1st International SPAD Sensor Workshop - ISSW

SPAD Based Streak Camera

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Outline

- High speed imaging
- What is and Why Streak Imaging
  - Rotating mirror
  - Vacuum tube
  - Solid state
- SPAD based Streak Imaging
  - Ultra fast photon counting and processing

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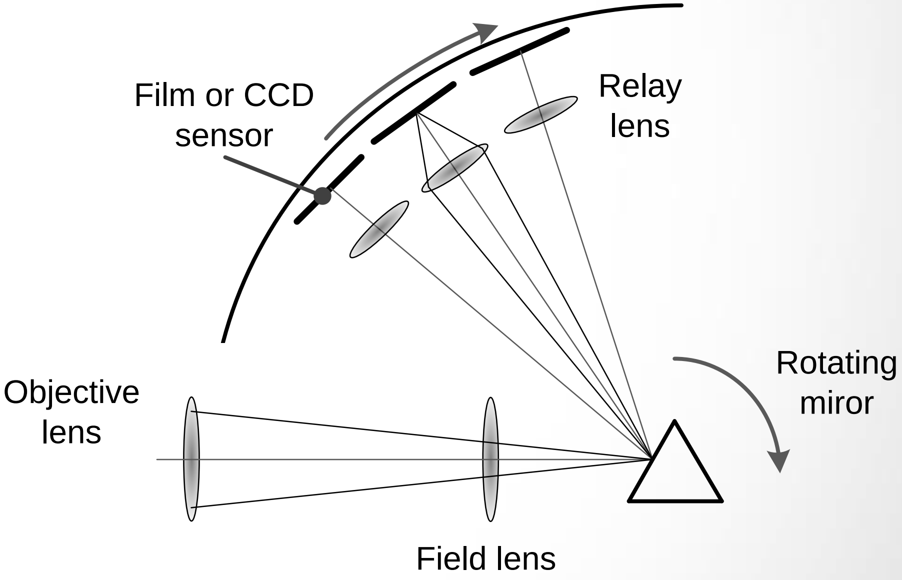
20th – The Manathan project

- Nuclear weapon research boosts the high speed imaging techniques
- 1939 first rotating mirror camera
  - by Miller
  - 500 000 fps.
- Patented in 1946 (Miller, 1946)
- 1955, Berlin Brixner : 1 millions fps
- Cordin’s Model 510 rotating mirror
  - 25 million fps
  - Still commercialized but Film replaced by CCD sensors



- Use Miller principle: Miller’s principle states that if an image is formed on the face of a mirror, then it will be almost static when relayed by lens to a film

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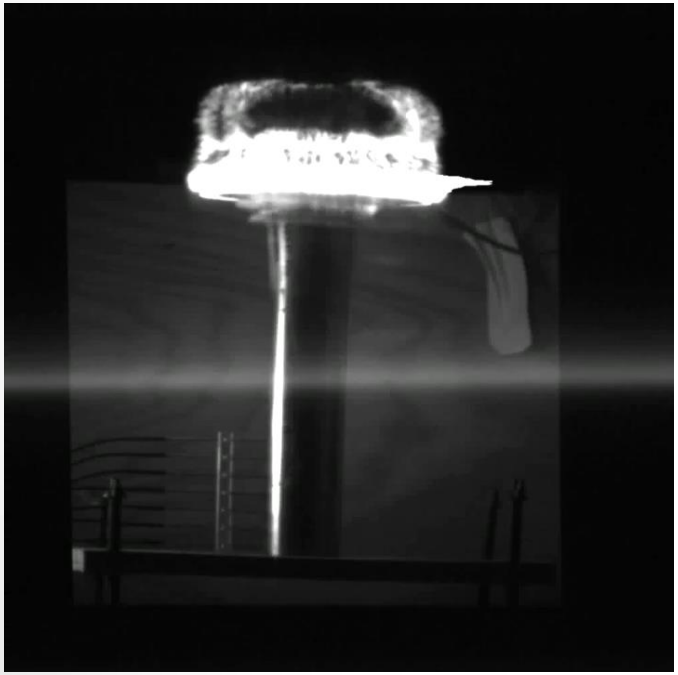
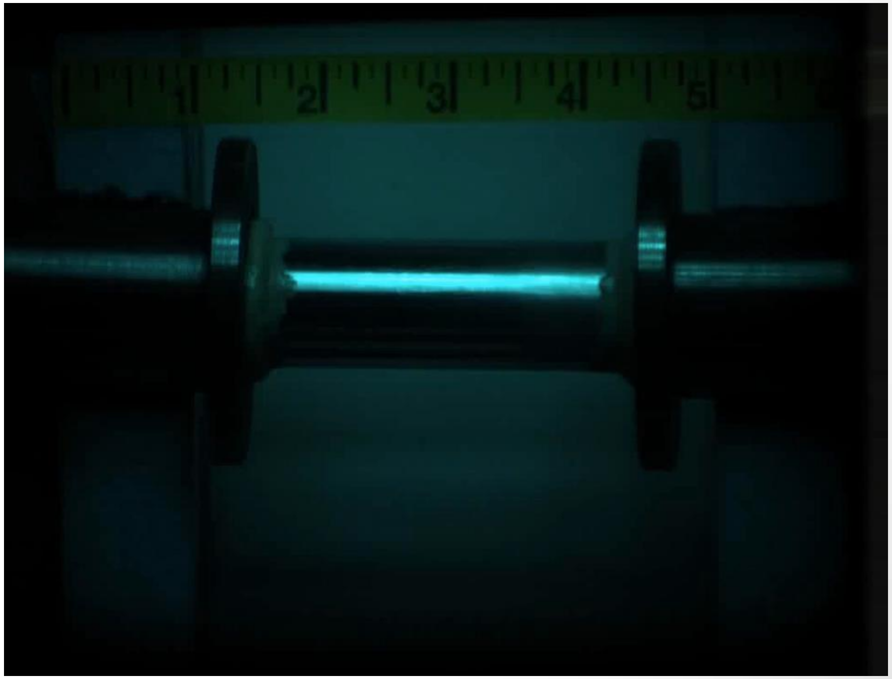
20th – The rotating mirror

- Rotating mirror camera applications



Exploding cylinder Model 550 380 kfps



Explosive captured by Model 570 at 2.5Mfps

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20th – The rotating mirror

- Rotating mirror camera limits
  - 25 Mfps
  - On a quarter of rotation
  - With 128 sensors
  - ➔25E6/(4*128)≈5000 rotation per second
  - ➔almost **3 millions rpm !**
- Use of:
  - an helium environment using a gas turbine
  - beryllium mirror centrifugal force
- How to increase speed ?
  - 25 Mfps ➔ inter frame 40 ns
  - Limit of this technology with a framing approach

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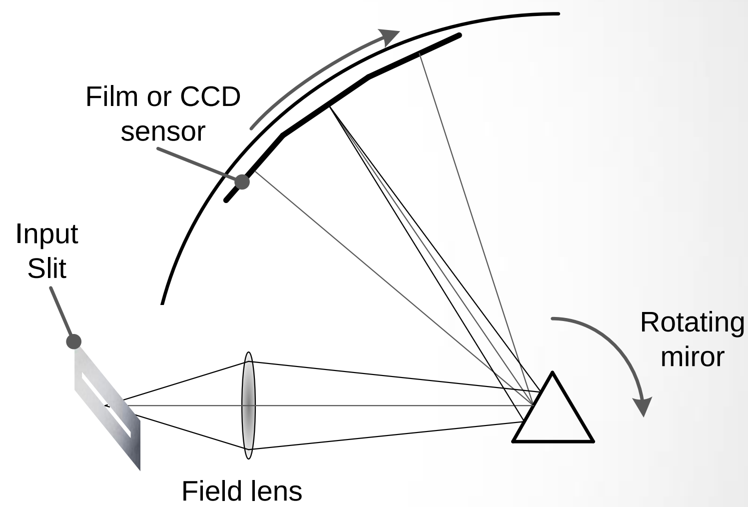
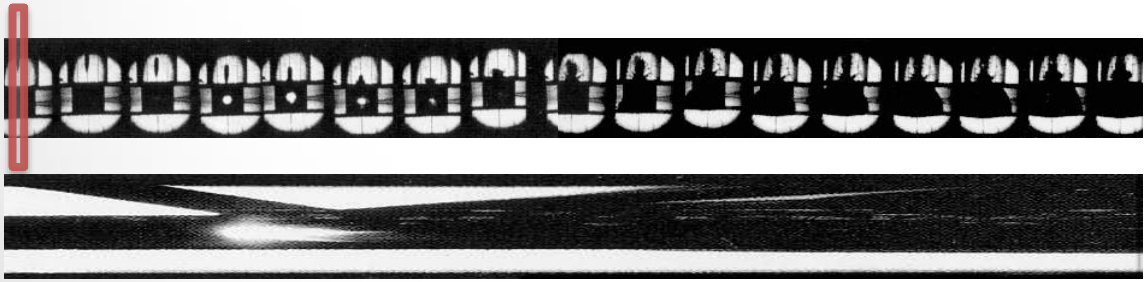
20th – The streak imaging

- The streak camera
  - Remove the lens then add a input slit
  - ➔ **Streak camera**



- Lost 2D information (1D + time)
  - Makes possible to see what happen between two frames
  - Example of a bullet against a explosive



  - Sweep speed up to 150ps/pixel
  - Temporal resolution **650 ps** (static slit width is 25 µm, i.e. 4.5 pixels)
  - **Temporal resolution about 600 x higher with streak imaging**

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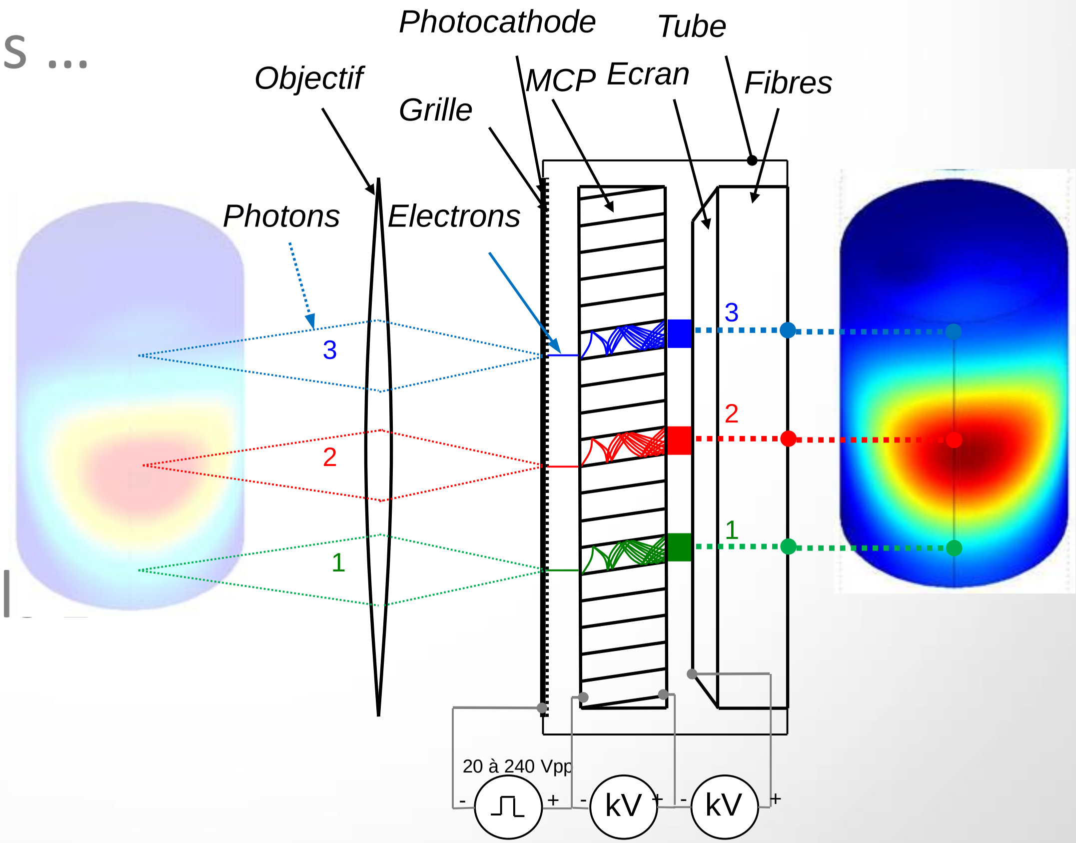
20th – framing with image intensifier tube

