Exploring the limits of time resolution in Cherenkov detection of electron-positron annihilation events

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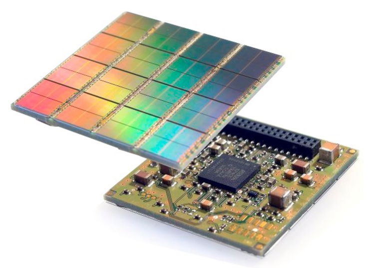
High time resolution is becoming increasingly important for many applications in nuclear medicine (e.g., Time-of-Flight Positron Emission Tomography, TOF-PET) and high energy and nuclear physics applications (e.g., Positron Annihilation Spectroscopy, PALS). Present commercial TOF-PET systems based on inorganic scintillators provide coincidence resolving times (CRT) in the order of 325 ps – 400 ps. Time resolutions at the level of 100 ps would drastically increase the signal-to-noise ratio of the reconstructed images. Ultimate time resolutions of 10 ps would allow to directly reconstruct the location of the electron-positron annihilation.

We have performed experimental studies on employing the Cherenkov effect for bypassing the relatively slow scintillation processes and thus improving the CRT. The measurements show competitive results with state-of-the-art TOF-PET-scintillators approaching CRTs towards 100 ps, with the potential to be improved even further.

The experiments were done using the Philips Digital Photon Counter (DPC), which provides excellent timing properties and single photon counting capability. For understanding the overall CRT, the intrinsic time resolution of the DPC and its individual single photon avalanche diodes were investigated using a femtosecond laser.

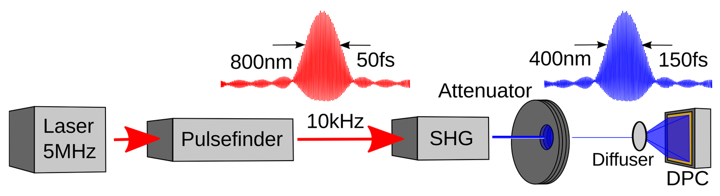
The Digital Photon Counter

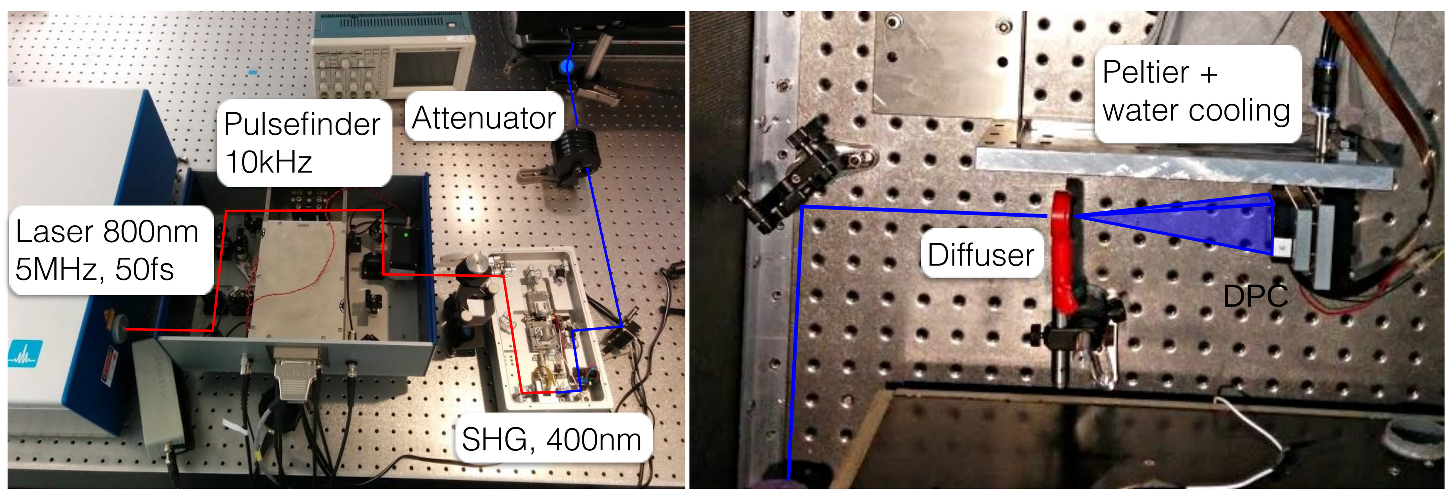


The DPC, produced by Philips, is a fully digital implementation of the silicon photomultiplier (SiPM). This fast and robust, fully digital photosensor has excellent single photon time resolution, high photon detection efficiency, and integrated readout and control electronics. It comprises 8 x 8 photon counting pixels measuring 4 mm x 4 mm each. Each group of 2 x 2 pixels share a time-to-digital converter (TDC) that outputs a time stamp after any of the 4 connected pixels has registered a user-configurable number of photons. For the presented Cherenkov measurements two DPCs with only one active pixel (3200 SPADs) were used.

