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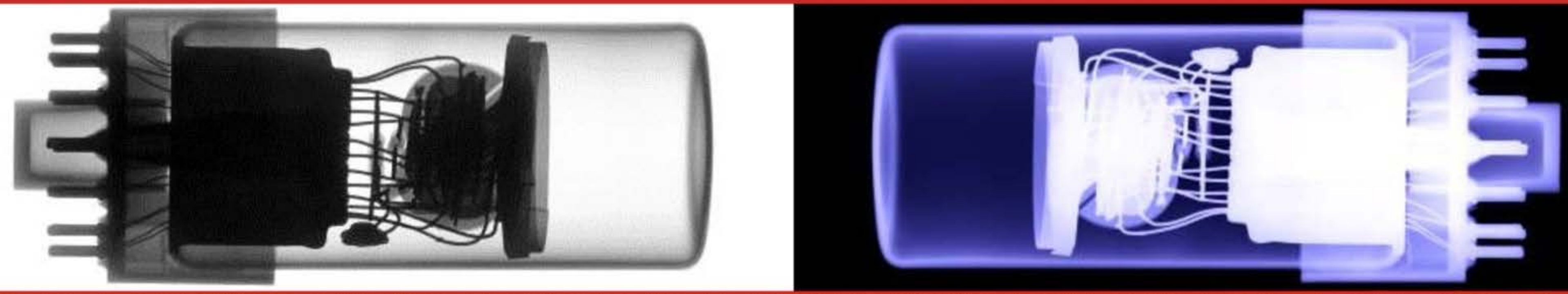

Optimization of Detectors for Time-of-Flight PET

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Possible improvements of the PET image

Increased radiopharmaceutical activity

- much higher radiation exposure of the patients
- maximum dose rates must be accepted by medical centers

Longer scanning time

- negative influence on the patient's psychological condition
- harder to realize stable patient position during PET and CT scan
- decrease of the total number of PET patients and higher costs

More efficient scintillation detectors

- the presently used scintillators BGO (30mm) and LSO (40mm) assure about 90% detection efficiency for 511 keV gamma rays

Extended energy spectrum below the photopeak

- 2 times higher sensitivity, but the Compton scattered photons destroy the image quality

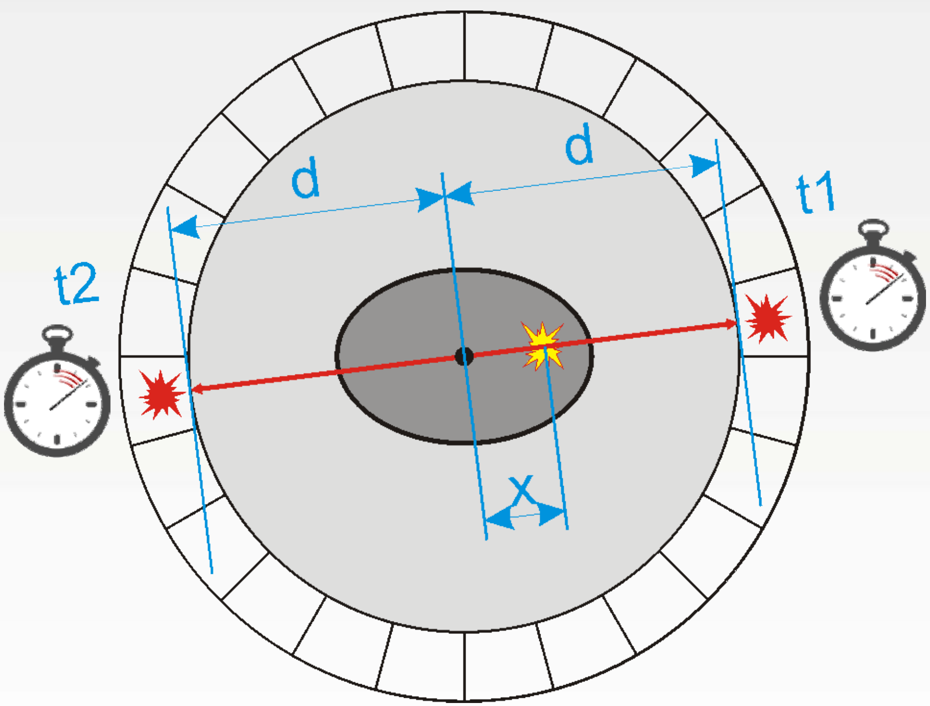
Increased solid angle – 3D PET

- sensitivity to true coincidences increased by a factor of 5, but followed by 3 to 4 times larger acceptance of the scattered events

<u>Time-of-Flight</u>

Time-of-Flight PET

$$x = \Delta t \cdot c/2$$



Problems:

- Gamma quanta speed is a speed of light
- Spatial resolution of a PET scanner is approximately 5 mm
- For gamma quanta this 5 mm corresponds to 17 ps
- 5 mm spatial resolution requires scintillation detectors with timing resolution of 30 ps
- Timing resolution of the best presently known PET detectors is at the level of only 500 ps

Benefits of TOF PET

500 ps is only 7.5 cm but allows:

- Reduction of statistical noise (f – noise variance reduction factor, D – emission source size):

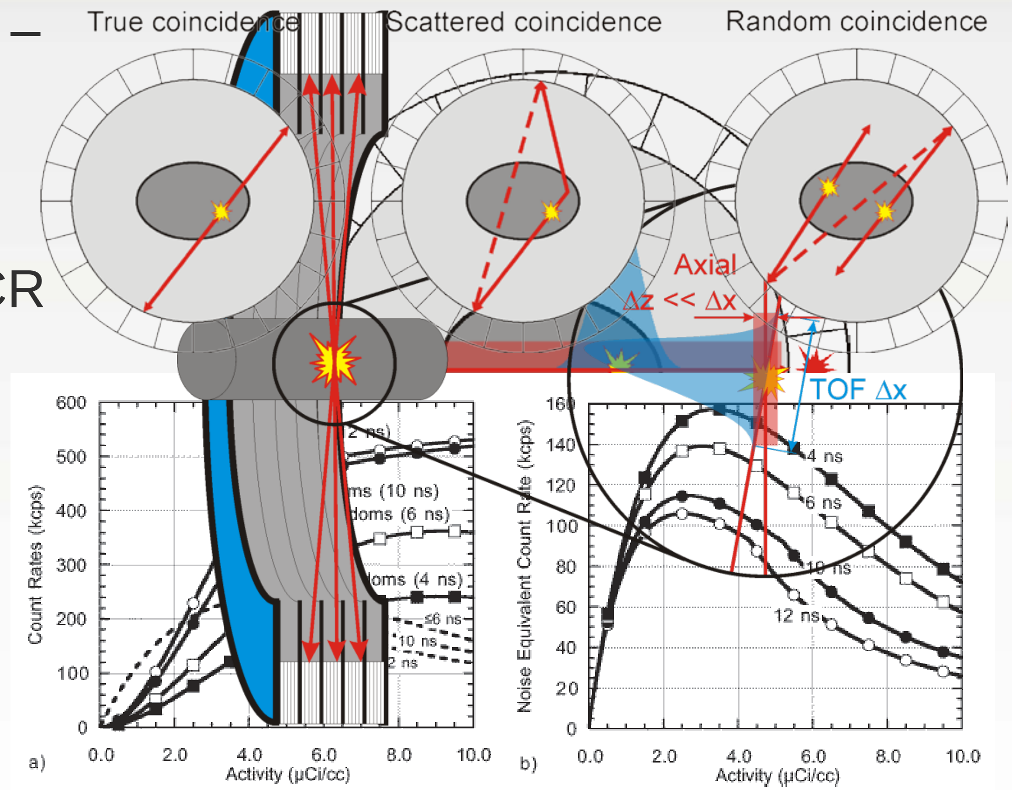
$$f = \frac{D}{\Delta x} = \frac{2D}{c\Delta t}$$

- Reduced random event rate (NECR – Noise Equivalent Count Rate)

