Testing and Evaluation of Scintillators

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Preface: Moved to IZM (With a Little Help from my Friends)

Preface: Proud Father

Preface: Table of Contents

Positrons in 5 Minutes

How to explain positrons in 5 minutes (or less).

One talk to teach them all.[1]

[1] Sorry for that cheap "Lord of the rings" reference:-)

Antimater and Albert Einstein

- Dirac[1] found solutions with positive charge in his electron-theory (1928)
- Anderson[2] found that the particle was not the proton but the positron, anti-particle of the electron (in 1933)
- positrons annihilate with electrons, always one e^+ with one e^-

- thanks to Einstein[3] the annihilation results in γ-Radiation where $E_\gamma = (m_{e^+} + m_{e^-})c^2$

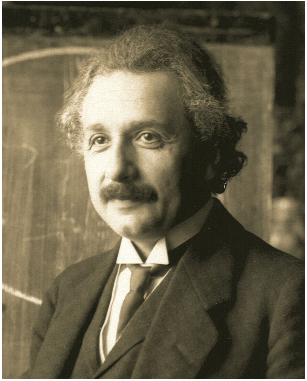


Figure: Einstein 1921

Conservation of the pulse

Another physics law

$\sum \mathbf{p}_i = 0$
The pulse of a system has to be conserved.

Effect on positron-electron-annihilation:

- Two γ-quants are emitted in opposite directions
- Both have energy of 511keV

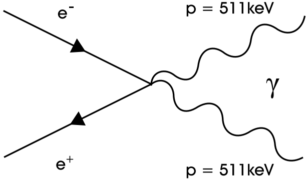


Figure: Feynman-diagram of electron-positron-annihilation

Conservation of the pulse

Another physics law

$\sum \mathbf{p}_i = 0$

The pulse of a system has to be conserved.

Effect on positron-electron-annihilation:

- Two γ-quants are emitted in opposite directions
- Both have energy of 511keV
- Positron is in ground-state
- But: Electron is in excited state
  - $\longrightarrow$ γ-energy changes due to $\mathbf{p}$ of the electron
  - $\longrightarrow$ Electron-energy depends on the state, core-electrons have higher energy than valence-electrons

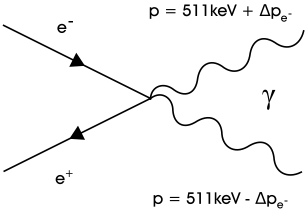


Figure: Feynman-diagram of electron-positron-annihilation (extended)

Statistics (More or less:)

Important

Electron-positron-annihilation is a highly statistical process!
Because the diffusion of the positron in the solid is a random-walk.

Annihilation is influenced by:

- Electron density
- Electron energy
- Atomic structure
- Defects, voids, charge

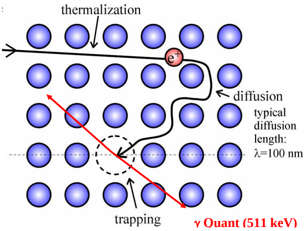


Figure: Positrons in the solid

Lifetime

Lifetime of the positron is influenced mainly by two effects:

1. The lower the **electron density** the lower the chance to hit an electron the higher the lifetime.
2. One (or many) missing atoms/cores build a potential well the positron can't escape (because normal cores repulse the positron).
   - positron lifetime increases
   - but this only works in neutral or negativ traps

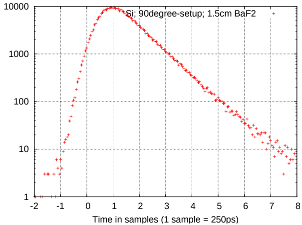


Figure: Positron-Lifetime in Cz-Silicon

Doppler-broadening and Angular-correlation

- two techniques for one effect
- both measure the electron-energy from the energy-shift of the γ-quants

Doppler-broadening:

- measures the energy-shift in γ-direction (usually p_z)
- can be measured with one detector, $\rightarrow$gives high background
- two detectors in coincidence give low background but longer measurement-time
- energy-range is 511keV $\pm$ 10 keV

While the spectra can be calculated theoretically, most times results are compared to a defect-free spectrum.

