Imaging and time-stamping single photons with nanosecond resolution for QIS applications

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23 October 2020
Types of fast Imaging

- "normal" cameras: 0.1 ms → 10 µs
- Burst mode cameras: 1 µs → 10 ns
- Data-driven cameras: 10 → 0.01 nsec
- Streak cameras: 1 psec
- Repetitive "pump/probe cameras": fsec
‘Normal’ fast CMOS camera: 5 kfps = 0.2 ms/frame

- Soap bubble
Normally signal is integrated in a slice of time

5 kframe per second camera

0.2 msec

Quite far from 1 nanosecond!
Can achieve faster imaging by gating (of intensifier)

- Smaller time window = Less signal = Lower occupancy
- Ultimately resolve single photons
Imaging with photon counting

Photons appear as standalone objects $\leftrightarrow$ data driven readout
Has parallels with x-ray imaging and particle detection in HEP

Low occupancy

Integrated image

Alternative Approach to Optical Imaging

- Detect and time stamp photons, one by one, using intelligent pixels with data-driven readout
- Accumulate statistics for images, also for more complex analysis (coincidences, correlations etc)

Frame-by-frame imaging →
continuous stream of time stamped single photons

TpX3Cam: time-stamp 10 MHz flux of photons with 1 ns precision

Timepix Optical Cameras
Hybrid pixel detectors

Have roots in R&D for LEP/LHC vertex detectors

Lukas Tlustos and Erik H. M. Heijne, Performance and limitations of high granularity single photon processing X-ray imaging detectors, in CERN proceedings (2005)

- Decouple readout chip and sensor
- Optimize technologies for chip and sensor separately

Use different sensors with same readout, versatile approach for x-rays (Si, CZT)
→ we will use OPTICAL sensors
Photon absorption in silicon

- Blue photons are absorbed near the surface (~0.25 um for 430 nm, P47 max emission)
- ~1 um for 500 nm, ~10 um for 800 nm

![Graph showing photon absorption in silicon]

A photocathode converts light into electrons. This conversion efficiency depends on the wavelength of light. The relationship between this conversion efficiency (photocathode radiant sensitivity or quantum efficiency) and wavelength is called the spectral response characteristic. (See spectral response characteristics on page 1.)

An MCP is a secondary electron multiplier consisting of an array of millions of very thin glass channels (glass pipes) bundled in parallel and sliced in the form of a disk. Each channel works as an independent electron multiplier. When an electron enters a channel and hits the inner wall, secondary electrons are produced. These secondary electrons are then accelerated by the voltage ($V_{MCP}$) applied across the both ends of the MCP along their parabolic trajectories to strike the opposite wall where additional secondary electrons are released. This process is repeated many times along the channel wall and as a result, a great number of electrons are output from the MCP.

The dynamic range (linearity) of an image intensifier depends on the so-called strip current which flows through the MCP during operation. When a higher linearity is required, using a low-resistance MCP is recommended so that a large strip current will flow through the MCP.

The channel diameter of typical MCPs is 6 $\mu$m. Please select the desired type according to the readout method.

![Diagram of MCP structure and operation]

The phosphor screen generally absorbs ultraviolet radiation, electron beams or X-rays and emits light on a wavelength characteristic of that material. An image intensifier uses a phosphor screen at the output surface to convert the electrons multiplied by the MCP into light. Phosphor screen decay time is one of the most important factors to consider when selecting a phosphor screen type. When used with a high-speed CCD or linear image sensor, a phosphor screen with a short decay time is recommended so that no afterimage remains in the next frame. For nighttime viewing and surveillance, a phosphor with a long decay time is suggested to minimize flicker. Figure 5 shows typical phosphor spectral emission characteristics and Figure 6 shows typical decay characteristics.

We also supply phosphor screens singly for use in detection of ultraviolet radiation, electron beams and X-rays.

