The Performance of Silicon Photomultipliers in Cherenkov TOF PET

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Introduction

- Contrast of images obtained with positron emission tomography (PET) can be improved by measuring the time-of-flight (TOF) of annihilation gammas
- Time resolution in TOF PET limited mainly by
  - photodetector response
  - scintillation rise and decay time constants
  - optical photon travel time spread in the crystal
- Limitation due to scintillator can be avoided by using Cherenkov light instead
  - produced promptly by a passage of charged particle trough dielectric when speed > c_0/n
- This talk:
  - Use of Cherenkov radiation in TOF PET
  - First experiments with timing < 100 ps FWHM
  - Experimental results using Silicon Photomultipliers (SiPMs)
  - Summary

Use of Cherenkov Radiation in TOF PET

- Comparison between typical scintillation and Cherenkov TOF PET methods:

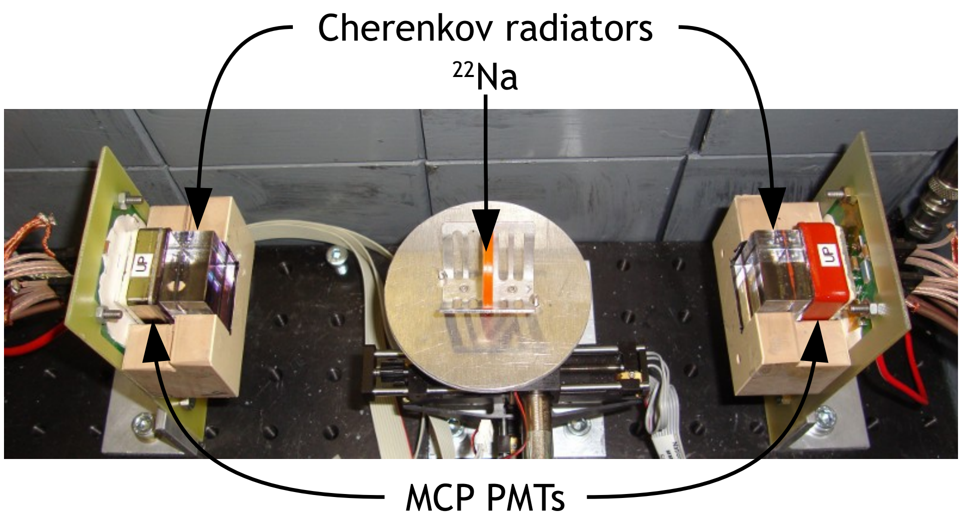
	Scintillator (LSO)	Cherenkov (PbF_2)
<Z>	56	71
μ_{511keV} [cm^{-1}]	0.87	1.06
Photofraction (511 keV) (*)	0.32	0.46
Light Rise/Decay Time	87 ps (†) / 40 ns	prompt
Light Yield [photons/511keV]	15,000	10 (‡)
Light Production Threshold	-	$v_{Thr} = c_0/n$ $E_{e-} > 104$ keV

(*) [XCOM: Photon Cross Sections Database]
(†) [NIM A 767 (2014) 206]
(‡) in 250-800 nm wavelength interval

- Benefits:
  - gamma absorption & photofraction
  - prompt light production
- Drawbacks:
  - single photon detection

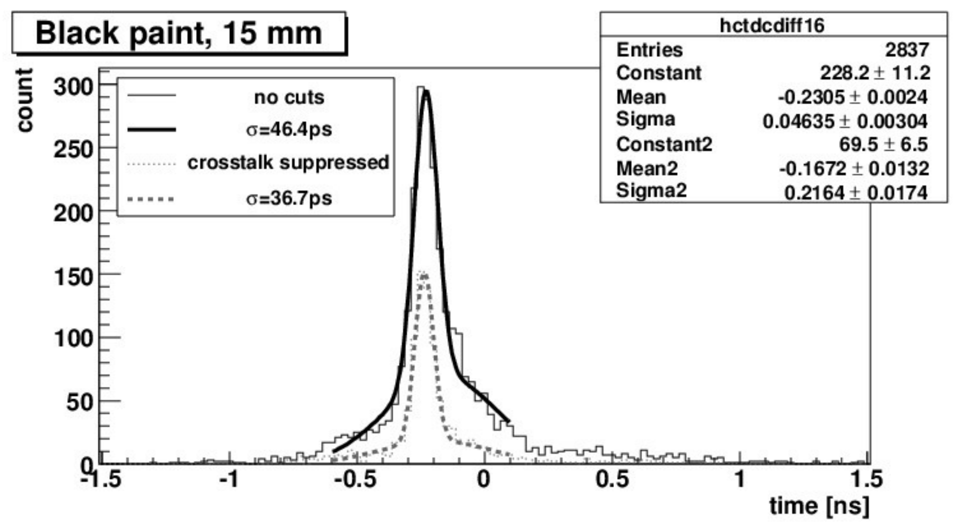
First Experiments

- Two detectors in back-to-back configuration
- Cherenkov radiators: **25x25x(5, 15) mm^3 PbF_2**
- Photodetectors: **microchannel plate photomultiplier tubes** (MCP PMTs)
  - single photon timing ~ **50 ps** FWHM
  - active surface 22.5x22.5 mm^2



- TOF resolution:
  - 5 mm thick, black painted PbF_2: **71 ps** FWHM
  - 15 mm thick, black painted PbF_2: **95 ps** FWHM

[NIM A 654 (2011) 532]

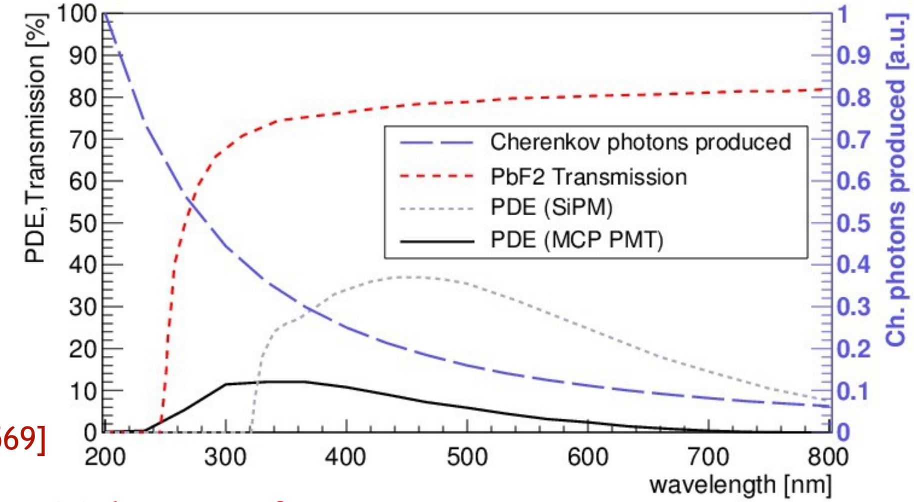


- Single side detection efficiency ~ **6%** [Physics Procedia 37 (2012) 1531]
  - with LSO scintillator in ideal conditions ~ 30%
  - main limitation: photon detection efficiency of MCP PMT samples used

Experiments using SiPMs

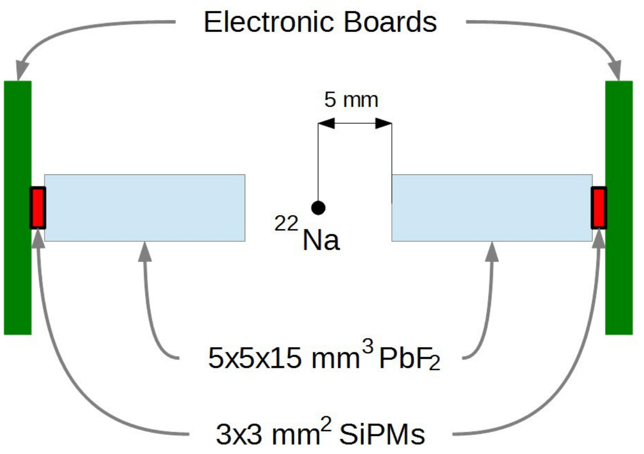
- SiPMs as Cherenkov TOF PET photodetector:
  - **high photo detection efficiency**
  - insensitivity to high magnetic field (PET/MR)
  - potentially low cost
  - slightly limited single photon timing