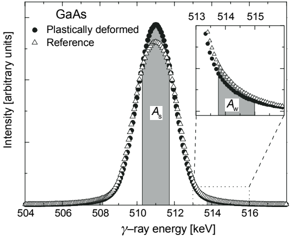


Figure: Doppler-Spectrum[4]

Doppler-broadening and Angular-correlation

- two techniques for one effect
- both measure the electron-energy from the energy-shift of the γ-quants

Angular-correlation:

- measures the energy-shift perpendicular to the γ-direction (p_x and p_y)
- has to be done in coincidence
- 1D- and 2D-measurements are possible
- typical range is $\pm 10 - 20 mrad$, resolution is $0,2 mrad$
- measurement for one spectrum is typically several days

Gives good results on the electronic structure, but evaluating the spectra requires many theoretical calculations.

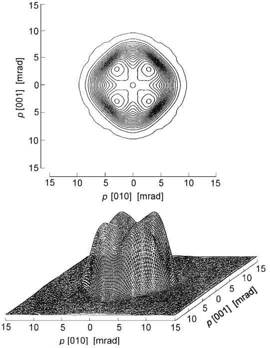
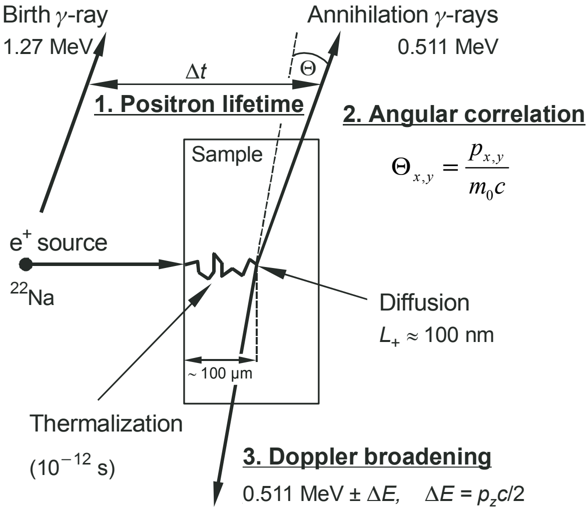
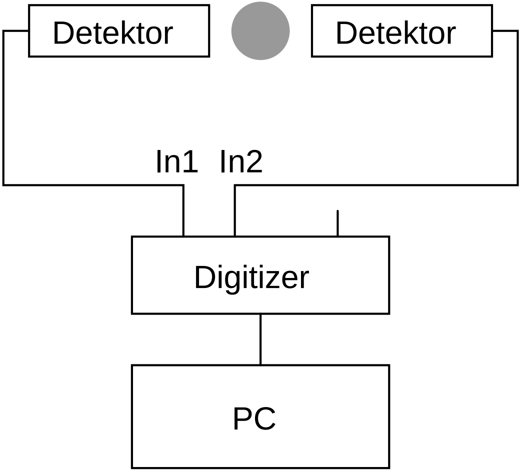


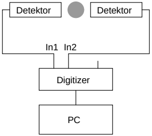
Figure: ACAR-Spectrum[4]

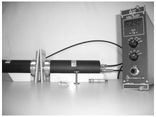
Overview

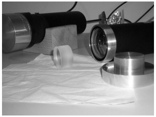

Birth γ-ray
1.27 MeV
Annihilation γ-rays
0.511 MeV
Δt
Θ
1. Positron lifetime
2. Angular correlation
$\Theta_{x,y} = \frac{p_{x,y}}{m_0 c}$
Sample
e^+ source
^{22}Na
Diffusion
$L_+ \approx 100$ nm
~ 100 µm
Thermalization
(10^{-12} s)
3. Doppler broadening
0.511 MeV ± ΔE, $\Delta E = p_z c/2$

