NetWare 2015

Keynote :

High Speed Imaging

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Outline

- Just history and a state of the art …

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Icube, University of Strasbourg and CNRS

19th century - Fathers of Photography

- **1826 - Joseph Niépce**
  - Plate coated with Judea bitumen
  - Mean exposure time **10 hours**

- **1838 - Louis Daguerre**
  - Silver plate exposed to chemical vapor
  - latent image that has to be « fixed »
  - Daguerréotype
  - Mean exposure time **30 min**
  - **French government bought the invention and give it to the world**

Boulevard du temple - Paris

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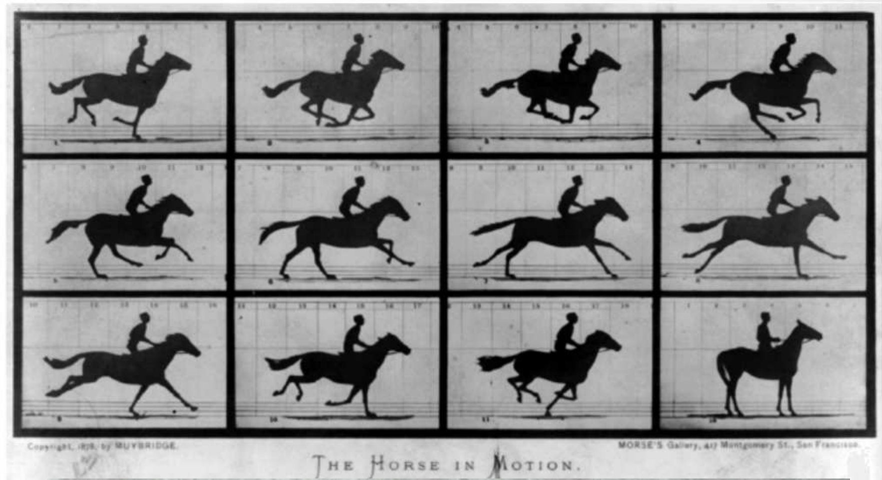
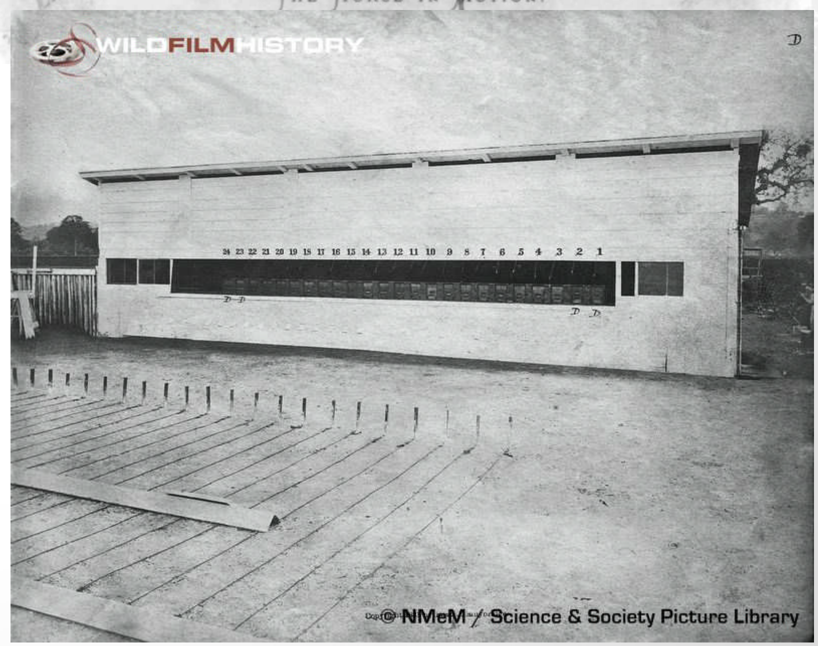
19th – Birth of High speed photography

- **1878 Eadweard Muybridge**
  - Use of *collodion* ➔ allows short fast exposure time but have to be used before It get dry
  - Mean exposure time **500µs**
  - **Use 24 different cameras triggered by a string**

  ➔ Only 24 frames





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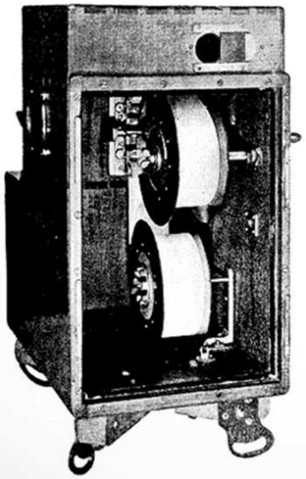
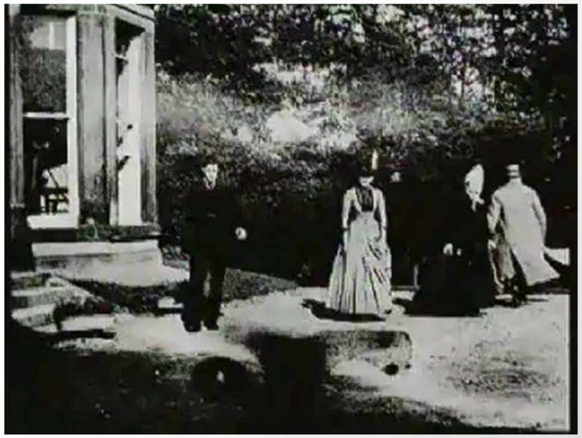
19th – birth of cinematography

- **Louis Le Prince**
  - 1886: Use of multi lens device
    - Only 16 frames: a recurrent problem in high speed imaging ……
  - 1888: single lens with stripping film
    - 10 – 20 frames per second





Roundhay Garden Scene

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20th century – first real high speed camera

- 1926: two high speed camera systems

British Heape-Gryll

- 4 tonnes, 8 horsepower
- 5000 frames per second
- Film drum

American Francis Jenkins

20th - popular science October 1926

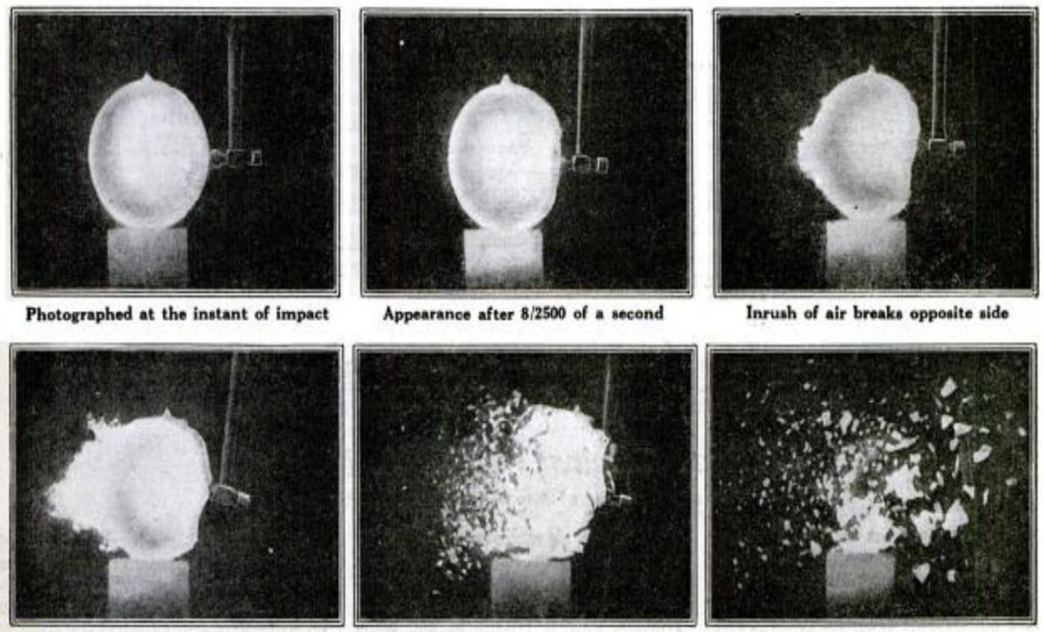
Under the eye of the super-high-speed camera a rubber ball dropped to the ground is shown to be flattened almost into a hemisphere at the moment of impact, a circumstance which, by showing resiliency in detail, is of scientific value to tire manufacturers in deciding on the design and construction of their products. Other secrets of rapid mechanical action that the cameras will disclose are expected to lead to industrial and scientific improvements.

The American machine was developed by C. Francis Jenkins, of Washington, D. C. The British camera is known as the Heape-Gryll rapid cinema machine. They are large contrivances (weight of the English machine is four tons) operated by electric motors.

Movie film; showing how a rubber ball flattens at instant of impact

High-Speed Movies—5000 a Second

Marvelous New Camera Watches a Hammer Smash a Vacuum Bulb



Photographed at the instant of impact — Appearance after 8/2500 of a second — Inrush of air breaks opposite side

The impact side still little altered — The whole bulb is crumbling now — 1/100 of a second after impact

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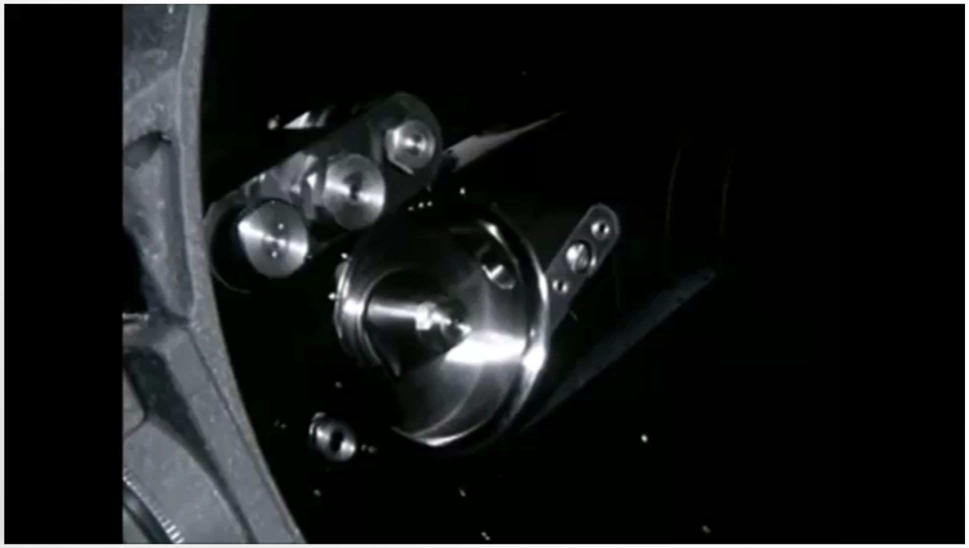
20th – technology maturity

- 1930: rotating prism camera
- Kodak and Bell telephone lab
  - The Fastax
  - 5000 fps
  - 30 meter tape max load capacity



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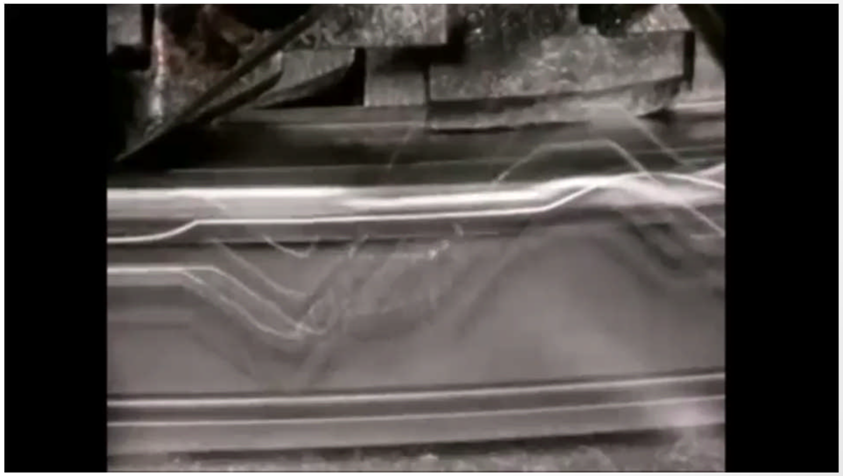
20th – technology maturity

