Development of a PET module using Silicon Photomultipliers as Photon Detectors

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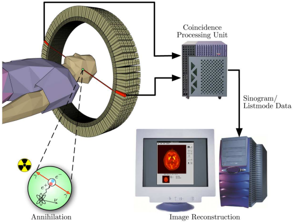
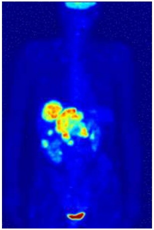
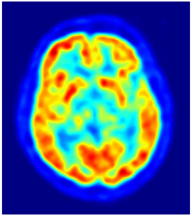
4. Summary

Positron Emission Tomography?

- Nuclear Imaging technique often used for medical imaging.
  - β^+ emitter added to tracer molecule
  - Can be used to study functional processes in the body
- Indirectly measures the 3D distribution of emitted positron radiation.
  - Back-to-Back γ's from e^+e^- annihilation are measured

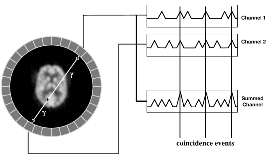


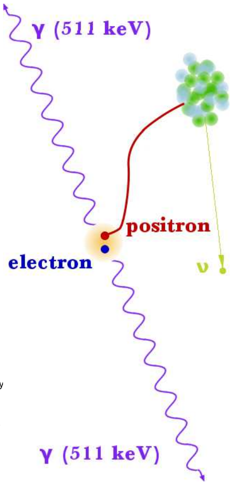




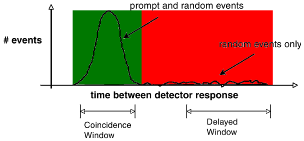
Basics of PET

1. Positron (β^+ decay) slows down in tissue
2. e^+e^- annihilation $\rightarrow$ 511 keV γ pair
3. To measure distribution of annihilation events requires:
   - Coincidence measurement γ pair $\rightarrow$ line of response (LOR)
   - Segmented detector ring for 360° or 2 rotating modules



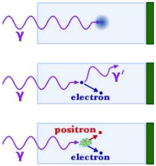


Accept events within coincidence time window
&
Reject events outside coincidence time window



Photon Interaction with Matter

- Photon can interact with material in 3 ways:
  - Photo-electric effect → entire photon energy is absorbed → full energy measured
  - Compton scattering → photon scatters on e^- & some energy is transfered to e^-
  - Pair production → γ interacts with a nucleus & e^+e^- pair is produced (requires $E_\gamma \geq 2\times 511 keV$) → no issue for PET



Compton Scattering:

↓

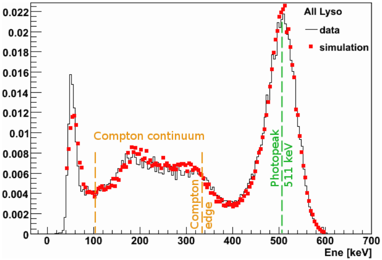
electron-photon energy sharing!

$$E'_\gamma = E_\gamma \frac{1}{1+\epsilon(1-\cos\theta_\gamma)} \quad \& \quad \epsilon = \frac{E_\gamma}{m_e c^2}$$

$$E'^{min}_\gamma = \frac{E_\gamma}{3} \text{ for } \epsilon \rightarrow 1 \ \& \ \theta \rightarrow 180^\circ$$

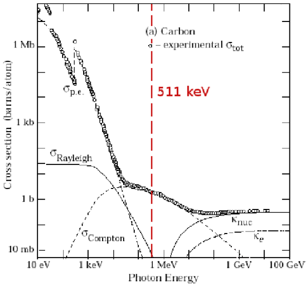
$$\downarrow$$

$$E^{max}_{e^-} = E_\gamma - E'^{min}_\gamma = \frac{2}{3} E_\gamma \qquad E^{max} \approx 340 \ keV$$

