Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras

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Abstract

This contribution describes fast time-stamping cameras sensitive to optical photons and their applications.

Keywords: time-stamping camera, imaging mass spectrometry, fluorescent lifetime imaging, single photon imaging, Tpx3Cam, TimepixCam

1. Imaging with photon counting

Imaging of fast processes with nanosecond-scale timing resolution is necessary in many applications. Detection of individual photons is ultimately the best route to capture all available information for the process, in which they were created. This information then can be used to do simple imaging by counting all detected photons or, if desired, to perform more complex operations with the data, which could involve timing analysis of individual hits or some correlation analysis. Photon counting is already a widely used modality in x-ray imaging where the signal is large enough to detect individual photons directly without external amplification, and to enable measurement of the time and energy for each of them. Here we describe the concept of time stamping for optical photons including single optical photons, and present recent results on TimepixCam and Tpx3Cam cameras, which can be used for this purpose.

Framing versus time-stamping: In conventional imagers the signal is integrated in a slice of time and stored in the pixel for consequent readout, frame by frame. Currently this approach makes it impossible to achieve nanosecond
resolution for continuous readout because the data rates are becoming prohibitively high. Imagers for the 400-1000nm wavelength range are commercially available for framing rates of up to 10kHz with their pixel output rates of Gpix/s. This corresponds to time resolution of 100 µs, which is orders of magnitude inferior than the nanosecond-scale requirement. More specialized cameras based on CCD or CMOS technology are becoming available which can achieve faster rates by buffering multiple frames in the sensor [1, 2]. However this approach is not scalable and cannot be used for continuous readout. When the buffer is full one must stop and transfer the data to the outside world so the overall duty cycle is small.

An alternative approach is based on the so-called data-driven readout when only the data of interest is captured. To reduce the rate and support continuous readout, only those pixels, in which the signal exceeds a certain predefined level, are measured and read out. In the context of light detection this technique was implemented in the PImMS camera for mass-spectrometry applications [3, 4], and, as described in the following, in the optical cameras based on readout chips of the Timepix family [5, 6].

In the data-driven approach the signal shaping in the front-end electronics is fast, with peaking time of ~ 100 ns, in order to be compatible with nanosecond timing resolution. With enough photon statistics images can be formed by counting the photons as well as more complex analyses can be performed. For example, one can use the measured photons to determine coincidences, to calculate correlations, invariant masses etc. This has close parallels with registration of x-rays at the synchrotron light sources and of ionizing particles in the high energy physics experiments, where they are detected as standalone objects.

High rate capability of the readout electronics is essential for fast accumulation of statistics. Assuming a similar back-end bandwidth as for the framing approach, Gpix/sec, and a 0.1-1 Mpix array it is easy to calculate that this would correspond to an average pixel (and frame) readout rate of 1-10 kHz. Therefore the "effective" frame rate for a data-driven system is similar to the framing approach but in addition to the "normal" imaging one has a precise
time-stamp for each photon. The price for this, of course, is complexity of the pixel as for the data-driven approach it needs to accommodate considerably more than just a few transistors as in simple framing architectures. It is typical to have hundreds of transistors per pixel, this also leads to a larger pixel size: 55x55 and 72x72 square micron respectively for Timepix and PImMS sensors.

**Optical versus direct detection:** The pixel noise is too high to be sensitive to single photons so currently their detection for the applications discussed in this paper requires an external amplification in the form of micro-channel plate (MCP), which produces an avalanche of electrons in the MCP pores. In principle, these electrons can be collected to sensing electrodes on the readout chip directly, and indeed Timepix was used before to directly detect electrons from the MCP both for optical photon and ion imaging applications [7, 8, 9]. Another approach would be to send the MCP electrons to a thin layer of fast scintillator so they produce a flash of light, which can be registered with an optical camera. This approach is very common in the ion imaging and in the intensified cameras for night vision and other applications though normally for much slower scintillators and cameras. The two approaches are illustrated in Figure 1.

![Figure 1: Comparison of direct and optical detection.](image)

Both PImMS and Timepix cameras adopted the optical approach, which has three important advantages over the direct detection approach. Firstly, the direct collection of MCP electrons requires close (∼ mm) proximity of the readout chip in vacuum to the kV-scale voltages, a considerable complication, which may
cause sparks damaging the detector. The optical approach completely avoids it. Secondly, the camera is placed outside of the vacuum and is fully decoupled from the rest of the setup. In many cases it just replaces a slower camera used in these experiments beforehand. At last, the optical approach allows flexible mapping between the scintillator screen and sensor by introducing demagnification so a larger scintillator can be fully imaged in a smaller sensor. Other optical schemes with magnification, relay lens and mirrors are also possible.