- Designed in 1930, the Fastax push up to 18000 fps and used until the 60s



Extracts of a documentary from 1965

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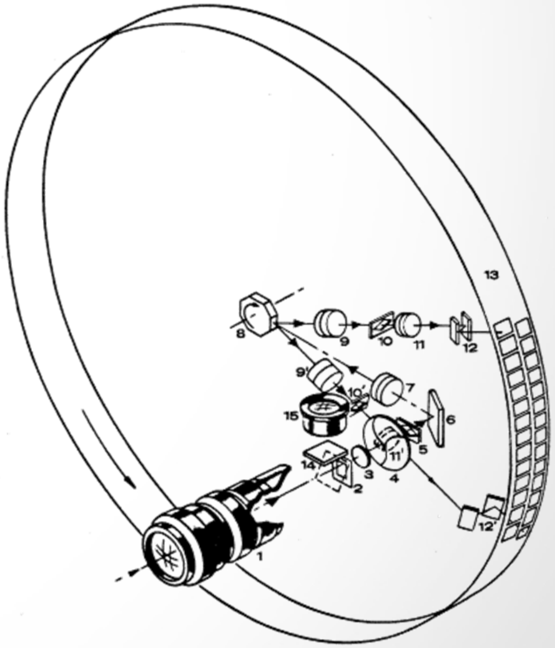
20th – technology maturity

- In the Fastax, the max speed is limited to the strain on the film

➔ Solution: do not move the film or applied it to a solid drum

- the rotating drum cameras
  - Rotating mirror
    - 6 to 8 faces
  - Rotating Drum
  - Single lens or
  - Up to 200 kfps
  - 224 frames



Cordin model 350 Rotating Drum Camera 35,000 fps H3/713

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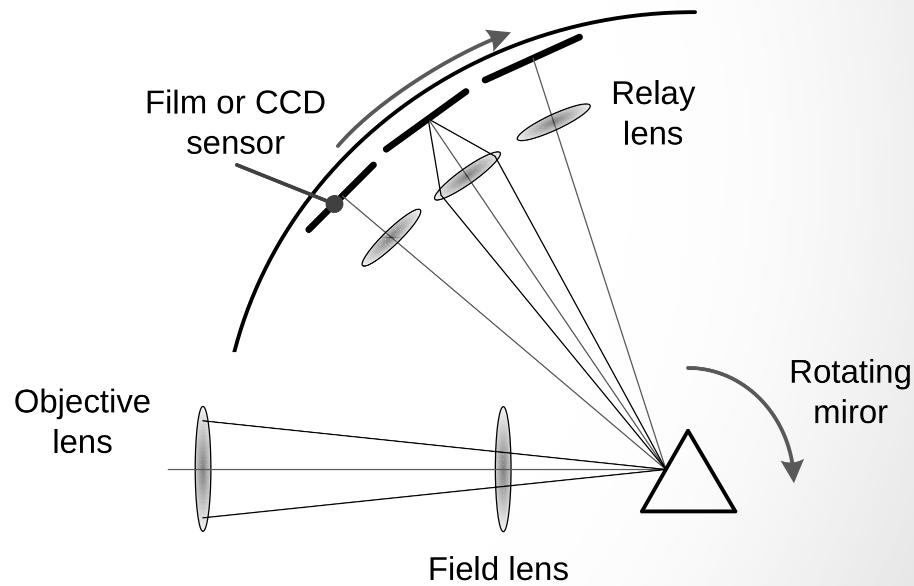
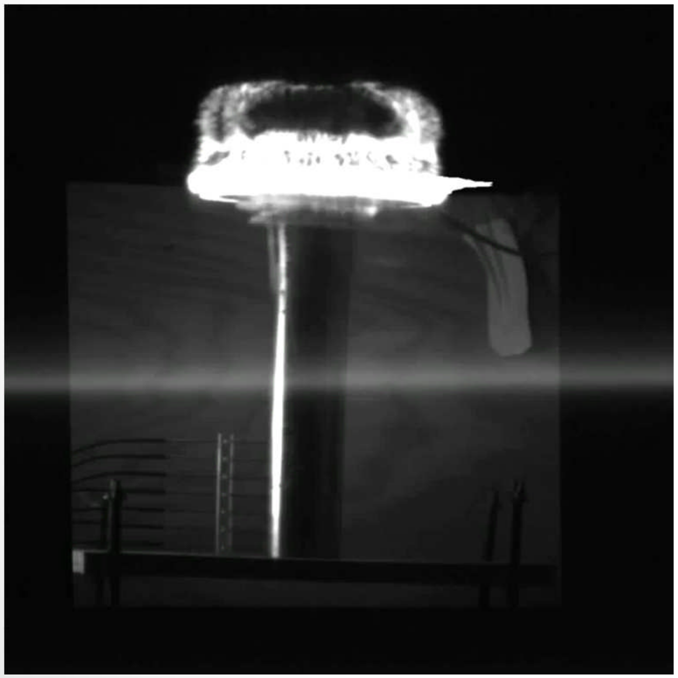
20th – The Manathan project

- 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 a commercial product 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

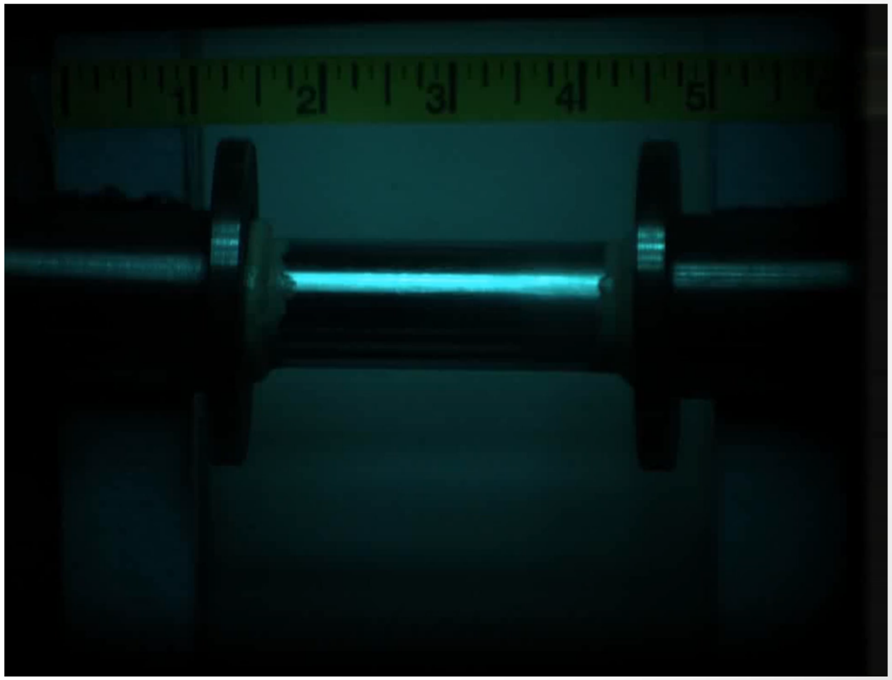


20th – The rotating mirror

- 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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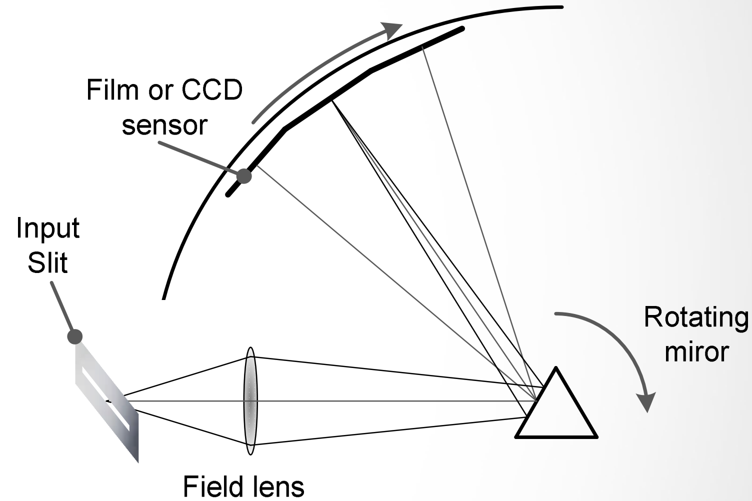
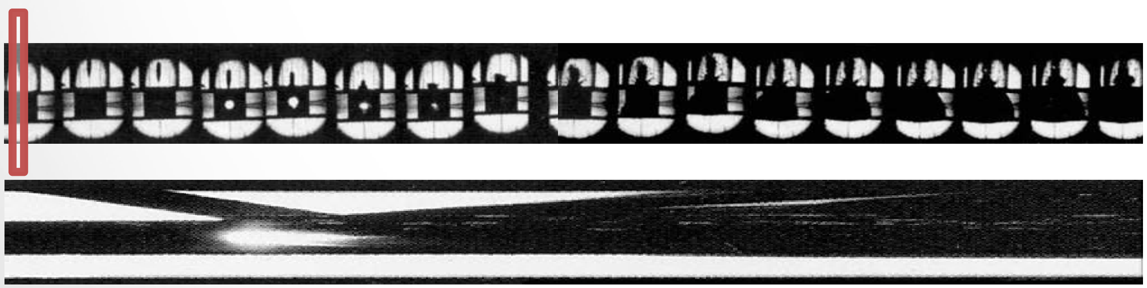
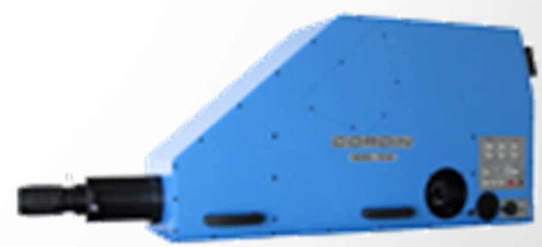
20th – The streak imaging

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



- Lost 2D spatial 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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Flashback to the 19th

- All previously systems employ mechanics and photochemistry effect, but ….
- The photoelectric effect
  - 1839, Antoine Becquerel and his son discovered a photoelectric effect (photo resistance effect)
  - 1887, This effect is understood by Heinrich Rudolf Hertz (publish in Annalen der Physik 1)
  - 1905 Albert Einstein explained the photoelectric effect with the photon concept → nobel price in 1921
  - **Optoelectronic** began with the vacuum tube

Here come the Electronic imaging ages …

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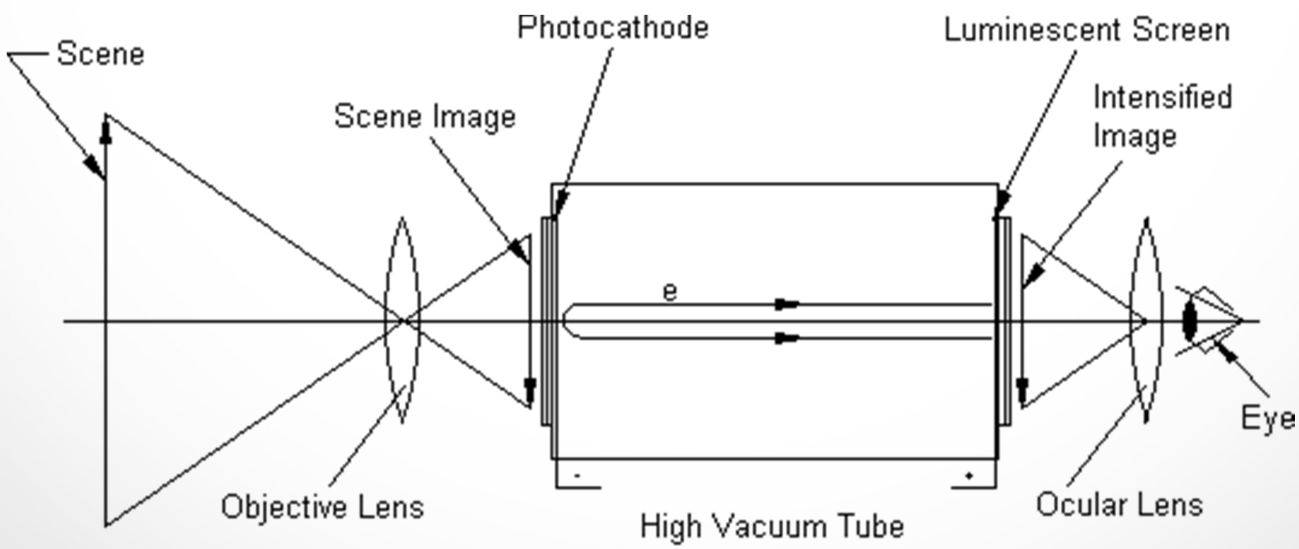
Electronic imaging