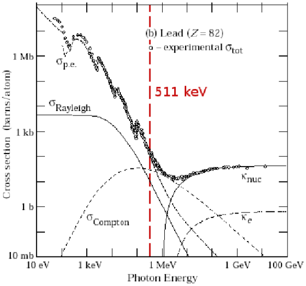


Photon Interaction with Matter

- Cross section of γ interaction is Z-dependent:
  - Photo-electric effect (PE) $\propto E^{-3.5}\ Z^5 \rightarrow$ dominant at low energies BUT strongly dependent on Z
  - Compton scattering (CS) $\propto Z \ln E/E \rightarrow$ dominant at medium energies & only linearly dependent on Z



Carbon $\rightarrow$ Z=6

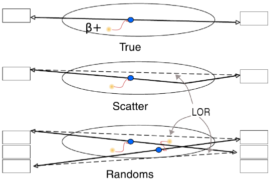


Lead $\rightarrow$ Z=82

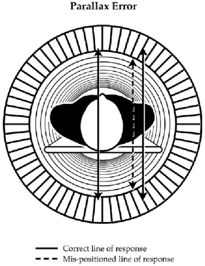
very important for maximizing scintillator efficiency!

Fundamental limits of PET

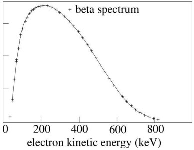
- Range effect → e^+e^- annihilation not at location of β^+ decay (few mm)



- Incorrect Line of Response (LOR) effects:
  - Compton scattering of γ's in tissue and material in the path of the γ → angular deviation on LOR
  - Random events coupled incorrectly to each other
  - Parallax error when LOR is at edge of transaxial view PET scanner
- β^+ emitter has to be chosen based on:
  - half-life $t_{1/2}$ → minimise absorbed dose vs good measurement statistics
  - Energy spectrum of β^+ decay → range

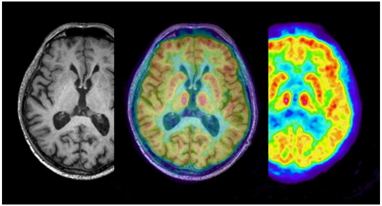


Isotope	$t_{1/2}$ (min)	E_{av} (MeV)	R_{av} (mm)
^{11}C	20.4	0.385	1.7
^{13}N	10	0.491	2.0
^{15}O	2	0.735	2.7
^{18}F	109.8	0.242	1.4



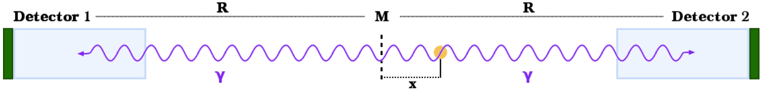
PET and MRI

- Why combine MRI scan with a PET scan?
  - MRI → tissue identification
  - PET → physiological and biochemical tissue activities
  - Combine MRI & PET scanners for ease of alignment and increased accuracy
- Requires magnetic field (MRI!) insensitive photon detectors
  - classical PMT's (~~magnetic field~~, expensive, fragile, power)
  - Silicon Photomultipliers (magn. field insensitive, can be cheap, robust, low power)

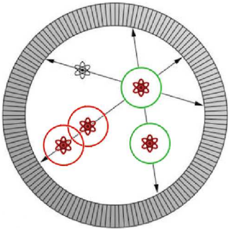


left	MRI image
middle	Combined MRI & PET image
right	PET image

Time of Flight PET

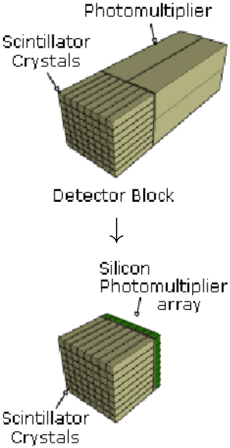


- Use time difference between detection of back-to-back γ's
  - ~~Infinitely sharp~~ timing $\rightarrow x = \frac{\Delta t \cdot c}{2}$
  - Detector timing resolution $\sigma_t \rightarrow x + \sigma_x = \frac{\Delta t \cdot c}{2} + \frac{\sigma_t \cdot c}{2}$
- Better σ_t $\rightarrow$ more accurate position
  - Speed of light 33 ps/cm $\rightarrow$ ~~sub-cm resolution~~ $\rightarrow$ ~~improve spatial resolution~~
- If $\sigma_x <$ size of emission source:
  - distance between annihilation events $> \sigma_x \rightarrow$ decouple events
  - distance between annihilation events $< \sigma_x \rightarrow$ ~~decouple events~~
  - improvement of S/N