Digital Positron Lifetime: Setup

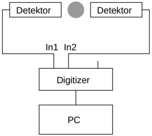


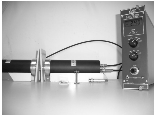


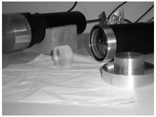




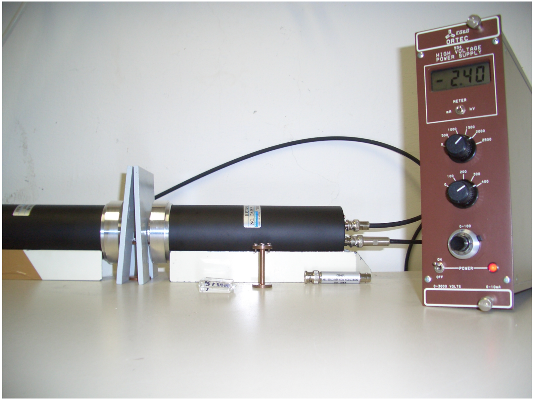
Digital Positron Lifetime: Digitizer

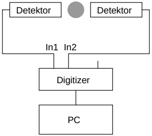


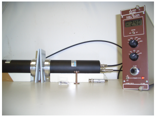


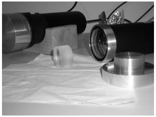


Digital Positron Lifetime: Photomultiplier

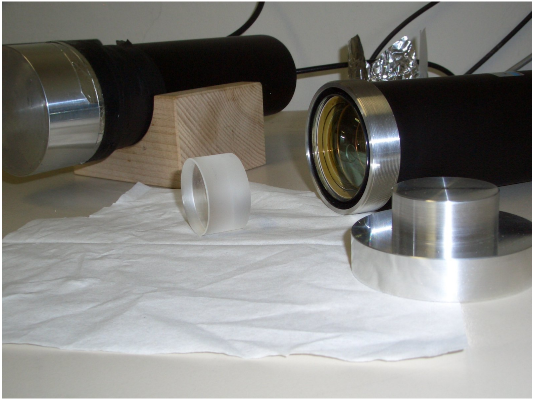


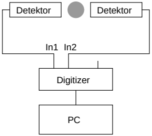


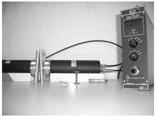


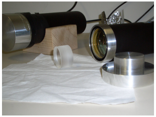


Digital Positron Lifetime: Scintillator





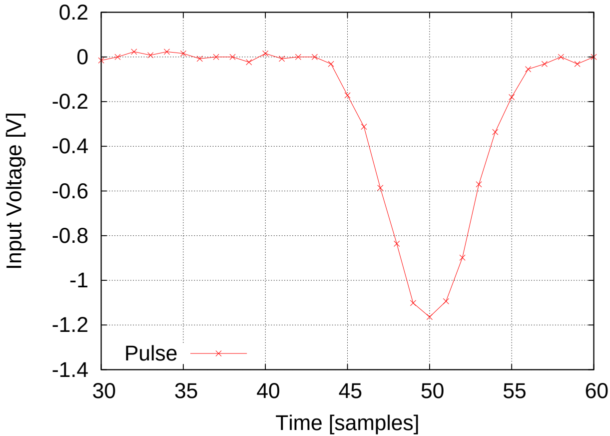




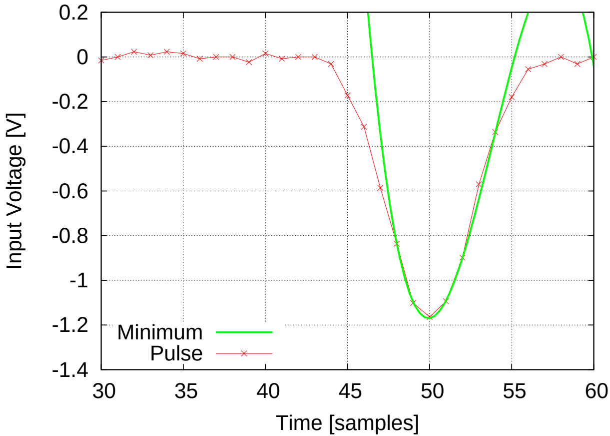
Methods

- Time between two signals is needed
- Independent method: Correlation of channels $\Rightarrow$ not so exact
- Time of minimum: Hard to determine
- Constant threshold trigger: Very inaccurate because of variable pulse height
- Constant fraction: Best method so far