- 1934 Philips first infrared image converter
  - Called 1st Gen intensifier tube
  - Designed for night vision, which is still major application of the Image Intensifiers



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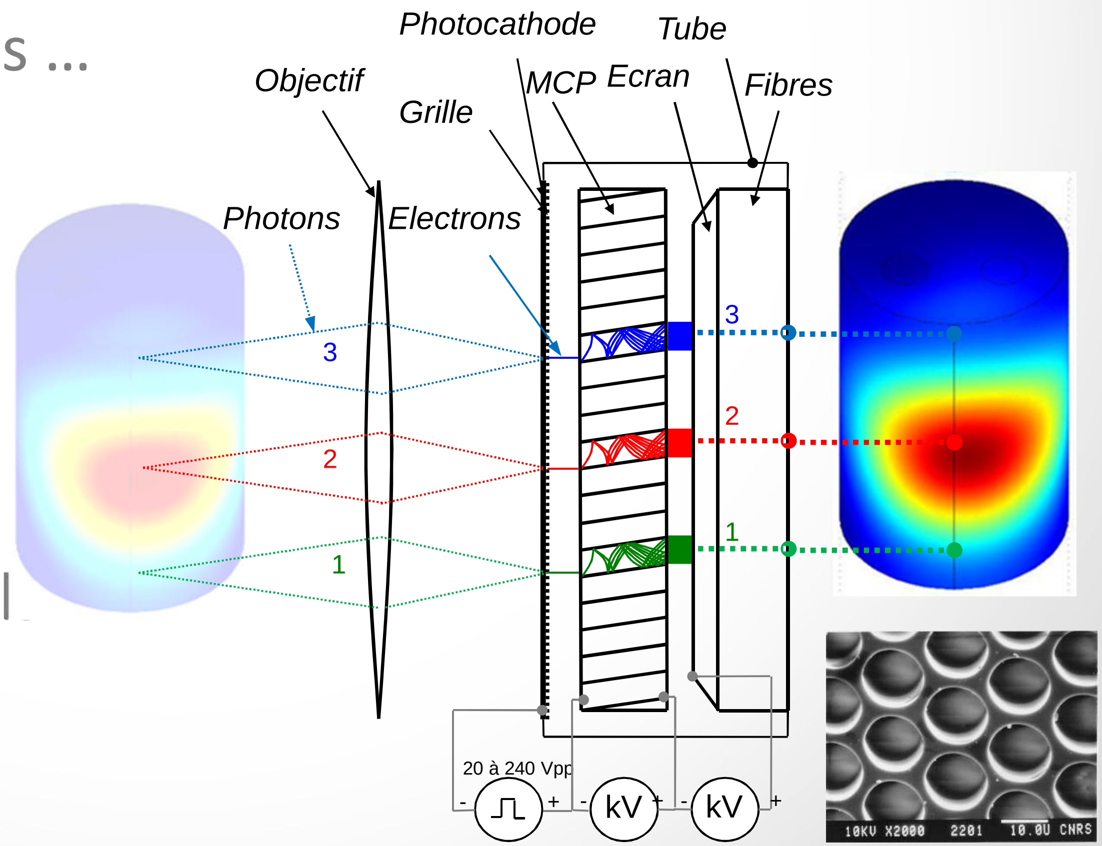
20th – framing with image intensifier tube

- 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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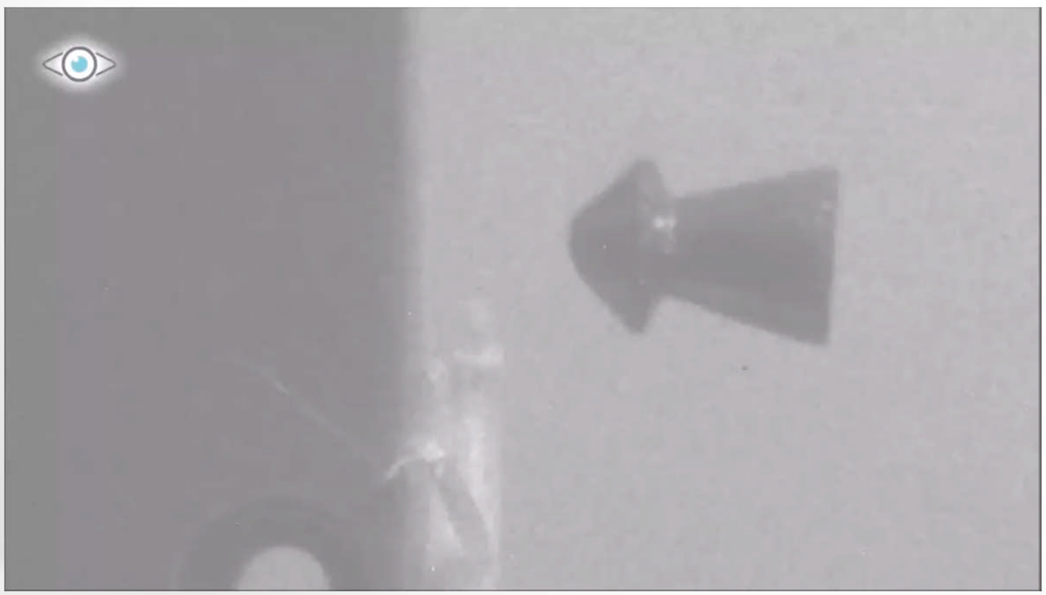
Multiframing with image intensifier tube

- Back again to **Muybridge concept**
  - Use several cameras optically and electrically coupled in the same box
- SIMX from specialized imaging (16 frames)
- XXRapidFrame from standford computer optics (8 frames)



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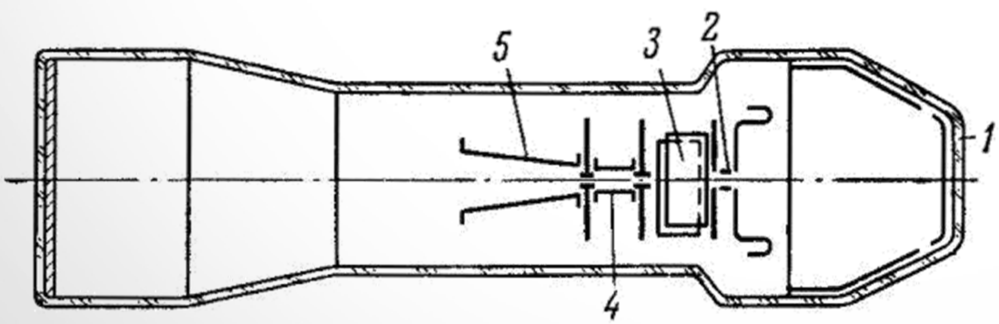
20th – The first streak tube

- 1949, the Russian Butslov designed a image converter tube for observation of ultra fast phenomena in infrared range
- 1: photocathode - 2,5: shutter plates - 3,4: scanning plates
- Allows
  - framing down to 10 ns exposure time, shutter plates → 1 frame
  - Streak imaging , scanning plates, by time to space conversion



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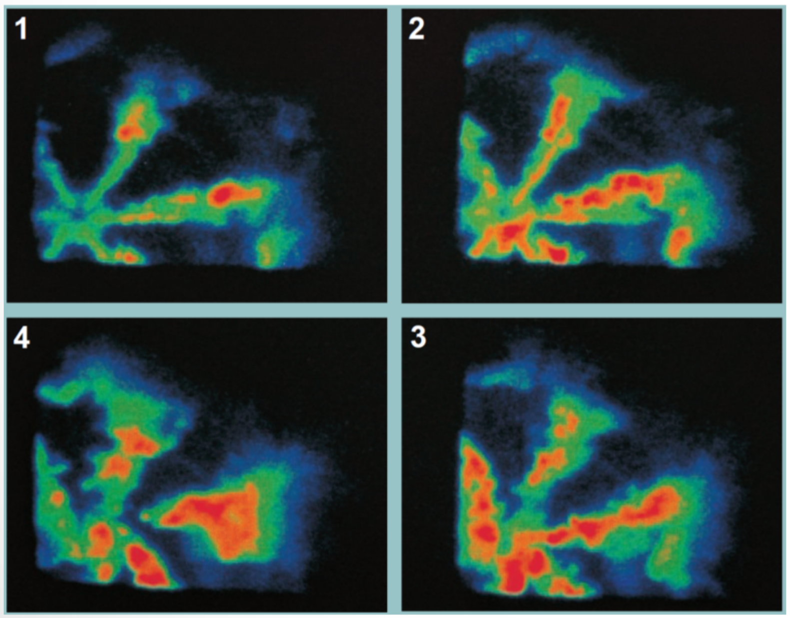
20th – framing with streak tube

- The deflection plate in both direction (x,y) of the tube allows a framing mode



Diesel fuel combustion flames

5 Framing Unit M4189

Number of frames	1, 2, 4 (a, b), 8
Exposure time	50 ns to 1 ms
Frame interval	300 ns to 10 ms
Shutter closing time	200 ns min.
Resolution (at phosphor screen center)	13 lp/mm
Repetition rate	100 Hz (at max. frame rate)
Frame size on Phosphor Screen (V × H)	● 8 Frame: 1 2 / 4 3 / 5 6 / 8 7, 7 × 10 mm ● 4 Frame (b): 1 / 2 / 3 / 4, 7 × 20 mm ● 4 Frame (a): 1 2 / 4 3, 10 × 10 mm ● 2 Frame: 1 / 2, 10 × 20 mm ● 1 Frame: 20 × 20 mm
Screen mode	Framing, multi-exposure, focus
Operating mode	MODE1, MODE2, MODE3
Trigger delay	Approx. 500 ns
Trigger signal input	3 to 5 V/50 Ω, more than 50 ns

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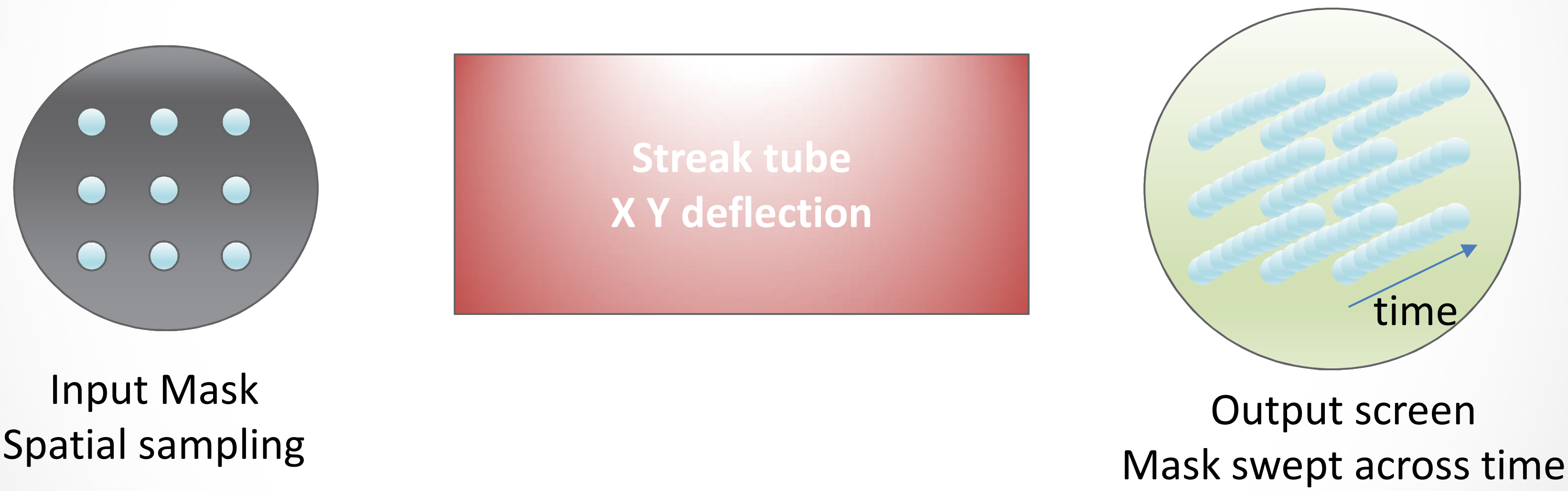
20th – framing with streak tube

- Add a mask in front of the photocathode allows to makes picosecond framing



  - After image processing, the movie can be reconstructed
  - Low spatial resolution, limited number of frame