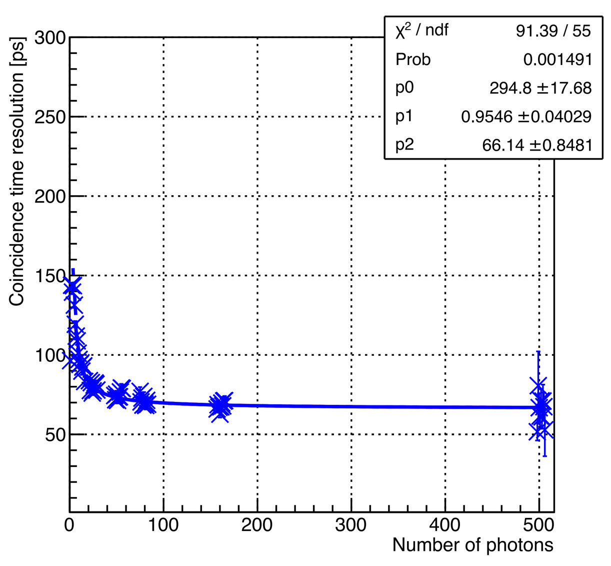
DPC time resolution

For a better understanding of the composition of the overall CRT, the intrinsic time resolution of the DPC has been measured in a separate experiment using a femtosecond laser (Femtolasers). For this study short laser pulses were directed on two channels of the DPC. One channel is defined as either being a die, a pixel or a SPAD. Investigations have been performed for all of these possibilities. Hence, as the time resolution is dependent on the number of detected photons, the measurements were done for a broad dynamic range, from single photon level up to high illumination.

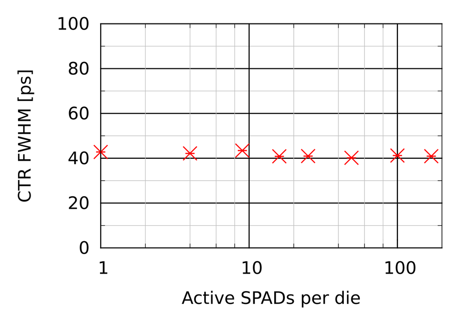




DPC	Active area	Temp. [°C]	Inactive cells [%]	CRT FWHM [ps]	System TR [ps]
3200	die	0	0	265 ± 8.4	67 ± 2.7
3200	die	0	20	238 ± 4.3	60 ± 1.2
3200	die	0	50	216 ± 3.3	64 ± 0.8
3200	die	10	20	361 ± 17.7	66 ± 0.9
3200	pixel	10	20	143 ± 3.9	22 ± 3.4
3200	pixel	20	20	160 ± 4.9	20 ± 4.4
6400	die	0	20	350 ± 4.3	57 ± 0.6



The coincidence resolving time has been measured over a broad intensity range starting from single photon level, to high illumination. The saturation at high photon level indicates the system time resolution due to the intrinsics SPAD time resolution and electronics (left). Additionally, measurements of the coincidence resolving time with a rising number of activated single photon avalanche diodes (SPADs) have been performed (right).