- 1960 first Micro Channel Plate (MCP) electron multiplier
- Still in use and in progress …
- Allows fast gating by driving photocathode with electrical pulses
- 1 frames with exposure time below 10 ns
- 1 frames 1000x1000 pixel 1 ns ➔ **1 Peta Pixel/s**



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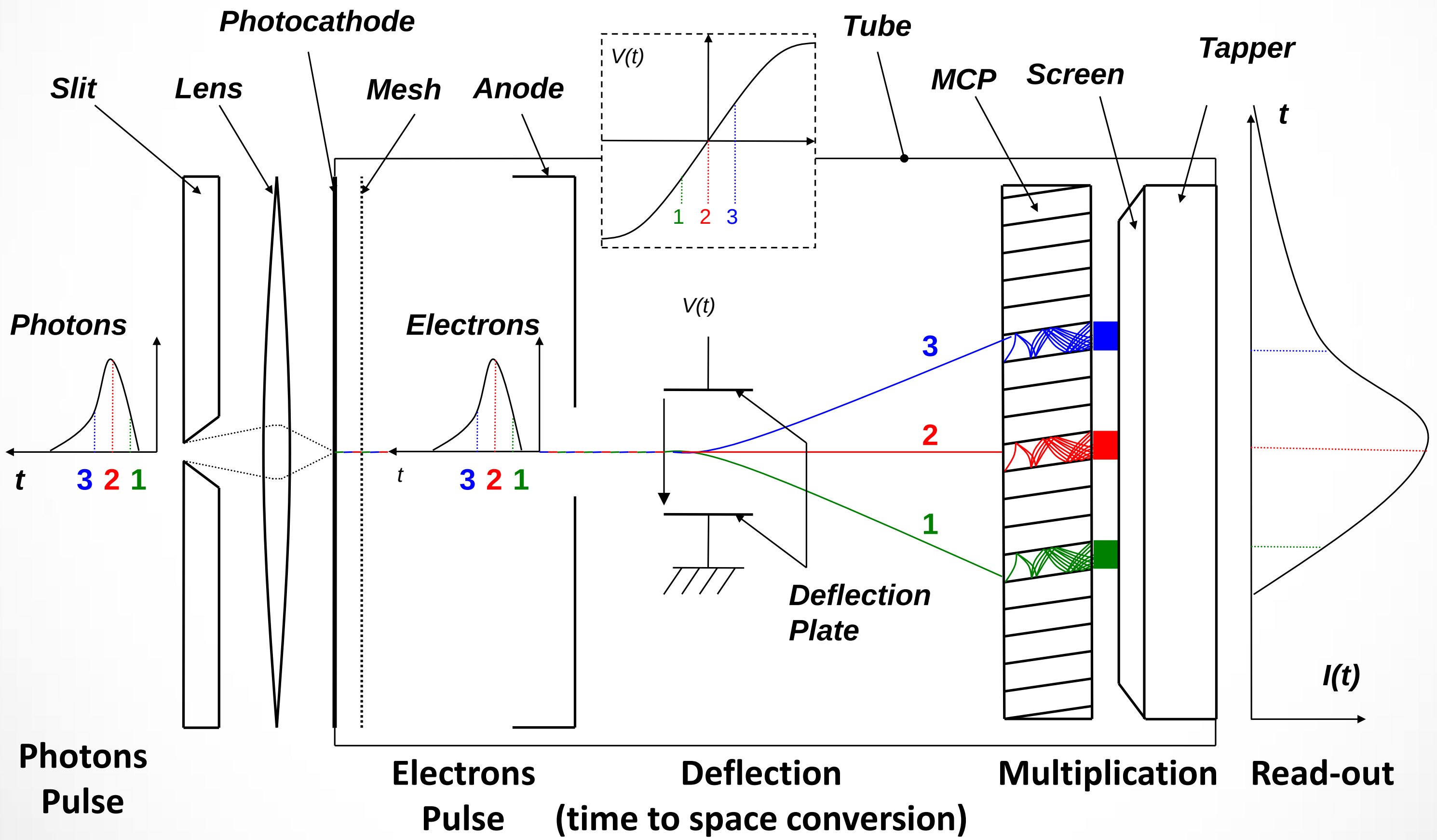
20th – The streak imaging tube



- Temporal resolution down to 1 ps ➔ Tfps
- 1000 spatial pixels ➔ **1 Peta Samples per second !**

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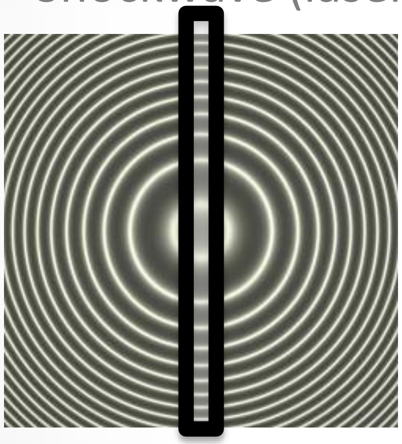
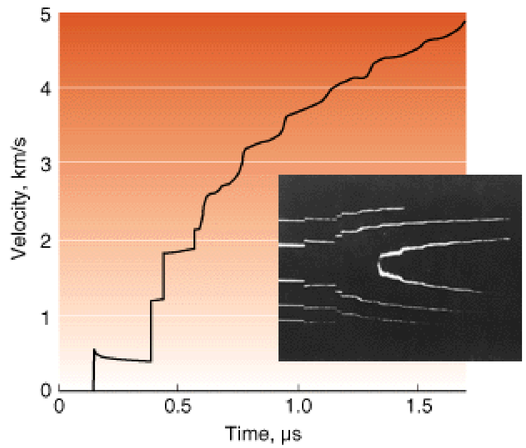
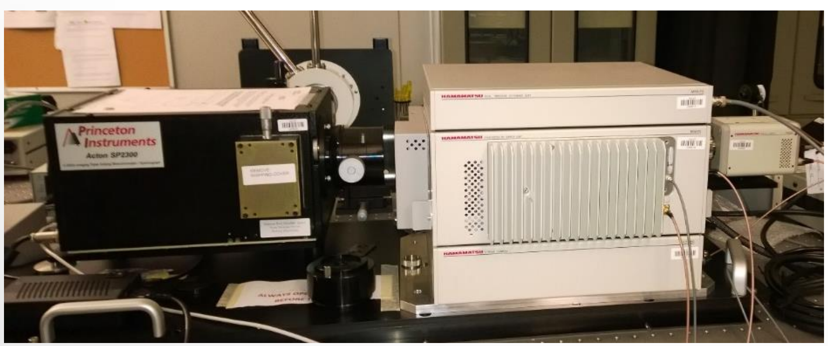
20th – The streak imaging

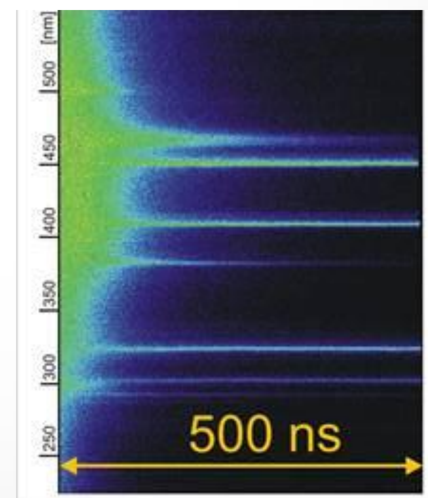
- The streak camera applications
  - Shockwave (laser Doppler velocimetry, speed up to several km/s)





  - Time resolved spectroscopy





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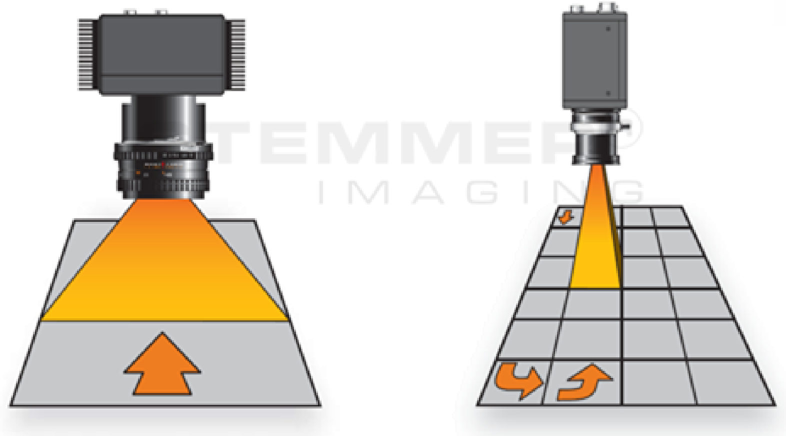
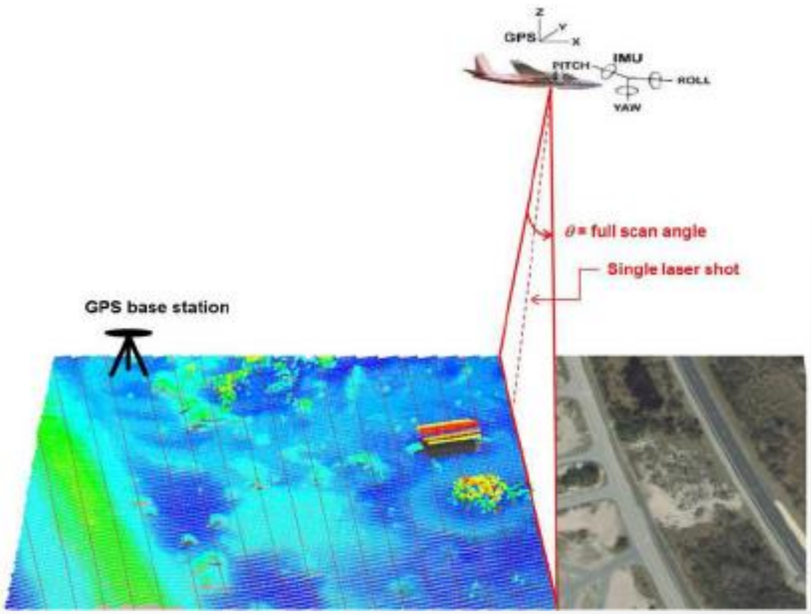
20th – The streak imaging

- The scanning line
  - Food safety/Packaging



  - Lidar



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21th - Current High speed video

- State of the art high speed video camera
  - **Phantom v2511**,
    - 25kfps @ 1280 x 800
    - 1,000,000 @ 128 x 16
    - Record time : 96 GB filled in 2.6 second

  - The limit of conventional high speed video is due to I/O chip max speed
    - 25 Gpixel/s, 12 bits → 300 Gb/s !!
    - Present **fastest** commercial single-**laser**-single-fiber **network connections** max out at just **100Gbps**, 4 wavelengths at 25Gbps

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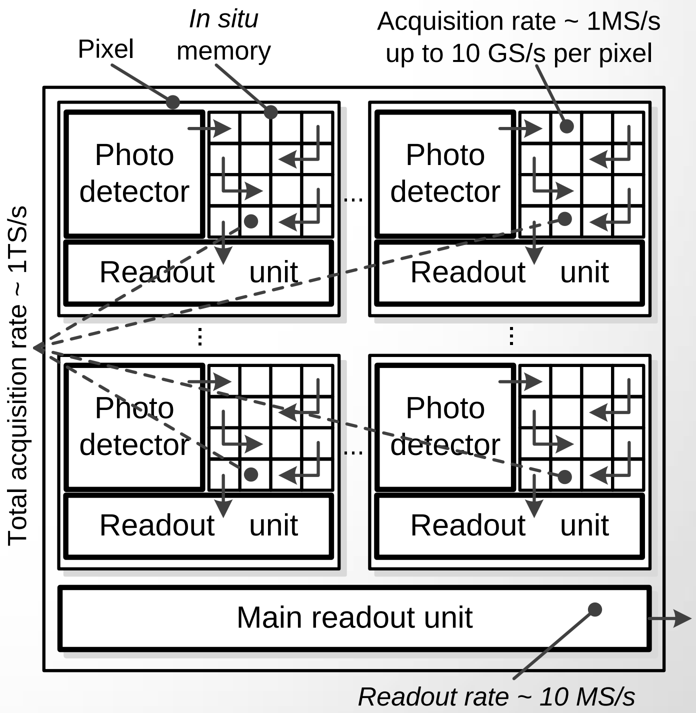
21th - Ultrahigh Speed solid state camera

