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Recent progress in Cherenkov based TOF PET

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We will report on the development of a novel PET scanner concept which is potentially cost-effective, could have a higher patient throughput, and would also allow for a construction of a full-body PET apparatus. The resulting detection system would provide the basis for increased sensitivity in cancer detection, providing a more robust diagnosis for an early therapy selection in an individual patient. The scanner will be based on the detection of annihilation gammas by using Cherenkov-light, thus translating basic physics experiments to clinical PET. We will report on a series of experimental and simulation studies that have shown that with this detection concept TOF resolutions below 100ps are possible, that SiPMs present a very promising device for Cherenkov light detection in TOF PET, and that such an apparatus offers a very interesting cheaper alternative to scintillating crystal based scanners.

Summary

The information on flight time difference of the two gamma rays emitted simultaneously during positron annihilation can be incorporated in the image reconstruction algorithm in the time-of-flight positron emission tomography (TOF PET), resulting in a lower image noise. The reduction depends on the TOF resolution, which is in the range of 500 ps in current clinical scanners, and reaches 300 ps in prototype developments. Gain in variance is around 3 in this case. It has been shown [1] that a TOF resolution of 100 ps would reduce variance by a factor up to 18.

In positron emission tomography the annihilation gammas are traditionally detected using scintillation crystals. Gamma interactions in the crystal produce thousands to tens of thousands of optical photons, a large fraction of which can be detected with a photodetector. As better scintillators and faster photodetectors became available, the main limiting factor for the resolution of time measurement in time-of-flight (TOF) PET became the time constants characteristic for the production and decay of scintillation light. This limitation can be avoided by basing the method on detection of Cherenkov photons, which are produced by a passage of fast charged particle (i.e. an electron resulting from gamma interactions) through suitable material. The Cherenkov photons are emitted instantaneously, however only about 10 are produced by a 511 keV gamma, meaning that the method must be based on detection of single photons.

The proposed scanner concept has a number of advantages. The cost of a Cherenkov based scanner will be significantly lower than that of a scintillator based apparatus since the contribution of the sensitive detector material, which typically amounts to one half of the system cost, will be reduced by about a factor of three. In addition, for a whole-body PET with 100 ps TOF information a significant increase of signal-to-noise ratio is expected if compared to the currently available TOF PET systems. This improvement could be used in a number of ways, by shortening the acquisition time and thus increasing throughput, by reducing the radiation exposure, or by allowing for an individually measured bio-kinetics of tracers in an effort towards an individualized diagnosis and therapy.

Using 25×25×15 mm3 lead fluoride (PbF2) crystals as Cherenkov radiators and microchannel plate photomultipliers (MCP PMTs) as photodetectors, a coincidence timing of 87 ps FWHM has already been experimentally demonstrated [2]. With only a couple of photons available for detection, the photon detection efficiency (PDE) of the light sensor becomes the limiting factor for the efficiency of the method. To improve the relatively low PDE of original sensors, silicon photomultipliers (SiPMs) were used to improve the efficiency of the method [3]. The SiPMs can have a very high peak PDE and also have other desirable properties: they operate at low voltages, are insensitive to high magnetic fields, could be more cost effective than other photodetectors and are suitable for a 1:1 coupling with crystals used in TOF PET.

The high photon detection efficiency (PDE) of SiPMs led to a large improvement in detection efficiency in the first set of tests [3]. On the other hand, the time response of available SiPMs was not as good as that of MCP PMTs, and further detailed studies of timing properties of several recently developed SiPMs produced by four different manufacturers were carried out with single photon level picosecond laser illumination.

Simulations were performed in order to estimate the performance of TOF PET scanner based on the Cherenkov method of gamma detection. The main building block of the simulated scanner was a gamma detector composed of a PbF2 crystal and a SiPM. The performance of a single gamma detector was explored in depth using GEANT4. The simulation was then transferred to GATE [5] and a full body scanner was simulated, and the performance of the scanner based on the Cherenkov method was compared to that of a state-of-the-art LSO scanner. First preliminary Monte Carlo simulation studies have shown that a Cherenkov-PET scanner using Lead fluoride with the same size of detector elements and the same ring geometry as a state-of-the-art PET scanner will have a 20% improved spatial resolution, as is now achieved using one-to-one coupling. Sensitivity will be about one half, but noise equivalent count rate can be expected to be as good as or better than the standard PET scanner, if TOF resolution is 200 ps or better.

We will report on a series of experimental and simulation studies that have shown that with this detection concept TOF resolutions below 100ps are possible, that SiPMs present a very promising device for Cherenkov light detection, and that such an apparatus offers a very interesting cheaper alternative to scintillating crystal based scanners.

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Author: S. KORPAR, LJUBLJANA UNIV.

Co-author: KRIZAN, Peter (University of Ljubljana)

Presenter: S. KORPAR, LJUBLJANA UNIV.

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