True Constant Fraction pcf



True Constant Fraction pcf



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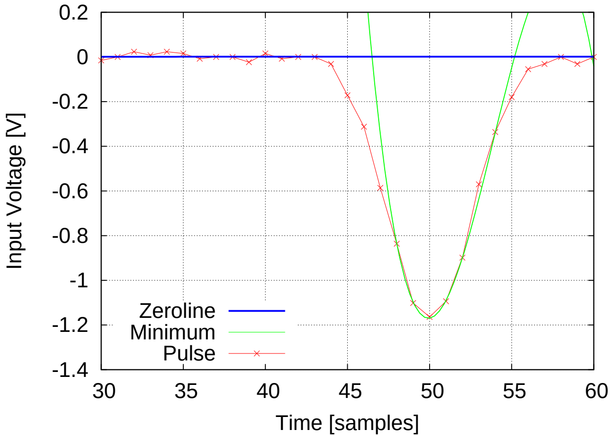

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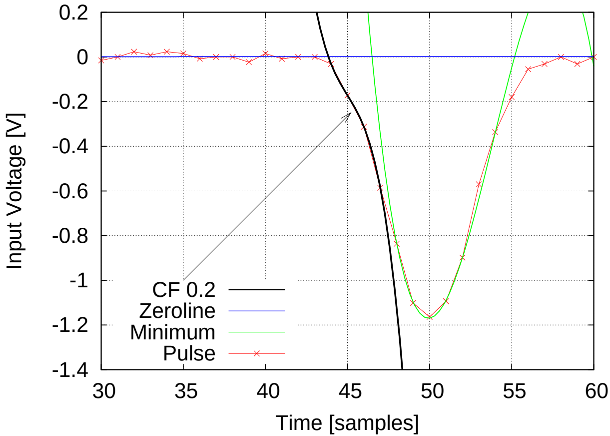
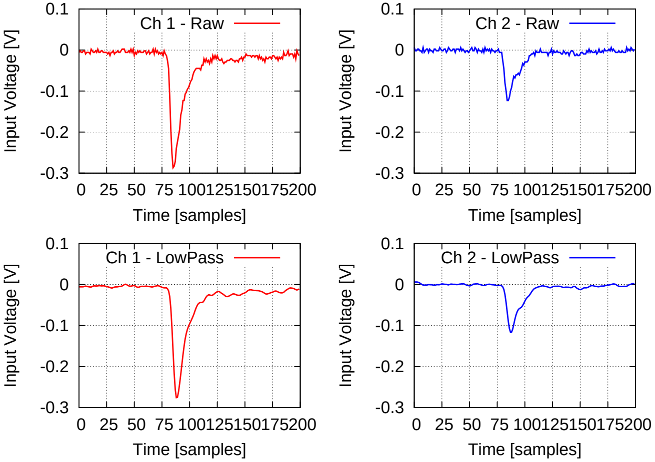
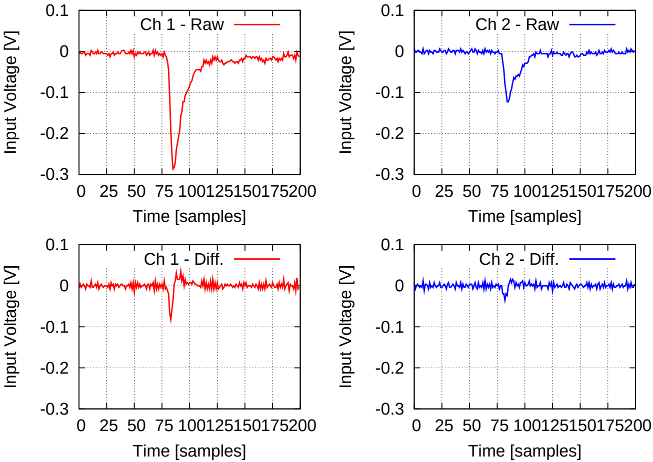