Picosecond framing technique using a conventional streak camera, H. Niu, T. Chao, and W. Sibbett, Rev. Sci. Instrum. 52(8),pp 1190, 1981

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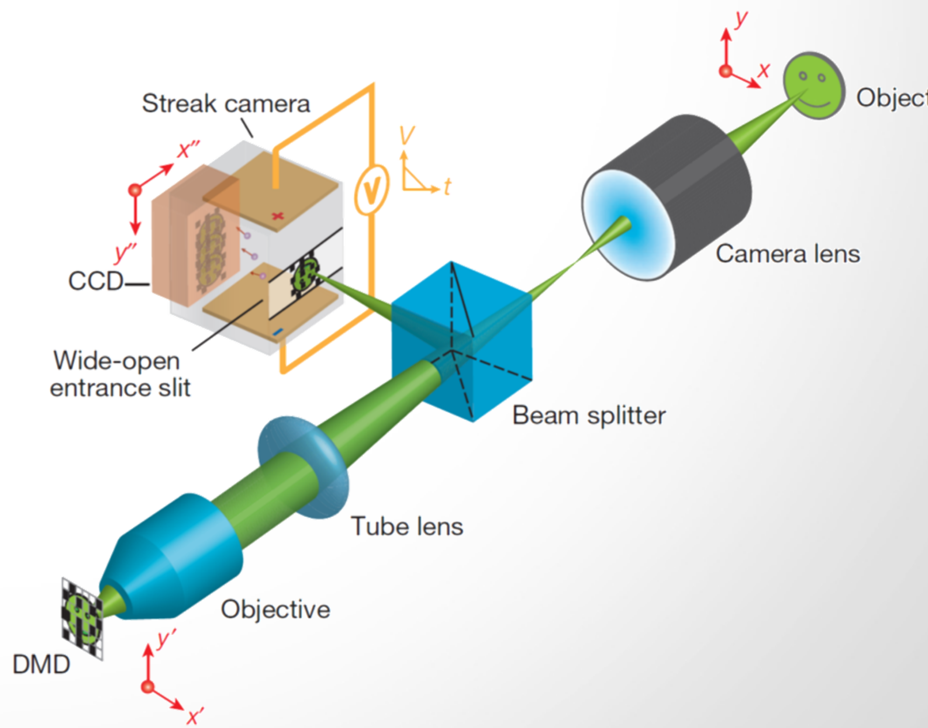
Framing with streak tube

- December 2014 – Letter Nature (Gao) : **"Single-shot compressed ultrafast photography at one hundred billion frames per second"**
  - Compress sensing theory, Inverse problem
  - Temporal resolution ~ 30 ps
  - Low spatial resolution

Liang Gao et al. (2014),
Nature,
DOI:10.1038/nature14005



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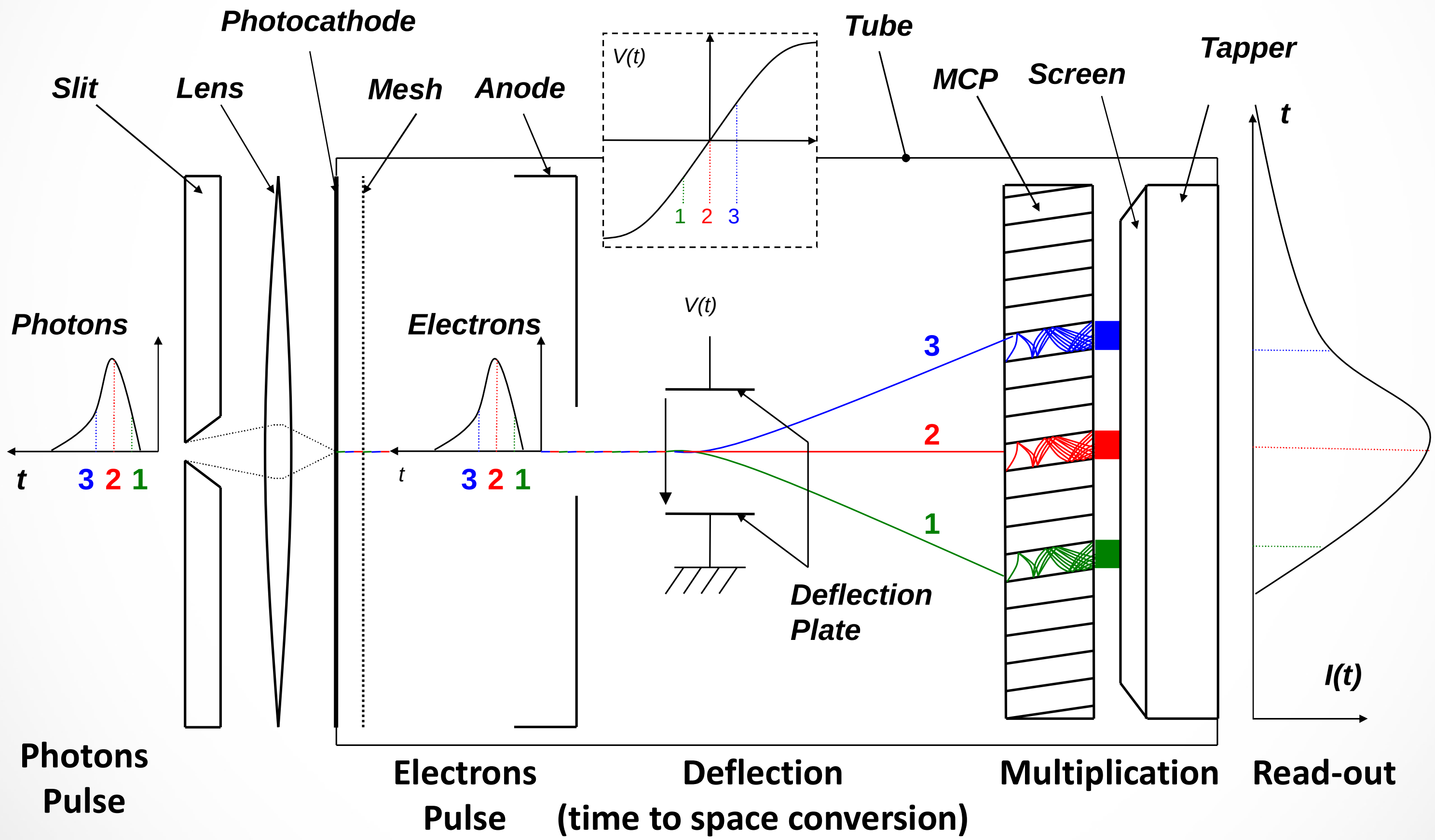
20th – The streak imaging tube



- Temporal resolution down to 1 ps ➔ Tfps (100x faster than Image intensifier)
- 1000 spatial pixels ➔ **1 Peta Samples per second !**

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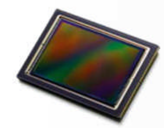
20th – 70s The transition …

- From Vacuum technology to solid state sensor



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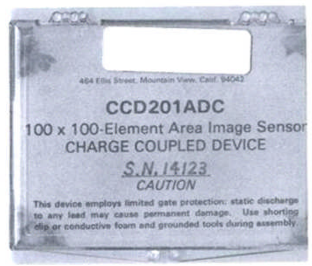
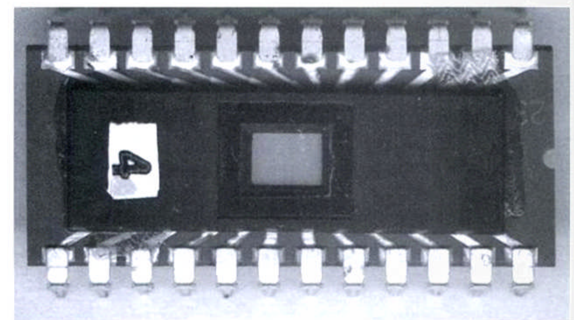
20th – Digital high speed video

- 1973, Fairchild first CCD image sensor (100x100)





- 1991 KODAK EKTAPRO Motion Analyzer 4540
  - Frame rate
    - 4500 fps (256 x 256 Pixel),
    - 40500 fps (64 x 64 Pixel)
  - max. frames 1024
  - Resolution 256 x 256 Pixel
  - Grey levels 256

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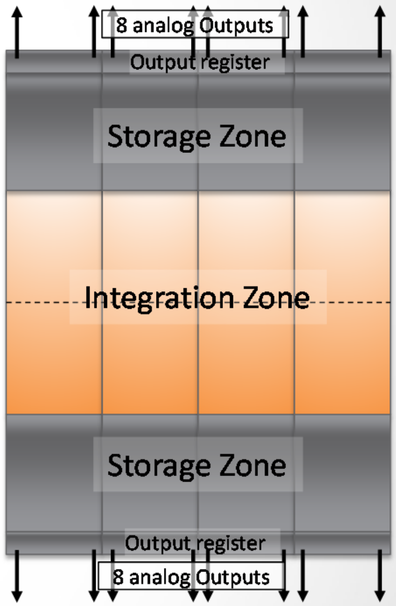
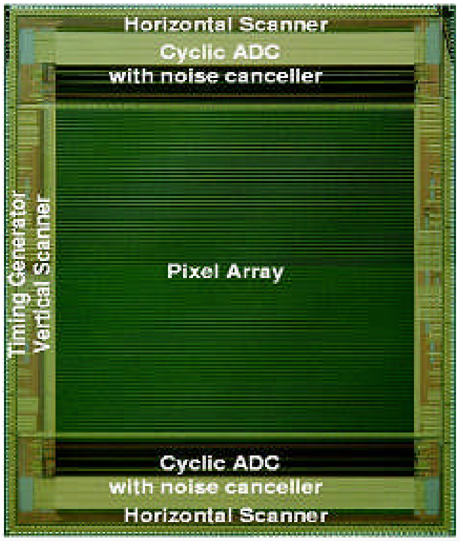
2000 – The CMOS revolution

- 2000, ICube lab designed camrecord 1000 fps @ 512x512
  - 16 output **CCD** Sensor with frame transfert CCD
  - ➔ 16 external ADCs and 256MB memory
  - ➔ Time to Design the camera : **3 years**



- Meanwhile, **CMOS** sensors for high speed imaging appeared
  - 1500 fps @ 512x512
  - 512 collumn ADC
  - ➔ Time to design the camera : **5 months**



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21th - Current High speed video

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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 wavelength at 25Gbps

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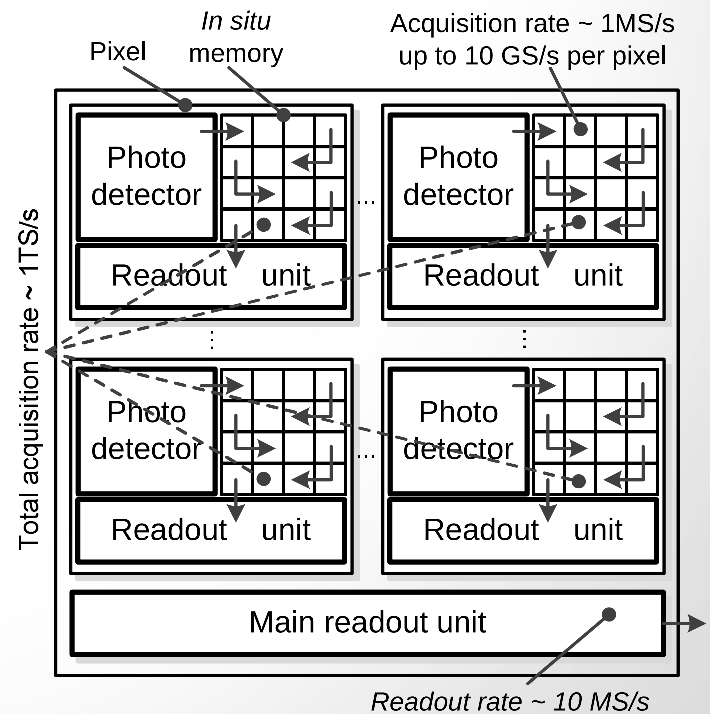
21th - Ultrahigh speed solid state camera