![Graph showing transmittance of window materials]

![Graph showing phosphor spectral emission characteristics]

![Graph showing phosphor decay characteristics]
Thin window optical sensors

Surface preparation is very important, inspired by astronomical CCDs (LSST)

Developed at BNL, first produced at CNM (Barcelona, Spain) in 2015

High QE


Backside illuminated optical sensors
Anti-reflective coating, thickness 300 um
Timepix3 Camera → Tpx3Cam

Camera = sensor + ASIC + readout

Timepix3 ASIC:
• 256 x 256 array, 55 x 55 micron pixel
  – 14 mm x 14 mm active area
• 1.56 ns timing resolution
• Data-driven readout, 600 e⁻ min threshold, 80 Mpix/sec, no deadtime
• each pixel measures time and flux, ~1 µs pixel deadtime when hit

Sensor is bump-bonded to chip

Use existing x-ray readouts:
SPIDR (Nikhef & ASI)
www.amsbins.com


Zhao et al, Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution, Review of Scientific Instruments 88 (11) (2017) 113104.
Use existing readouts of x-ray detectors:

TPX3Cam @ ASI

SPIDR readout for Timepix3 (Nikhef, ASI)


eX readout for Timepix2 (Imatek)
Applications & Results

• Ion imaging - briefly

• Quantum imaging – in more detail

• HEP applications – briefly

• Lifetime imaging – next time
Ion Imaging

Advantages of optical approach

Outside of vacuum
- Decoupled from setup
- No cooling in vacuum
- No HV close to electronics

Power of optics
- lens & mirrors
- magnification/ demagnification, flexible mapping between scintillator screen and sensor

“Hybrid” approach
- Use same camera for different applications
- Easily upgradable: different cameras with same setup
- Use different photocathodes/ intensifiers with same camera
Ions in TimepixCam


https://doi.org/10.1107/S16005775170
Single (optical) photons
Intensified camera: use off-the-shelf image intensifier

Intensified cameras are common:
- iCCD
- iCMOS cameras
Choice of photocathodes

Photonis photocathodes
Single Photons in Tpx3Cam

1 ms slice of data
1.5ns time-stamping

TpX3Cam + intensifier by Photonis
data taken by J. Long (ASI)
Each photon is a cluster of pixels → 3D (x,y,t) centroiding

Spatial resolution: 0.1 pixel / photon

Time resolution: < 1 ns / photon
Quantum Information Science, Quantum-Assisted Imaging for telescopes and others

Will mention other applications only briefly
Quantum Network

- Attenuation in fibers \(\rightarrow\) need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state
- Qubit teleportation: produce entangled photons and send them to two locations
- Bell State Measurement (BSM) on one photon will collapse the wave function of the other one (or swap entanglement)

A.Zeilinger
Quantum Communications

Collaboration with Stony Brook U (Figueroa group)

Long-term goals:

Long-distance quantum network with quantum repeater using a modular approach based on
- room temperature Rb quantum memories;
- entangled photon sources compatible with memories;
- characterization devices for single photons

Quantum sensing: investigate how photonic quantum systems entangled at long distances can be applied to sensing

Demonstration of scalability: connect multiple & diverse quantum devices

Path to quantum internet
SBU BNL Quantum repeater test bed

Quantum Memories and Bell measurement

Entangled Source

Free space link

Quantum Memory

Entangled Source
Characterization of Single Photon Down-Conversion Source

qubit: use H, V photon polarization states

\[ |\phi^\pm\rangle = \frac{(|HH\rangle \pm |VV\rangle)}{\sqrt{2}} \]
• Find coincidences, plot as function of two polarizations
• Figure of merit: $S$-value
  - If $> 2$: photons are entangled
  - Max value: $2 \sqrt{2} = 2.82$

• Measurement:
  $S$-value = $2.72 \pm 0.02$

Time resolution: 2ns
Spatial characterization of tanglement

Measure S-value for 81 combinations of subareas

Uniform within errors as expected
Characterization of entanglement for long-distance network

Instrumentation 535/C20

TPx3Cam

Physics 510/2-225A

TPx3Cam

0.8 km

0.3 km

ESnet Fiber Loops (~8 km each)