- **How to overcome the limit of the sensor I/O speed ?**

Keep the data in the sensor ! ;-)

- Concept introduce by Elloumi In 1994
- Acquire the scene in a burst of images stored inside the pixel
- Readout the sequence of images at a conventional data rate



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Burst imaging concept

- Continuous Imaging

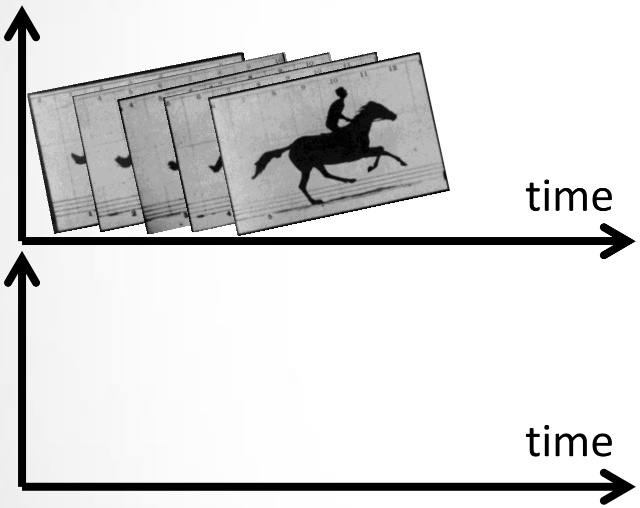
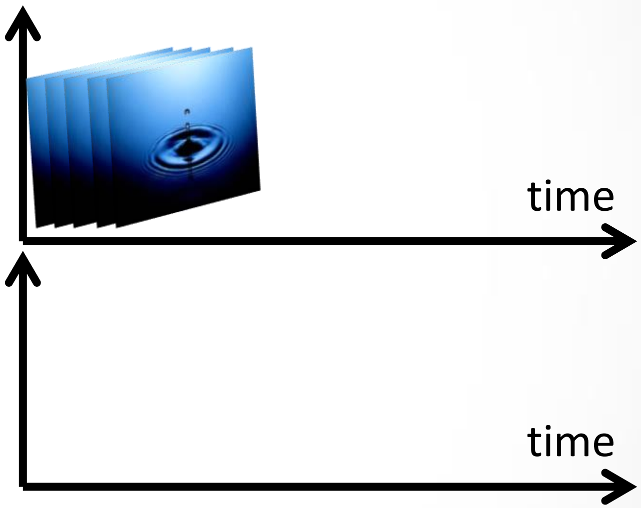


Image Acquisition

Image Readout

- Burst Imaging



Up to 25 kfps @ 1 Mpix
→ up to 25 Gpix/s

100 kfps up to 1 Gfps
→ up to ~ Tpix/s

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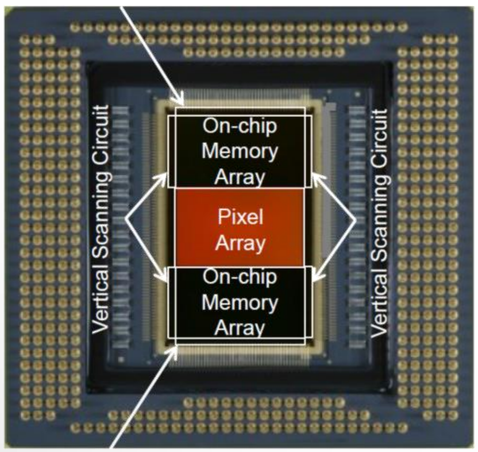
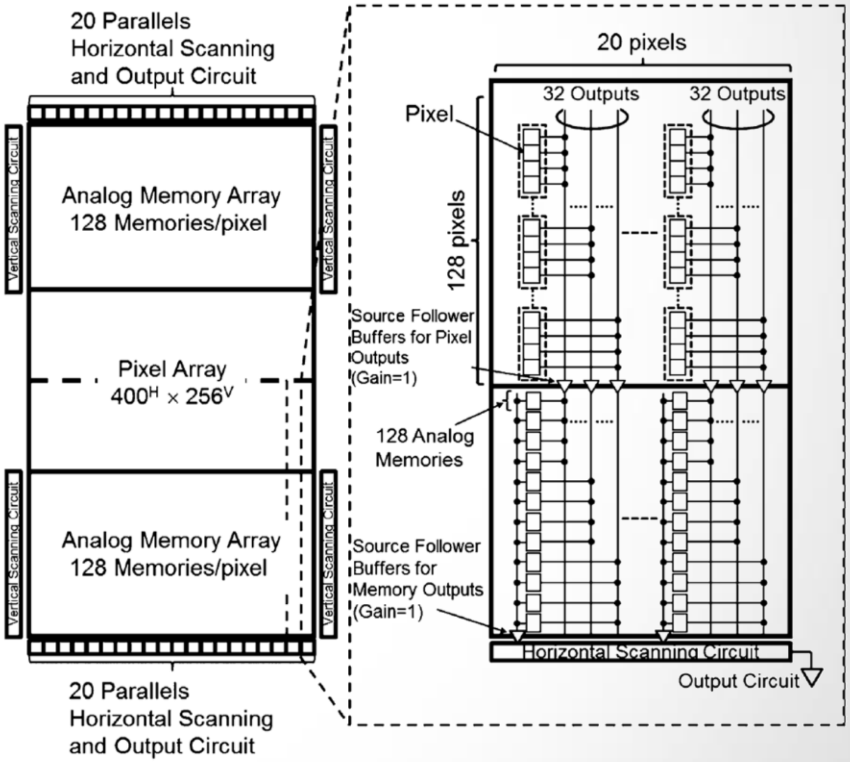
21th - Ultrahigh speed solid state camera

- **CMOS Technology** (by Sugawa)
- 2013, 180 nm
- Up to 20 Mfps, 100k pixels
- 128 frames
- CMOS cap memories
- Good fill factor 37%





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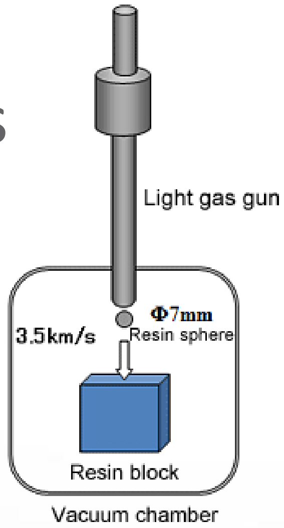
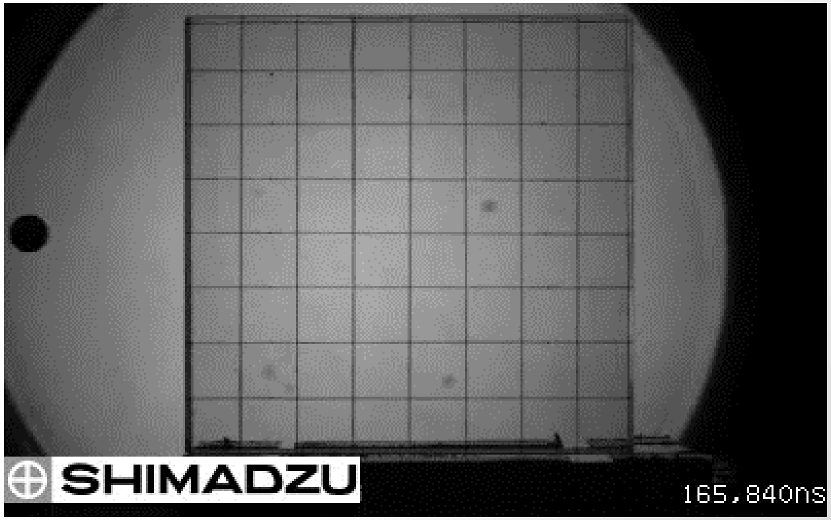
21th - Ultrahigh speed solid state camera

- Shimadzu
  - Model HyperVision HPV-X
  - 400 x 250
  - 128 frames
  - 10 Mfps
  - Acq. rate 1 Tpixel/s





High-Speed Collision of Resin Sphere
Recording Speed: 2 million frames/s

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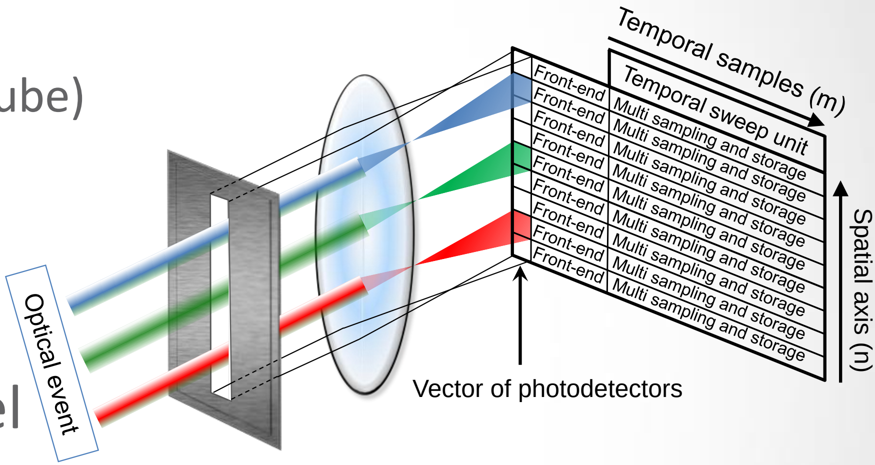
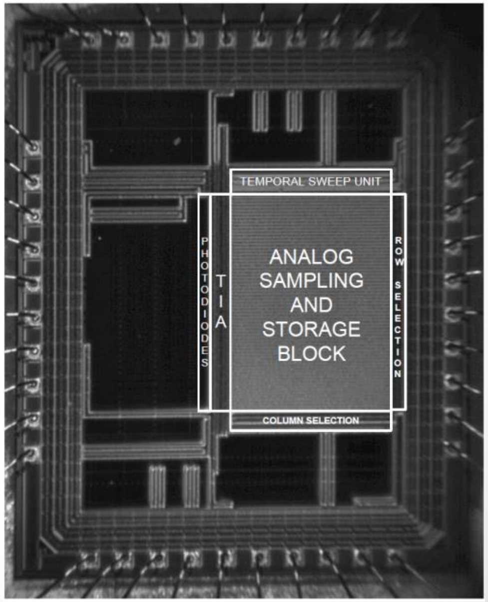
Toward to the GigaFps

- **CMOS Streak imaging**(by ICube)
  - 2013, 350 nm SiGe BiCMOS
  - Release of 2D Imaging contraints
    - Aera limited electronic for pixel pitch
  - Up to 8 Gfps, 128 frames
  - 64x1 pixels (streak imaging)
  - Pixel pitch 32 µm
  - Fill factor 84 %
  - Touching the physical limit of the technology
    - Single gate propagation time