- **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 date rate



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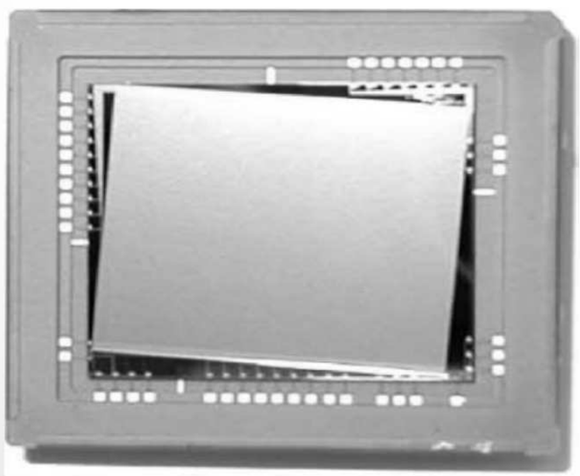
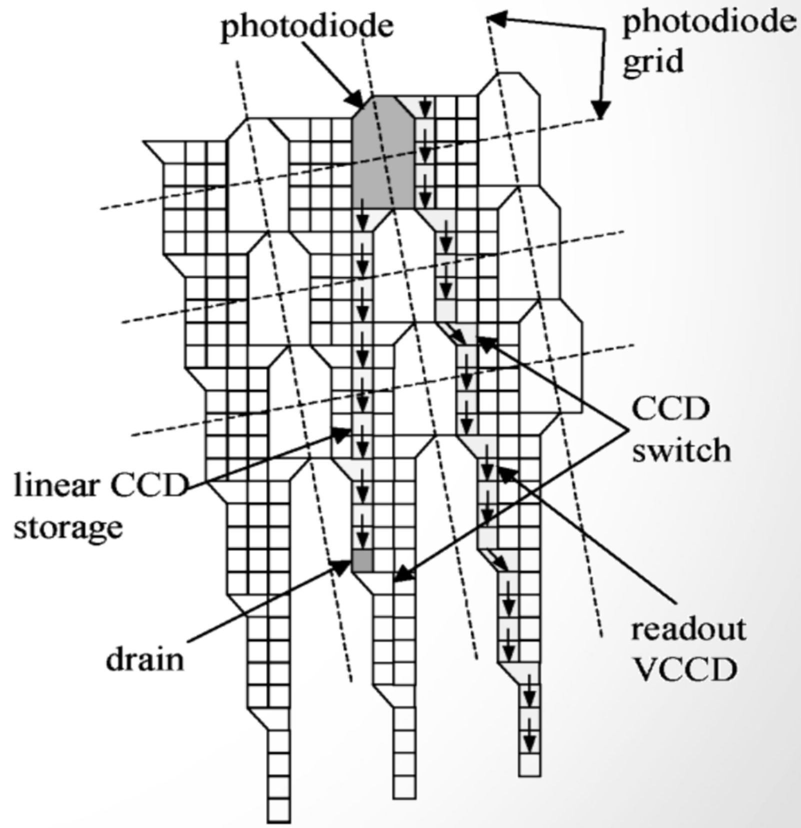
21th - Ultrahigh speed solid state camera

- **CCD technology** (by Etoh)
  - 1999
  - 1 Mfps, 100k pixels
  - 100 frames
- Speed limited by CCD transfer efficiency





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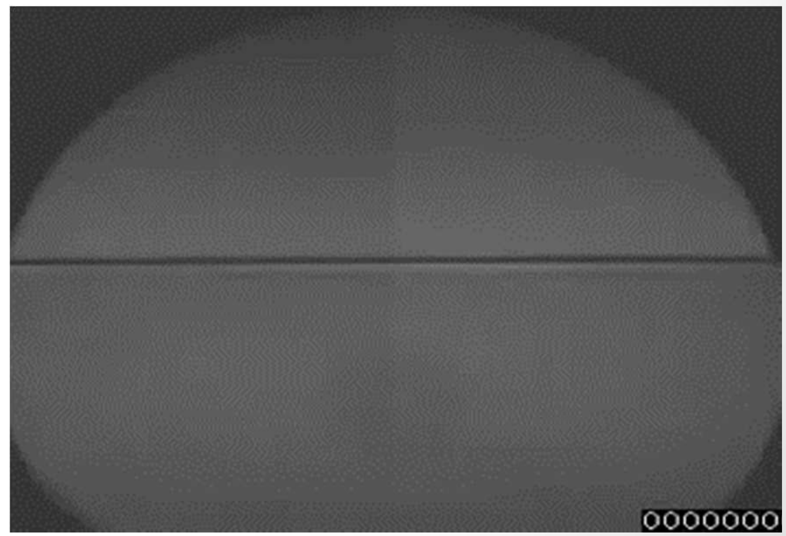
21th - Ultrahigh speed solid state camera

- Shimadzu
  - Model HyperVision HPV-2
  - 312x 260
  - 100 frames
  - Up to 1 Mfps
  - Acq. rate 81 Gpixel/s



Shock wave from an explosive exploding underwater (Recording speed: 1,000,000 fps)

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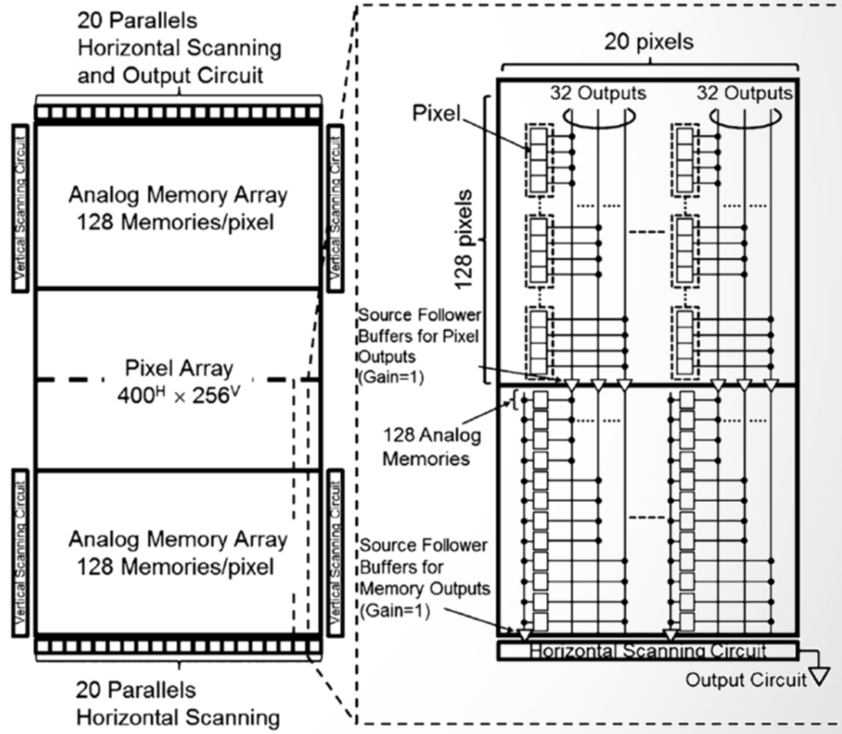
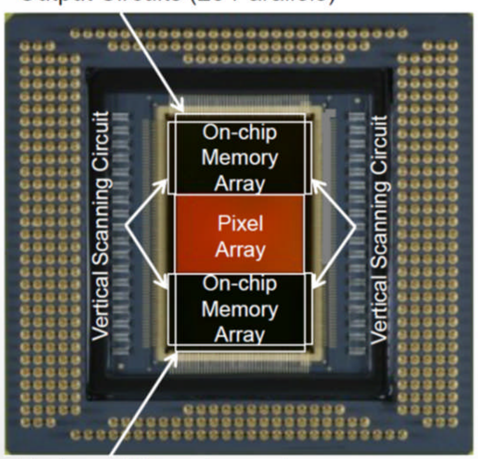
21th - Ultrahigh speed solid state camera

- **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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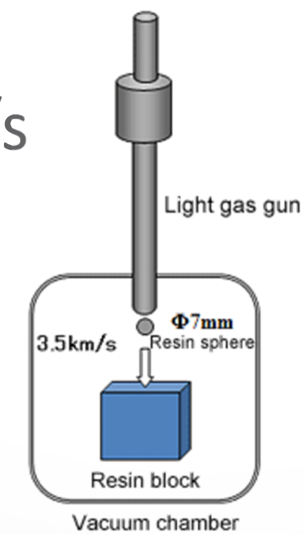
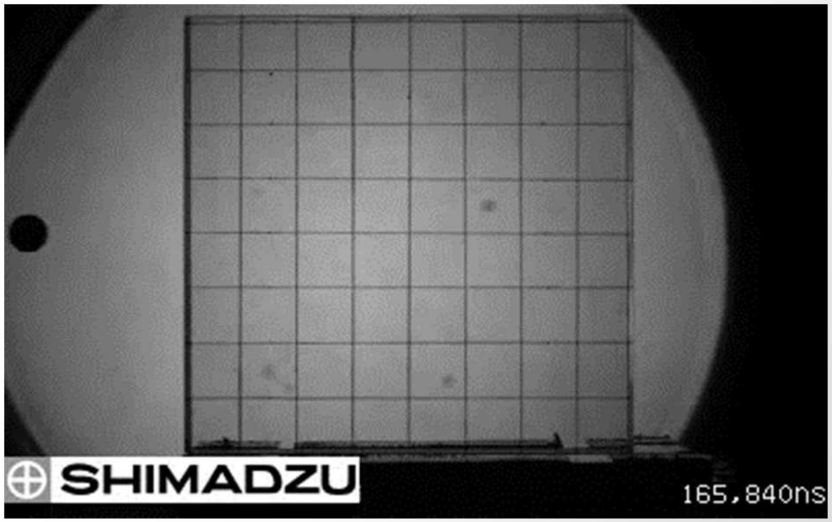
21th - Ultrahigh speed solid state camera

- 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





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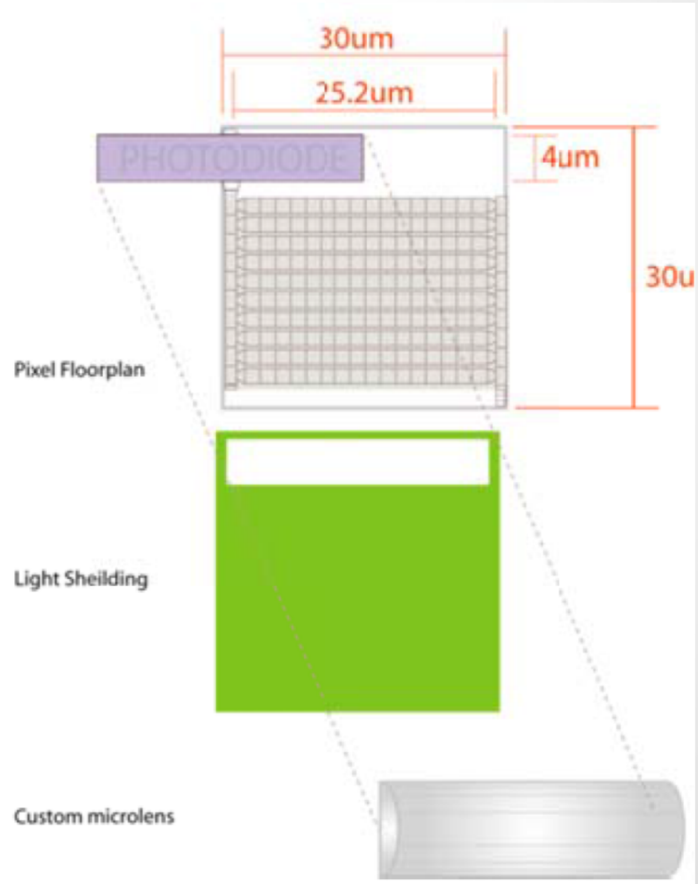
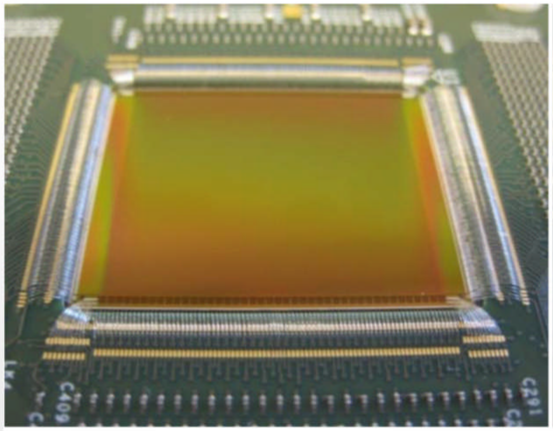
21th - Ultrahigh speed solid state camera