    ~200 ps FWHM for larger devices [NIM A 718 (2013) 569]
  - **high dark count rates at room temperature (~ 100 kHz/mm²)**



- Experimental setup:
  - 3x3 mm² SiPMs:

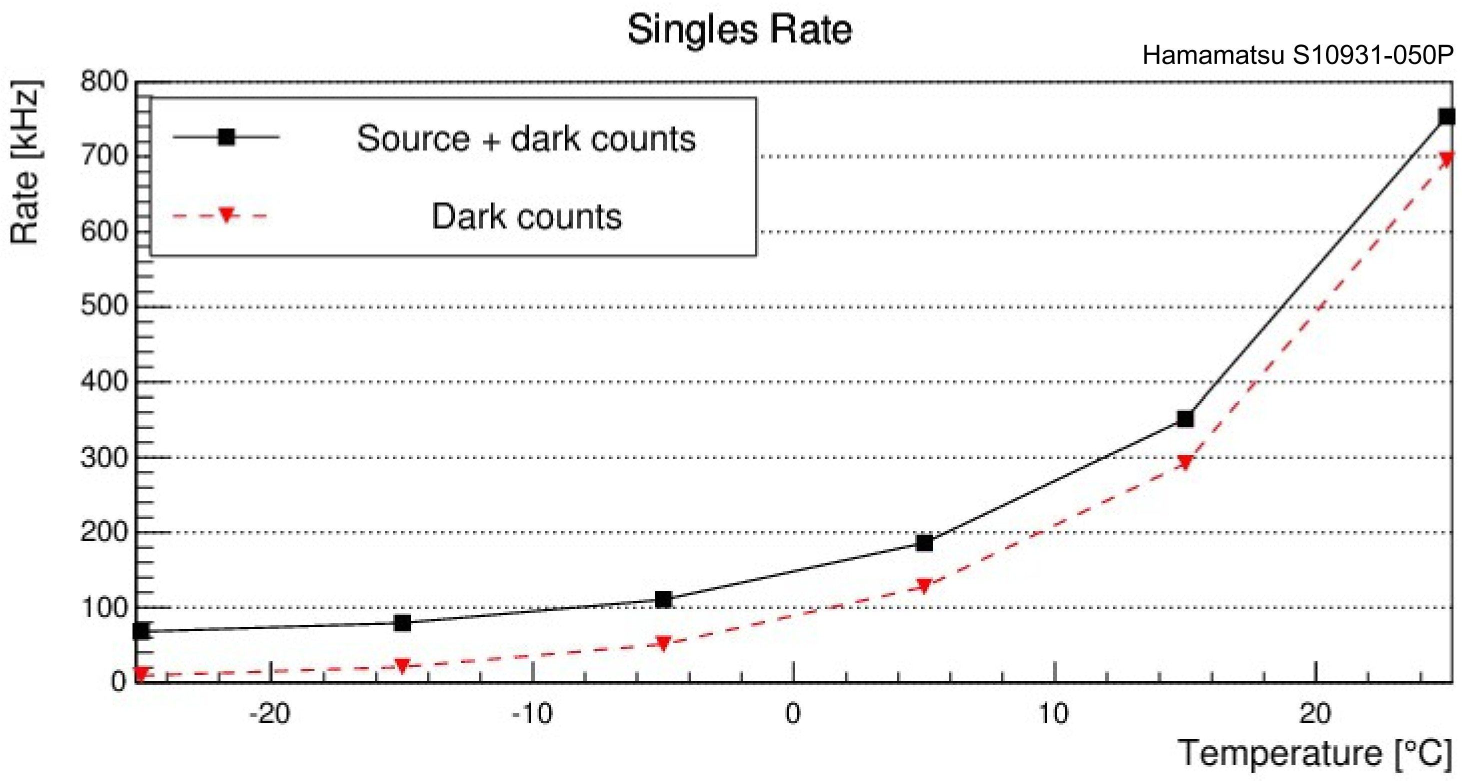
Producer	Model	Pixel Pitch [µm]	Breakdown [V]
Hamamatsu	S10931-050P	50	69
Hamamatsu	S12641-PA-50	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3375TS-SBO	75	25
SensL	MicroFC-30050-SMT-GP	50	25



  - 5x5x15 mm³ PbF_2 (available at the time of measurements)
  - temperature controlled freezer box (down to -25°C)

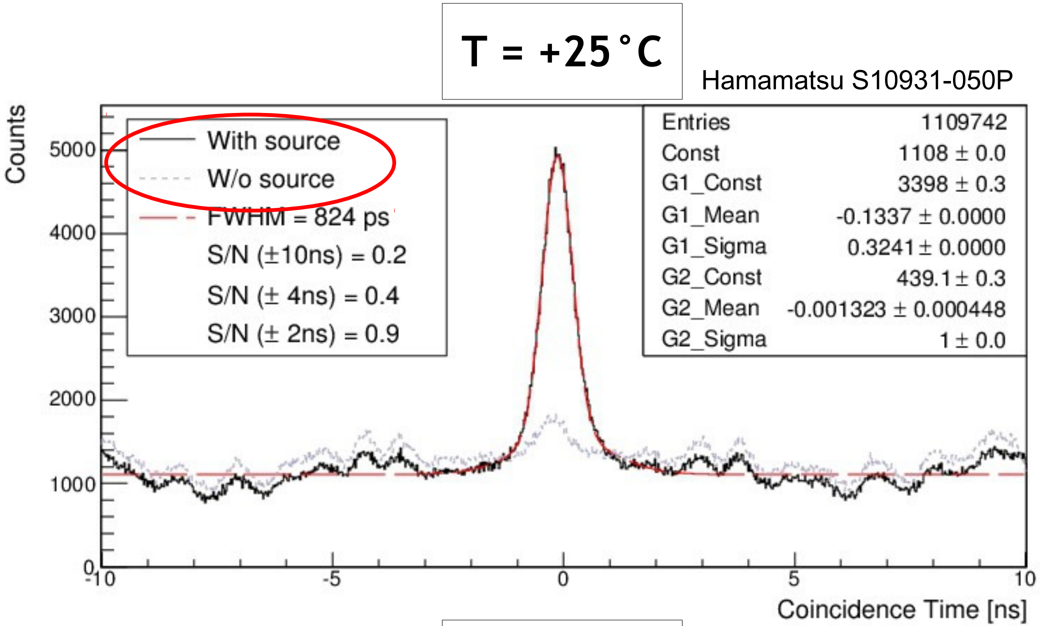
Results (SiPM)