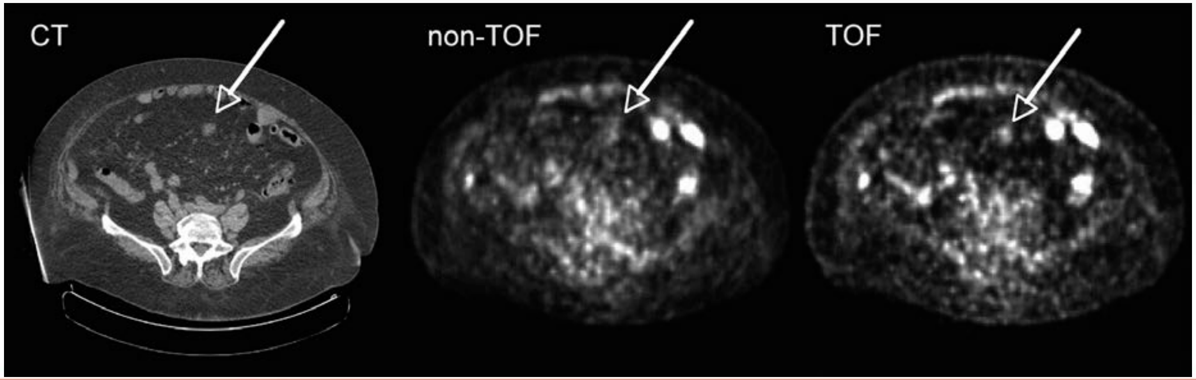
$$R = 2R_1R_2\Delta T \qquad NECR = \frac{T^2}{T+S+2R}$$

- Reduced axial blurring

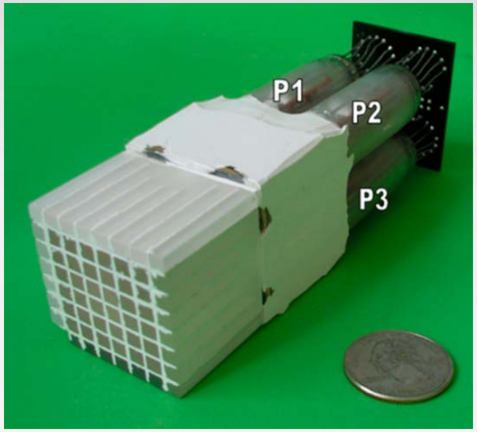
- Possibility of a simultaneous emission (anihilation quanta) and transmission (attenuation correction) scan

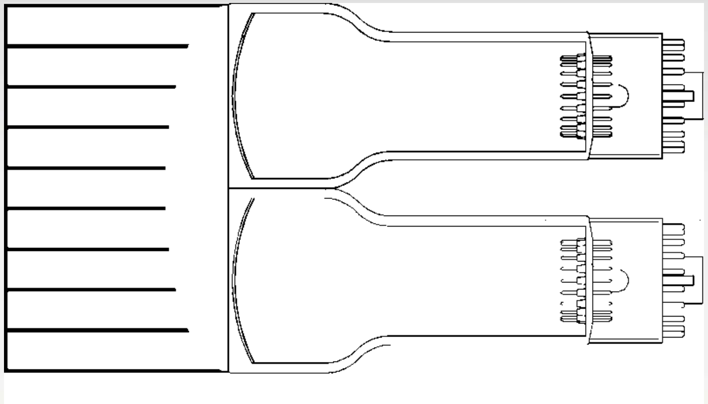


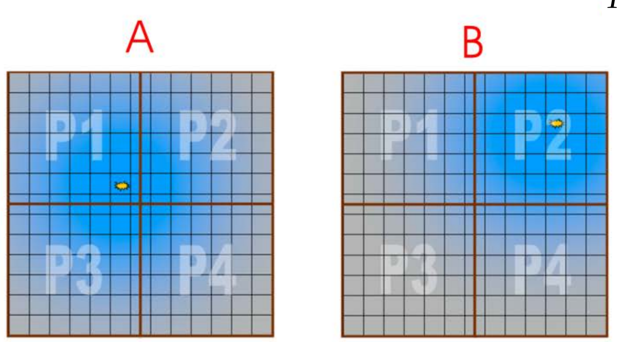
Examples of PET and TOF PET images



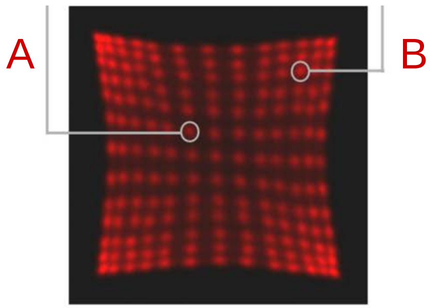
Block-Detector design







$$Y = \frac{P1 + P2 - P3 - P4}{P1 + P2 + P3 + P4}, \quad X = \frac{P2 + P4 - P1 - P3}{P1 + P2 + P3 + P4}$$



Block-Detector:

- Matrix of **<u>scintillators</u>** – dozens of pixels (number and size defined by the crystal type, 64 for BGO, 169 for LSO)
- Light readout by means of several **<u>photodetectors</u>** (in most cases 4 photomultipiers)
- Interaction point calculated using *Anger logic*

Scintillators possible to use in PET

Scintillator	Light output [ph/MeV]	Decay constant [ns]	Emission wavelength [nm]	Density [g/cm^3]	Effective atomic number	Index of refraction	Hygroscopic
NaI:Tl	38 000	230	410	3.7	51	1.85	yes
CsI:Tl	66 000	900	550	4.5	52	1.80	slightly
BGO	8 000	300	480	7.1	75	2.15	no
LSO/LYSO	30 000	40	420	7.4	66	1.82	no
BaF_2 fast/slow	2000/10000	0.6/620	220/310	4.9	53	1.51	slightly
$LaBr_3$	75 000	16	380	5.1	45	1.9	yes
GSO	8 000	60	440	6.7	59	1.85	no
LGSO	23 000	40	420	7.5	63	1.82	no
LuAP	12 000	18	365	8.3	64.9	1.94	no
YAP	17 000	30	350	5.5	33.5	1.95	no

A photomultiplier (PMT)

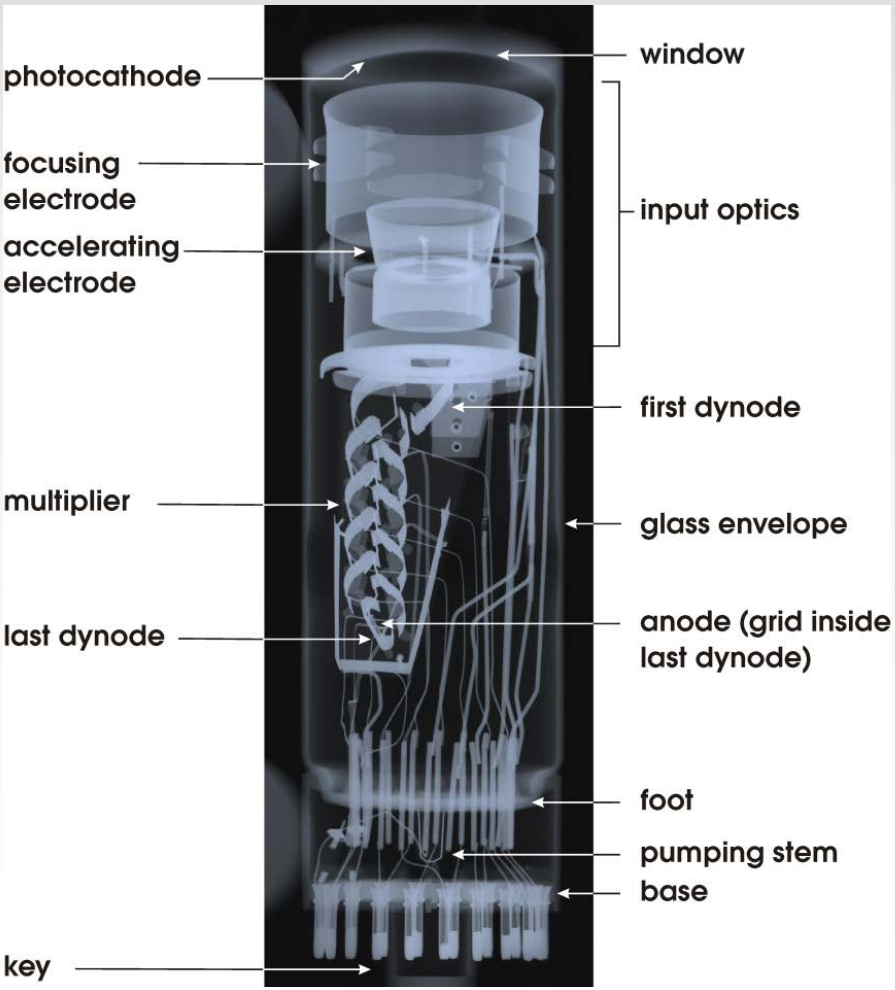


Fig. 1. An X-ray image of Photonis XP2020 timing photomultiplier.