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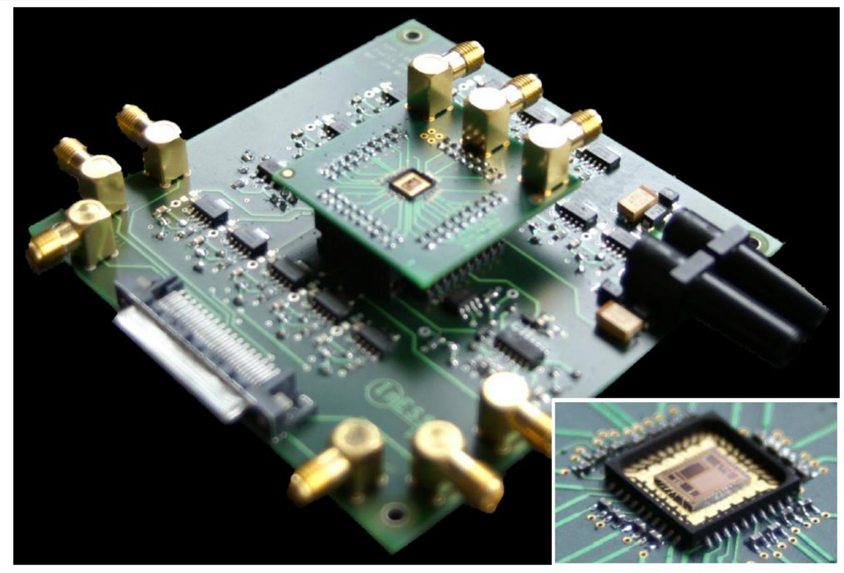
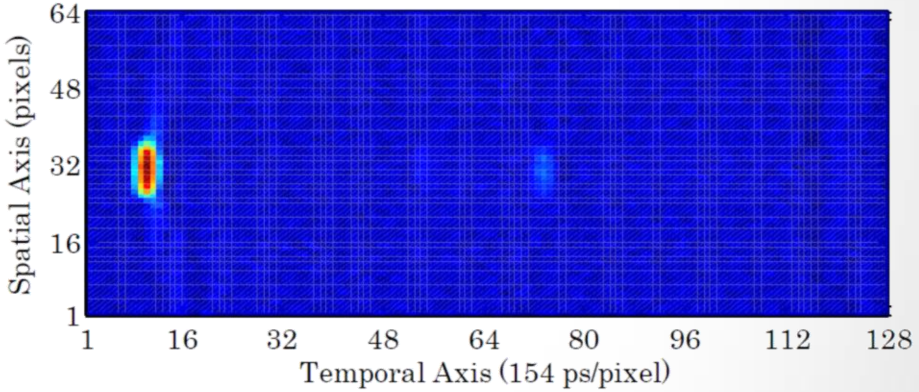
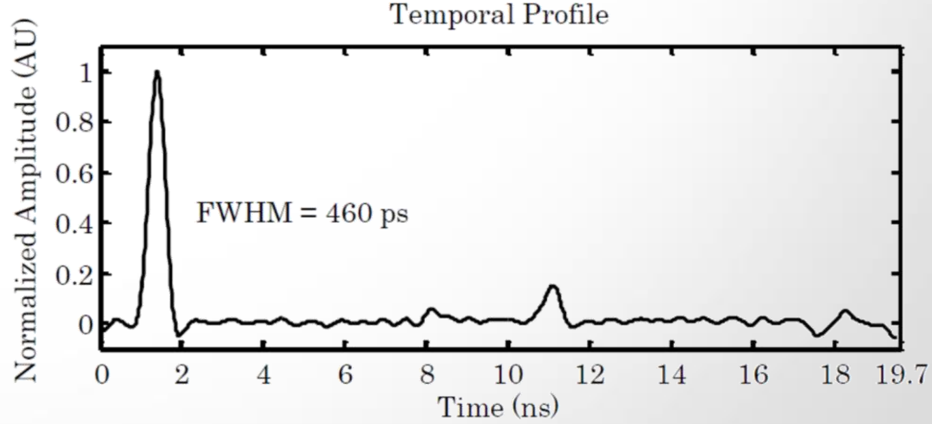
Toward to the GigaFps

- **CMOS Streak imaging** (by ICube)
  - subnanosecond temporal resolution
  - 100x faster than 2D Ultrafast image CMOS sensors







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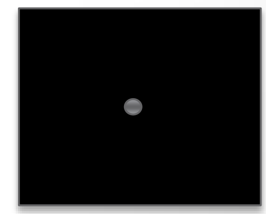
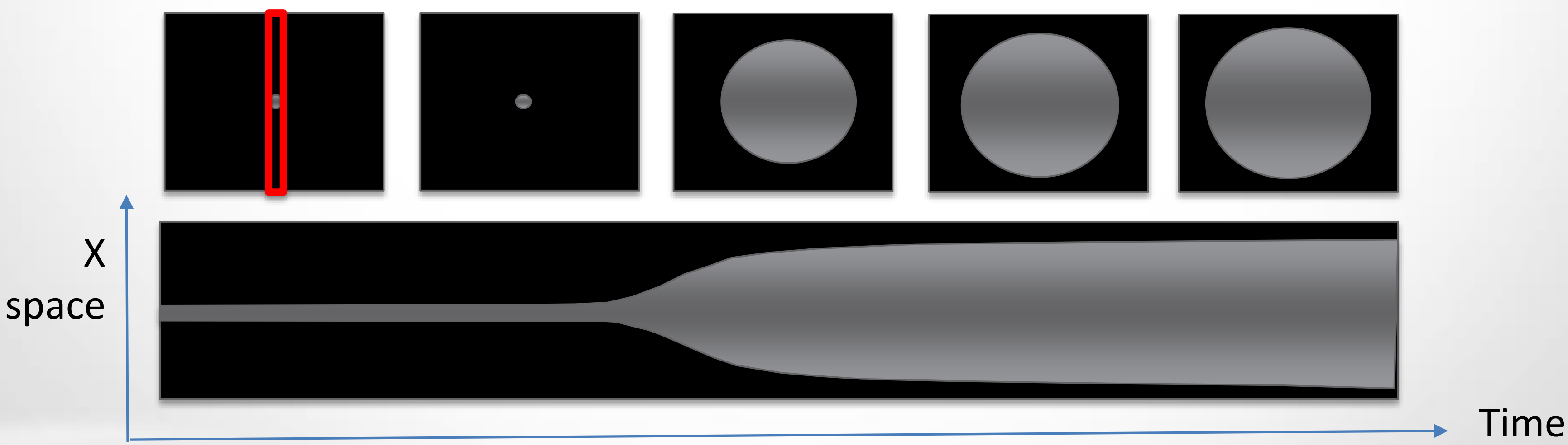
Streak Imaging

- Reducing the spatial resolution increase the frame rate
- Optimal speed obtain for one single column

➔Streak imaging

- About 100 times faster with whatever the technology
  - Rotating mirror 40 ns Frame➔ 600 ps Streak
  - Vacuum tube 200 ps Frame➔ 2 ps Streak
  - Solid state 100 ns Frame➔ 1 ns Streak





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Single shot / repeatable event

- All previously described systems are single shot system
  - A **single** event is acquire
  - ➔Require the large data rate
- Many fast events are repeatable
  - Fluorescence, Tomography, LIDAR, Laser induce events …
  - The phenomenon can be sampled in several time

➔Require much less data rate

➔The temporal resolution can be highly increased

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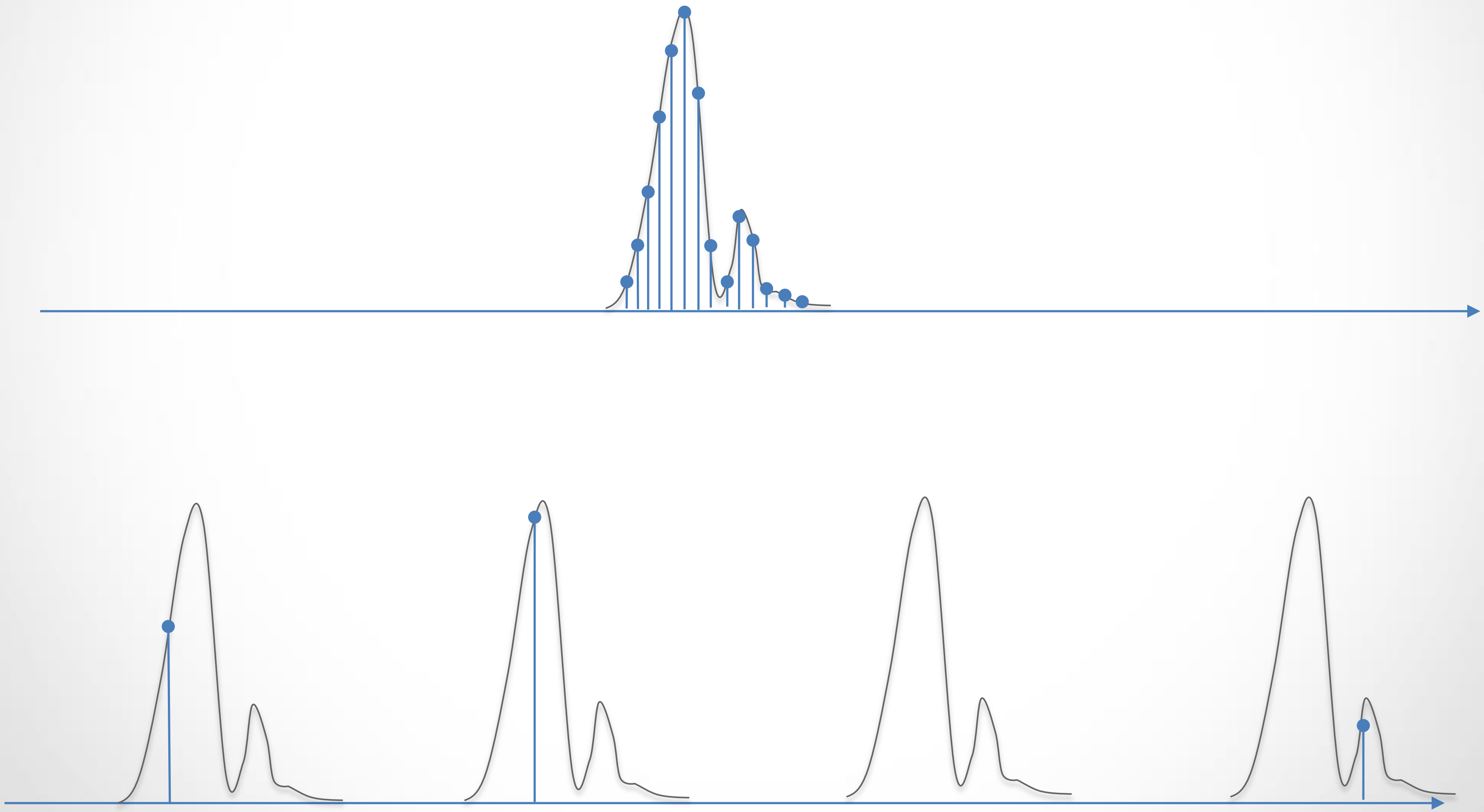
Single shot vs repeatable event



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SPAD based Image Sensor

- So the data rate is no more an issue for SPAD based Image Sensor
  - True if you have all the time to make your measurement
  - False if you have to count a high number of photon in a restricted time
- Releasing the 2D array area constraints
  - More accurate timing or more processing electronic
  - Optimized data flow

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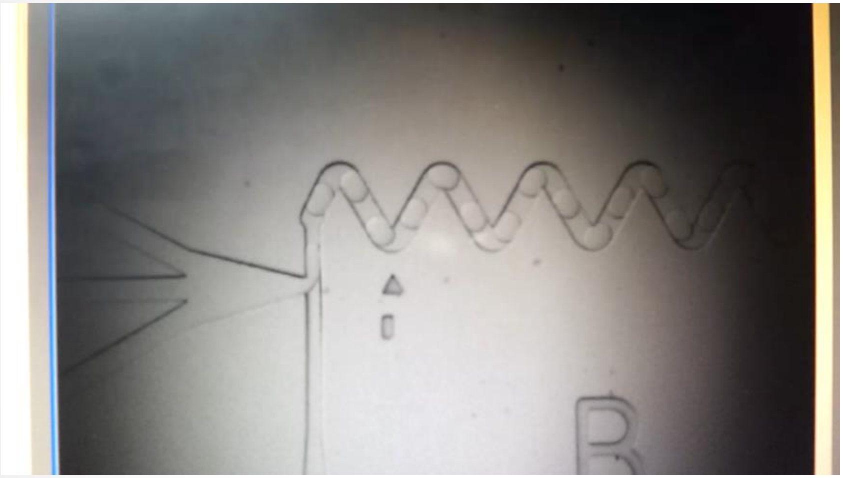
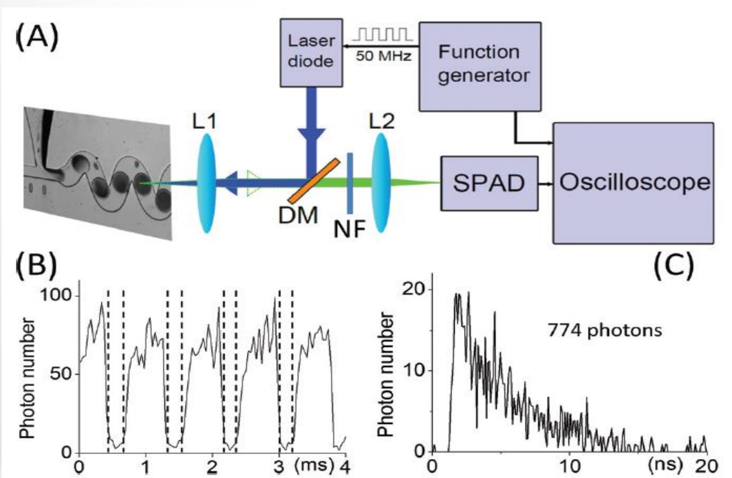
Time constrained TCSPC measurement