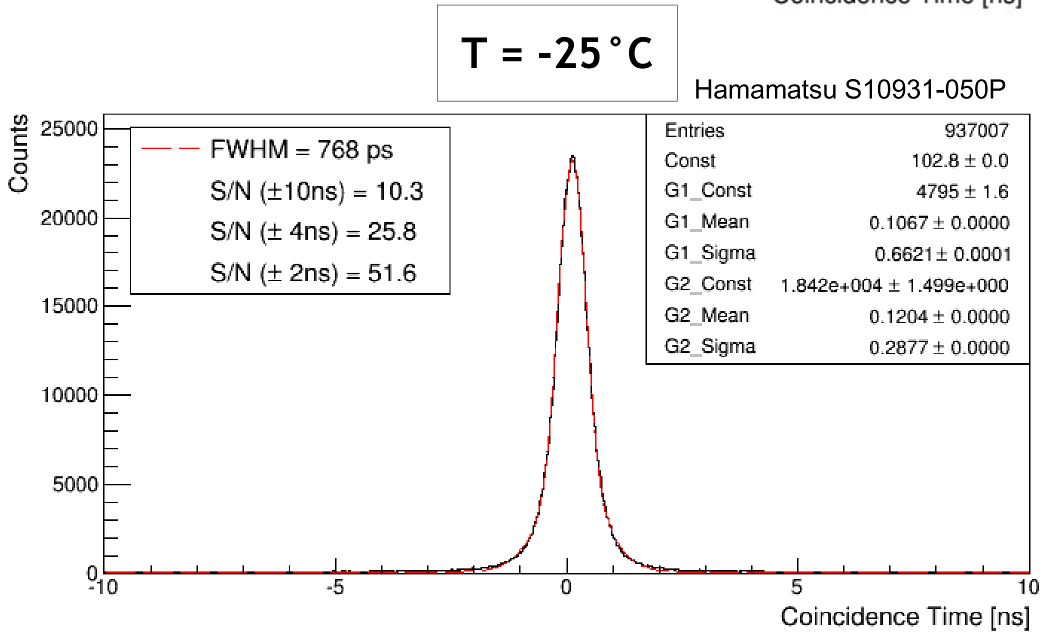
- Dark count rate vs. Temperature
  - Hamamatsu S10931-050P at constant gain (V_{ov} = 1.5V)
  - dark noise reduces with temperature by ~ 2.4x / 10°C



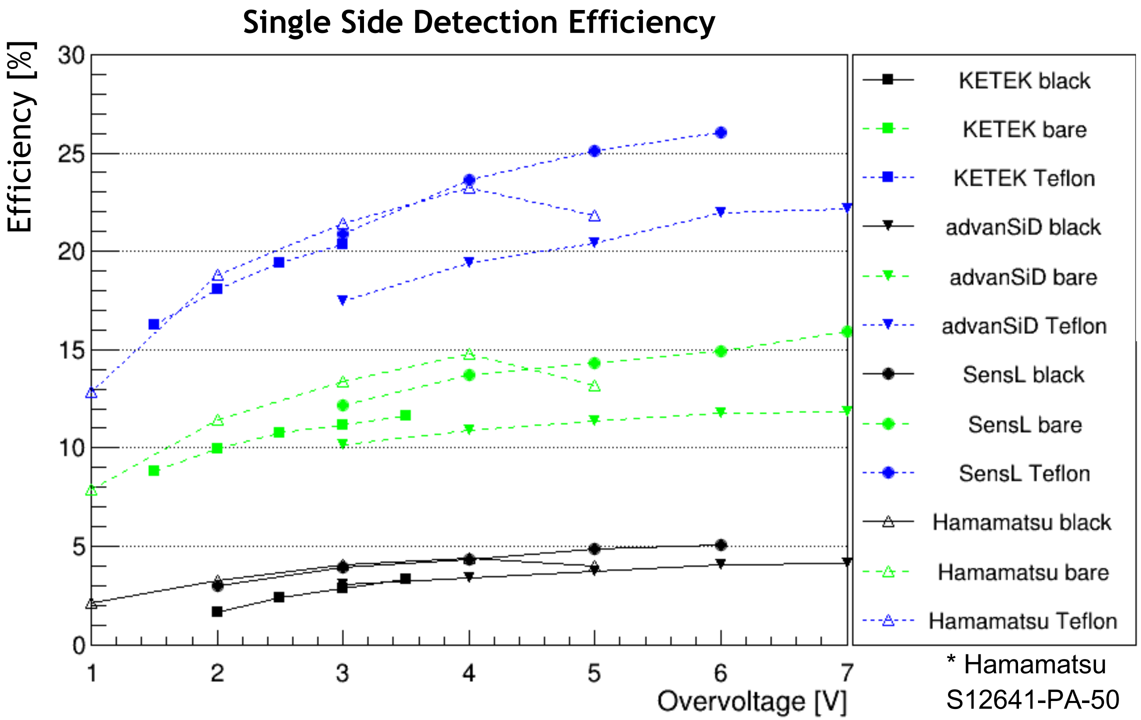
Results (SiPM)

- First results for coincidence timing ~ **800 ps** FWHM
  - Hamamatsu S10931-050P
  - SiPM overvoltage V_{ov} = 1.5V
  - bare PbF_2

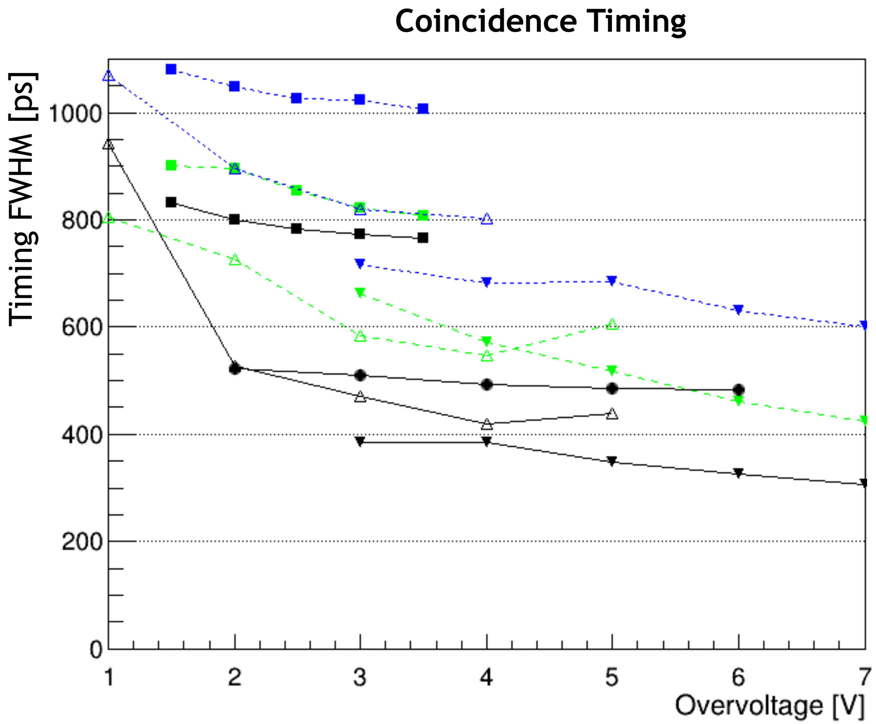




Results (SiPM)