Entangled Photon Source
Bell State $|HH\rangle + |VV\rangle$

ΔT = 2068 ns
0.8 & 0.3 km

ITD 515/BCF

0.81 km
Signal from fiber

Stokes parameters

Long-distance qubit transfer experiments between BNL and SBU are in progress
Quantum entanglement distribution between BNL and SBU

BNL (view from SBU)

SBU (view from BNL)

Top of SBU HST

Entanglement source

Quantum Receiver

Entanglement detection

Quantum Transmitter
Quantum Astrometry

• BNL QuantISED project, started in Sept 2019
  – DOE QIS-HEP program

• Idea: employ quantum entanglement to improve precision of optical interferometers

Two-photon amplitude interferometry for precision astrometry
Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich
Astronomy picture of the decade

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines
Classical optical interferometer

- Need to bring light to the same location
- Baselines limited to 100 m

\[ \frac{b \sin(\theta)}{\lambda} = \phi \]

Objects

\[ \Delta \theta \sim \frac{\lambda}{b} \]

sensitive to features on angular scale
Optical Interferometers

CHARA (Center for High Angular Resolution Astronomy) Observatory at Mt. Wilson in CA


Beam line path length control at CHARA

Path lengths must be balanced so arrival times on two legs match to within $\Delta t \sim 1/\nu$ i.e. $1$/photon bandwidth
Optical interferometry examples

Dynamic convection on Antares (VLTI, ESO)

~ 1 mas

Nova in progress (CHARA)
Two-photon techniques
(quantum mechanical)
• Measure photon wave function phase difference performing Bell State Measurement at one station so teleporting the sky photon to the other station
• Enables long baselines and could improve astrometric precision by orders of magnitude
Possible impact on astrophysics and cosmology

it is a blue-sky research

BUT if successful: orders of magnitude better astrometry

- Imaging of black holes → general relativity checks
- Parallax: improved distance ladder → SN science → DE
- Proper motions: local DM patterns
- Microlensing, see motions and shape changes, DM hunting
- Gravitational waves, coherent motions of stars
- Exoplanets
- etc
Quantum Astrometry

Proof of principle experiments: demonstrate two-photon interference using two sky sources

- Relative path phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and f
- Different from Hanbury Brown Twiss intensity interferometry, can produce both negative and positive rate oscillations $\rightarrow$ amplitude interferometry
- Requirements to detectors: photons must be similar enough to interfere $\rightarrow$ excellent (<ns) time resolution and spectral resolution $\rightarrow$ 1 ns & 0.001 nm (can be traded)
Observables

Earth rotation fringe rate

- Path differences gradually modulated by Earth’s rotation

\[
\langle N_{xy}(t) \rangle = \bar{N}_{xy} \left[ 1 \pm V \cos(\omega_ft + \Phi) \right]
\]

\[
\omega_f = \frac{2\pi B\Omega_\oplus \sin \theta_0}{\lambda} \Delta \theta
\]

For magnitude 2 stars (bright!)

- 0.1 Hz coincidence rate in 0.15 ns bin & 1 GHz bandwidth
- Assuming \(4\times10^4\) 1 GHz bins and one night (\(10^4\) sec) get 10 \(\mu\)as resolution
  - for 500 – 1000 nm range \(\rightarrow 3\times10^5\) 1 GHz bins
First experiments

Lab demonstration of two-photon interference (Hong-Ou-Mandel effect) and spectroscopic binning using various single photon sources: coherent, down-conversion and thermal

Time correlation of two channels
SC nanowires
100 ps time resolution
narrow Ar thermal line 795 nm

Demonstrates HBT effect → photon coherence time

Work in progress, not published yet
Hong-Ou-Mandel effect

1) HOM dip for coincidences of two fibers
2) Bunched photons in single fibers

credit: Wikipedia HOM article
HOM Setup

SPDC source
- CW $P_{\text{max}} \approx 30 \text{ mW}$
- $\lambda_p = 405 \text{ nm}$ $\Delta \lambda_p = 0.7 \text{ nm}$

2x BBO

Delay module
- $P_1$, $P_2$
- PMF
- Step: $0.3 \mu \text{m}$
- Range: $10 \text{ mm}$