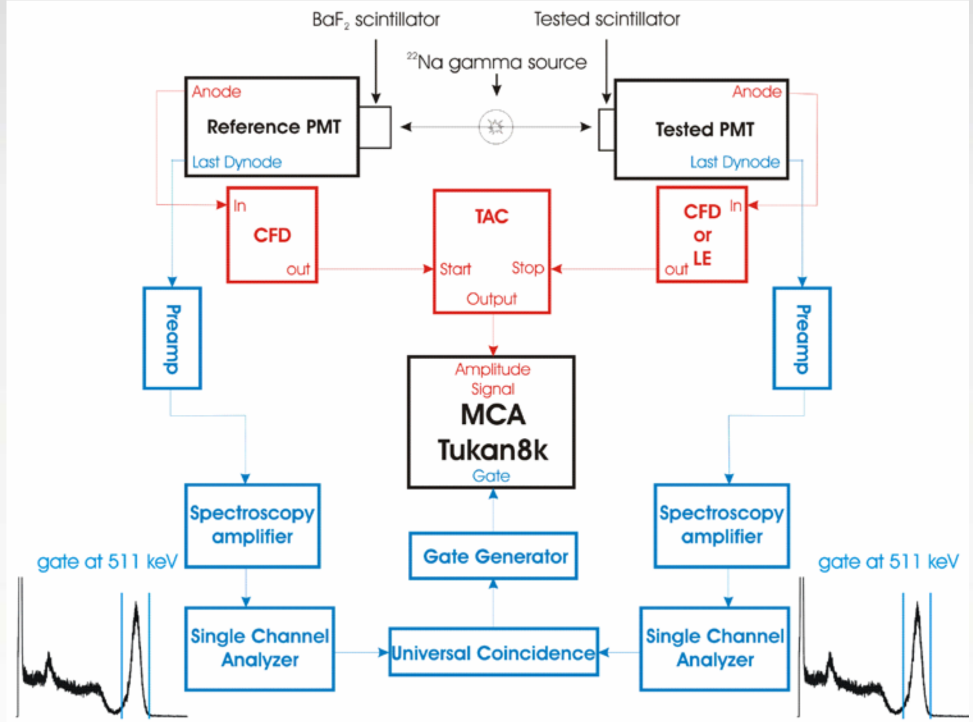


Fig. 2. Experimental setup for timing resolution measurements.

Major photodetector properties

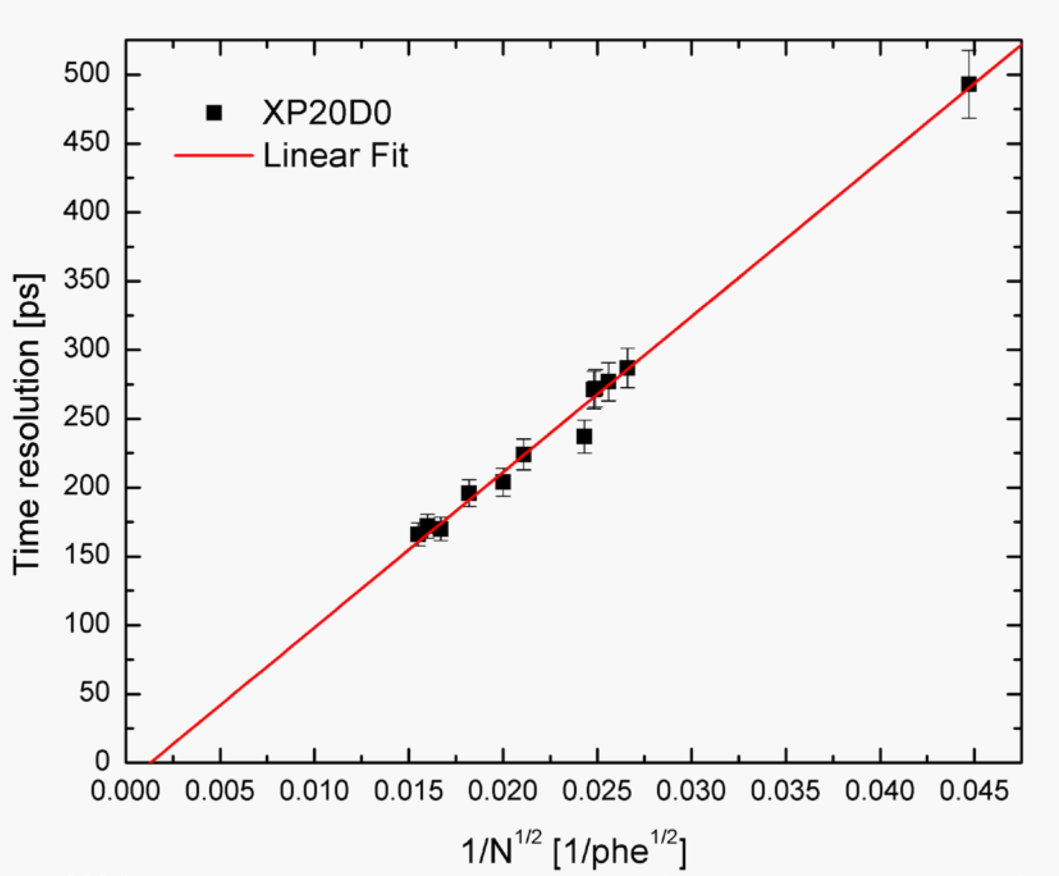
The final result of timing performance is a composition of three major parameters of a photodetector:

- **number of photoelectrons** released from the photocathode (which is a function of the photocathode sensitivity) and photoelectron collection efficiency on the first dynode

- the transit **time jitter** of electrons traveling from the photocathode to the anode