* Hamamatsu S12641-PA-50

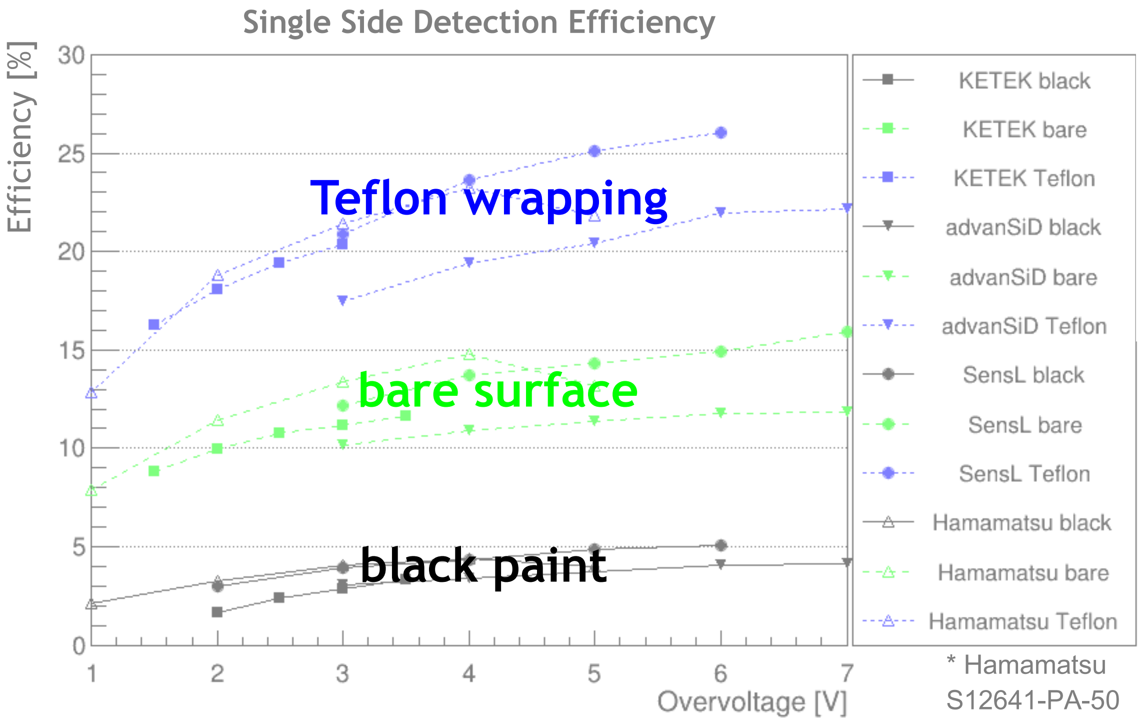


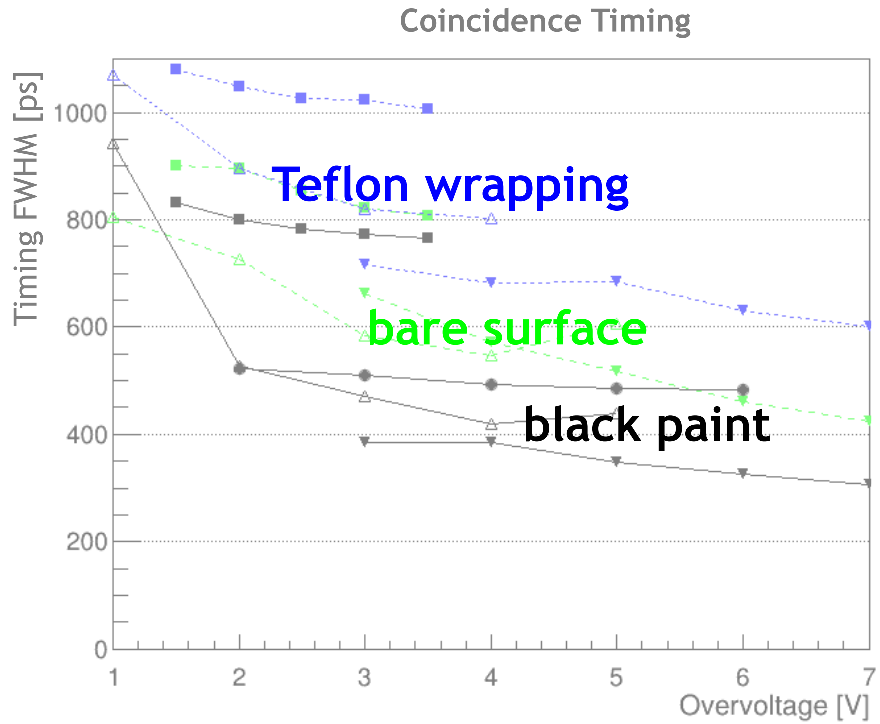
- Singles Efficiency & Coincidence Timing at **T = -25°C** for different:
  - SiPM samples:

Producer	Model	Pixel Pitch [µm]	Breakdown [V]
Hamamatsu	S12641-PA-50	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3375TS-SBO	75	25
SensL	MicroFC-30050-SMT-GP	50	25

  - crystal surface treatments (**black painted**, bare, **Teflon wrapped**)

Results (SiPM)





- Efficiency improves with:
  - SiPM overvoltage
  - surface reflectivity (Teflon wrapping)
- Best: **26%** with SensL

- Timing improves with:
  - SiPM overvoltage
  - suppression of reflections (black paint)
- Best: **306 ps** FWHM with AdvanSiD

Imperfect coupling: 5x5 mm^2 crystals on 3x3 mm^2 SiPMs!

