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

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AQUA lab Users Meeting

21 March 2022
Will talk about

• Fast, data driven approach to optical imaging
• Quantum applications
• Quantum assisted telescopes
Timepix Optical Cameras
Hybrid pixel detectors

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

- 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
Thin window optical sensors

Developed at BNL, first produced at CNM (Barcelona, Spain) in 2015
Surface preparation is very important, inspired by astronomical CCDs (LSST)

Backside illuminated optical sensors
Anti-reflective coating, thickness 300 um

High QE

M. Fisher-Levine, A. Nomerotski, Timepixcam: a fast optical imager with time-stamping,

Nomerotski et al, Characterization of TimepixCam, a fast imager for the time-stamping of optical photons,
**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.amsccins.com

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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

- Quantum imaging
- High Energy Physics applications
- Neutron imaging
- Lifetime imaging
Single (optical) photons
Intensified cameras: 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
1.5 ns 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
Quantum Astrometry

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
Radio $\bar{n} \gg 1$

Can literally record entire waveform, over some band, separately at each receiver station and interfere later offline

Optical $\bar{n} \ll 1$

One photon at a time! Need to bring paths to common point in real time

Need path length compensated to better than $c$/bandwidth

Need path length stabilized to better than $\lambda$

Accuracy ~ 1 mas
Max baselines to ~ 100 m
Two-photon techniques
Second photon for quantum assist

Quantum (two-photon) interferometer

- 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.
- Major impact on astrophysics and cosmology.

\[ \Delta \theta \sim \frac{\lambda}{b} \]
Idea: use another star as source of entangled states for the interference

• 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

• Can provide 10 microarcsec resolution for bright stars
• Perfect to start exploring this approach

Full QFT calculation

$$N_c(xy) = \eta_1 \eta_2 A^2 \int_0^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau =$$

$$A^2 \eta_1 \eta_2 T_r \left[ (I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \right] \pm$$

$$2I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos \left( \frac{\omega_0 B \left( \sin \theta_1 - \sin \theta_2 \right)}{c} + \frac{\omega_0 \Delta L}{c} \right)$$

New oscillatory term!
Requirements for detectors

• Photons must be close enough in frequency and time to interfere → temporal & spectral binning: need ~ 0.01 ns * 0.2 nm for 800 nm

• Fast imaging techniques are the key
  – Several promising technologies: CMOS pixels+MCP, SPADs, SNSPDs, streaking
  – Target 1-100 ps resolution

• Spectral binning: diffraction gratings, Echelle spectrometers

• Photon detection efficiency: high
Spectroscopic binning

In collaboration with NRC (Ottawa) D. England, Y. Zhang et al.


$\delta \lambda \cdot \delta t \sim 5 \text{ ns} \cdot 0.5 \text{ nm}$
Experiments in progress

Bench-top model of two-photon interferometry
Ar vapor lamps with ultra-narrow band filters
Superconducting nanowire single-photon detectors

Supported by DOE HEP QuantISED program
Current setup at BNL: SPDC source as spectrometer characterization tool
Argon lamp spectrum

0.2 nm resolution
794.8 nm line

HBT peak with 5 ns resolution? no

6 ns resolution

filter 794.8 ± 1 nm

150 ps resolution
Next steps: spectrometer based on LinoSPAD2

Two diffracted photon stripes projected on to single linear array

Spectrometer time resolution: ns $\rightarrow$ 100 ps
More Quantum Imaging
Hong-Ou-Mandel effect

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

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

2x BBO

Delay module
- $P_1$
- $P_2$
- PMF
- Step: 0.3 $\mu$m
- Range: 10 mm
- Fiber-coupled beamsplitter

Tp3Cam module
- Intensifier
- Camera

qutools.com
Examples of bunched HOM photons

![Distance between two photons, pix](image)

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

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

Coincidence of photons in two fibers

Coincidence of photons in single fibers

HOM effect with post-selection

In collaboration with NRC (Ottawa) D. England, Y. Zhang et al

2 nm filters at 805 nm and 817 nm.