Low-Pass Constant Fraction lp-pcf



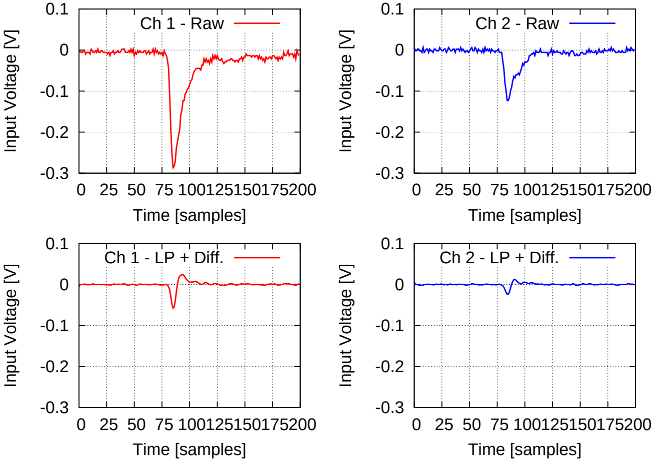
- Butterworth-Filter (implementation taken from [5])
- Followed by true constant fraction as before

Differentiated Constant Fraction dpcf



- Noise disturbs the direct differentiation especially on small pulses
- Therefor...

Differentiated Constant Fraction dpcf

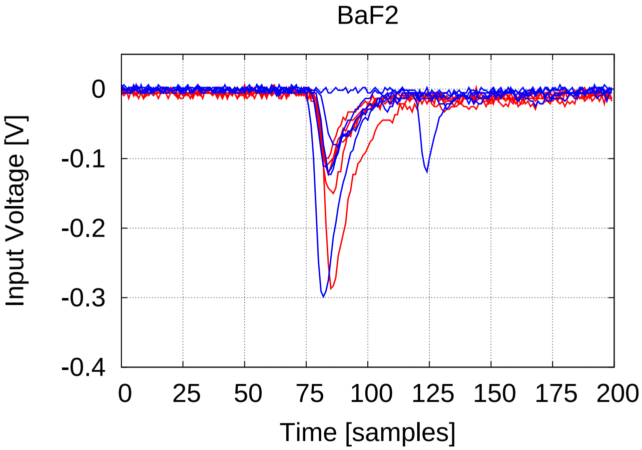


- ...Signal is filtered by low-pass first
- Then true constant fraction is applied.

Scintillators

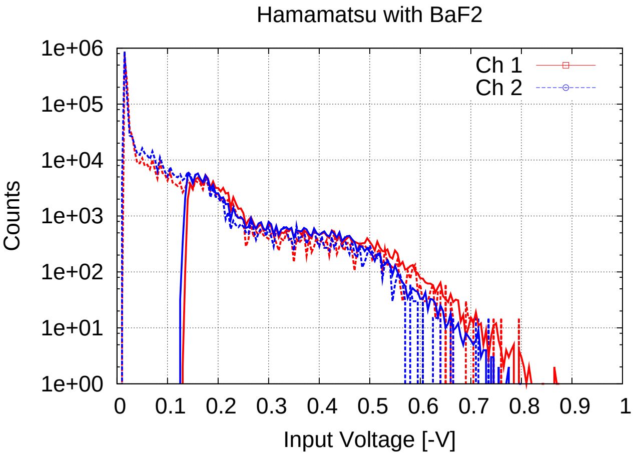
Looking at different scintillation materials for pulse-shape, energy resolution and timing resolution.

BaF_2 Barium fluoride



- Fast and slow component
- Fastest risetime currently available (1.1ns)