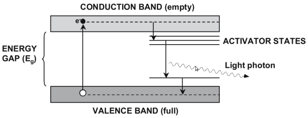


PET Module Requirements

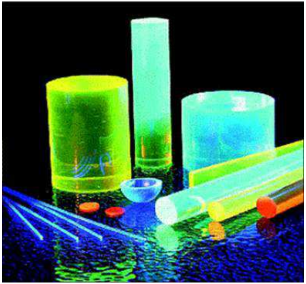
- PET module should consist of:
  - Scintillator $\rightarrow$ convert γ into light
  - Photon detector to detect the scintillation light
- Ideal characteristics of PET module:
  - High stopping power (total absorption of 511 keV γ)
  - High spatial resolution $\rightarrow$ detector segmentation
  - Good Energy resolution $\rightarrow$ rejection of scattered events
  - Inexpensive
- Additional requirements for components:
  - Magnetic field insensitive detectors $\rightarrow$ PET & MRI
  - Very fast detectors (sub-*ns* range) $\rightarrow$ ToF to improve S/N
  - Silicon Photomultiplier $\rightarrow$ promising candidate as photon detector for ToF PET & MRI combination (B-field insensitive, fast, relatively cheap $\rightarrow$ segmentation, ...)



Scintillators



- Convert γ to visible light:
  - Visible light is easiest to detect (shallow penetration depth)
  - Scintillation crystal has to be clear material
- Production of scintillation light:
  - γ interacts with e^- in crystal valence band $\rightarrow$ creates photo-e^-
  - Photo-e collides with e in valence band $\rightarrow$ multiple e get excited
  - each e in conduction band decays $\rightarrow$ emits a photon
- A good candidate for ToF PET should have:
  - Fast decay time $\rightarrow$ ToF information
  - High light yield $\rightarrow$ energy resolution & ToF
  - High density $\rightarrow$ high stopping power $\rightarrow$ small crystals for fine segmentation
  - Preferably non hygroscopic $\rightarrow$ easy to handle



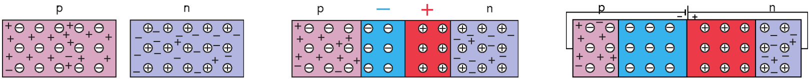
Scintillator Materials

Physical properties of some scintillator materials often used for PET

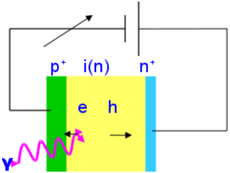
Scintillator Material	Density (g/cm^3)	Absorption length (cm)	Light Yield (% NaI)	Decay time (ns)	Wavelength (nm)
BGO	7.13	1.04	20	300	480
LYSO	7.1	1.2	75	40	420
NaI:Tl	3.67	2.91	100	230	410
GSO	6.7	1.41	20	60	440
LuAP	8.3	1.05	30	18	365
$PbWO_4$	8.28	0.85	1	15	440

Solid-state Photon Detectors

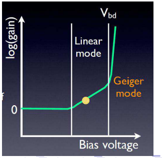
- p-doped Si + n-doped Si → depletion region (↑ with V_{bias} ↑!)