2. Fast optical cameras based on Timepix and Timepix3

The fast cameras described below are the so-called hybrid pixel detectors: a pixelated optical sensor with high quantum efficiency (QE) is bump-bonded to a Timepix ASIC (application specific integrated circuit). The design of the back-side illuminated silicon sensor, in particular its thin entrance window was inspired by the fully depleted astronomical CCDs, such as used, for example, in LSST [10], while the readout chip is a product of the Medipix collaboration [11] at CERN employing technologies developed for the LHC experiments. The data acquisition system for the camera uses a commercial readout of an x-ray detector. The first fast camera based on the Timepix readout chip [5], TimepixCam [12], was built in 2015, followed in 2017 by the next generation camera, Tpx3Cam [13], based on Timepix3 [6]. Both cameras employ the same sensor. Figure 2 shows the optical sensor inside Tpx3Cam and intensified version of the camera with attached image intensifier and 50 mm f/0.95 Navitar lens.

In Timepix3 each pixel has a predefined threshold and only the pixels above the threshold perform the time measurements and are read out making the chip completely data-driven. It uses a free running 40MHz clock and does not require any external triggering. The fired pixels provide the time-of-arrival (TOA) information with 1.6 ns granularity and time-over-threshold (TOT) information with 25 ns granularity. The individual pixel deadtime is equal to the pixel TOT + 475 ns.

Fast scintillator, P47, used in combination with MCP has the rise and decay
time of 7ns and 100ns, respectively, and maximum emission in blue at 430 nm [14]. The absorption depth for the blue photons is only 250 nm so it is very important that the passive layer on the sensor surface is thin to let the photons through. At the same time it should be conductive to ensure uniform electric field and full depletion of the 300 micron thick sensor because the photoelectrons
need to drift from the sensor window on the back side to the collection pads on the front-side, which are bump-bonded to Timepix. Anti-reflective coating on the sensor was optimized for the P47 emission spectrum. Figure 3 shows the measured quantum efficiency as function of the wavelength for several types of sensors with varying thickness of passivation layer and with/without the anti-reflective coating. The measurements are described in detail in [15] together with other testing results for the optical sensors.

![Figure 3: Quantum efficiency of the Timepix compatible optical sensor as function of wavelength.](image)

The Tpx3Cam camera readout is based on the SPIDR data acquisition system [16][17], which is available commercially [18]. The SPIDR maximum output rate is 80 Mpix/s. It also implements a time-digital-converter (TDC), which provides a time-stamp with 0.26 ns granularity for an input signal and is synchronized to the Timepix3 data. This input can provide a precise time reference for the Timepix3 hits using, for example, a pulse synchronous with respect to the laser employed in the experiments. It also can be used to synchronize multiple cameras to each other and to external devices.
2.1. Detection of single photons

Detection of single photons requires external amplification so the intensified version of the camera employs an image intensifier, a vacuum device with photocathode followed by a MCP and scintillator. The MCP can operate at gains up to few times $10^5$ making the device sensitive to single photons. The back-end of the intensifier used for the measurements discussed below consists of the MCP/P47 assembly so is very similar to the assembly routinely used for the ion imaging as illustrated in Figure 4. This similarity in detection of various particles: ions, electrons, single photons and, as proposed below, x-rays and neutrons, makes this approach very versatile because the same camera can be used for all of them without any modifications.

![Image of detection systems](image.png)

Figure 4: Comparison of ion and single photon detection using the MCP and fast scintillator.

The photocathode in the intensifier can be selected to match the QE requirements for a particular application. There is a wide choice of available photocathodes with different spectral sensitivities, an example is given in Figure 5, which provides QE as function of wavelength for a variety of Photonis photocathodes [19]. The 18mm Photonis intensifier tested with the cameras had High-QE Red photocathode with QE equal to 18% at 800 nm, the wavelength relevant for the quantum information science applications [20], and dark count rate of $\sim 80$ kHz over the full photocathode area at room temperature.