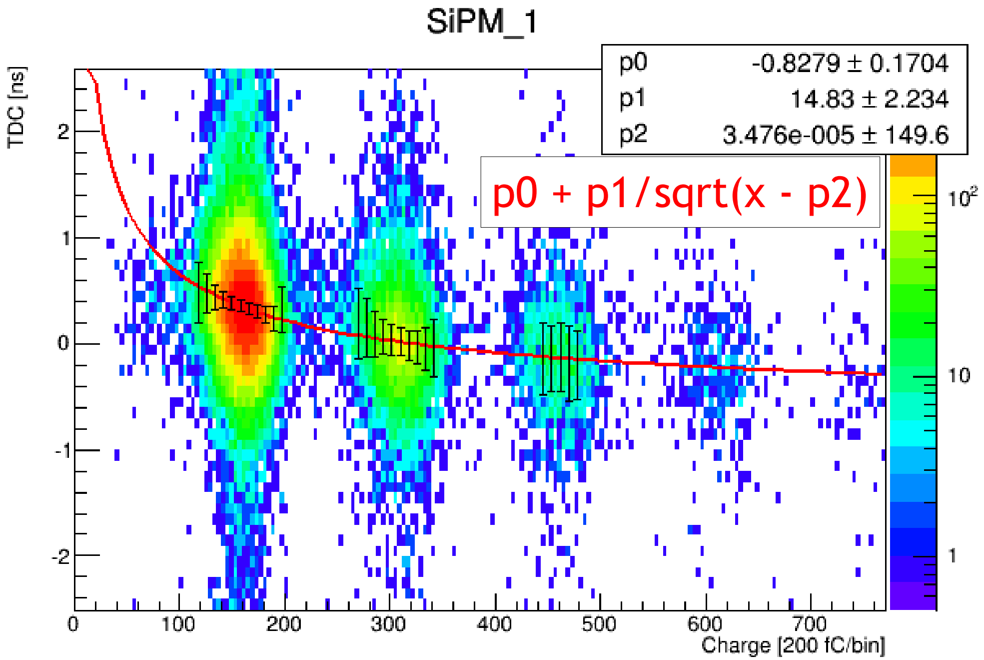
Summary

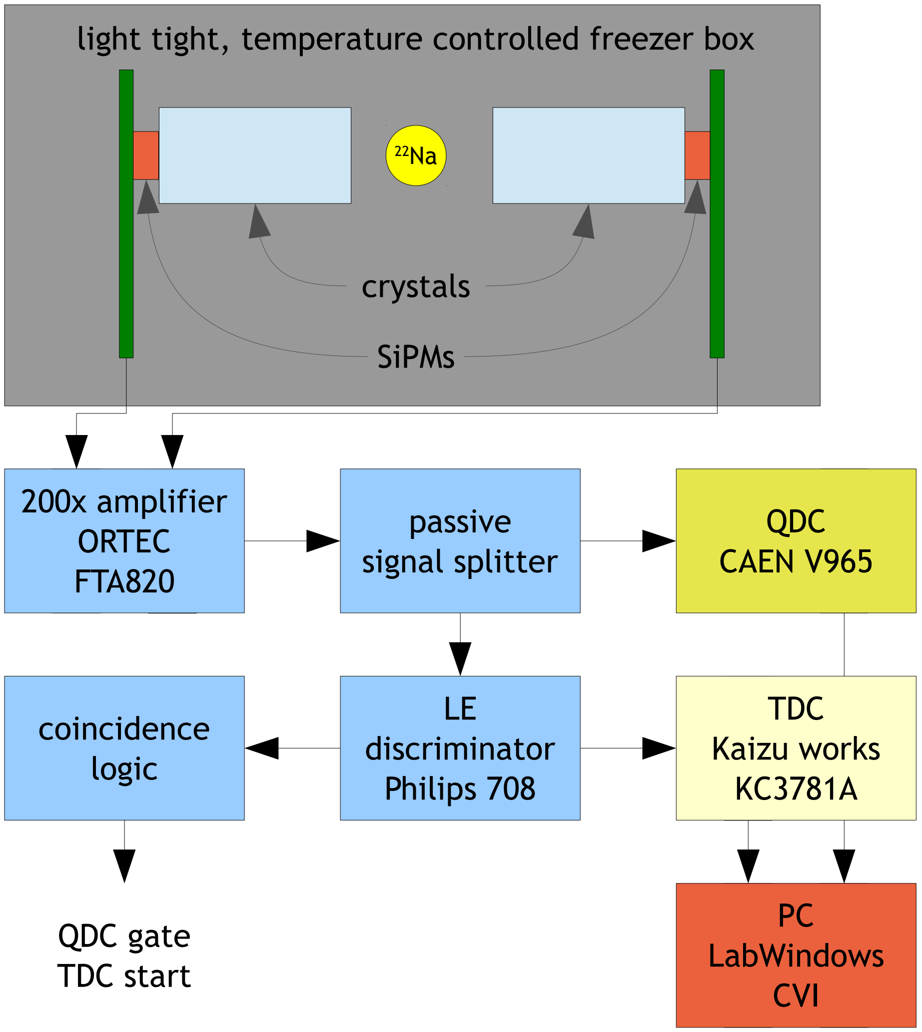
- Cherenkov TOF PET is a promising new method for PET
  - coincidence timing < 100 ps (with MCP PMTs)
  - efficiency competitive to scintillator PET (26% single side with SiPMs)
  - high requirements for photodetector (single photon detection)
  - PbF_2 vs. LSO:
    - significantly lower cost
    - higher Z (better stopping power & photofraction, less scattering)
- SiPMs as photodetectors in Cherenkov TOF PET:
  - very good efficiency
    - could be even better with PDE extended in UV (250 nm) [NIM A 732 (2013) 427]
  - slightly limited timing
    - more suitable device
    - data analysis, electronics, waveform sampling
  - high dark count rates
    - cooling
    - improvements in SiPM technology
  - low cost, operation in magnetic field (PET/MR)

Backup slides

Experimental setup - readout

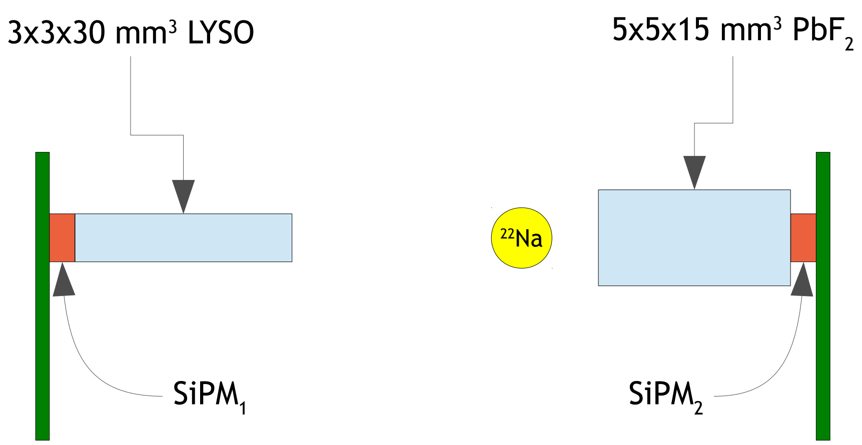
- custom electronics board with NEC uPC2710TB preamplifier
- ORTEC FTA820 amplifier
- Philips scientific mod.708 LE discriminator
- Kaizu works KC3781A TDC (25ps/bin)
- CAEN V965 QDC
- time-walk correction applied in analysis

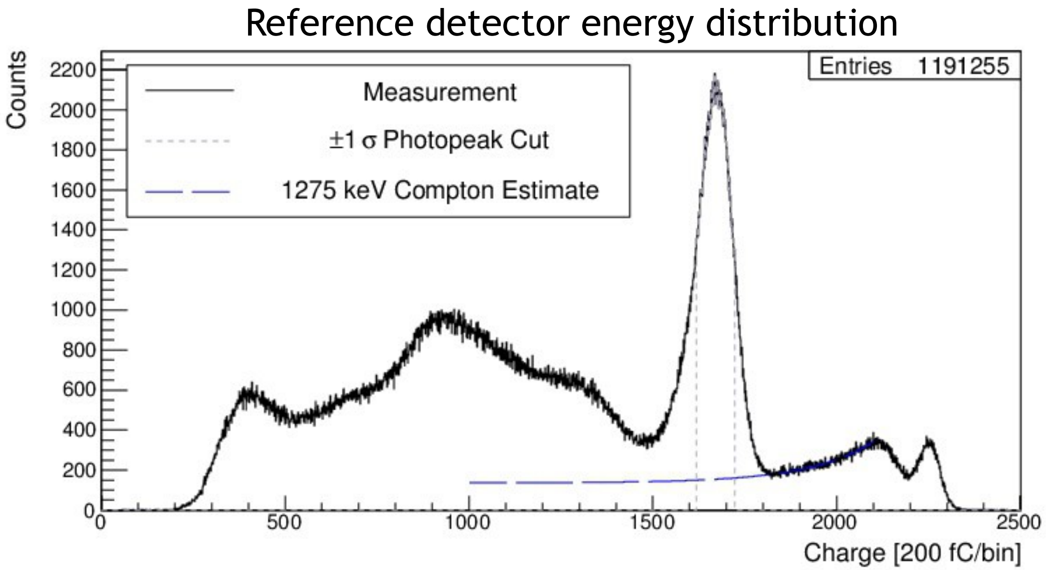




Efficiency measurements

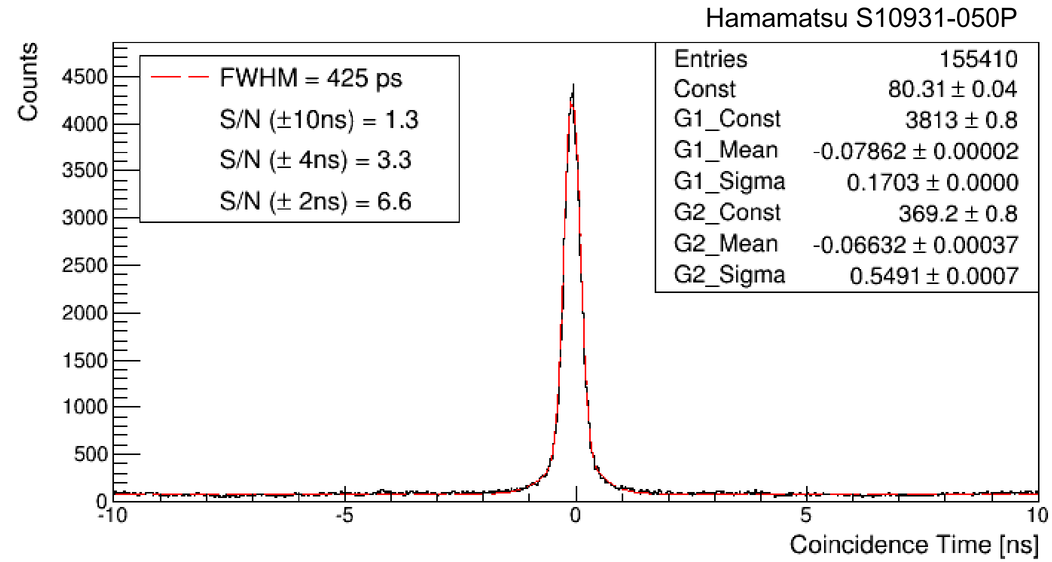
- one Cherenkov detector replaced with a reference scintillation detector
- tight collimation of coincidence gammas on Cherenkov detector
- photopeak cut on reference detector → single side detection efficiency on Cherenkov detector
- corrected for
  - SiPM dark count rate
  - Compton scatter of 1275 keV gammas from ^{22}Na