- **rise time** of the anode pulse

Timing dependence on the number of photoelectrons

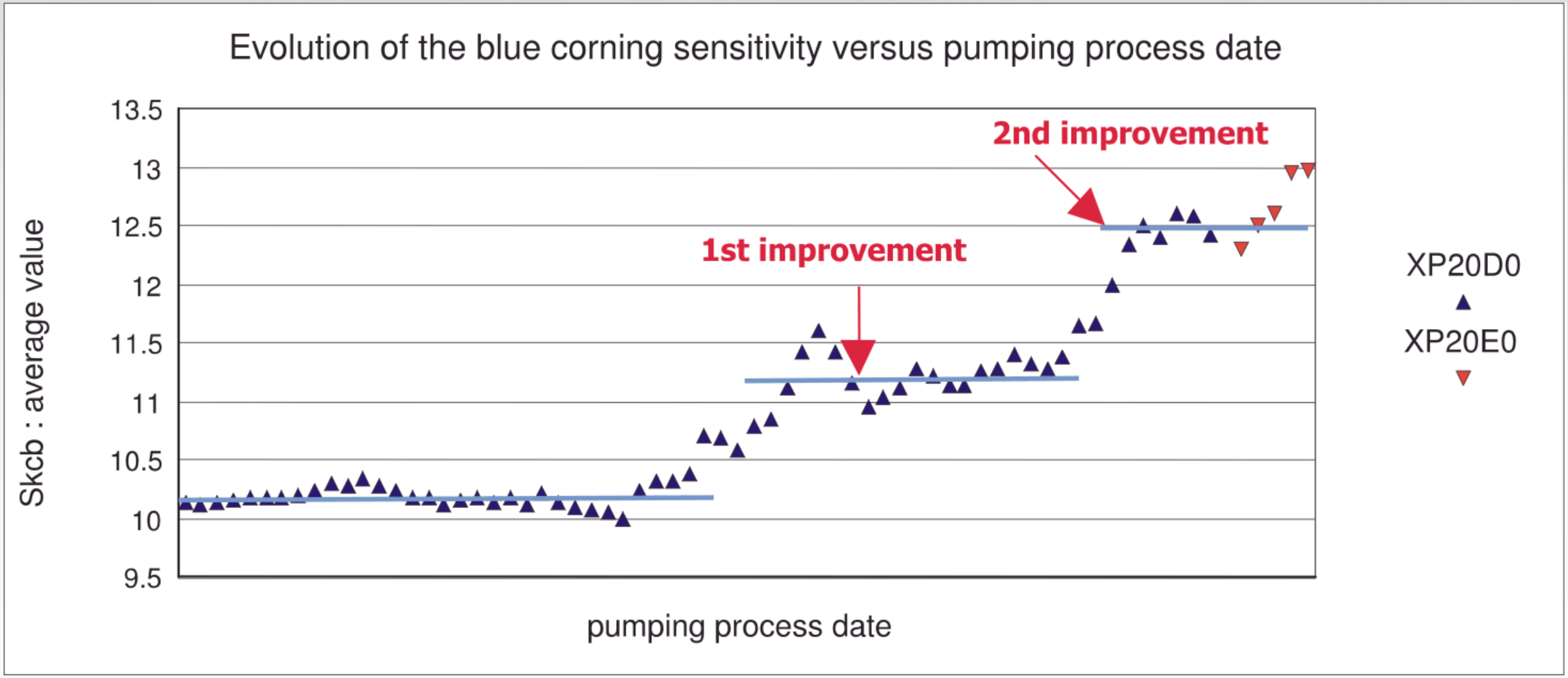


Measured time resolution versus number of photoelectrons (Nphe) collected in the PMT

Measurements done for the $10x10x5\ mm^3$ LSO and $4x4x20\ mm^3$ LSO crystals

The linear dependence of the time resolution on reversed square root of the number of photoelectrons shows the importance of high quantum efficiency of the photocathode

Development of photomultipliers' QE



An improvement of the photocathode QE in the XP2020 family. We have tested XP20D0 and XP20E0 with the blue sensitivity close to 14 uA/lmF (QE up to 35%). The best values - above 40%.

Photoelectron collection efficiency

Fast tubes are optimized for collecting photoelectrons from the whole of the photocathode surface that arrive almost simultaneously on the first dynode surface.

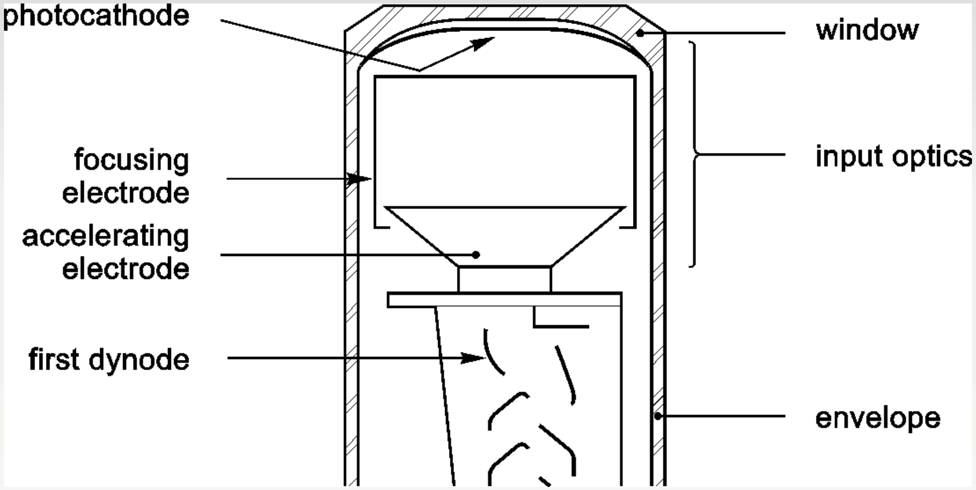
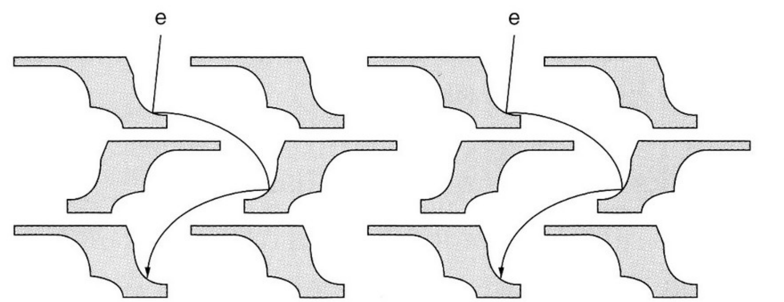


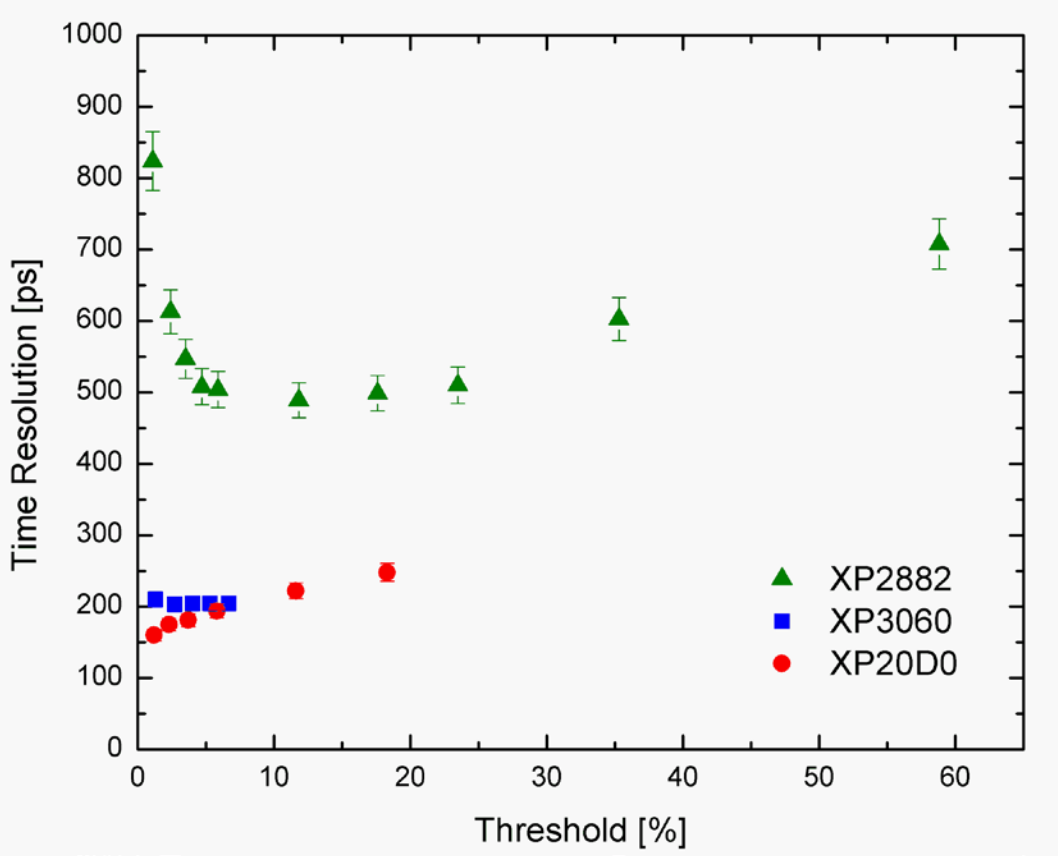
Figure 23 : Cross Section of Metal Channel Dynode with Electron Trajectories



Metal channel dynodes:

- position sensitive PMTs:
- low crosstalk
- photoelectron collection efficiency **of about 60 – 70%,** limited by the geometrical open area of dynodes

Dependence on the anode pulse characteristics



Time Resolution dependence on the LE threshold for PMTs representing different constructions

Only in the case of photomultipliers optimized for timing measurements like XP20D0 the lowest threshold could be achieved leading to the best time resolution

Screening grid at the anode in Photonis XP20D0

Commonly used anode construction – anode built as a grid inside the last dynode.