The intensifier in a cricket [21] is shown together with the camera in the right part of Figure 2. The cricket integrates into a single unit the intensifier,
the power supply and collimating relay optics between the intensifier output and camera sensor. The cricket is fetched with C-mounts on both ends for attachment to the camera and to a lens.

Figure 6 shows examples of single photon hits recorded by the camera in a time slice of 5 ms. The hits are shown as heatmaps in TOT representation (left) and TOA representation (right). One can see that each hit typically consists of several pixels which have signals above a threshold. Since all fired pixels measure TOA and TOT independently and have position information, it can be used for centroiding to determine the photon coordinates. The centroiding considerably improves the spatial resolution, easily to sub-pixel values. The
timing resolution can be improved at the pixel level correcting for the time-
walk, an effect caused by the dependence of the front-end pixel electronics time
response on the amplitude of the input signal. Since the latter is measured
in TOT, the TOA can be corrected achieving 2-3 ns timing resolution (rms)
\cite{13,20}. The resolution per photon can be further improved to sub-nanosecond
values by combining timing information in multiple pixels, which belong to the
same photon hit.

2.2. Applications

During the last three years the Timepix time-stamping cameras have been
used in a variety of applications.

\textbf{Ion and electron imaging:} In this case the ions impinge a micro-channel
plate producing light flashes in fast scintillator behind the MCP, which are im-
ageed by the Timepix camera. This approach works particularly well for the co-
incidence velocity map imaging (VMI), an essential tool in the study of reaction
dynamics and strong field laser matter interactions. VMI projects the transverse
momenta of charged particles to positions on a 2D detector such that for a given
particle species, its distance to the center of the detector is proportional to the
initial transverse velocity. It also requires simultaneous measurement of all re-
action fragments, which is not possible with a slow camera. The measurements
with TimepixCam and Tpx3Cam were performed at FLASH in DESY \cite{22} and
in the ultrafast spectroscopy lab at Stony Brook University \cite{13}. Several other
groups interested in the ion and electron imaging used the cameras with the
data analysis currently in progress.

\textbf{Phosphorecent lifetime imaging:} The camera performance for single
photons was first validated in experiments on the photon counting phospho-
rescence lifetime imaging. In this type of measurements the camera is time-
stamping photons, which are emitted with characteristic lifetime after excitation
of a substance under study with a short laser pulse. The results are described
in \cite{23} and \cite{24}. 
**Imaging of entangled photons**: in the single photon mode the camera was also used for characterization of sources of entangled photons and measurements of their temporal and spatial correlations [20].

**Optical readout of TPC**: recently Tpx3Cam was employed for the first demonstration of three-dimensional optical readout of a dual phase liquid Ar TPC (time projection chamber) [25]. The approach is described in detail in [26, 27].

**Other possible applications**: the camera can be used to register light flashes in thin scintillators produced by x-rays with energy 10keV and higher, where the direct detection with silicon sensors becomes inefficient. This approach, currently under testing, requires an intensified version of the camera since only a handful of photons will be collected per x-ray. However, it should allow a simple technique of time-stamping for individual x-rays with nanosecond resolution. Also it will avoid placing the detector in the direct beam of x-rays. Similar approach of registration in a thin scintillator can be employed for neutrons.

### 3. Future R&D directions

It is not possible to detect a single optical photon with good time resolution in a silicon sensor without amplification because of the intrinsic noise. The amplification can be achieved outside of the sensor using an image intensifier as described above or, alternatively, inside the sensor. Sensors with internal amplification are based on technologies such as SPAD (single photon avalanche devices) [28] and LGAD (low gain avalanche devices) [29, 30], which have multitude of applications including high-energy physics applications as, for example, in tracking of charged particles with 50ps timing resolution. Advances in the CMOS technology is enabling integration of these devices in to pixelated silicon sensors. This lead to production of the first SPAD arrays capable to count and time stamp single photons with resolution below 100 ps [31]. The HgCdTe imagers with internal amplification, which are compatible with single photon
detection, also received recently a lot of attention in astronomy in the context of extremely low light level applications [32]. In terms of the charge collection all the above sensors should be able to support the fast nanosecond timing. They also should be compatible with the hybrid approach as described above, which will benefit from future improvements of the time resolution for readout ASICs as, for example, in Timepix4, which is aiming at 200 ps accuracy [33].

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