10, 5, 3 nm post-selection filters
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 error: ~ 5 ppm
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

Ion micromotion

• 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
Ion micromotion in 2D

2D ion crystals, RF period 92 ns

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
5.5 MeV alphas in CF$_4$ gas in Tpx3Cam

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

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 et al 2021 JINST 16 P02006
Neutron detection with Tpx3Cam

- $^6\text{Li}$-based scintillator
- Neutrons produce alphas
- Time resolved

A. Losko et al, DOI: 10.21203/rs.3.rs-257513/v1

J. Yang et al, arxiv.org/abs/2102.13386

Material characterization with Bragg edges
Future directions
# Timepix3 → Timepix4

by Medipix4 collaboration

<table>
<thead>
<tr>
<th></th>
<th><strong>Timepix3</strong></th>
<th><strong>Timepix4</strong></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, PC (10-bit) and TOT (14-bit)</td>
<td>CRW: PC and iTOT (12...16-bit)</td>
</tr>
<tr>
<td></td>
<td>Frame based</td>
<td>TOT and TOA</td>
</tr>
<tr>
<td><strong>Zero-Suppressed Readout</strong></td>
<td>Data driven, &lt; 80 MHits/s</td>
<td>&lt; 500 MHits/s</td>
</tr>
<tr>
<td></td>
<td>Frame based, YES</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 with triggering capabilities,
- 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
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: $10 \text{ nsec} \rightarrow 0.1 \text{ nsec}$

• Photon sensitivity: $1000 \text{ photons} \rightarrow \text{single photon}$

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

Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt
Mael Flament
Guodong Cui
Sonali Gera
Dimitros Katramatos
Michael O’Connor
Gabriella Carini
Anand Kandasamy
Michael Keach
Steven Paci
Alex Parsells
Jonathan Schiff
Denis Dolzhenko
Stepan Vintskevich
Anze Slosar
Zhi Chen
Jesse Crawford
Rom Simovitch
Jingming Long
Martin van Beuzekom
Bram Bouwens
Erik Maddox
Jord Prangsma
Duncan England
Yingwen Zhang
Boris Blinov
Mila Zhukas
Maverick Millican
Alex Kato
Peter Svihra
Michal Marcisovsky

BNL team

SBU team
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

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.

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.
Ions in TimepixCam

https://doi.org/10.1107/S16005775170
https://doi.org/10.1107/S16005775170
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, or teleport photon)
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
  – $\text{max value: } 2\sqrt{2} = 2.82$

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

Time resolution: 2ns
Spatial characterization of entanglement

Measure S-value for 81 combinations of subareas

Fast camera spatial characterization of photonic polarization entanglement

Christopher Ianzano, Peter Svihra, Mael Flament, Andrew Hardy, Guodong Cui, Andrei Nomerotski & Eden Figueroa

Scientific Reports 10, Article number: 6181 (2020) | Cite this article

Imaging enables scalability
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
Scalability

Goal: storage of multiple qubits in single $^{87}$Rb cell
HBT with two sources?

New idea: Coincident pair detections now sensitive to *phases* of incoming photons.
Possible impact on astrophysics and cosmology

offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder (DE)
- Proper star motions (DM)
- Microlensing, see shape changes (DM)
- Black hole imaging
- Gravitational waves, coherent motions of stars
- Exoplanets

Lifetime Imaging
Lifetime imaging with ns timing

Lifetime imaging with oxygen sensors

Sensor lifetime depends on oxygen concentration → in-vivo monitoring of oxygen in tissues

Papkovski group, University College Cork (Ireland)

Oxygenation and Deoxygenation of PtBp Solid State sensors

New luminescence lifetime macro-imager based on a Tpx3Cam optical camera, R Sen et al, Biomedical optics express 11 (1), 77-88 (2020)
Measurements with biosamples

Intraluminal application (Mice2)

Large Intestine

Small Intestine

Large Intestine Time Lapse

Papkovski group, University College Cork (Ireland)

Mapping $O_2$ concentration in ex-vivo tissue samples on a fast PLIM macro-imager, R Sen et al, Scientific reports 10 (1), 1-11 (2020)
Single photon imagers for NIR

HgCdTe sensors with avalanche amplification

– developed for astronomers to study the black hole in our Galaxy

- pure electron amplification
- "noiseless" gain > 1000
- sub-e noise @ 5 MHz, QE ~= 80%
- suitable for telecom wavelength 1660 nm
- single photon counting
- Compatible with fast timing

320x256 diode array, Saphira readout ASIC