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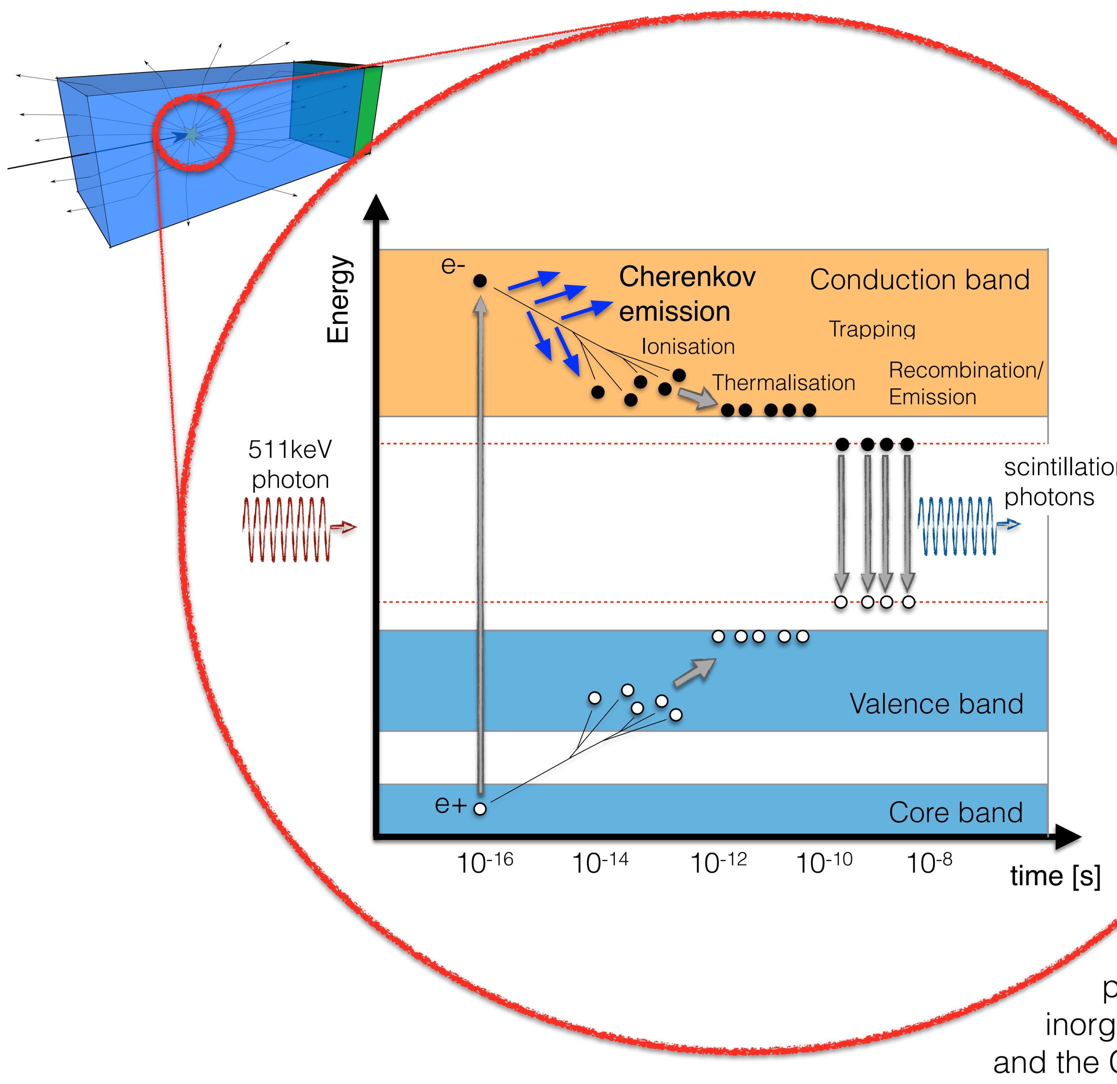
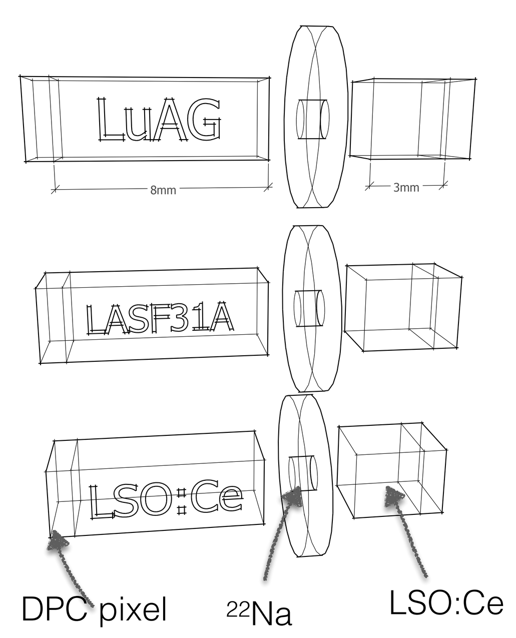


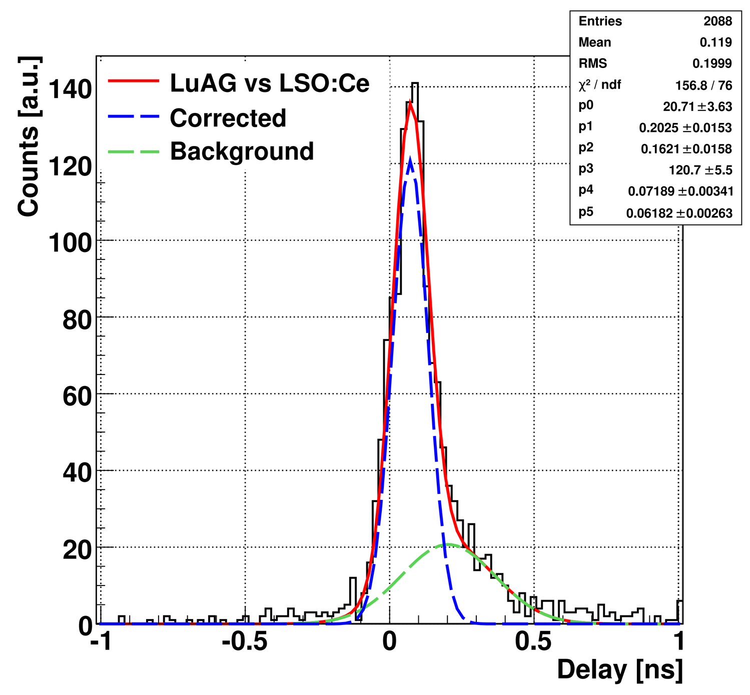
Fig: Relaxation processes in inorganic scintillators and the Cherenkov effect.