- **Hybride CMOS-CCD Technology** (by Crooks)
- 2013, 180 nm
- Buried Channel CCD
- 5 Mfps, 700k pixels
- 180 frames
- Fill factor 11%





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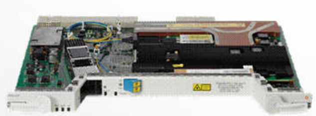
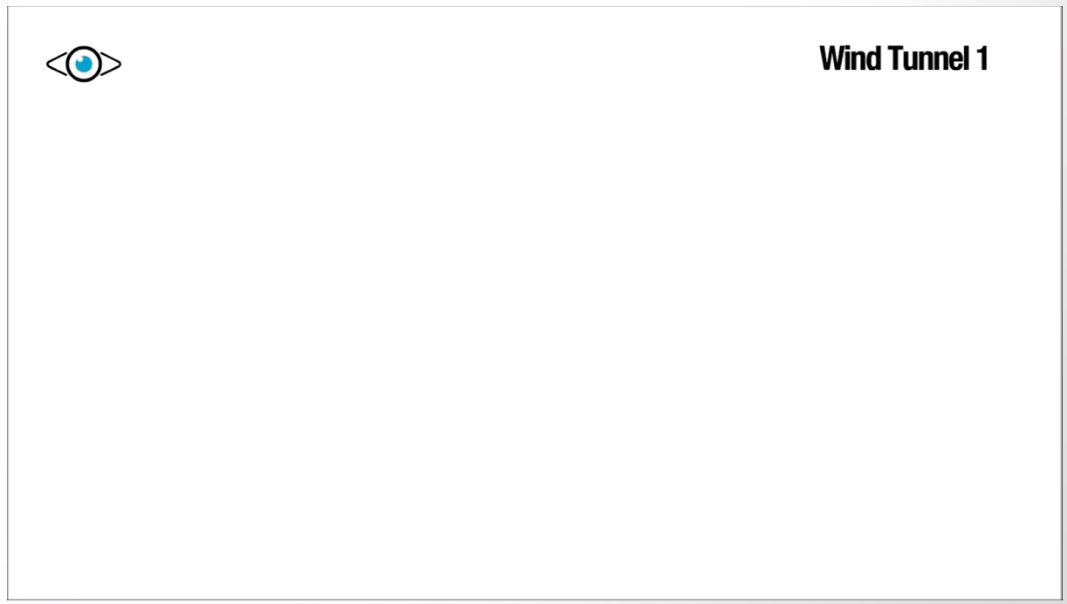
21th - Ultrahigh speed solid state camera

- Specialised-imaging
  - Model Kirana
  - 924 x 768pixel - 180 frames
  - 5 Mfps
  - Acquisition rate : 3.5 Tpixel/s
  - 10 bits

  ➔ 35 Tbit/s

Currently, fastest commercial single-laser-single-fiber network connections max out at just **100Gbps ➔ 350 modules** should be required to extract the data from the sensor in real time





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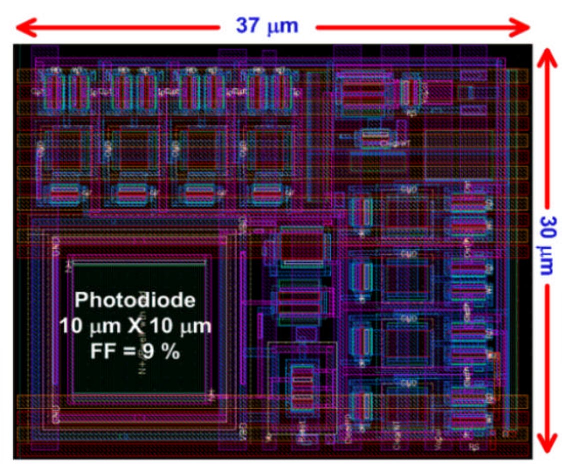
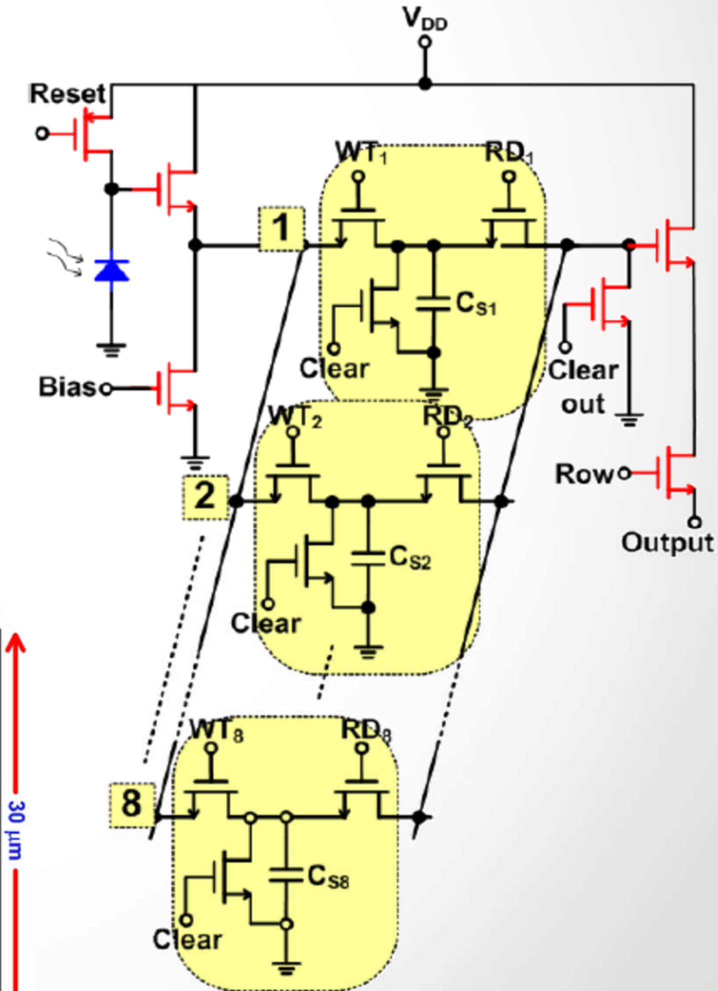
21th – Torward to the GigaFps

- **CMOS** (by Deen)
  - 2009, 130 nm
  - Up to 1.3 Gfps, 32x32 pixels
  - 8 frames
  - Speed limited by electronic bandwidth
  - Fill factor 9 %
  - No image





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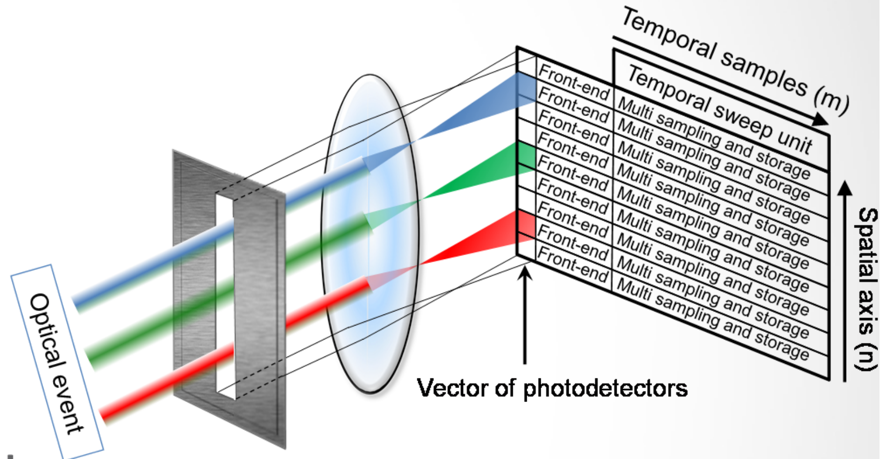
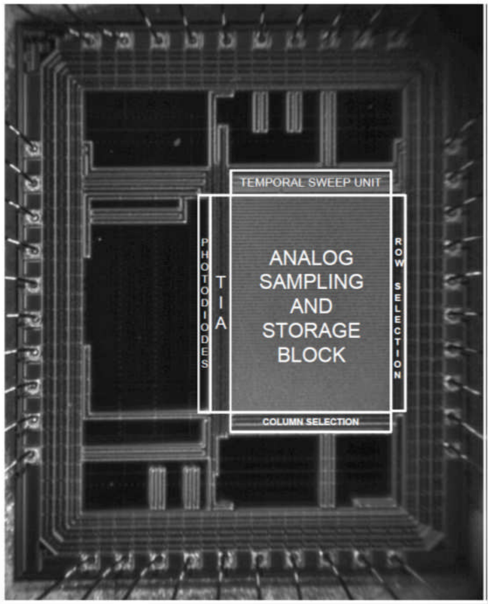
21th – Toward to the GigaFps

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





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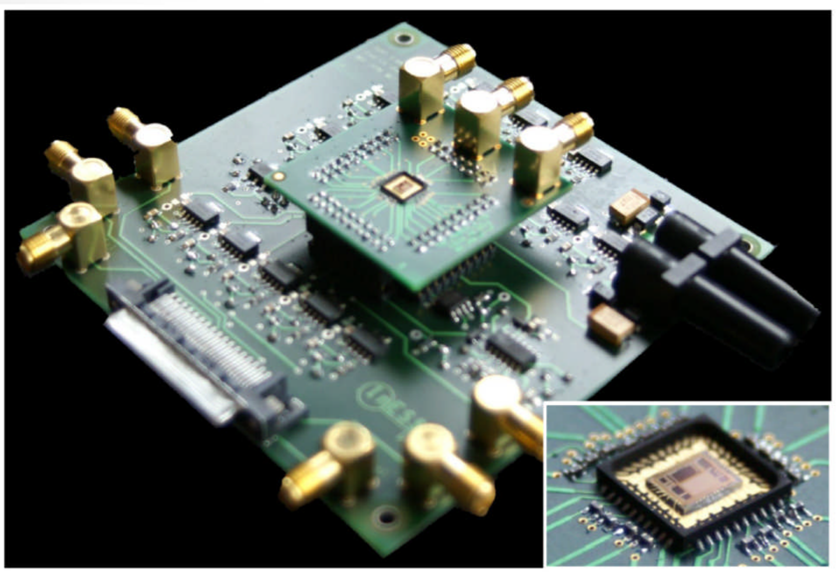
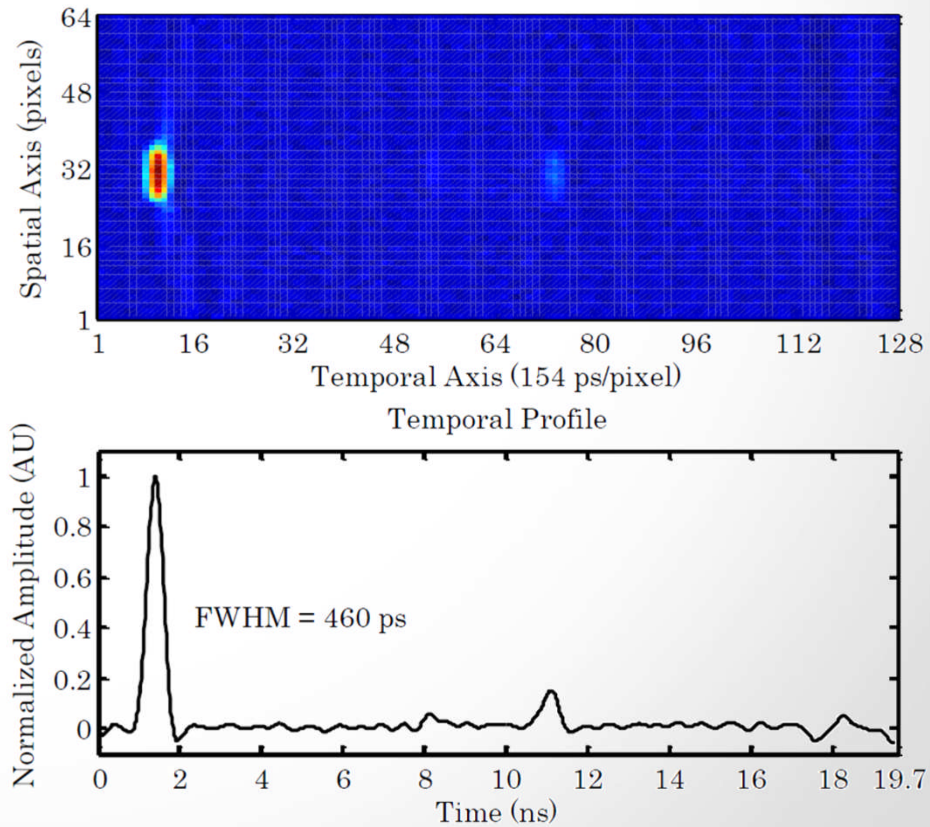
21th – Toward to the GigaFps