- Internal Photo-effect converts visible light into an e-h pair ($\sim$ 1.1 eV needed)
- Si-Photodiode:
  - Visible light is absorbed within $\sim 1\ \mu m$ → very thin p layer
  - High QE (80% $\lambda \approx 700\ nm$)
  - No gain: ~~single photon detection~~

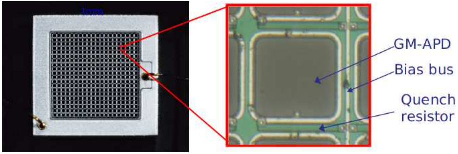


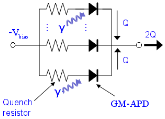
- Avalanche Photodiode:
  - High reverse bias voltage, typically 100-200 V
  - High gain, typically 100-1000
- Very high gain ($\sim 10^5$-10^6) with Avalanche Photodiode operation in Geiger-mode!

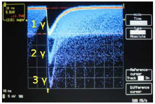


Silicon Photomultiplier

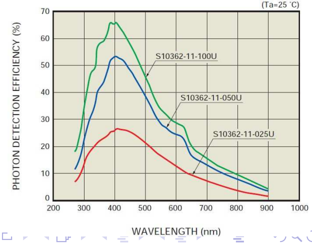
- Array of Avalanche Photo-Diodes (APD) operating in Geiger Mode
- Geiger discharge $\rightarrow$ dead time of APD $\rightarrow$ 1 photon / APD!
- Array of APD's $\rightarrow$ dynamic range of SiPM, ~~position sensitivity~~!





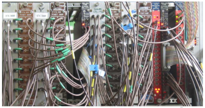


- Advantages:
  - Low operation voltage ~ 10-100 V
  - Gain $\sim 10^6$
  - peak Photon Detection Efficiency (PDE) up to 40% (400 nm)
    $PDE = QE \times \epsilon_{Geiger} \times \epsilon_{geo}$ (ϵ_{geo} ~ dead space between cells)
  - Time resolution ~ 100-200 ps
  - Works in magnetic field
- Disadvantages:
  - Dark Counts ~ several 100 kHz/mm^2
  - Radiation damage (p, n), but not an issue for PET

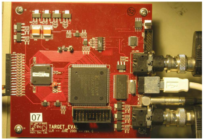


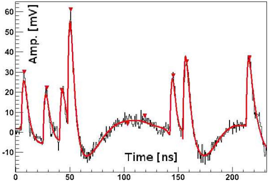
Readout Electronics for Waveform Sampling

- Digital sampling of electronic signal:
  - Switched Capacitor Array (SCA) stores total signal
  - Charge on each capacitor is measured → sampled waveform
  - Rebuild waveform for testing (slow readout)
  - Analyse waveform on FPGA (fast readout)
- Very POWERFULL tool because:
  - Incorporate waveform analysis algorithms on FPGA for deconvolution of piled-up signals (~~classic electronics~~)
  - QDC and TDC all in 1 device!
  - High density of channels, cheap (VLSI), fast (up to 20 GSa/s), FPGA → flexible, low power



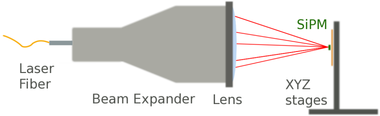
V.S.



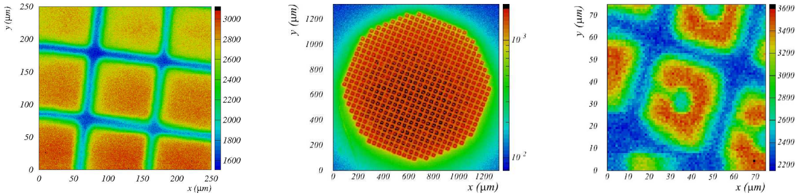


Silicon Photomultiplier: Surface Sensitivity

- Setup for position scan
  - Single photon light intensities → light filters
  - Beam expander → parallel light → strong lens for sharp focus
  - Focus needs to be < pixel pitch

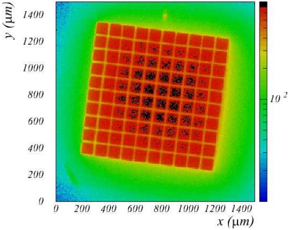


- Position scan → internal structure of SiPM:
  - Internal SiPM structure determines ϵ_{geo} which mainly determines PDE of SiPM
  - Higher ϵ_{geo} → better energy resolution → improved S/N
  - Full surface scans → overall uniformity of sipm