Advantages:

- Low time-of-flight of electrons from the last dynode to the anode
- Good charge collection at the anode

Disadvantage – two components:

- Main one due to the collection of the electrons from the last dynode
- Parasitic (shifted in time) induced in the anode by the electrons travelling from the penultimate dynode to the last dynode

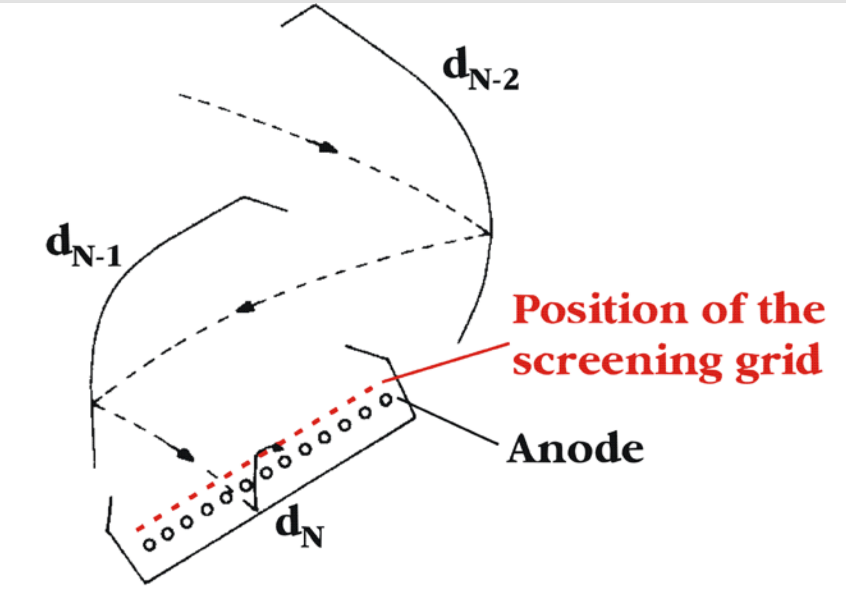


Fig. 2. Geometry of the last dynodes and the anode in a typical linear-focused photomultiplier. Note that the anode is built as a grid inside the last dynode. The position of the screening grid is also shown.

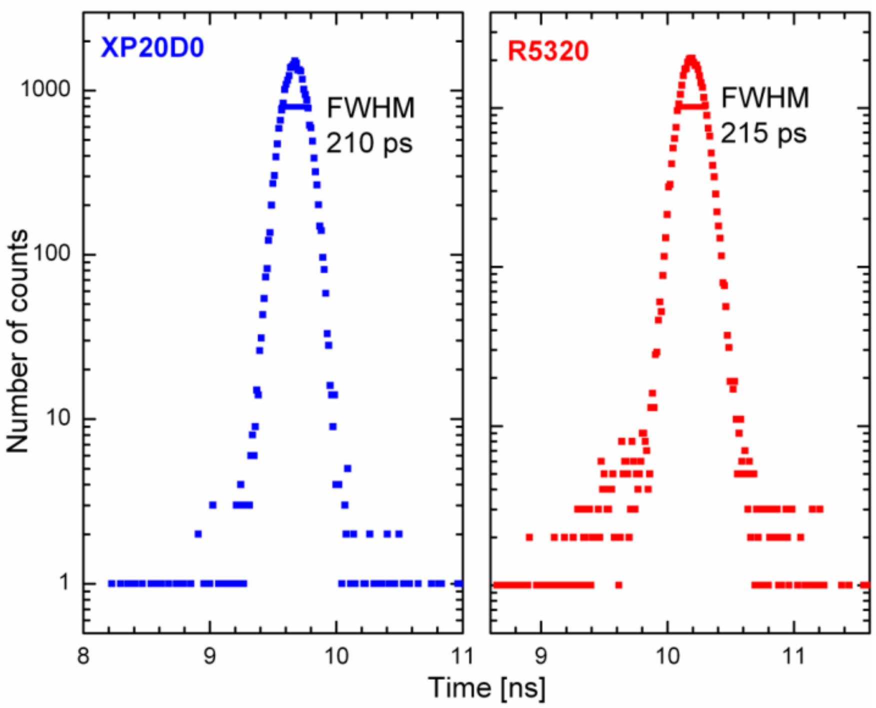
Solution – SCREENING GRID

Timing photomultipliers Photonis XP20D0 and Hamamatsu R5320

Type	XP2020 No. 25377	XP20Y0/DA No. 021	XP20D0 No. 2025	XP20D0 No. 2026	R5320 No. BA0091
Diameter	51 mm				25 mm
Photocathode	Bialkali				
Window	borosilicate glass				Quartz
Blue sensitivity [μA/lm F]	10.4	12.2	13.2	$\boxed{13.7}$	$\boxed{8.9}$
White sensitivity [μA/lm]	70.5	110.2	150	150	81.3
Time jitter [ps]	500±25	660±30	610±30	$\boxed{520\pm25}$	$\boxed{140\pm7}$
Screening grid	No	Yes	Yes	Yes	No
No of dynodes	12	8	8	8	10

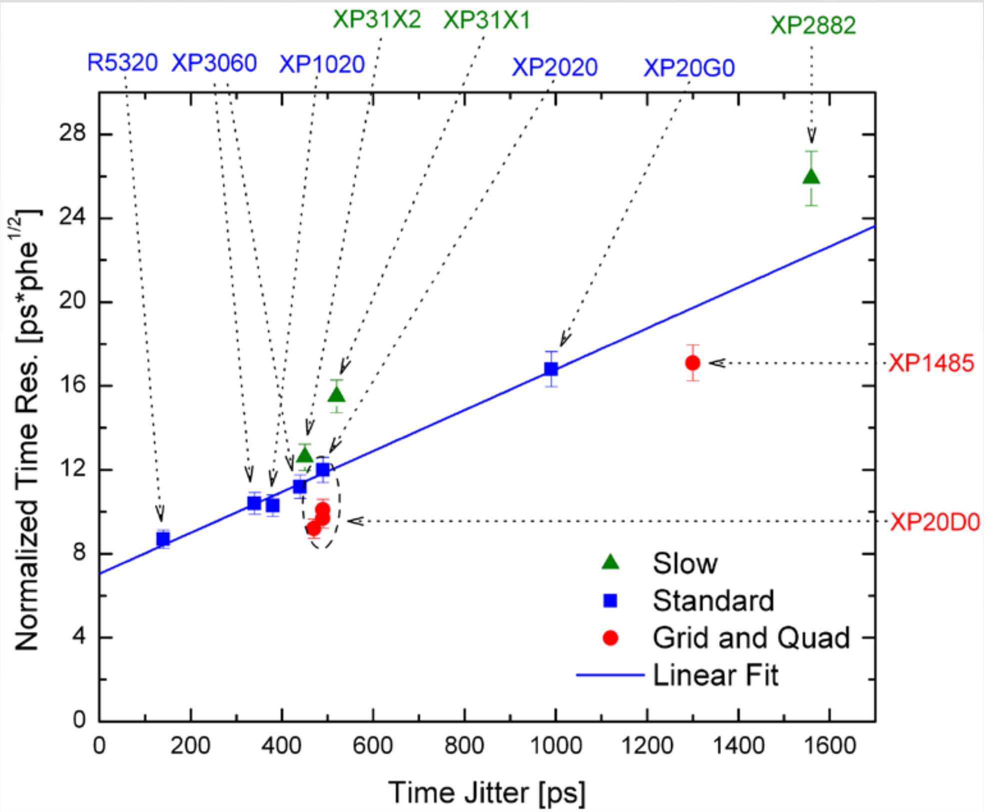
PMT	Time resolution, δt [ps]		Phe number[b)] [phe]	δt√N [ps√phe] x 10^3
	Measured	Tested detector[a)]		
XP2020 No. 25377	257±5	222±6	3200±100	12.6±0.4
XP20D0 No. 021	225±4	185±5	3500±100	10.9±0.4
No. 2025	214±4	172±5	3930±100	10.8±0.4
No. 2026	210±4	$\boxed{166\pm5}$	4140±100	10.6±0.4
R5320 No.BA0091	215±5	$\boxed{173\pm5}$	2760±100	9.1±0.4

a) corrected for the contribution of the BaF_2 reference detector of 128 ps.
b) photoelectron number for 511 keV