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





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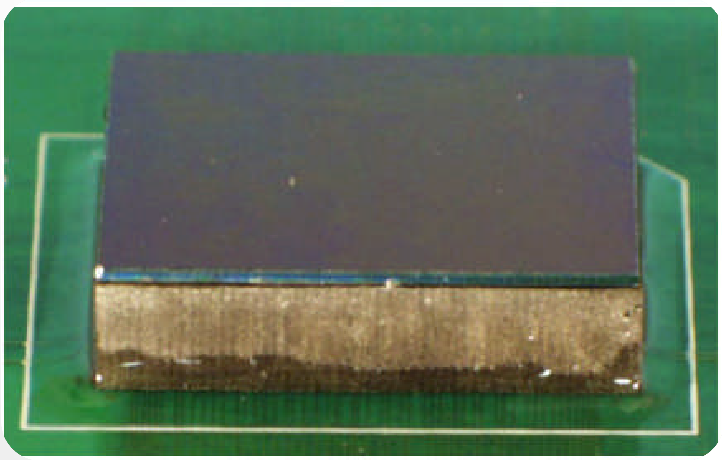
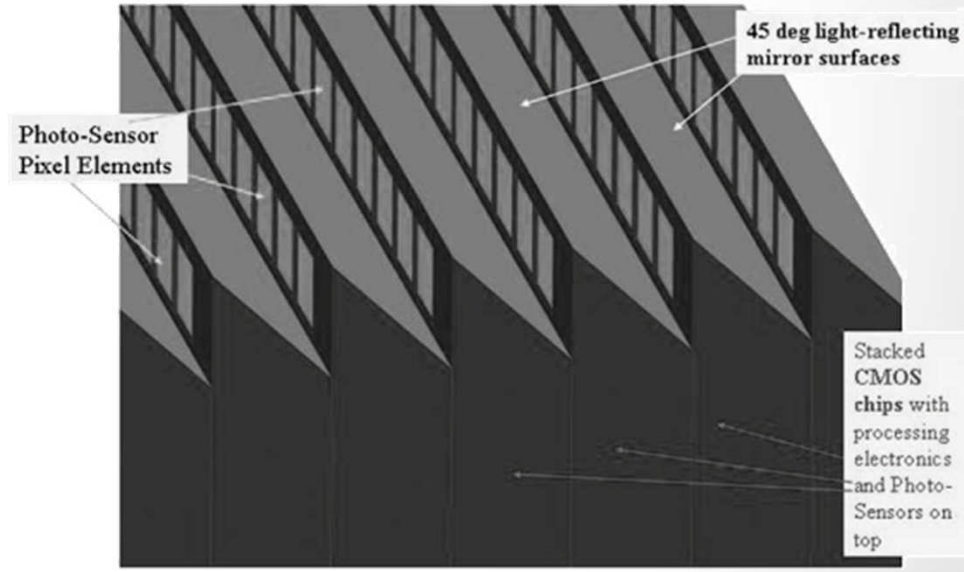
21th – Torward to the GigaFps

- **Streak imaging to video imaging**
  - 3D microelectronic
  - Assembly of streak camera (Proposed by Kleinfelder)





➔ **The ultimate solid state video imager**
- 10 Gfps, up to 200 frames
- Does not exist for the moment …

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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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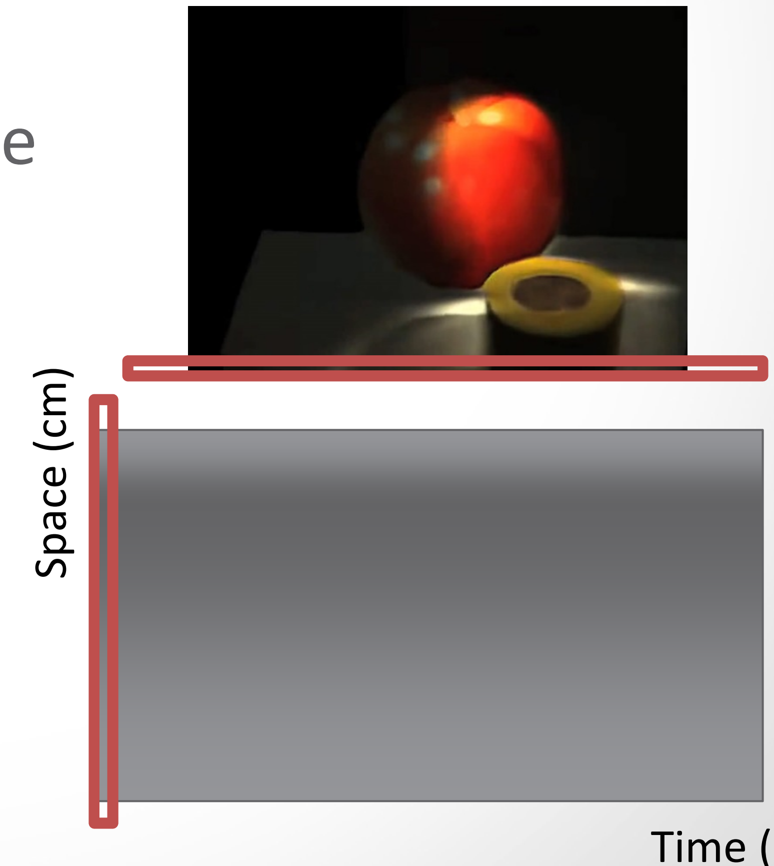
Streak to framing once again

- Streak Camera + 2 mirrors = 1 000 000 000 000 fps
- Each spatial slice of the scene can be captured time after time
- Image processing → full movie



- MIT patented

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Streak to framing once again

- Several hour of acquisition
  - Streak camera stability is a issue
- Example: femtosecond laser in a soda bottle

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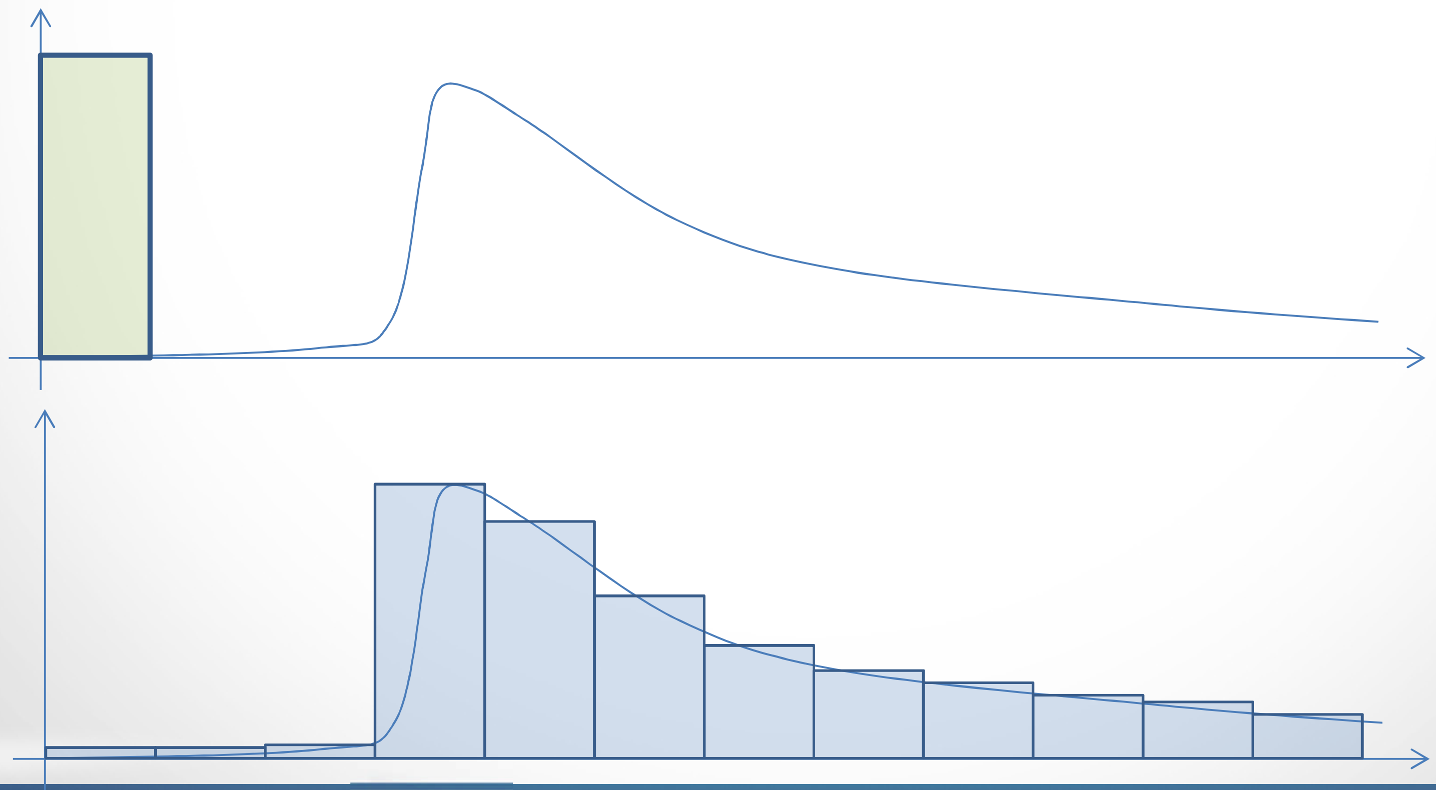
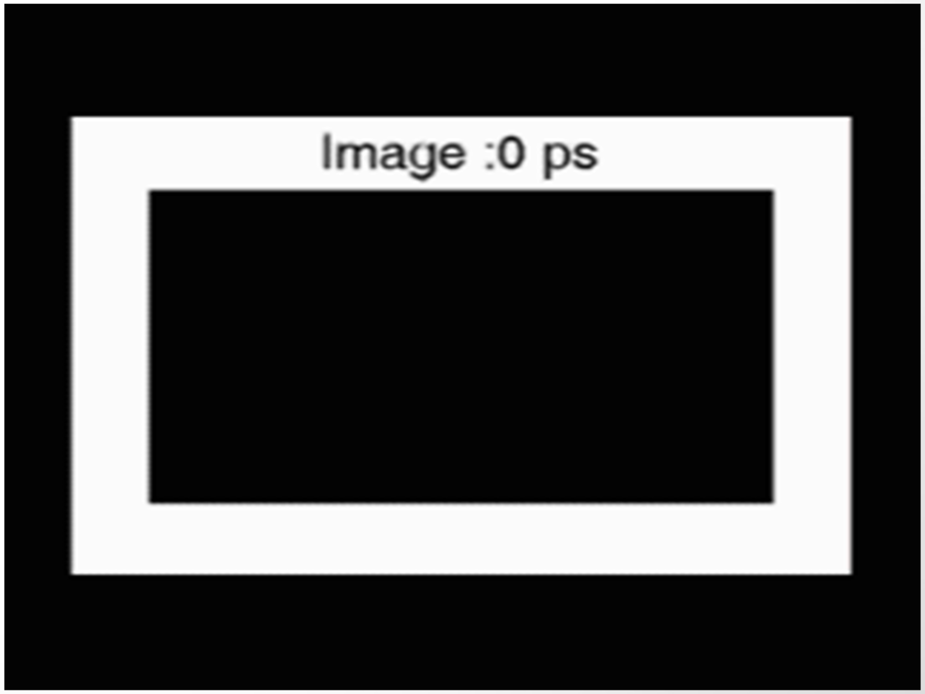
Time gated approach

- Shifting a short temporal gate synchronized with the optical event
- Acquisition of the different frames time after time
  - Eventually : repeat the event several time with the same gate to enhanced signal to noise ratio