Scintillation time resolution and the Cherenkov effect

In a basic coincidence setup consisting of two Cherenkov radiators—each coupled to a DPC—the 511keV annihilation quanta originating from a 22-Na source were detected. As a reference, the CRT was measured with two LSO:Ce crystals (EPIC crystals) which represent the state-of-the-art material for TOF-PET. Each crystal was attached to a single pixel of the DPC. The measurements using the reference crystals yielded in a CRT of 191ps FWHM.

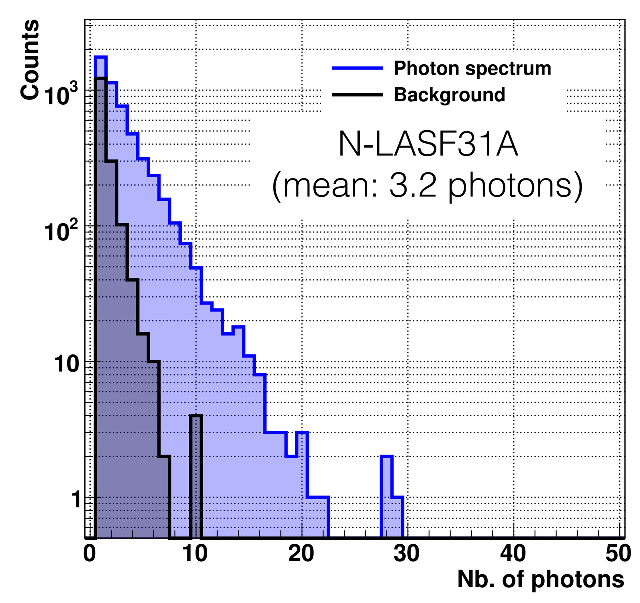
By replacing one of the LSO:Ce crystals by potential Cherenkov radiators, i.e., LuAG (Crytur) and N-LASF31A (Schott) a significant Cherenkov signal could be detected with mean numbers of 5.9 and 3.1 Cherenkov photons per event, respectively. Although the photon numbers are small, the obtained CRTs exceeded the results of LSO:Ce and reached down to 145ps FWHM for both materials, dependent on the photon threshold. These results show that applying the Cherenkov effect for annihilation detection might be used to push the limits of time resolution of PET-like detectors towards and below the 100ps mark. Further promising materials and crystal dimensions are currently under investigation.

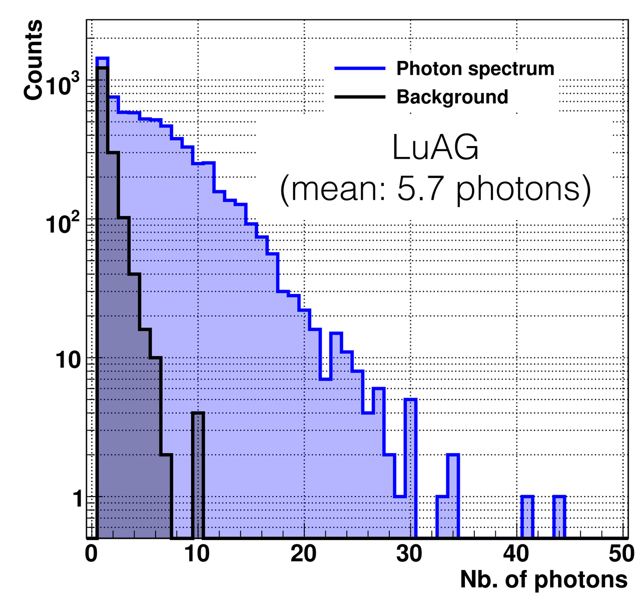




	Crystal 1	Crystal 2	Length 1 [mm]	Length 2 [mm]	Threshold 1	Threshold 2	CRT FWHM [ps]
Cherenkov effect	LuAG	LSO:Ce	8	3	4 - 6 photons	photo-peak	145 ± 6
	N-LASF31A	LSO:Ce	8	3	6 photons	photo-peak	178 ± 16
Reference	LSO:Ce	LSO:Ce	8	3	photo-peak	photo-peak	192 ± 4

Cherenkov photon yield





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