Dependence on the time jitter

PMT	Phe number for 511 keV [phe]	Time resolution at FWHM [a], Δt [ps]	$\Delta t\sqrt{N}/r$ [ps√phe] x10^3	Time jitter in center [ps]
XP2882 SN029	3100 ± 100	489 ± 24	25.9 ± 1.3	1560 ± 80
XP31X1	3100 ± 100	287 ± 14	15.5 ± 0.8	520 ± 30
XP31X2	2600 ± 100	254 ± 13	12.6 ± 0.6	450 ± 20
XP3060 SN193	3300 ± 100	200 ± 10	11.2 ± 0.6	440 ± 20
XP3060 SN018	2700 ± 100	205 ± 10	10.4 ± 0.5	340 ± 20
XP1020 SN1021	2500 ± 100	212 ± 11	10.3 ± 0.5	380 ± 20
XP20G0 SN162	2900 ± 100	332 ± 17	16.8 ± 0.8	990 ± 50
XP2020 SN25377	3200 ± 100	223 ± 11	12.0 ± 0.6	490 ± 20
XP20D0 SN2026	4100 ± 100	166 ± 8	10.1 ± 0.5	490 ± 20
XP20D0 SN2083	3200 ± 100	173 ± 9	9.2 ± 0.5	470 ± 20
XP20D0 SN2087	3600 ± 100	169 ± 8	9.7 ± 0.5	490 ± 20
XP1485 SN1789	3300 ± 100	324 ± 16	17.1 ± 0.9	1300 ± 70
R5320 BA0091	2800 ± 100	173 ± 9	8.7 ± 0.4	140 ± 7



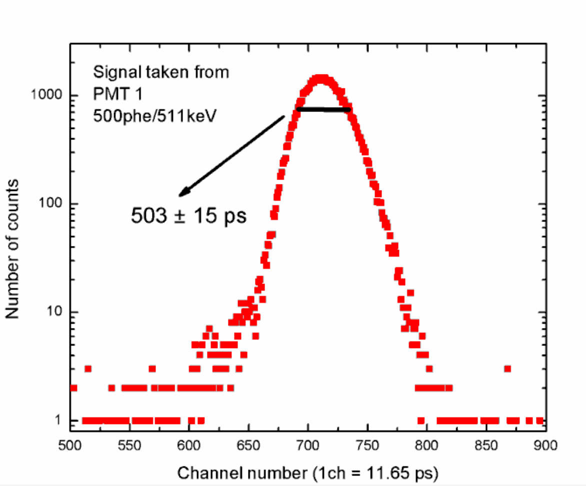
Normalization: $\Delta T = \Delta t\sqrt{N}/r \cdot 10^3$

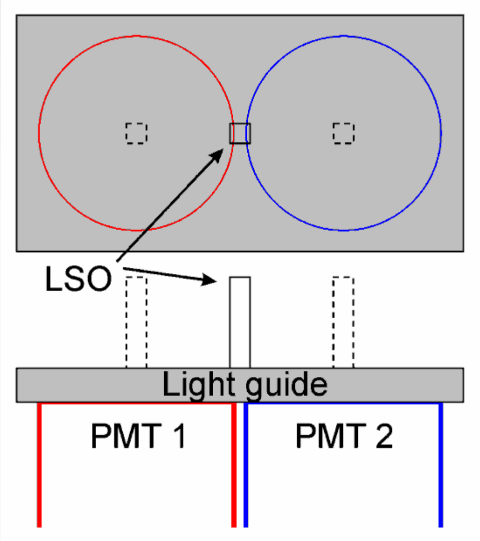
Δt – measured time resolution,

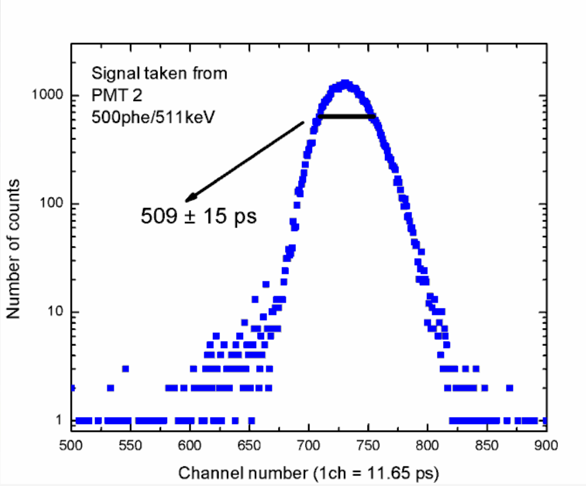
N – number of photoelectrons for 511keV,

r – gain dispersion

Simultaneous readout of several PMTs

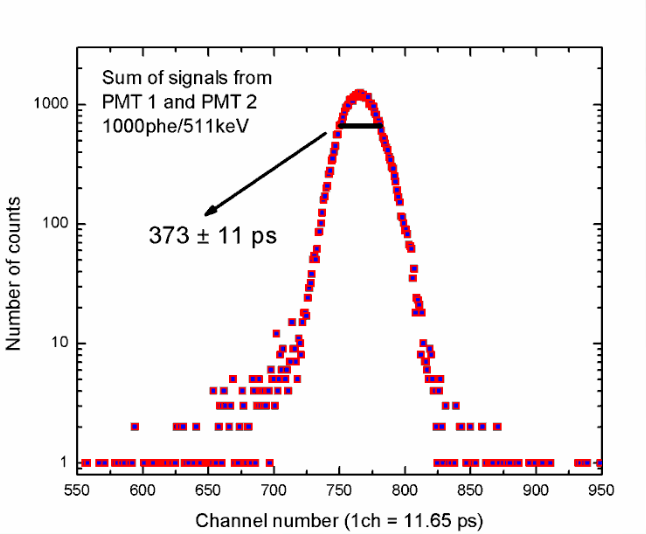




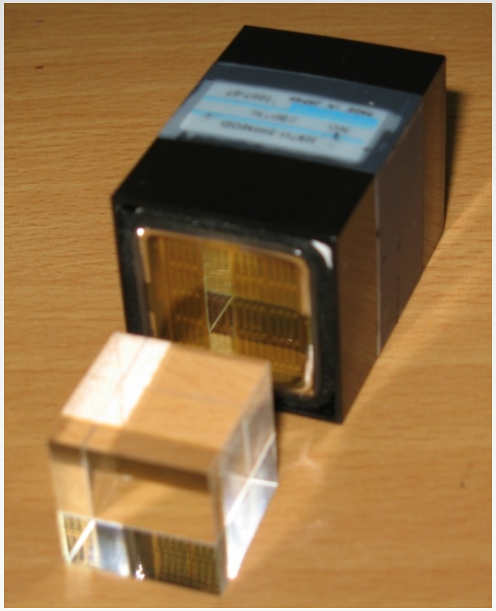


Signal taken from	Time resolution at FWHM, δt [ps] Measured	Corrected[a)]	Phe number for 511 keV [phe]	$\delta t\sqrt{N}$ [ps$\sqrt{\text{phe}}$] x10^3
PMT 1	503 ± 15	486 ± 16	500 ± 50	10.9 ± 0.6
PMT 2	509 ± 15	493 ± 16	500 ± 50	11.0 ± 0.7
PMT 1 + PMT 2	373 ± 11	350 ± 12	1000 ± 70	11.1 ± 0.5