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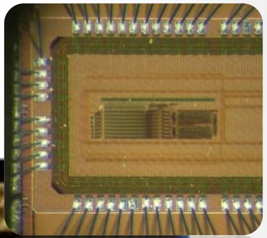
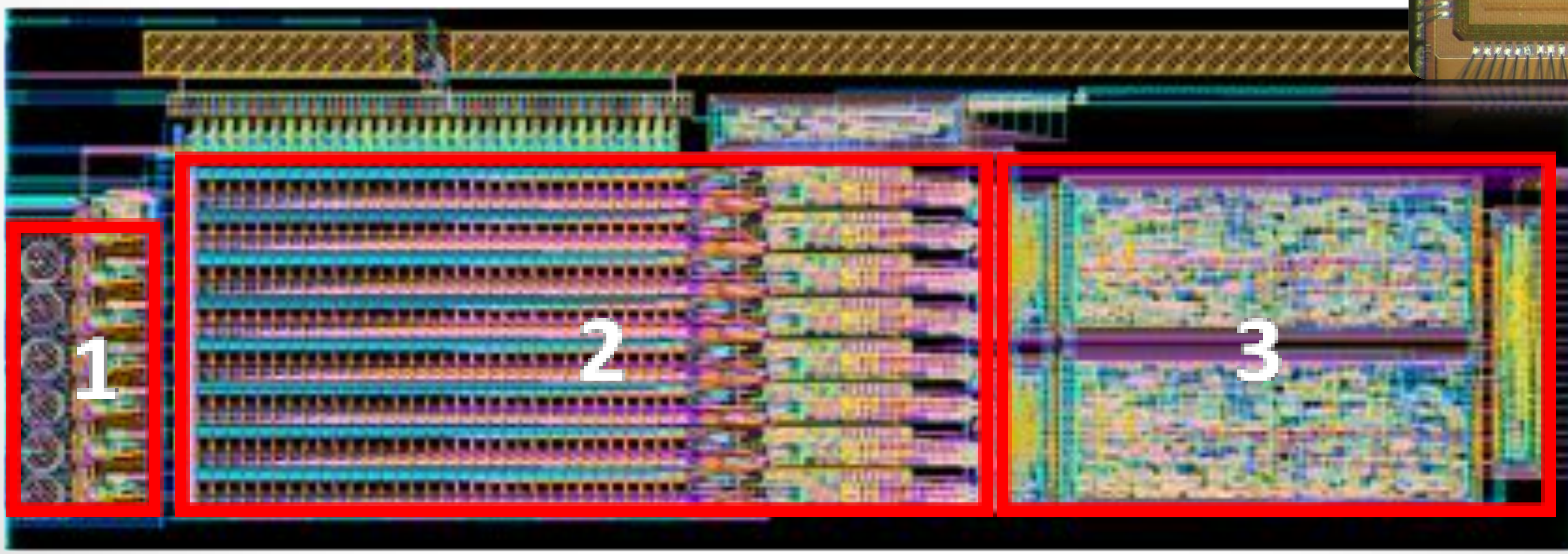
Time resolved integrated photon counting systems

- Streak imaging to push the limits once again
  - Example: (ICube) SPAD based streak camera
    - Temporal resolution 10 ps
    - Fill factor > 30%





1: Spad & Quench

2: High resolution Time to digital Unit 10 ps quantum

3: FIFO for high data rate acquisition (BW 4 Gbps for 8 SPAD)

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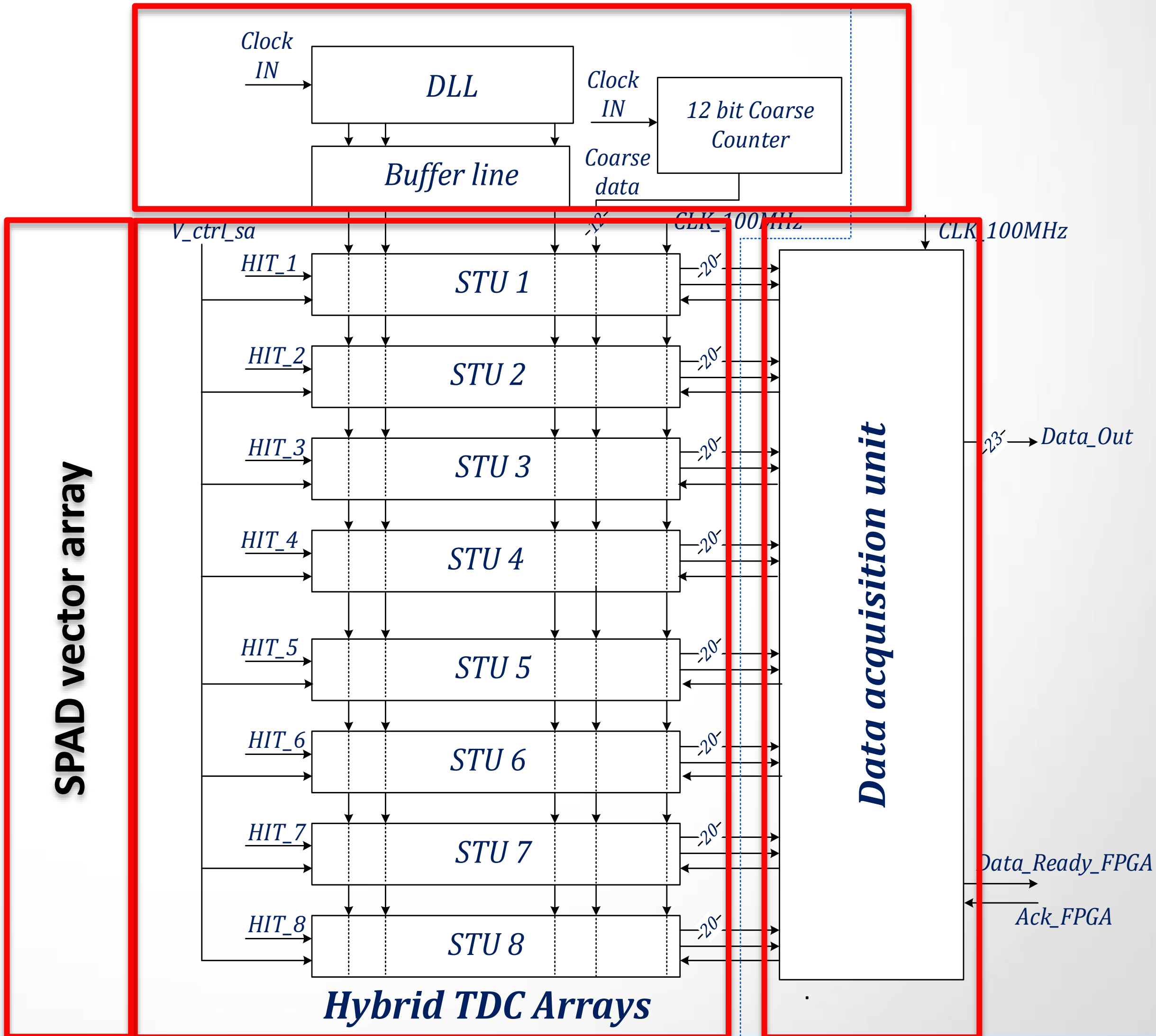
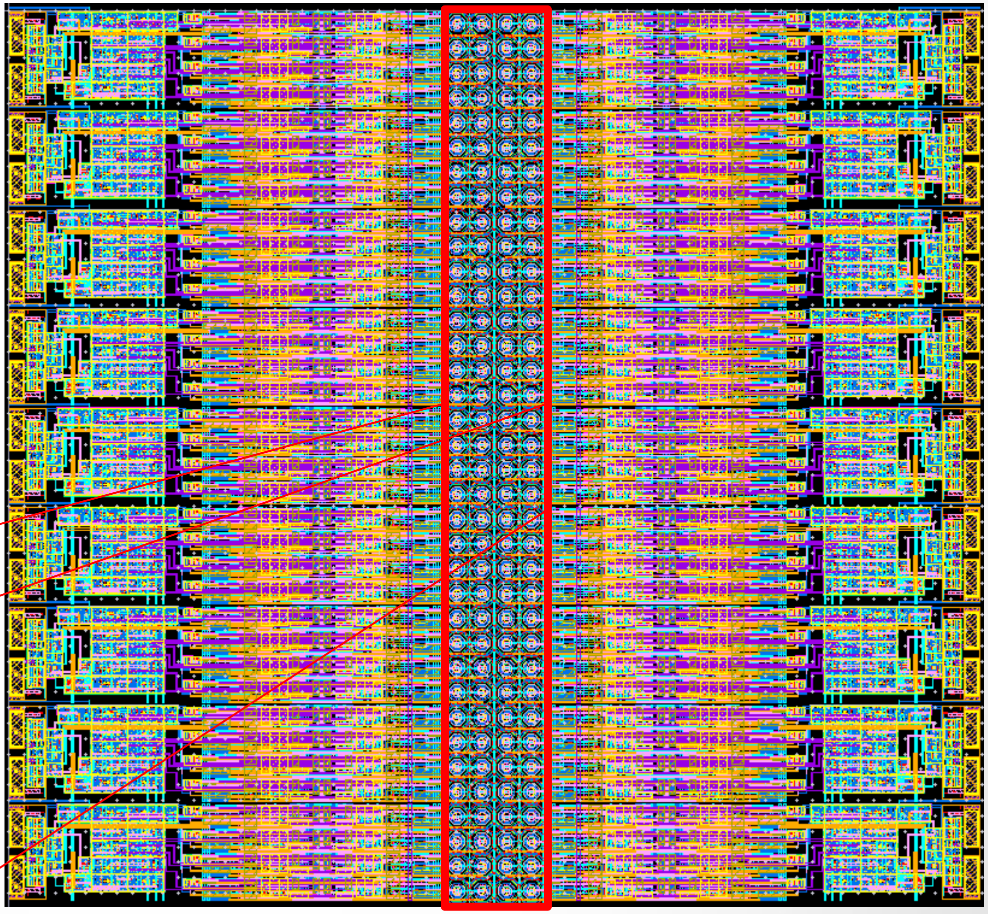
Better timing resolution: Streak sensor

- The streak lines share a unique time base
  - Ensure low timing dispersion
- Room for high resolution TDC
  - 10 ps bin

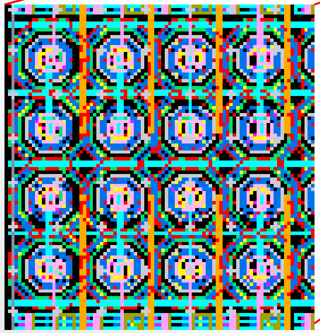


Streak TCSPC sensor architecture

- Possible to use a double TDC Array
  - Less dead time,
  - Parallel TDC conversion



Streak mode Imaging Sensor integrating a single line of Macropixels (SiPM)