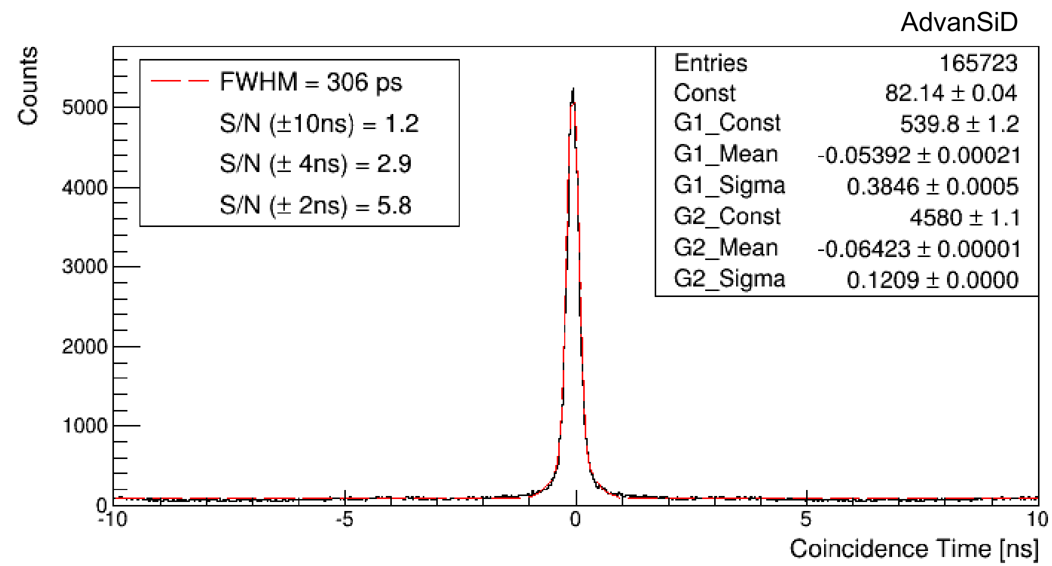


Results (SiPM)

- Improvements in timing: **425 ps** FWHM
  - Hamamatsu S10931-050P
  - V_{ov} = **2.5V**
  - **black painted** PbF_2
  - T = -25°C

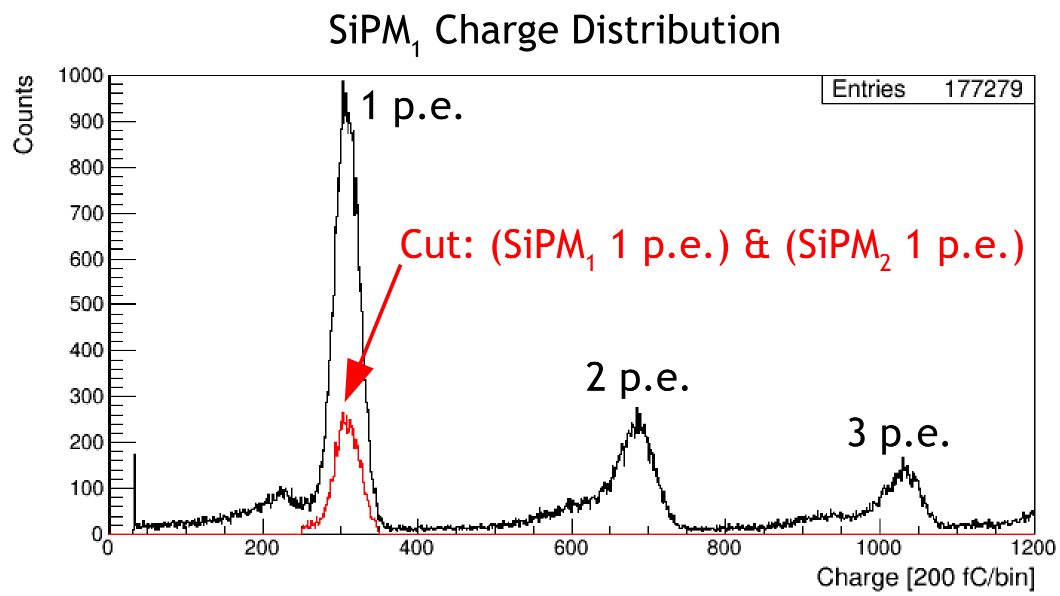


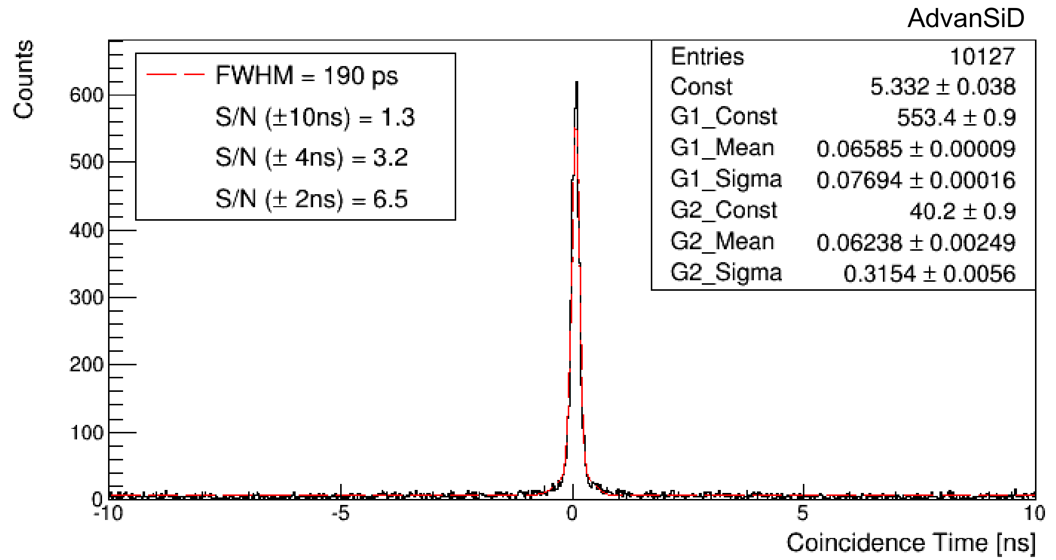
- Best timing so far: **306 ps** FWHM
  - **AdvanSiD**
  - V_{ov} = **7V**
  - **black painted** PbF_2
  - T = -25°C



1 p.e. cut

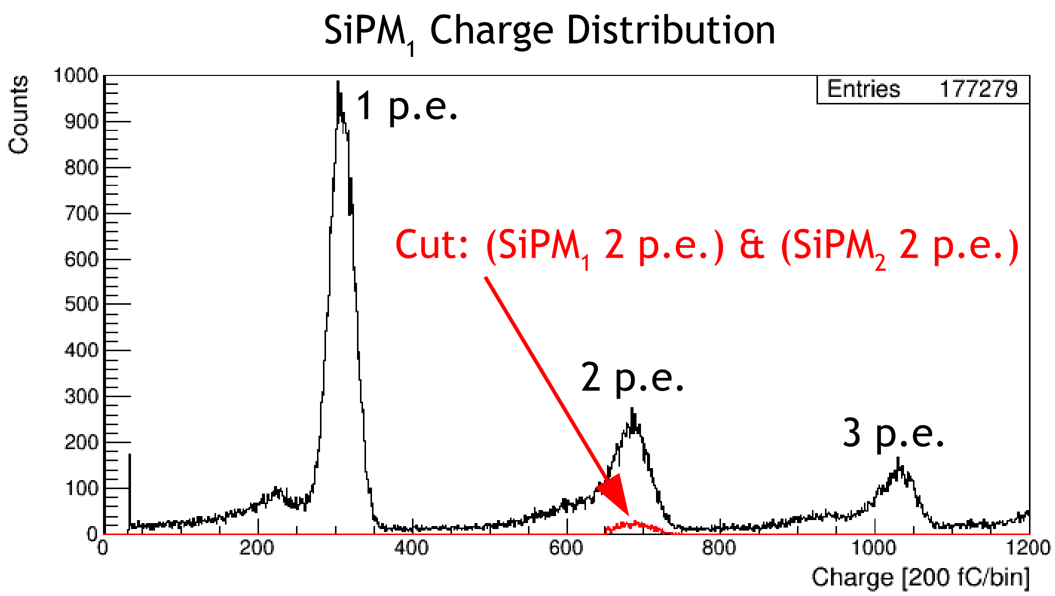
- Single photoelectron cut: **190 ps** FWHM
  - AdvanSiD
  - V_{ov} = 7V
  - black painted PbF_2
  - T = -25°C
- improvements in timing possible with waveform sampling?