BaF_2 Barium fluoride



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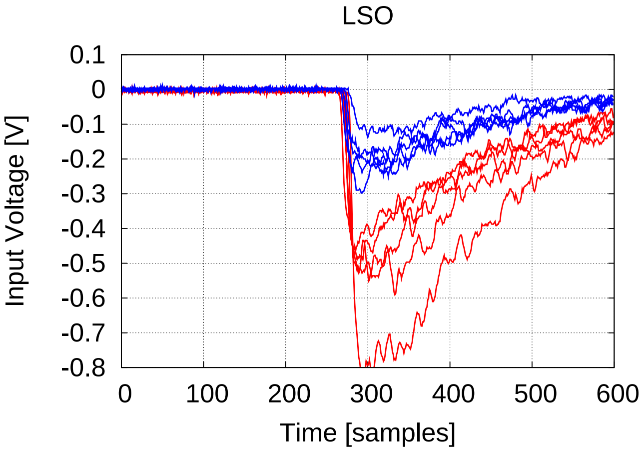
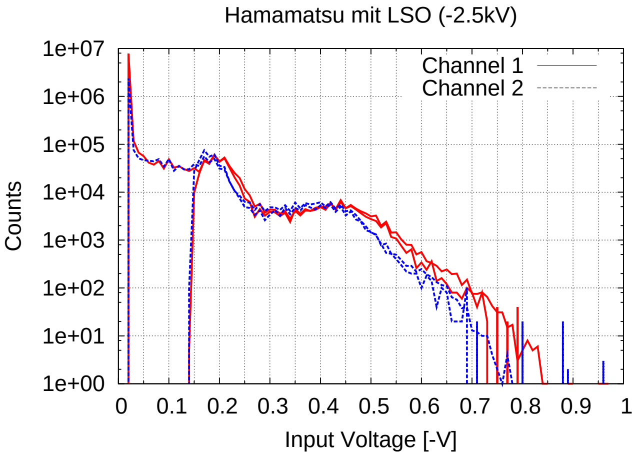
LSO Lu_2SiO_5 - Lutetium oxyorthosilicate



- Better energy resolution than BaF_2
- Has intrinsic decay of ^{1}67Lu

LSO Lu_2SiO_5 - Lutetium oxyorthosilicate



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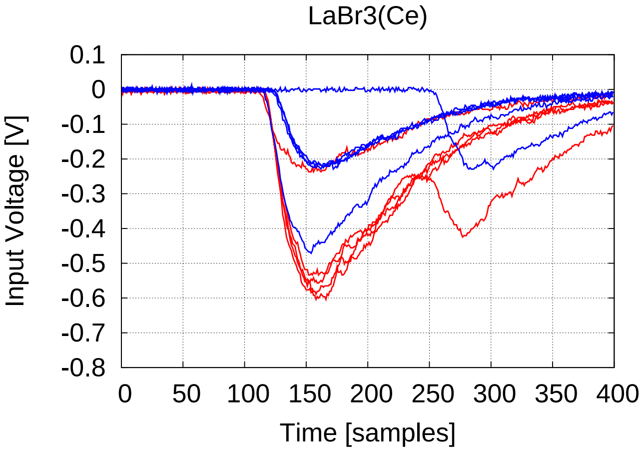
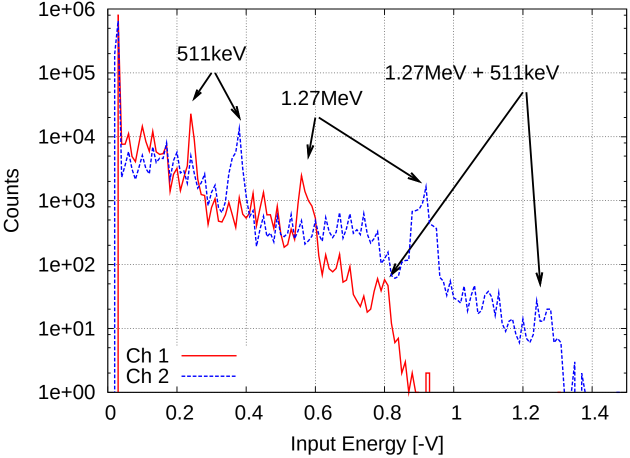
$LaBr_3(Ce)$ Lanthanum bromide