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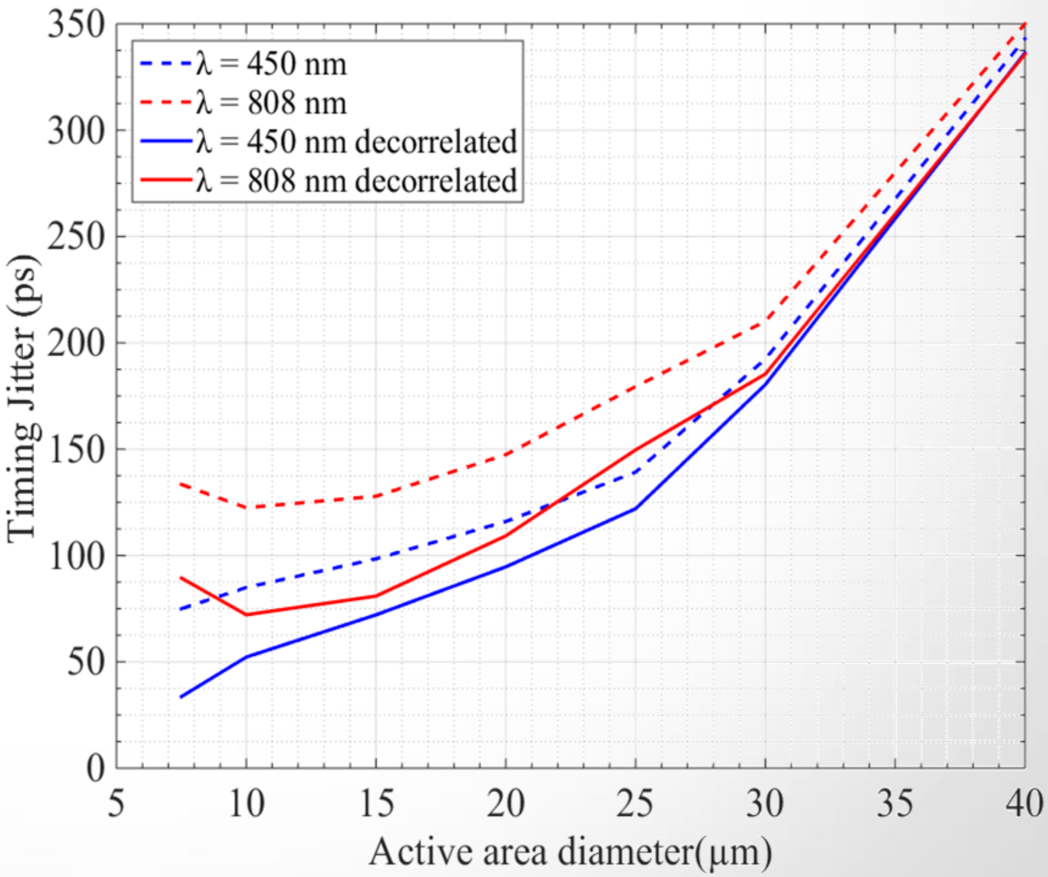
Smart mini SiPM pixel for better time resolution

- The smallest is the SPAD, the better is its time resolution
  - Better to use several small SPADs



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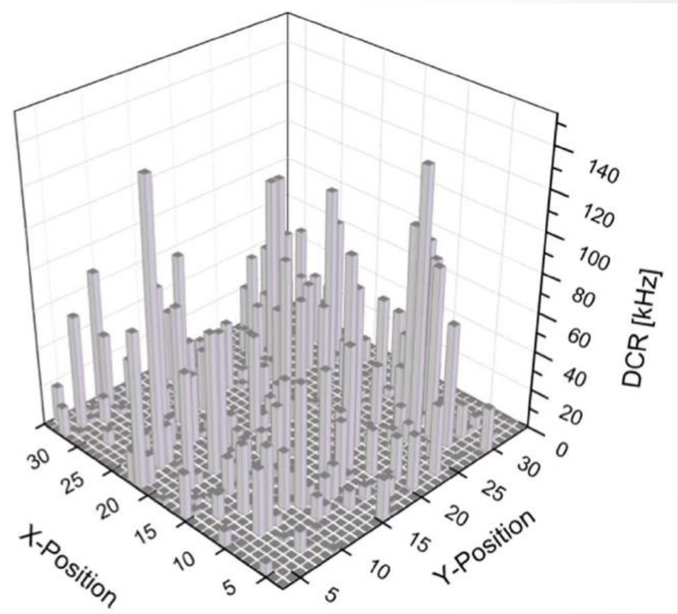
Smart mini SiPM pixel for better SNR

- Hot Pixel Elimination :
  - 20% of the SPADs in an array have a DCR 10 to 1000 times higher than the other 80%*
  - A 4x4 mini SiPM is very likely to
  - contain hot pixel(s)



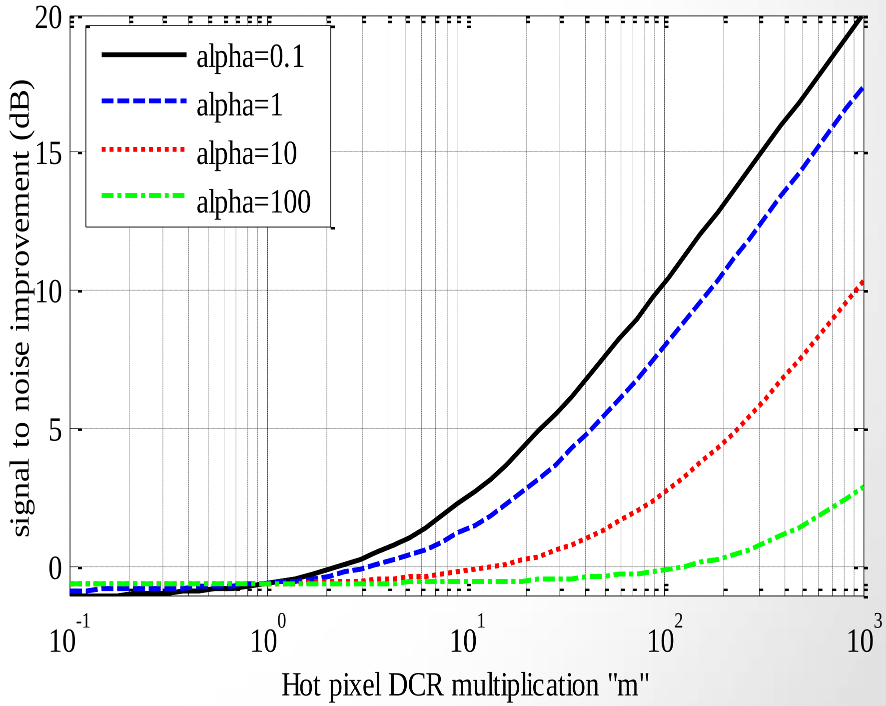
An example of DCR distribution across a 32×32 pixel array **

*Veerappan, C.; Richardson, J.; Walker, R.; Day-Uey Li; Fishburn, M.W.; Maruyama, Y.; Stoppa, D.; Borghetti, F.; Gersbach, M.; Henderson, R.K.; Charbon, E., "A 160×128 single-photon image sensor with on-pixel 55ps 10b time-to-digital converter," *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2011 IEEE International* , vol., no., pp.312,314, 20-24 Feb. 2011

**Gersbach, M.; Maruyama, Y.; Trimananda, R.; Fishburn, M.W.; Stoppa, D.; Richardson, J.A.; Walker, R.; Henderson, R.; Charbon, E., "A Time-Resolved, Low-Noise Single-Photon Image Sensor Fabricated in Deep-Submicron CMOS Technology," *Solid-State Circuits, IEEE Journal of* , vol.47, no.6, pp.1394,1407, June 2012

Smart mini SiPM pixel for better SNR

- Hot Pixel Elimination :
  - The Macropixel is considered to be uniformly lighted
  - SNR improvement ranging from 0 to 20 dB
  - One time calibration phase:
    - Measure the individual DCR for each SPAD
    - Disable the SPAD with High DCR



α= Mean Photo Count/Mean DCR
m = = individual DCR/ Mean DCR

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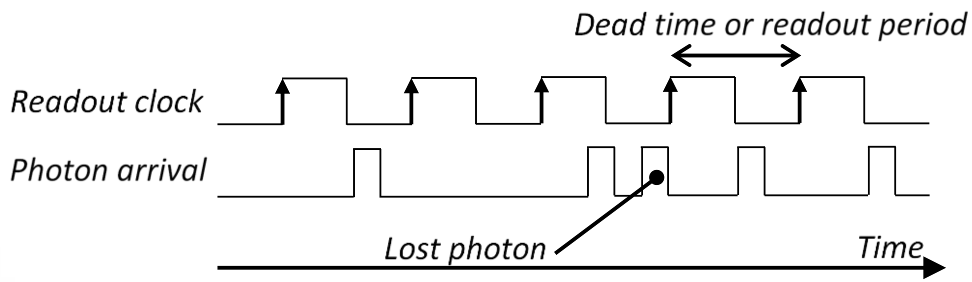
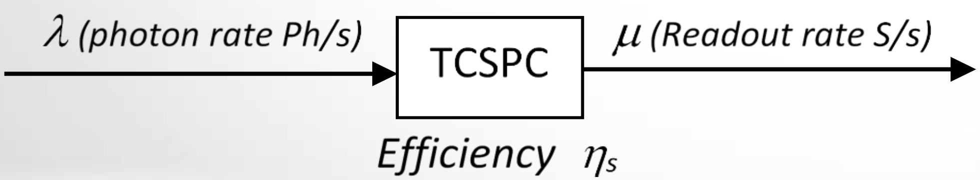
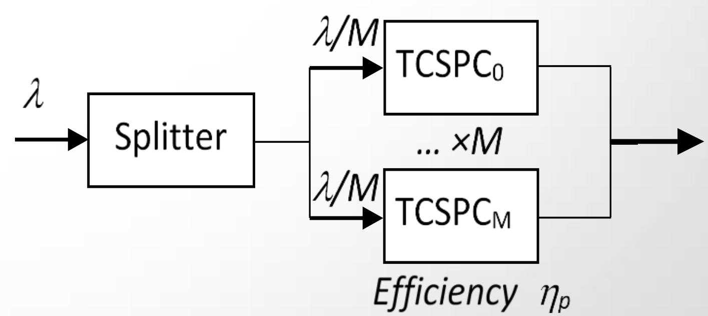
High rate photon counting

- Photon event is Poisson process
  - Asynchronous operation
  - Spikes of activity followed by low activity
  - A given dead time → photon lost



  - Parallelization
    - Reduce dead time





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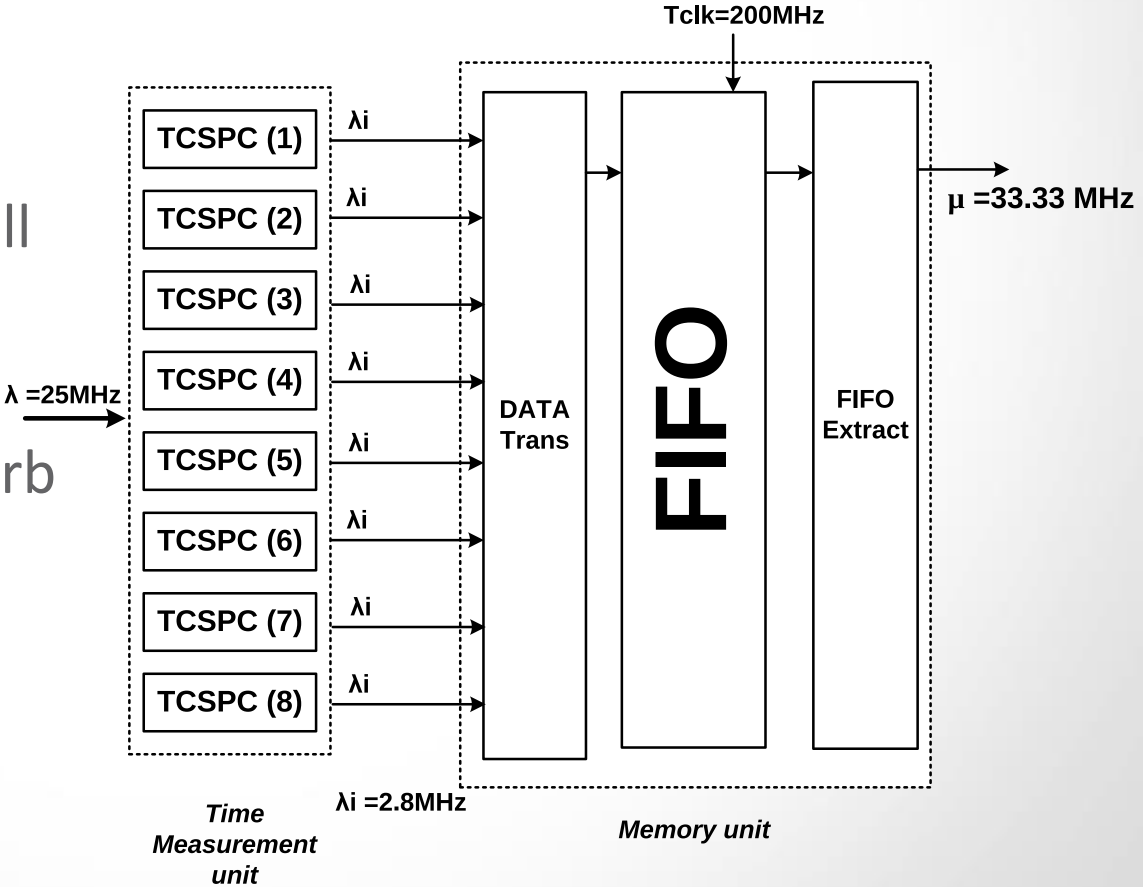
High rate photon counting

- But there is still a bottleneck at the data readout
  - If all TCSPC trig
    - Data rate spikes well above the readout rate (4Gbps for 8 SPAD)
    - FIFO allows to absorb data rate spikes
    - Fully asynchronous operation ?