a) corrected for the contribution of the BaF_2 reference detector of 128 ± 4 ps



Detector based on a monolithic scintillator and multi-channel PMT



Measurements made with 20x20x20 mm LYSO

PMT	Time resolution at FWHM, Δt [ps] Measured	Time resolution at FWHM, Δt [ps] Corrected[a)]	Nphe/MeV [phe/MeV]	Nphe for 511keV, N [phe]	$\Delta t\sqrt{N}/\sqrt{ENF}$ [ps√phe] x10³
H8711	301 ± 9	272 ± 10	4000 ± 100	2100 ± 100	11.6 ± 0.5
XP20D0	260 ± 8	226 ± 9	6000 ± 200	3000 ± 100	12.1 ± 0.5

a) corrected for the contribution of the BaF_2 reference detector of 128 ± 4 ps

Measurements made with 10x10x5 mm LSO

PMT	Time resolution at FWHM, Δt [ps] Measured	Time resolution at FWHM, Δt [ps] Corrected[a)]	Nphe/MeV [phe/MeV]	Nphe for 511keV, N [phe]	$\Delta t\sqrt{N}/\sqrt{ENF}$ [ps√phe] x10³
H8711	235 ± 7	198 ± 9	5900 ± 200	3000 ± 100	10.1 ± 0.5
R9800	237 ± 7	199 ± 9	6300 ± 200	3200 ± 100	10.3 ± 0.5
XP1020	247 ± 7	211 ± 9	4900 ± 100	2500 ± 100	10.3 ± 0.5
XP3060	238 ± 7	200 ± 9	6400 ± 200	3300 ± 100	11.2 ± 0.5
XP20D0	210 ± 6	166 ± 9	8100 ± 200	4100 ± 100	10.4 ± 0.5

a) corrected for the contribution of the BaF_2 reference detector of 128 ± 4 ps

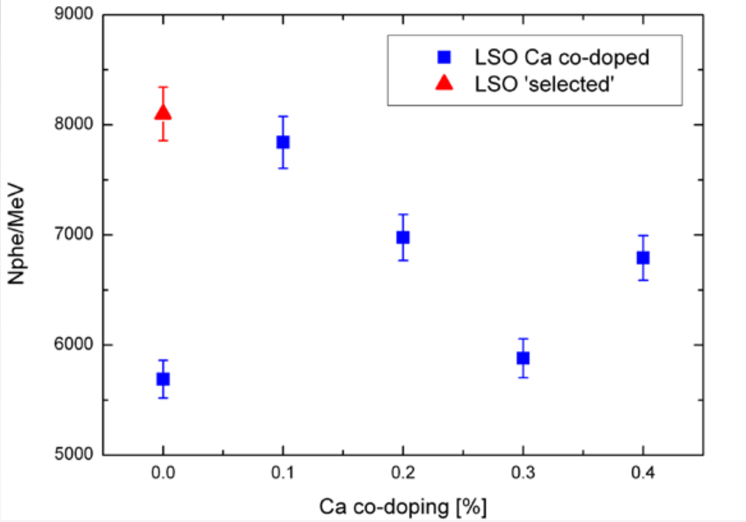
Type	Serial No.		
H8711-200MOD	ZB0730		
White Sens. [uA/lm]	Blue Sens. [uA/lm]	QE [%] at 350nm	Uniformity Max/Min
117	15.5	43	1.5
Photocathode	Window	Structure	Stages
Bialkali	Borosolicate Glass	Metal Channel Dynodes	12

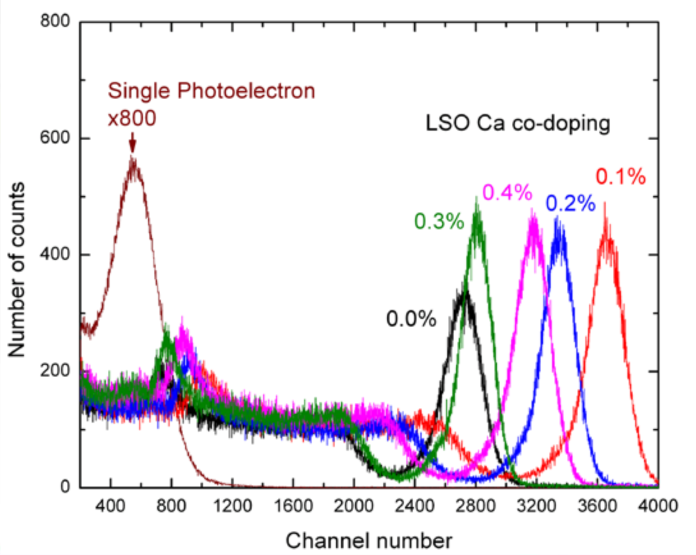
Experimental results did not show adventages of a monolithic crystal over the pixelated block-detector.

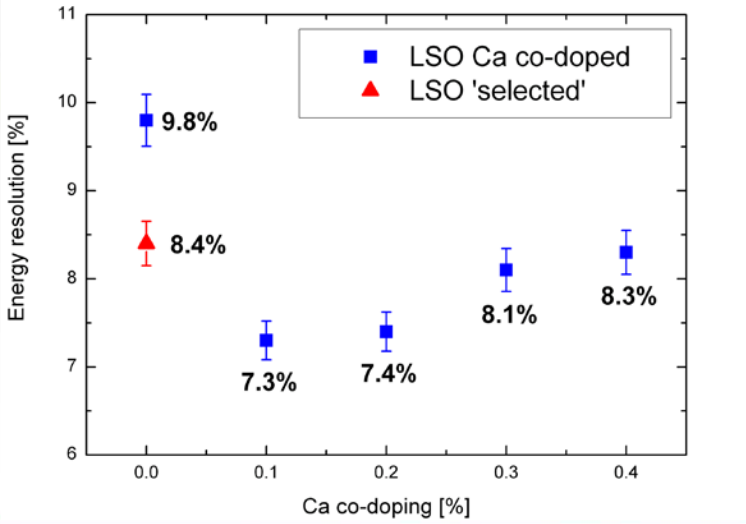
LSO scintillators co-doped with Ca

5 samples of LSO (Lu_2SiO_5:Ce) with different Ca co-doping

Crystal	Nphe/MeV [phe/MeV]
LSO2003 0.0% Ca	8100 ± 200
LSO 0.0% Ca	5700 ± 200
LSO 0.1% Ca	7800 ± 200
LSO 0.2% Ca	6900 ± 200
LSO 0.3% Ca	5900 ± 200
LSO 0.4% Ca	6700 ± 200