Tpx3Cam module
- Fiber-coupled beamsplitter
- Intensifier
- Camera

qutools.com
Examples of bunched HOM photons

Distance between two photons, pix
Hong-Ou-Mandel effect

\[ f(d - d_0) = \frac{3}{4\sqrt{\pi}} \int dy \left[ \text{sinc}(y^2) \right]^2 e^{-iy\sqrt{4 \log_2(d - d_0) \text{FWHM}}} \]

Coincidence of photons in two fibers

Coincidence of photons in single fibers

Sum of 3 coincidence rates = const

Proves that photon counting is real

Spectroscopic binning for Quantum-Enhanced Target Detection

In collaboration with NRC (Ottawa CA) D. England et al

Primary interest: quantum LIDAR and quantum illumination

Spectral and temporal correlations

Optimal multivariate discrimination

Since both temporal and spectral information is available on pair by pair basis we can do multivariate analysis, simplest one using likelihood ratios.

\[ Y = \frac{f^B(x_1, \ldots, x_n)}{f^S(x_1, \ldots, x_n)} = \prod_{i=1}^{n} \frac{f^B(x_i)}{f^S(x_i)} = \prod_{i=1}^{n} Y_i \]

Scalability

Tpx3Cam supports 10MHz single photon rate:
   = 10 x 10 x 100kHz beams

Photon router:
- Used acousto-optical modulators to create 8x8 grid
- Arbitrary routing between spots
- 10 ns time resolution, 1 μs switching

70 x 70 pixel area with 64 beams
total area 256 x 256 pixels
More quantum imaging
Imaging of trapped ions

Time resolved qubit manipulation (Blinov group, UWash)

Register 493 nm photons to probe dark/bright state of ion = state of qubit register


single qubit detection fidelity 0.99995
Time resolved ion oscillations

- Emission rate oscillations due to Doppler shift of laser light wrt moving ion
- Simultaneous time & position information allows to monitor ion micro-motions
- Powerful technique to characterize traps

Paper in preparation: Direct observation of micromotions in Paul trap
Ion micromotions

- Emission rate oscillations due to Doppler shift of laser light wrt moving ion
- Simultaneous time & position information allows to monitor ion micro-motions

- Period 54 ns
- Amplitude 0.4 micron

Direct Observation of Ion Micromotion in a Linear Paul Trap
Liudmila A. Zhukas, Maverick J. Millican, Peter Svihra, Andrei Nomerotski, Boris B. Blinov, arxiv: 2010.00159
Imaging with 30 ps timing

take precise timing from MCP

Electron spectroscopy at Wayne State U

D.Debrab, G.Stewart, G.Basnayake, A.Nomerotski, P.Svihra, S.K.Lee, and Wen Li
Developing a camera-based 3D momentum imaging system capable of 1 Mhits/s

- 32 ps timing resolution from MCP+digitizer
  - 0.7 ns deadtime
HEP applications
TPX3Cam on ARIADNE 1-ton dual phase Liquid argon TPC

LAr Cosmic Muons (10msec slice)

Image light from avalanches in gas phase in THGEM

hep.ph.liv.ac.uk/ariadne/index.html
Kostas Mavrokoridis et al

D. Hollywood et al, 2020 ARIADNE—A novel optical LArTPC: technical design report and initial characterisation using a secondary beam from the CERN PS and cosmic muons *JINST* 15 P03003

A. Roberts et al., 2019 First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera *JINST* 14 P06001
More ideas

• Scintillator flashes are imaged by intensified Tpx3Cam
• Alphas, hard x–rays, neutrons, ...