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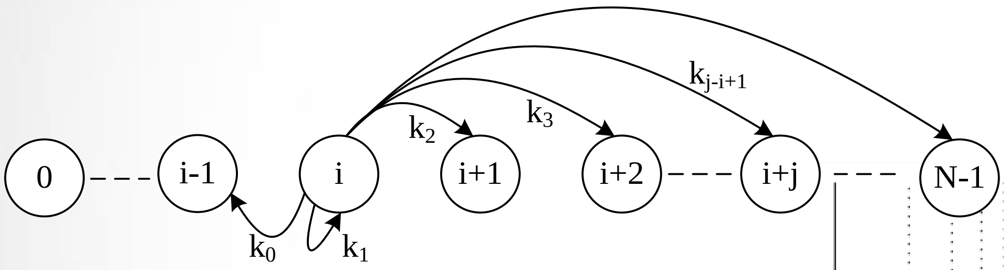
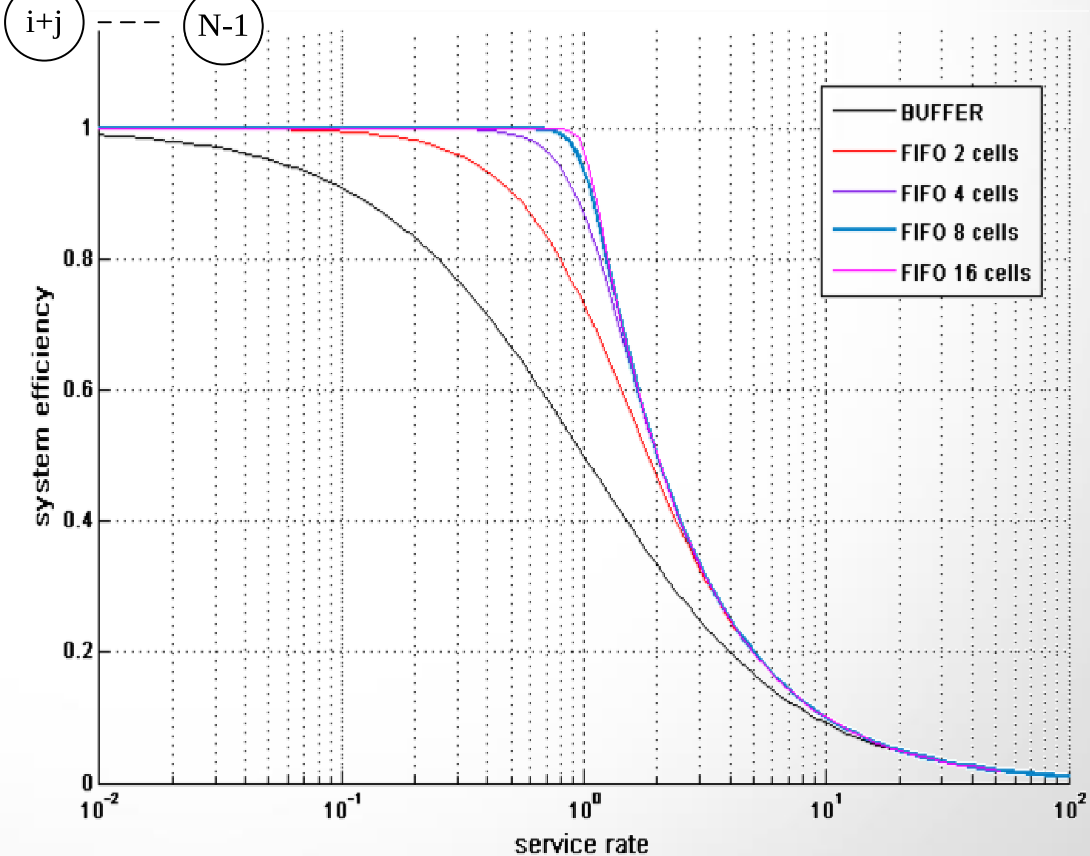
FIFO assisted data Extraction

- Markov chain to model the parallelized TCSPC





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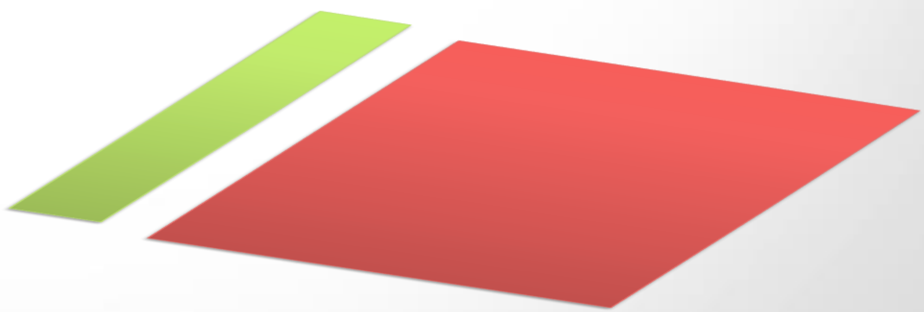
Hybrid technologies

- Best techno for SPAD sensor
- Best techno for signal processing
- Streak approach
  - Easy hybrid connection
  - Silicon interposer
  - Wire bonding



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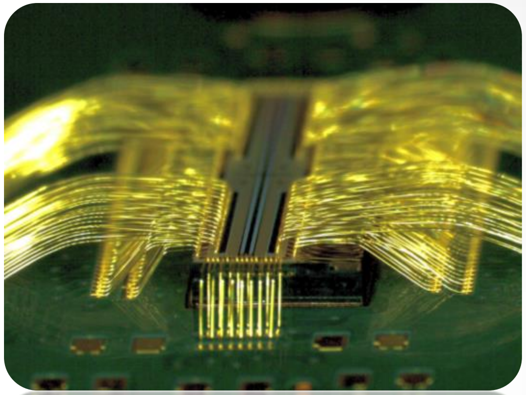
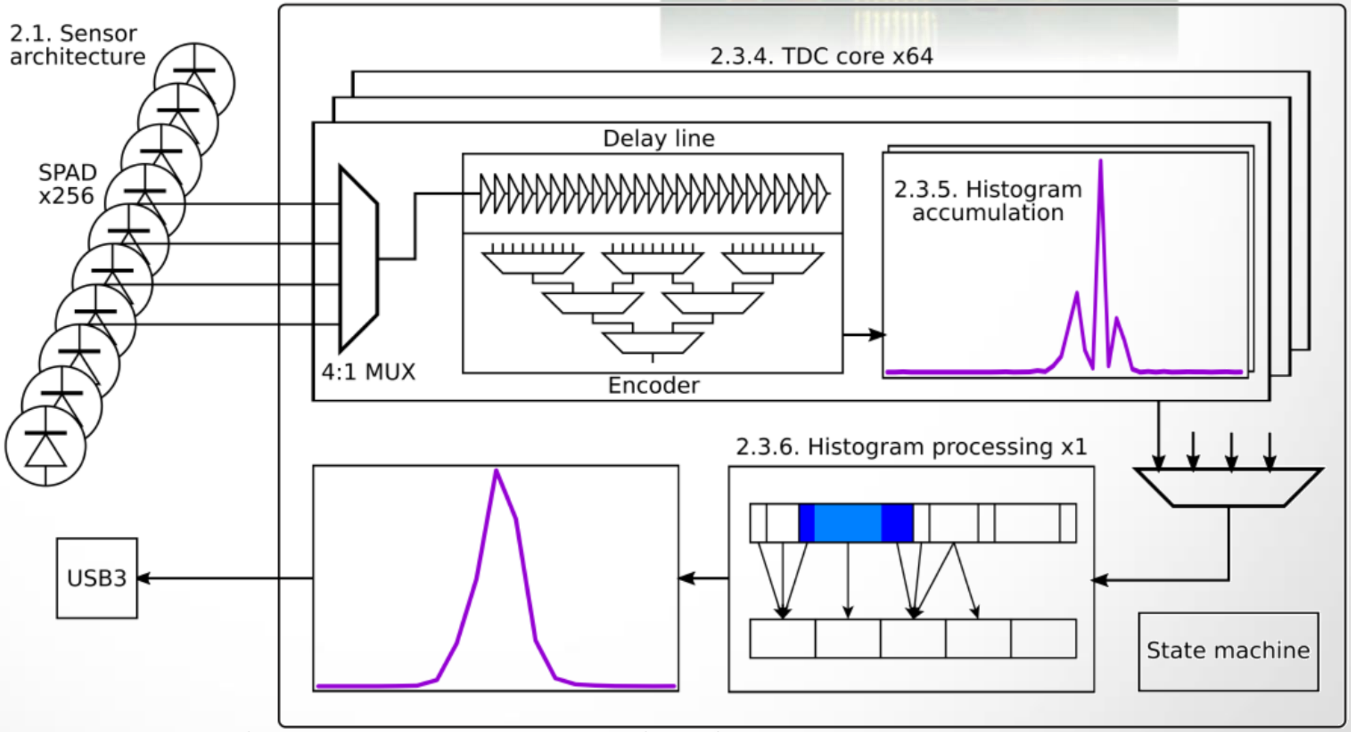
The LinoSPAD

- Hybrid CMOS AMS 0.35µm → FPGA





- Samuel Burri, Claudio Bruschini an Edorardo Charbon

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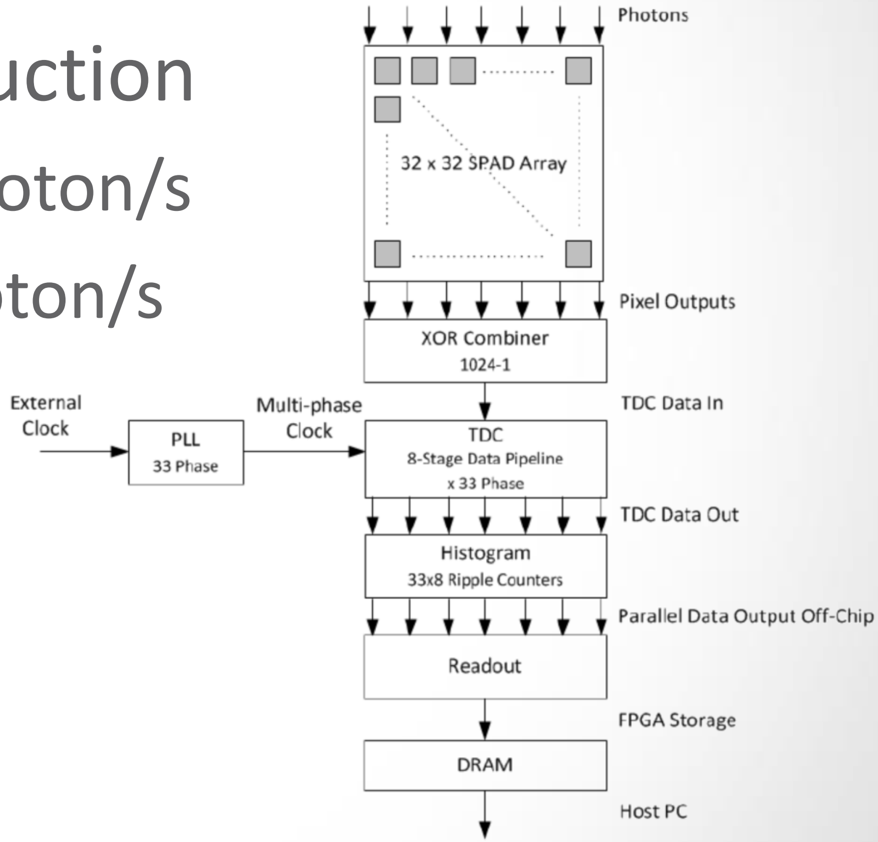
High speed on chip processing