Linearity of SiPM

- Finite number of SiPM pixels
  - Limited dynamic range
  - Linear behaviour $\propto$ number of pixels
  - Pixel has dead time when it discharges $\rightarrow$ non-linear behaviour when N_{phot} approaches N_{pix}
- Hamamatsu S10931-100P(X):
  - 900 pixels with 100μm pitch
  - radioactive samples with different decay energies used: ^{22}Na (511 keV & 1230 keV γ), ^{60}Co (1173 keV γ), ^{137}Cs (662 keV γ)



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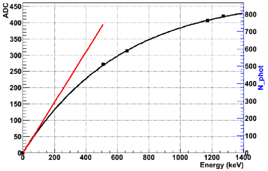
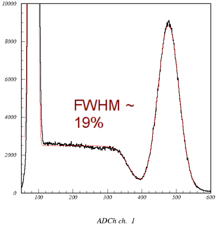


$$ADC = ADC_0(1 - \exp(-\frac{E}{E_0}))$$

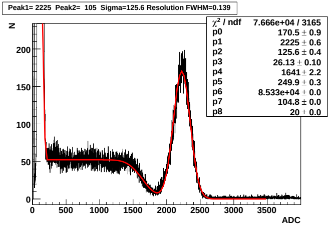
SiPM & LYSO Combination

- Energy resolution:
  - LYSO coupled to SiPM
  - Module energy resolution depends on $FWHM_{LYSO}$ and $FWHM_{SiPM}$
  - LYSO crystals from 2 companies tested (Sinocera & Saint-Gobain)

Manufacturer	Sinocera	Saint-Gobain
LYSO Intrinsic FWHM	20%	8%
Light Yield (NaI)	75%	75%
Peak Emission Wavelength	428 *nm*	420 *nm*



STMicroelectronics + Sinocera LYSO
19% FWHM

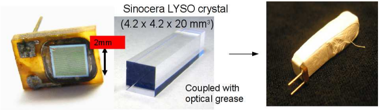


STMicroelectronics + Saint-Gobain LYSO
14% FWHM

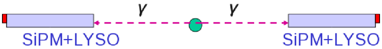
NO correction for non-linear behaviour!

Single Photon & Back-to-Back Gamma

- SiPM intrinsic timing limits the coincidence timing of back-to-back γ's?
  - Measure intrinic timing with single photon level
  - Different companies
  - Wavelength dependence of intrinsic timing?

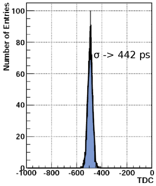


- Single Photon timing resolution:
  - Very short pulses $\rightarrow$ $<$ 40 ps laser pulse width
  - Red & Blue light



$1mm^2$ SiPM	S137	H100C
$\sigma_{red}(ps)$	182	145
$\sigma_{blue}(ps)$	151	136

- Timing resolution of back-to-back γ's?
  - Scintillator light used $\rightarrow$ threshold level at several photon
  - Threshold influences back-to-back timing resolution!
  - Preliminary result (Hamamatsu) $\rightarrow$ $\sigma_t = 442$ ps



Summary

Positron Emission Tomography:

- Measure 3D distribution of e^+e^- annihilation to determine β^+ tracer distribution (medical imaging)
- Combine PET & MRI $\rightarrow$ B-field insensitive detectors (SiPM)
- ToF PET $\rightarrow$ improve S/N
- γ detection requires:
    - γ conversion $\rightarrow$ LYSO scintillator (fast, high light yield)
    - Light detection $\rightarrow$ SiPM as photon detector
- Waveform sampling:
    - Development of waveform analysis was started and shows promising

Simple PET module $\rightarrow$ SiPM + LYSO:

- Different scintilator crystals have been tested $\rightarrow$ production has an influence on energy resolution
- Timing resolution for 2 back-to-back γ's in the sub-ns range (< 500 *ps*)
- Promising for ToF PET