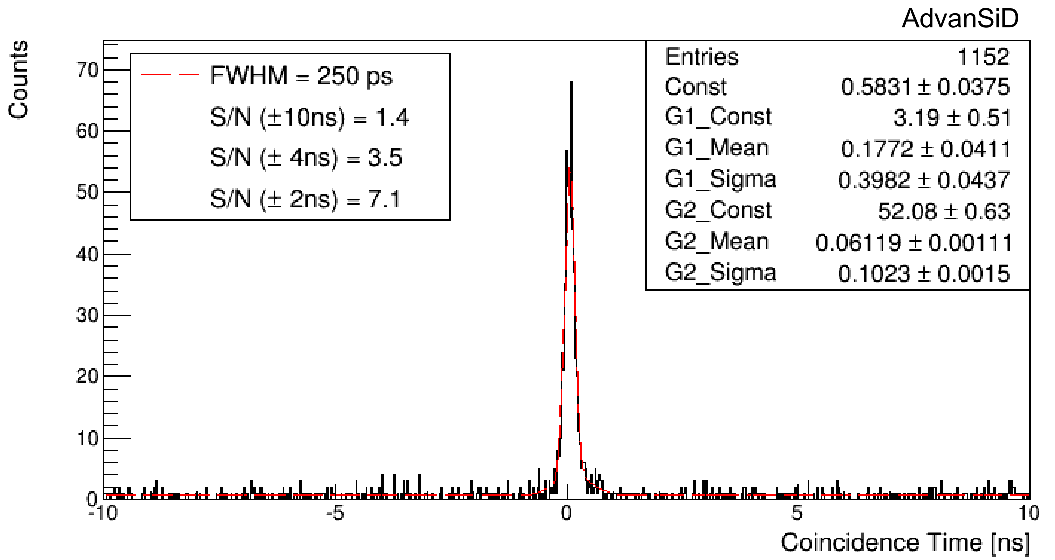




2 p.e. cut

- 2 p.e. cut: **250 ps** FWHM
  - AdvanSiD
  - V_{ov} = 7V
  - black painted PbF_2

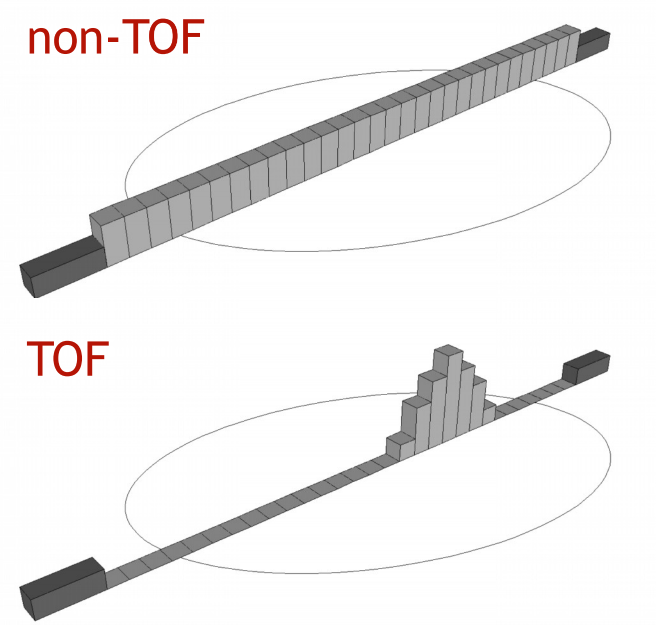




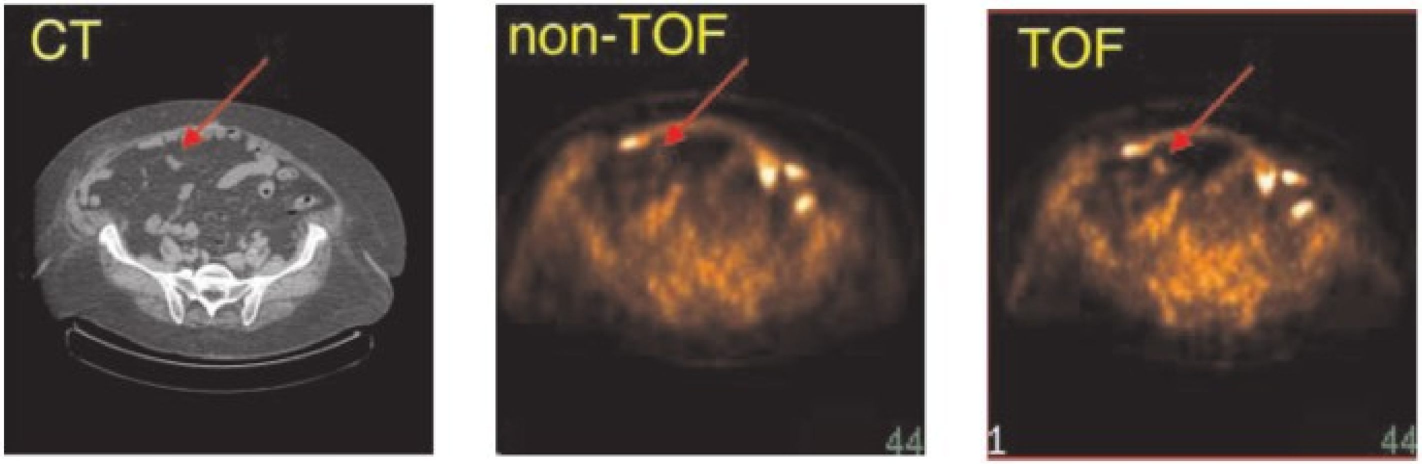
Time-of-flight Positron Emission Tomography

- Contrast of images obtained with PET can be improved by measuring the time-of-flight (TOF) of the two annihilation gammas
  - localizes source position on line of response (LOR)
  - reduces the spread of noise along the LOR
  - full body PET field of view D ~ 0.5 m

    → TOF better than $c_0 * D/2$ ~ 1 ns can improve the images



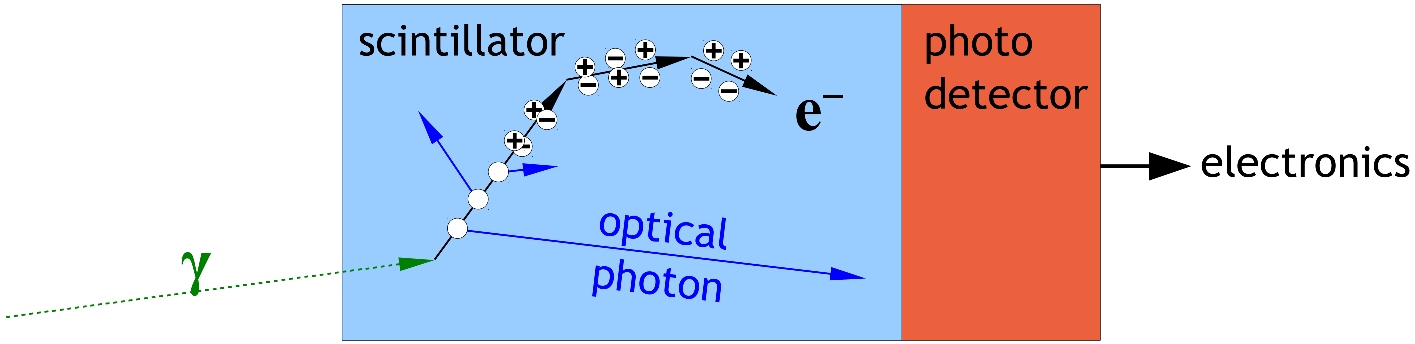
- Philips Gemini TF PET/CT with TOF resolution of 600 ps:



[PET Center of Excellence Newsletter, Vol.3 Issue 3 (2006)]

Annihilation Gamma Detectors

- Scintillating crystal (BGO - $Bi_4Ge_3O_{12}$, LSO - $Lu_2SiO_5(Ce)$)
  - convert gamma energy into optical photons
- Photodetector (photomultiplier tubes)
  - convert optical photons into electrical pulses

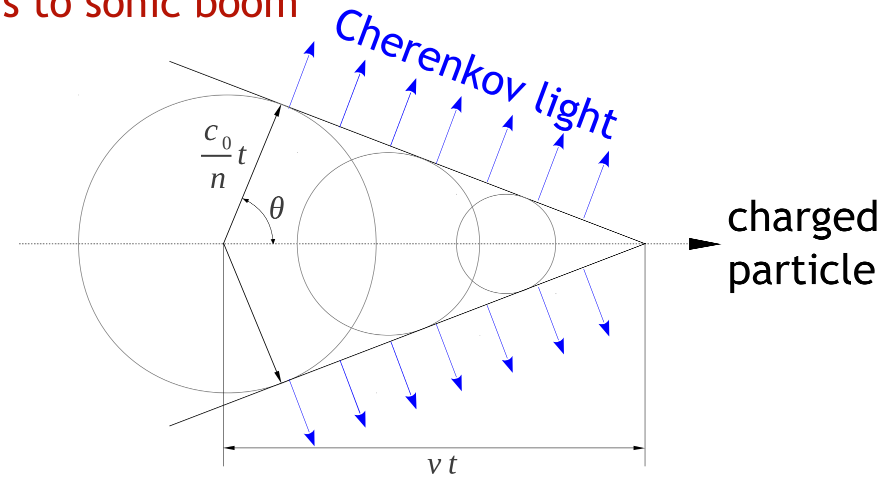


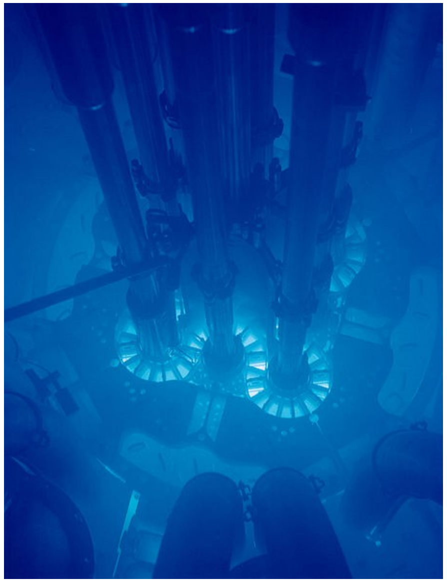
- with development of faster photodetectors, the TOF resolution became mainly limited by the scintillator time response (scintillation raise and decay time constants)

	NaI(Tl)	**BGO**	**LSO**	BaF_2	$LaBr_3(Ce)$
Density (g/cm^3)	3.7	7.1	7.4	4.9	5.1
μ_{511keV} (cm^{-1})	0.35	0.96	0.87	0.44	0.43
Decay time (ns)	230	**300**	**40**	0.6	17
LY (ph/511keV)	20,000	3,000	15,000	1,000	30,000

Cherenkov radiation

- Limitations due to scintillators can be avoided by using radiators of Cherenkov light instead
- charged particles (e^-) passing trough dielectric material at speed $v_{Thr} > c_0/n$
  → **prompt** Cherenkov photons
- analogous to sonic boom



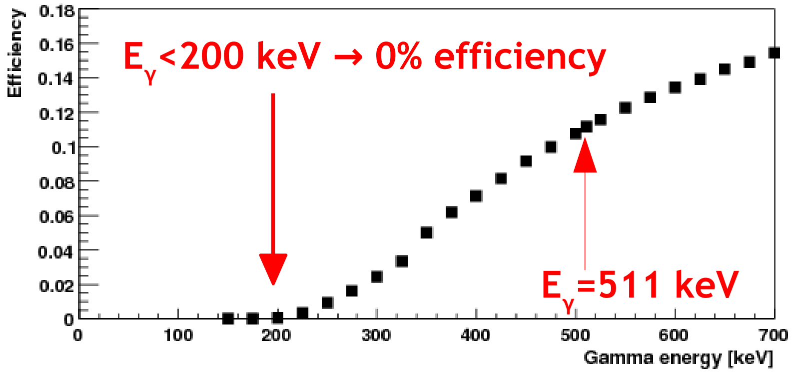


- Most promising available Cherenkov radiator for PET: lead fluoride (PbF_2)

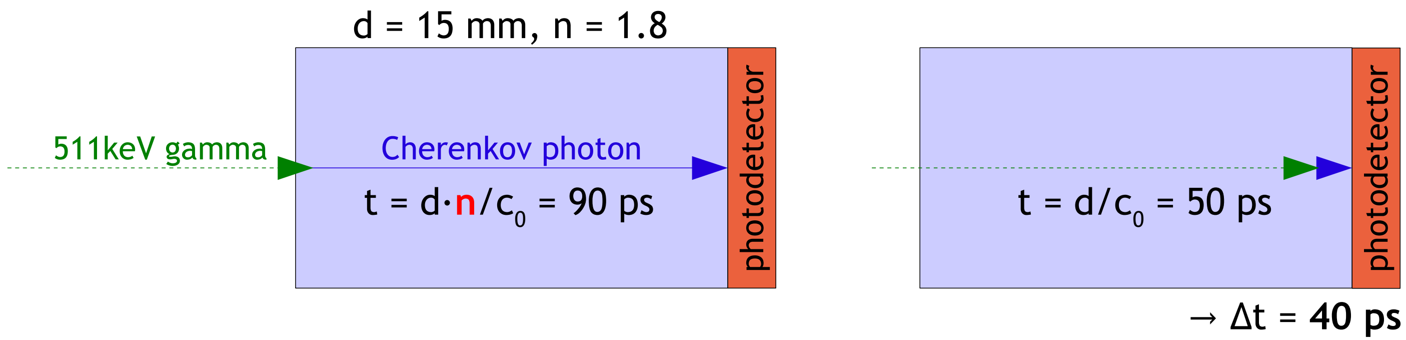
	PbF_2
Density (g/cm^3)	7.77
μ_{511keV} (cm^{-1})	1.06
Refractive index (λ = 400 nm)	1.8
Optical transmission λ_{cutoff} (nm)	250

Cherenkov radiation in TOF PET

- Only about 10 Cherenkov photons can be produced by 511 keV gamma, only a couple reach the photodetector → **single photon detection**
  - Photodetector efficiency a limit for efficiency of the whole method
  - No energy resolution, however there is an intrinsic Compton scatter suppression & less scattering in crystals (very high Z)



- New limitation for time resolution:
  - optical photon travel time spread in the crystal



  - For even faster timing the crystals can be:
    - bare (no reflections from Teflon wrapping)
    - painted with black paint (reduce even the total internal reflections)