Time gated intensifed camera

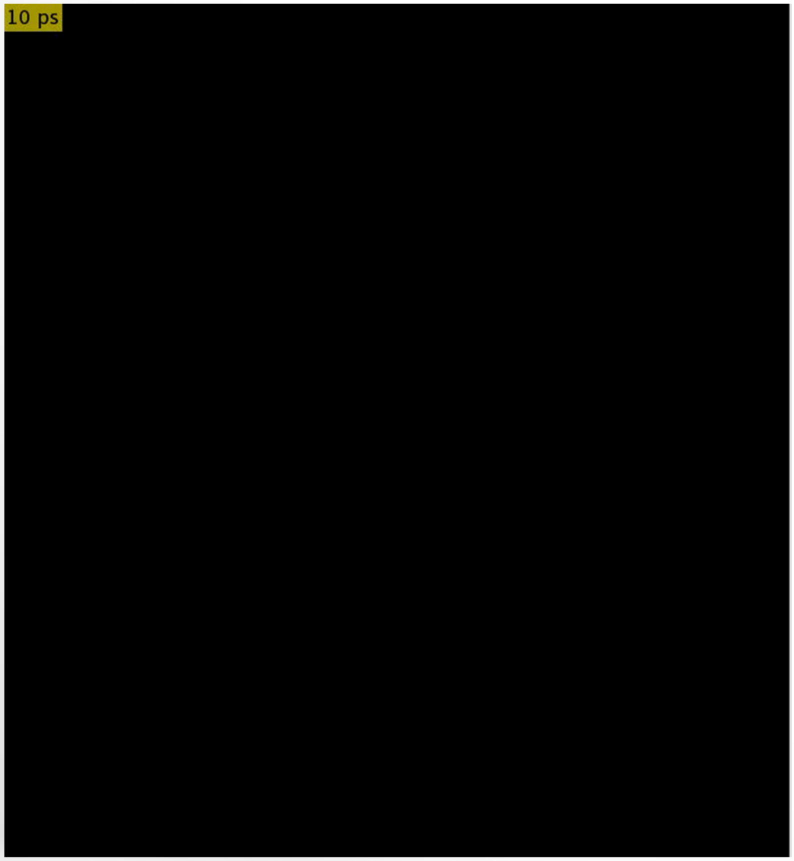
- ICube Time gated intensified camera
  - Image intensifier Photocathode gating
  - Special tube design for sub-nanosecond gating
  - Temporal gate width : 200 ps
  - Temporal gate position 10 ps
  - Repetition rate ~ 100 MHz
  - → 100 billion fps

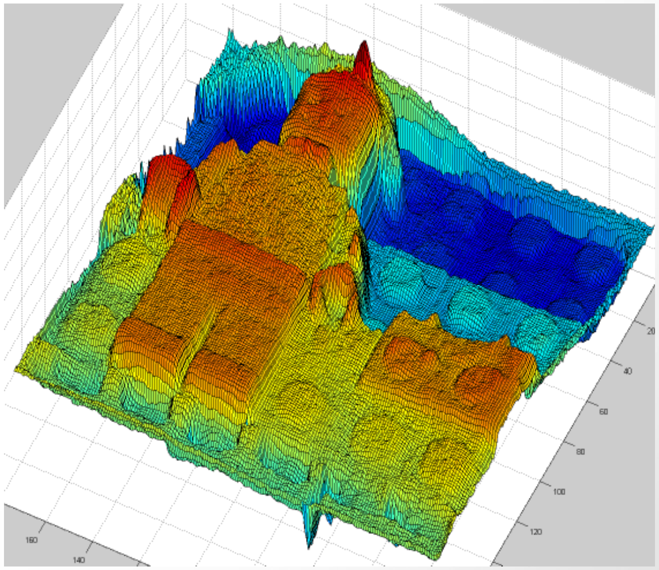


Example: propagation of a 50 picosecond pulse of light in an 60 cm optical fiber forming the « Icube » word

Time gated intensifed camera

- **ICube Time gated intensified camera**
  - Acquisition time 20 seconds !





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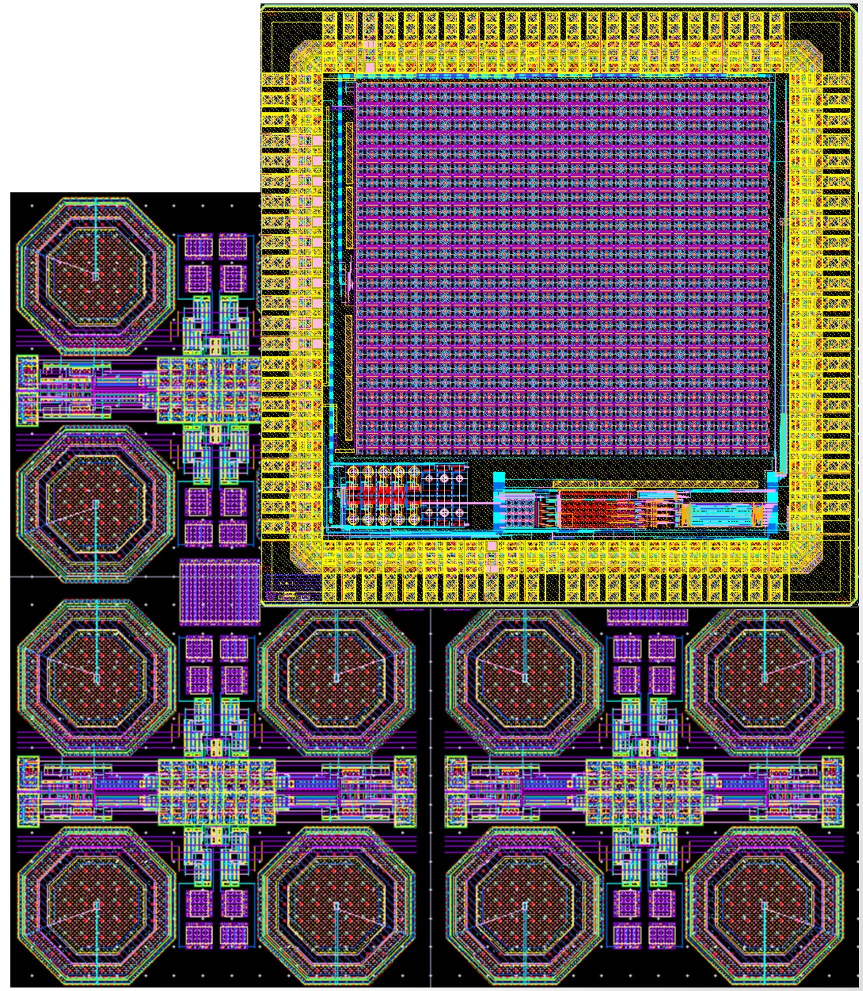
Time gated integrated sensor

- Smart CMOS sensor
  - Time gated SPAD for single photon counting
  - 3D real time video sensor
  - Temporal gate 200 ps
  - Repetition rate up to 100 MHz
  - 36x36µm² pixel size
  - 13.5% fill factor



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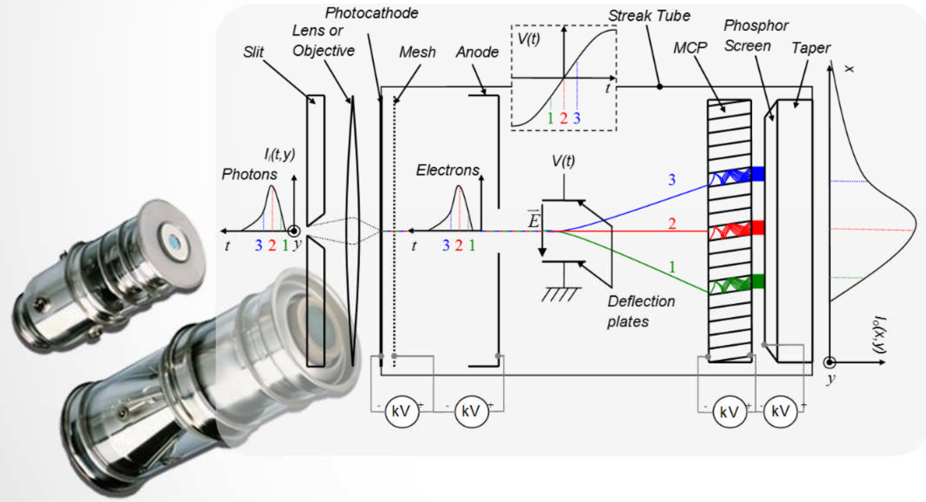
Conclusion

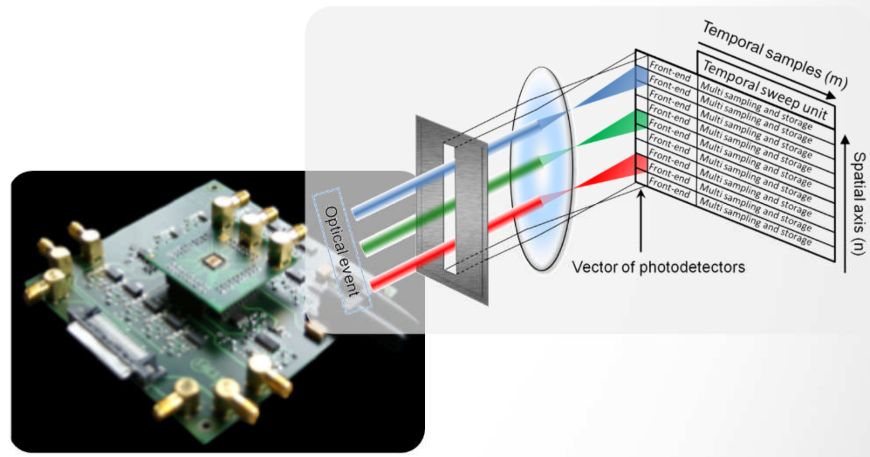
- High speed imaging always push the technologic limits
- Currently comes in two main technologies:

Vacuum tube ultrafast imaging



- **Streak camera, fastest direct imaging devices, with picosecond temporal resolution**
- **Time gated Intensified camera with hundreds picosecond temporal resolution**
  - ➔ Instantaneous sample rate : 1 Peta Sample/s
  - ➔ Physical accumulation and storage on phosphorus screen

CMOS ultrafast imaging



- **Solid state streak camera, with sub-nanosecond temporal resolution. Miniaturization of the vacuum tube technologies**
- **Ultra fast 2D burst video sensor with mega frames per second**
  - ➔ Instantaneous sample rate : 1 Tera Sample/s
  - ➔ Physical accumulation and storage on chip
- **Fully integrated time correlated single photon counting system**

- Solid state ultrafast imaging is young and very promising …

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Contact

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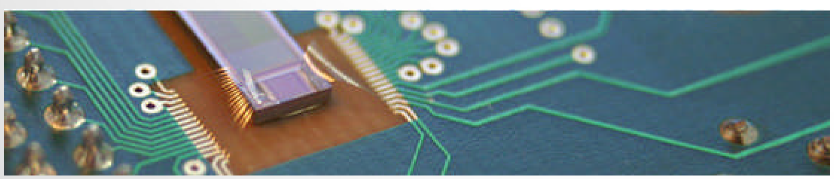
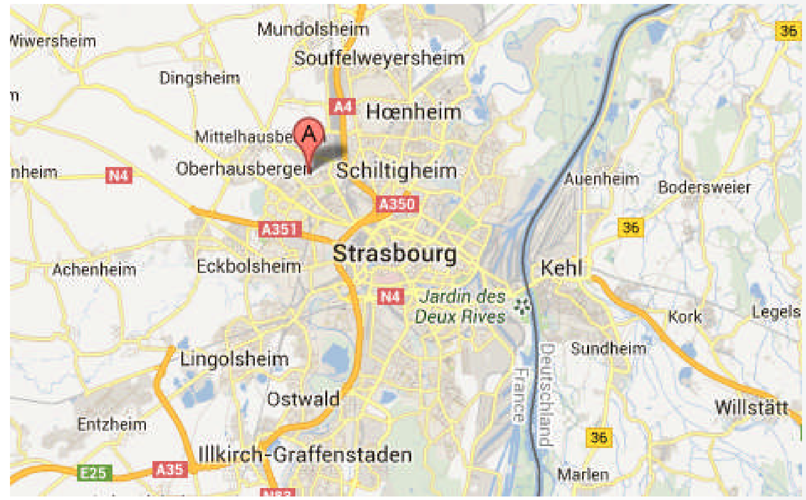
Icube SMH (Heterogeneous Systems and Microsystem) team member.





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