- On chip histogram construction
  - Theoretically up to 14 GPhoton/s
  - Practically up to 900 Mphoton/s
- Looks like a single point

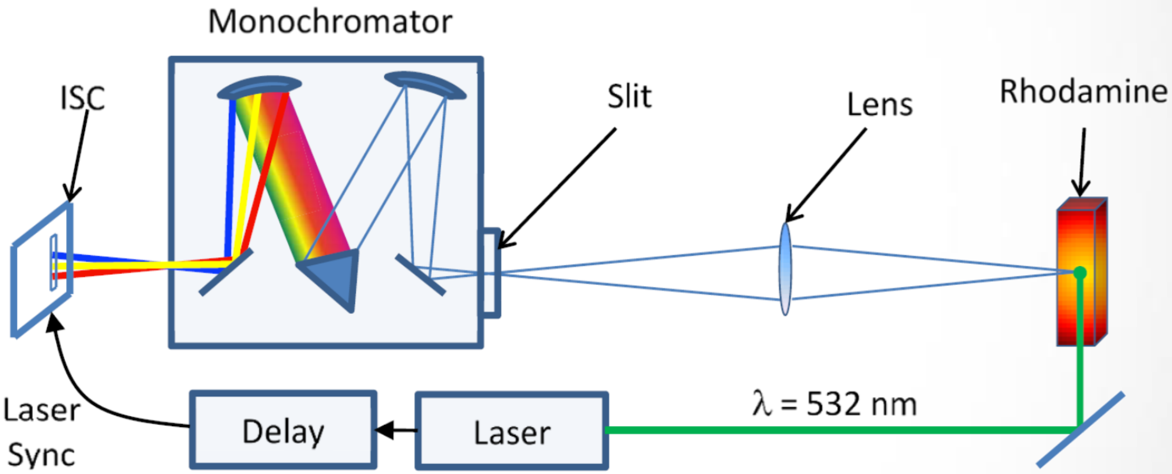


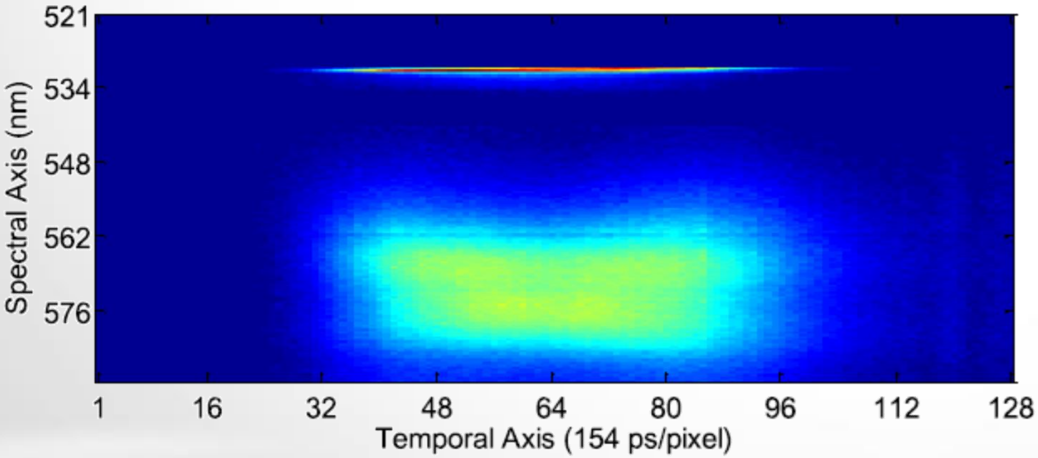
Hypervelocity Time-of-Flight Characterisation of a 14GS/s Histogramming CMOS SPAD Sensor

Neil Finlayson*[a], Tarek Al Abbas[a], Francescopaolo Mattioli Della Rocca[a], Oscar Almer[a], Salvatore Gnecchi[b], Neale A. W. Dutton[c], Robert K. Henderson[a]

Time resolved spectrometer

- The streak camera is the perfect device for spectroscopy





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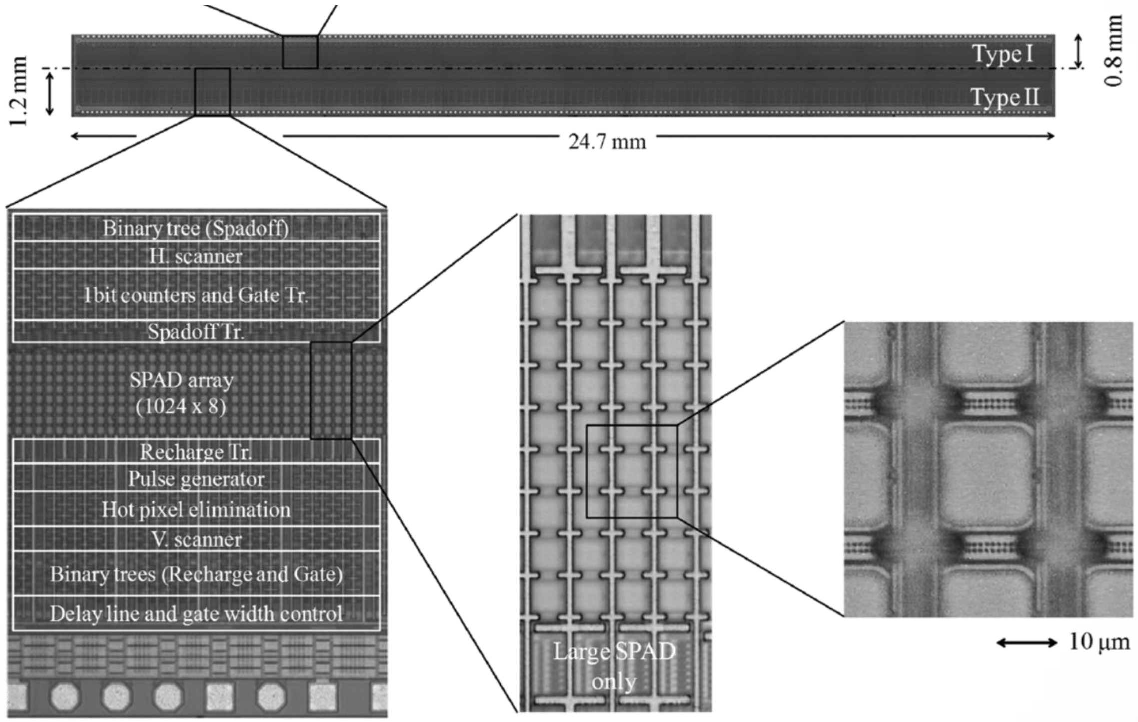
Time resolved spectrometer - Gated SBSC



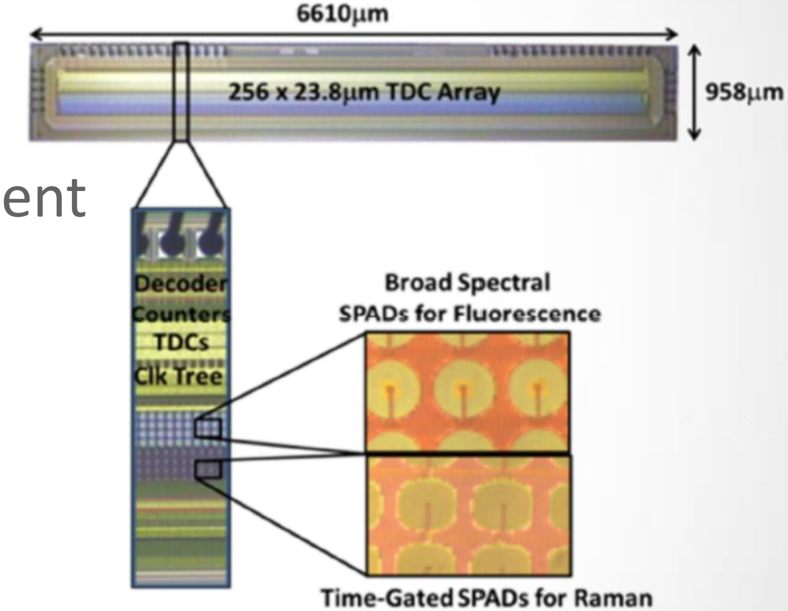
A 1024 × 8, 700-ps Time-Gated SPAD Line Sensor for Planetary Surface Exploration With Laser Raman Spectroscopy and LIBS

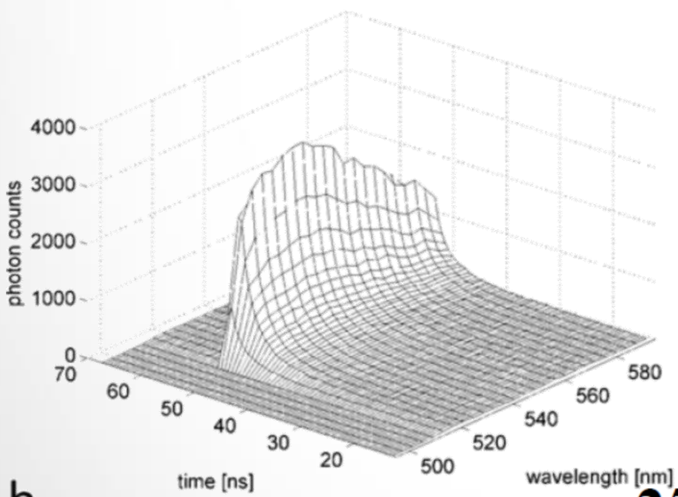
Yuki Maruyama, *Member, IEEE*, Jordana Blacksberg, and Edoardo Charbon, *Senior Member, IEEE*

Wilfried Uhring
Icube, University of Strasbourg and CNRS

Time resolved – TCSPC SBSC

- Integrated TDC
- On chip mono-exponential assessment





256 × 2 SPAD line sensor for time resolved fluorescence spectroscopy

Nikola Krstajić,[1,2,4] James Levitt,[3] Simon Poland,[3] Simon Ameer-Beg,[3] and Robert Henderson[1,*]

Conclusion

- Streak Imaging is just a matter of data rate and temporal resolution
  - With a constant data rate, streak imaging offer better temporal resolution
- A SPAD based streak camera
  - Faster data processing/extraction
  - Better temporal resolution (TDC and SPAD → 10 ps)
  - Better signal to noise ratio (smart activation)
  - Hybrid technologies

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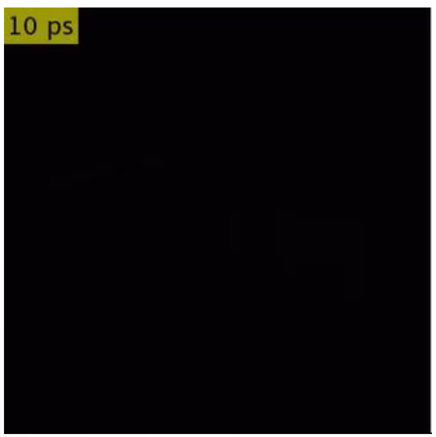
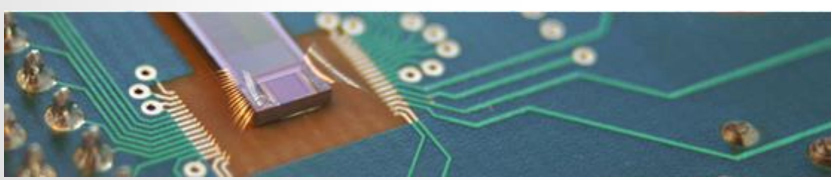
Icube SMH (Heterogeneous Systems and Microsystem) team member.





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