统提出了更高的要求；
  - 要满足这些要求，离不开先进的电子学；
  - ASIC的应用已非常普遍；
  - 更为先进的技术是：探测器与电子学一体化：Hybrid;
  - 国内的微电子技术发展空间还很大。

谢谢大家！