- Very good energy resolution (real photo-peaks)
- Very pricey, very hygroscopic

$LaBr_3(Ce)$ Lanthanum bromide



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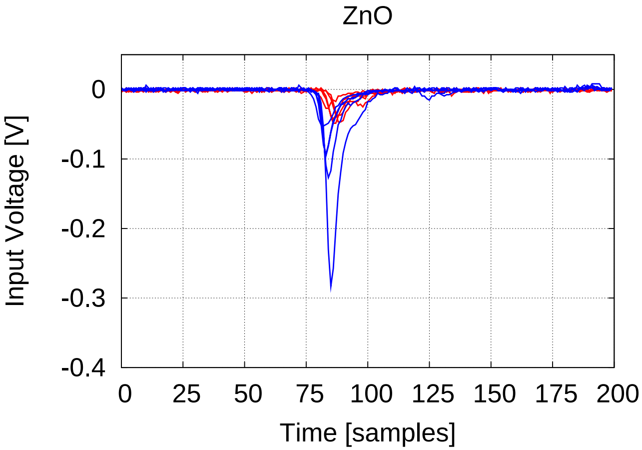
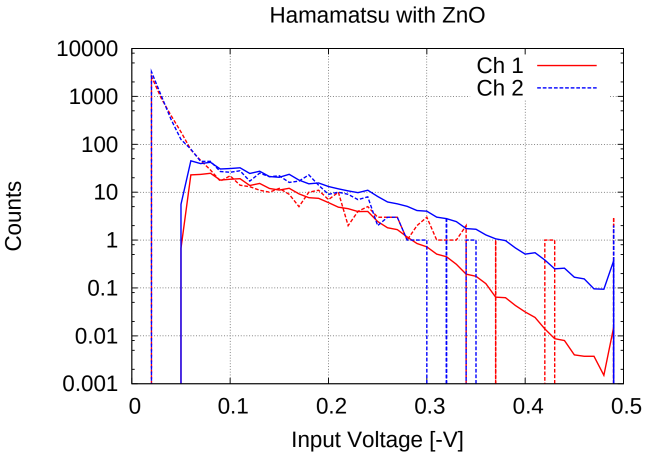
ZnO Zinc oxide



- Up to now only used as powder for α-particles
- Current research project...

ZnO Zinc oxide



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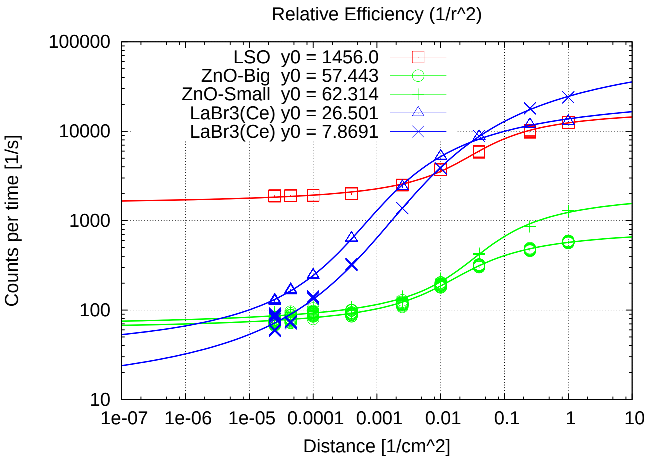
Efficiency

- Efficiency by comparison and $1/r^2$-rule.
- Lower limit ($x \rightarrow 0$, $r \rightarrow \infty$): efficiency of a single scintillator point
- Upper limit ($x \rightarrow \infty$, $r \rightarrow 0$): maximum digitizer transfer rate
- double-log plot fitted with arctan-function

Efficiency



Relation: LSO $\sim 6 \times BaF_2$ [6]

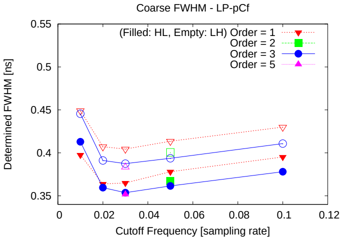
Timing Resolutions

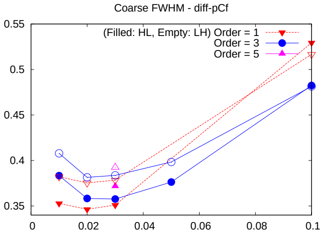
Lets take a look at the timing resolutions.

- Good energy resolution = good timing resolution?
- Best method for different pulse shapes?