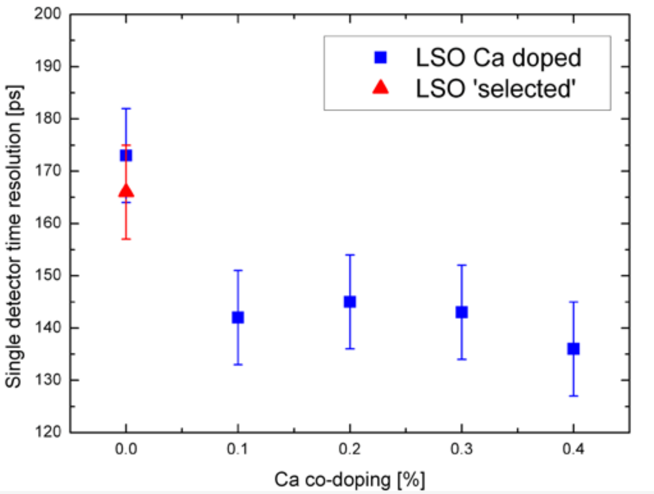




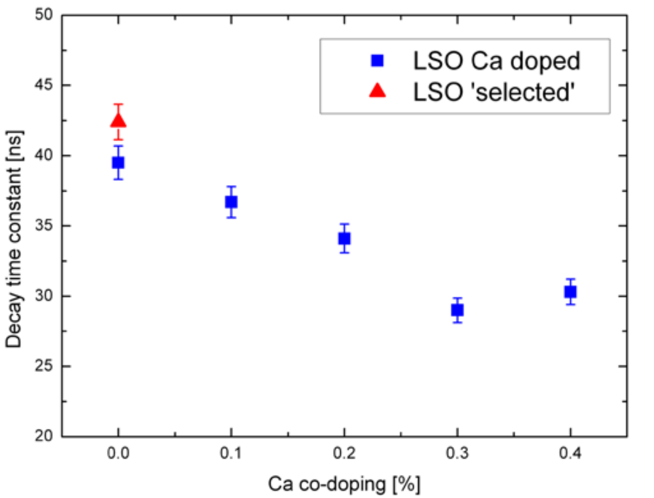
LSO scintillators co-doped with Ca

Crystal	Time resolution at FWHM, Δt [ps]		Nphe for 511keV, N [phe]	Δt√N/√ENF [ps√phe] x10[3]
	Measured	Corrected[a)]		
LSO 0.0% 'selected'[b)]	210 ± 6	166 ± 9	4100 ± 100	10.2 ± 0.5
LSO 0.0% Ca	224 ± 7	173 ± 9	2900 ± 100	8.9 ± 0.5
LSO 0.1% Ca	201 ± 6	142 ± 9	4000 ± 100	8.5 ± 0.6
LSO 0.2% Ca	204 ± 6	145 ± 9	3500 ± 100	8.2 ± 0.5
LSO 0.3% Ca	202 ± 6	143 ± 9	3000 ± 100	7.5 ± 0.5
LSO 0.4% Ca	197 ± 6	136 ± 9	3400 ± 100	7.6 ± 0.5

a) corrected for the contribution of the BaF_2 reference detector of 143±4 ps
b) following chapter 8



- All the tested Ca co-doped samples showed improved timing resolution
- Optimal co-doping is 0.1 % due to improved light output and also timing and energy resolution



A silicon photomultiplier

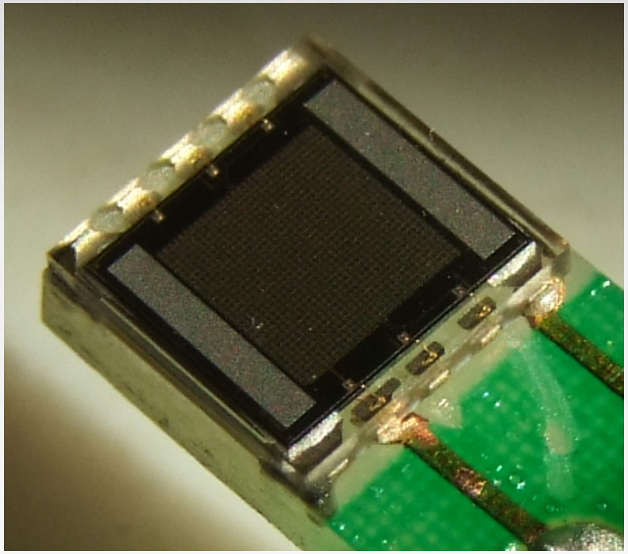
Silicon Photomultiplier (SiPM) or
Multi-Pixel Photon Counter (MPPC)

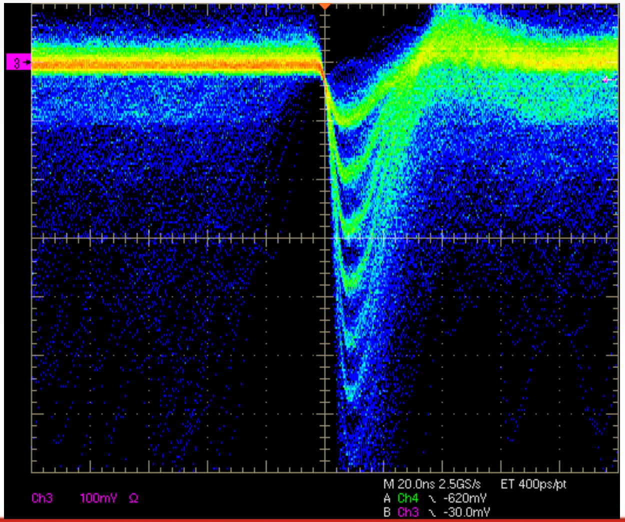
• photodetector based on a matrix of Avalanche Photodiodes (APD cells) working in a Geiger mode („binary" response)

• each APD-cell generates signal after detection of a single photon

• sum of the signals of all APD-cells is the SiPM output signal, proportional to the number of incident photons

Properties: gain: $10^5 – 10^6$, insensitivity to magnetic fields, single photon detection capability, bias voltage below 100V, small size

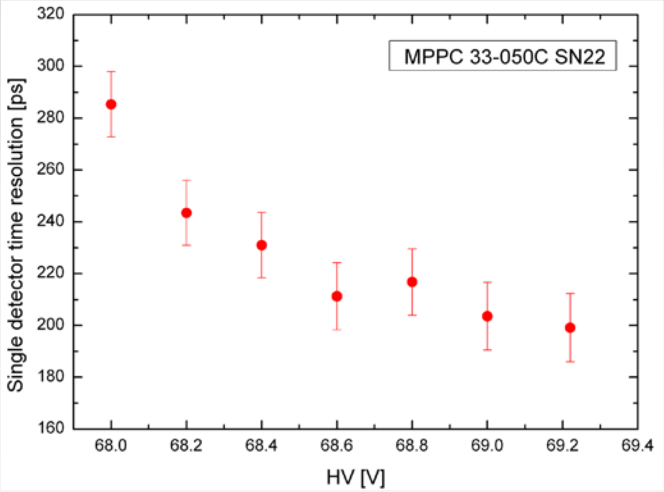




Timing resolution of SiPMs

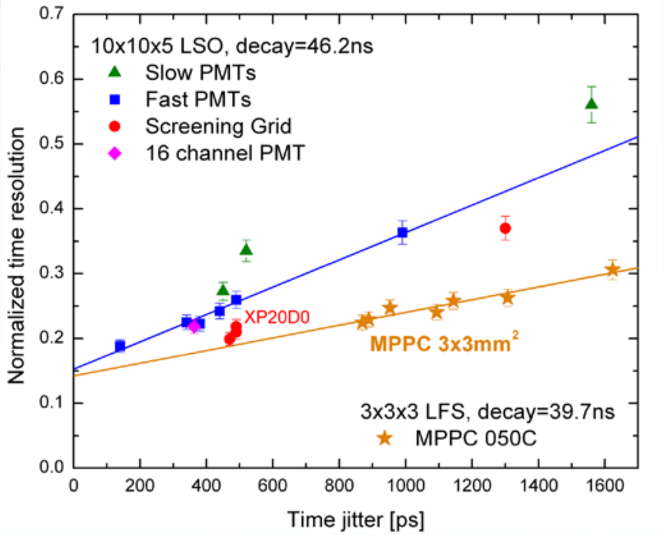
Experiments made with LSO or LFS
and Hamamatsu MPPC S10362-33-050C

Type	S10362-33-050C
Serial No.	22
Active area	3×3 mm^2
Number of pixels	3600
Pixel size	50x50 μm
Fill factor	61.5 %
Gain / bias voltage	$7.51x10^5$ / 68.66 V
Spectral resp. range	270 -900 nm
Q.E.	70% at 400 nm
Dark count	2.38 Mcts/s
Capacitance	320 pF



Photon Detecion Efficiency:

$$PDE = QE \cdot FF \cdot THR$$



Silicon photomultipliers are the real alternative for classic PMTs for application in PET and TOF PET

GE Healthcare showed SiPM based TOF PET system with timing resolution below 400ps

Conclusions

- The obtained time resolution at the level of 170 ps (or better) with various LSO based scintillation detectors shows that this type of a detector is presently the best proposition for TOF PET.
- The optimization of the PMT-based detetectors follows the predictions of the Hyman theory and hence is close to the possible limits.
- Timing resolution in the case of LSO-like scintillators is more dependent on the number of photoelectrons than on the time jitter.
- Timing resolution improvement in a block-detector can be achieved by common light readout of all photodetectors during a single event.
- Results obtained with a monolithic crystal and position sensitive photomultiplier did not show advantages over classic, pixelated block-detector.
- Experiments made with a new type of LSO crystal, co-doped with Ca showed that this type of modification leads to improvement of the timing properties of these scintillators.
- Measurements of the time resolution with silicon photomultipliers strongly suggest that this type of a photodetector can succesfuly replace classic photomultipliers.