Contribution ID: **150** Type: **not specified**

Towards a picosecond fully-photonic detector module for direct 3D PET and future HL colliders

One of the major challenges our society faces today is providing personalized high-quality healthcare to all citizens in a sustainable way. Several improvements in current Positron Emission Tomography (PET) scanners are needed to transform in-vivo molecular imaging into a standard tool for personalized medicine: reduce the radiation dose, scan time and costs per patient. A way to achieve it is pushing time-of-flight Coincidence Time Resolution (CTR) to ~10 ps, enabling direct 3D imaging [1].

Current PET technology is based on scintillating crystals. However, there is an intrinsic limit in the time resolution that can be achieved by scintillation in crystals. Together with photodetector technology limitations, makes that CTR achievable with current technology is at the level of 100 ps (300 ps for commercial scanners). For sub-100 ps time resolution, mechanisms involving the production of prompt photons need to be considered. Cherenkov emission and cross-luminescent materials can offer a solution [10]. However, the light yield is very low and happens in the UV part of the spectrum, where sensors detection efficiency is not very high. There are some transient phenomena in the relaxation process that can be possibly exploited for the generation of prompt photons [10]. Another interesting option are photonic crystals which an enhance the light output of dense scintillators with a high refractive index (between 1.8 and 2.2 for the majority of scintillators) by a large factor (2 in air and by at least 50% in grease). As a consequence, PhCs can offer attractive perspectives in the search for higher timing resolution in scintillator-based detectors [3]. Moreover, recent works open the possibility to use Cherenkov radiation for photonic crystals in medical imaging and particle physics [4].

In conclusion, achieving a CRT of 10 ps FWHM in PET technology would allow accessing the huge untapped potential of direct 3D PET and it requires the use of prompt light emission due to intrinsic limitations in the time response of the scintillating mechanism. As prompt light emission is weak (few photons) and in some cases happens in the UV region, to fully exploit it, new advances are required in photodetector and front end technology aiming for an overall Single Photon Time Resolution (SPTR) in the order of few tens of ps and enhanced UV sensitivity. The SPTR of Single-Photon Avalanche Diodes (SPADs) can be as low as 20 ps or less, as it was early recognized [5]. However, time resolution of SPAD imagers is much higher than 100 ps due to limited performance of a per-pixel Time to Digital Converter (TDC). In the same way, the SPTR of Silicon Phtotomultipliers (SiPMs) or Digital Photon Counters (DPCs) is severely degraded by cell non-uniformities and by interconnection parasitic.

As first step, we propose to develop a "digital"SPAD based sensor which shall be optimized for a detector based on prompt light emission, which provides the time of arrival of the n first impinging photons. We propose a hybrid sensor combining a sensor in a dedicated high quality process with a CMOS front end and readout electronics. The integration of the SPAD sensor IC and the readout IC requires 3D integration techniques. Developments in on-chip optical link integration (system on a chip and multi-chip-modules) may allow an optical interface to the readout and synchronization, which shall be extremely useful in terms of integration, noise and performance.

At this point, we would have a photon detector with optical output, so why don't go step further? *Why don't dream about afully photonic detector, including signal processing?* Photons can be used as information carriers, making it possible to reach ultrahigh-speed and ultrawide-band information processing based on optical computing, which is a long-term pursuit of researchers. Researchers dream of achieving a photonic computer with untiring efforts. A crucial point is to realize the photon center processing unit (CPU) which is mainly composed of all-optical logic devices. Several schemes have been proposed in the past years, such as using photonic crystals [6], silicon photonics or surface plasmon polaritons.

Since photonic crystals could eventually be used both for detection [3] and processing [6] and since optical links are often the best choice in high energy physics and medical imaging, a fully photonic detector (optical I/O) will open enormous opportunities do develop high speed and extremely compact detectors. Obviously, many technological challenges will be faced, but optical processing elements such as comparators are being developed [7]. This is an endeavour for the next 10 years, many new amazing possibilities will open for high-energy physics colliders, such as HL-LHC or CLIC, with a bunch-crossing rate of 2 GHz, as well as for direct 3D PET in medical imaging.

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doi:10.1038/srep03869

Summary

photonic crystals, optical processing, molecular imaging, direct 3D PET,Cherenkov detector, HL-LHC, CLIC, SPAD, SiPM, 3D integration, ASIC

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