$LaBr_3(Ce)$: Si - 20090119

Data File	Variance	**Lt_1** [ns]	Lt_2 [ns]	I_2 [%]	**fwhm1** [ns]
pcf-lt01-HL	1.413	0.210	0.38	7.6	0.454
pcf-lt02-HL	1.440	0.211	0.38	6.6	0.453
pcf-lt03-HL	1.440	0.211	0.38	6.6	0.453
pcf-lt04-HL	1.440	0.211	0.38	6.6	0.453
pcf-lt05-HL	1.304	0.212	0.38	6.1	**0.449**





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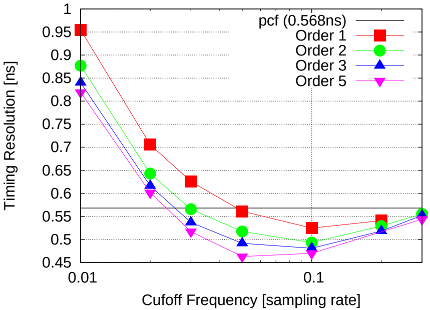
pcf-lt01-HL	1.413	0.210	0.38	7.6	0.454
pcf-lt02-HL	1.440	0.211	0.38	6.6	0.453
pcf-lt03-HL	1.440	0.211	0.38	6.6	0.453
pcf-lt04-HL	1.440	0.211	0.38	6.6	0.453
pcf-lt05-HL	1.304	0.212	0.38	6.1	**0.449**
lp_pcf-lt06-HL	7.744	0.231			0.354
lp_pcf-lt07-HL	8.773	0.232			0.360
lp_pcf-lt09-HL	8.966	0.232			**0.352**
dpcf-lt10-HL	3.208	0.228			0.351
dpcf-lt11-HL	3.522	0.228			**0.346**

LSO: Si - 20081124



LSO with lp-pcf

Method	Variance	**Lt**$_1$ [ns]	**fwhm**$_1$ [ns]
pcf (cf0.1)	0.948	0.232	0.275
pcf (cf0.5)	2.005	0.288	0.568
lp-pcf (cf0.5)	1.321	0.245	0.462
dpcf (cf0.5)	1.507	0.228	0.298

BaF_2: Si - 20090103

Method	Variance	**Lt_1 [ns]**	Lt_2 [ns]	I_2 [%]	**$fwhm_1$ [ns]**
pcf	1.6615	0.224			0.258
lp_pcf	1.8142	0.224			0.252
dpcf	1.8142	0.224			0.252
dpcf	1.1949	0.225			0.270
dpcf	1.0046	0.212	0.68(3)	0.32%	0.275
dpcf	1.0062	0.210	0.38	2.39%	**0.275**
pcf	1.0127	0.216	0.38	2.34%	**0.258**
lp_pcf	1.0410	0.218	0.38	2.13%	**0.252**

One slide to show them all.[2]

	pcf	lp-pcf	dpcf
$LaBr_3(Ce)$	449ps	352ps	**346ps**
LSO	**275ps** - 568ps	355ps - 462ps	298ps
BaF_2	258ps	**252ps**	275ps

[2]Sorry again.

Conclusions

Aim from literatur: timing FWHM 150ps to 100ps.

Feels like: *Back to square one*

What is missing?

- Efficiency measurement with BaF_2
- Lifetime measurements with ZnO

  Data is there, evaluation has to run.
- Measurements with plastic scintillators.
- Maybe its the tubes?
  - More testing with XP20Z8 with second electronics.
  - Gain experience with XP2020
  - Look at Hamamatsu R4700U

Conclusion: Thanks for your attention!

Get the slides at http://positron.physik.uni-halle.de/.

P. A. M. Dirac.
The quantum theory of the electron.
Proc. R. Soc. London, Ser. A, 118:351–361, 1928.

C. D. Anderson.
The positive electron.
Phys. Rev., 43:491–494, 1933.

A. Einstein.
Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?
Annalen der Physik, 323:639–641, 1905.

R. Krause-Rehberg and H. Leipner.
Positrons in Solids.
Springer-Verlag, 2001.

S. D. Stearns.
Digital Signal Analysis.
Hayden Book Company Inc., 1975.

A. Krille.
Aufbau und optimierung eines digitalen positronen-lebendauer-spektrometers, 2008.