Thin fast scintillator

Difficulty: light collection efficiency (but it’s single photon sensitive)
Advantage: outside of the beam, around the corner (with mirrors)
Alphas in LYSO in Tpx3Cam

Am241 5.5 MeV alphas
LYSO 0.5 mm thickness

Intensified Tpx3Cam

Alpha hits in Tpx3Cam

Occupancy map

LYSO decay 40ns

Single alpha hit

Novel imaging technique for $\alpha$-particles using a fast optical camera

G. D’Amen, M. Keach, A. Nomerotski, P. Svihra, A. Tricoli
Future directions
## Timepix3 → Timepix4

by Medipix4 collaboration

<table>
<thead>
<tr>
<th></th>
<th>Timepix3</th>
<th>Timepix4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>IBM 130nm</td>
<td>TSMC 65nm</td>
</tr>
<tr>
<td><strong>Pixel Size</strong></td>
<td>55 x 55 μm</td>
<td>≤ 55 x 55 μm</td>
</tr>
<tr>
<td><strong>Pixel arrangement</strong></td>
<td>3-side buttable 256 x 256</td>
<td>4-side buttable 256 x 256 or bigger</td>
</tr>
<tr>
<td><strong>Operating Modes</strong></td>
<td>Data driven</td>
<td>CRW: PC and iTOT (12...16-bit)</td>
</tr>
<tr>
<td></td>
<td>PC (10-bit) and TOT (14-bit)</td>
<td>TOT and TOA</td>
</tr>
<tr>
<td><strong>Zero-Suppressed</strong></td>
<td>Data driven</td>
<td>&lt; 500 MHits/s</td>
</tr>
<tr>
<td><strong>Readout</strong></td>
<td>&lt; 80 MHits/s</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>Frame based</td>
<td>YES</td>
</tr>
<tr>
<td><strong>TOT energy resolution</strong></td>
<td>&lt; 2KeV</td>
<td>&lt; 1Kev</td>
</tr>
<tr>
<td><strong>Time resolution</strong></td>
<td>1.56ns</td>
<td>~200ps</td>
</tr>
</tbody>
</table>

**WISH LIST:**
- ASIC with optimized timing for clusters and triggering capabilities, synchronization hooks for outside devices and multiple chips
- Readout with several 10 ps TDCs in synch with Tpx
Single Photon Sensitivity without intensifier?

- So far needed outside amplification (MCP) to have a detectable signal
- Limitation: QE ~ 35% (for 800nm)
Single Photon Sensitivity without intensifier?

- Can the amplification be integrated into the sensor? Silicon QE can be >90%

**SPADs**

- Currently PDE (photon detection eff) ~30-50% but there is no fundamental limit. High PDE is crucial for some QIS applications
100 ps 32x32 pixel SPAD Camera

Superb time resolution
BUT high dark count rate,
difficulties in integration of complex designs
in a monolithic sensor, try hybrid?
Summary

• Time stamping of optical photons with data-driven readout is an attractive alternative to frame readout.
  
  Works well for sparse data
  Needs intelligent pixels with complex functionality

• Timing resolution: 10 nsec → 0.1 nsec
• Photon sensitivity: 1000 photons → single photon

• New technologies for fast single photon detection → hot topic in QIS applications
Acknowledgements

Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt
Mael Flament
Guodong Cui
Sonali Gera
Youngshin Kim
Dimitros Katramatos
Michael O’Connor
Gabriella Carini
David Asner
Anand Kandasamy
Michael Keach
Steven Paci

Jingming Long
Martin van Beuzekom
Bram Bouwens
Erik Maddox
Jord Prangsma
Duncan England
Yingwen Zhang
Boris Blinov
Mila Zhukas
Maverick Millican
Peter Svihra
ToT vs ToF: time walk
Time resolution: TOT correction and centroiding

- After TOT correction < 2 ns (rms)
- Each pixel measure TOA independently → time centroiding
  
  Time resolution: < 1 ns / photon

Coincidences in multiple cameras

Camera clock is stable only to few ppm

1 ppm = 1 μsec per 1 sec
we aim for nsec resolution
so not acceptable

Need drift correction
Need to synchronize two camera clocks = find \( T_0 \)

Use White Rabbit system (CERN) to synchronize

Spatial and temporal characterization of polarization entanglement, A Nomeroski, D Katramatos, P Stankus, P Svihra, G Cui, S Gera, ..., International Journal of Quantum Information, 1941027
Optimal multivariate discrimination