Wir schaffen Wissen – heute für morgen

Gemma Tinti on behalf of the SLS Detector Group

Hybrid pixel detectors for photon science at synchrotrons and FELs

RD51 meeting

10 June 2015

Outline

- Synchrotrons (SwissLightSource as example) and typical experiments
- FELs (Swiss-FEL as example)

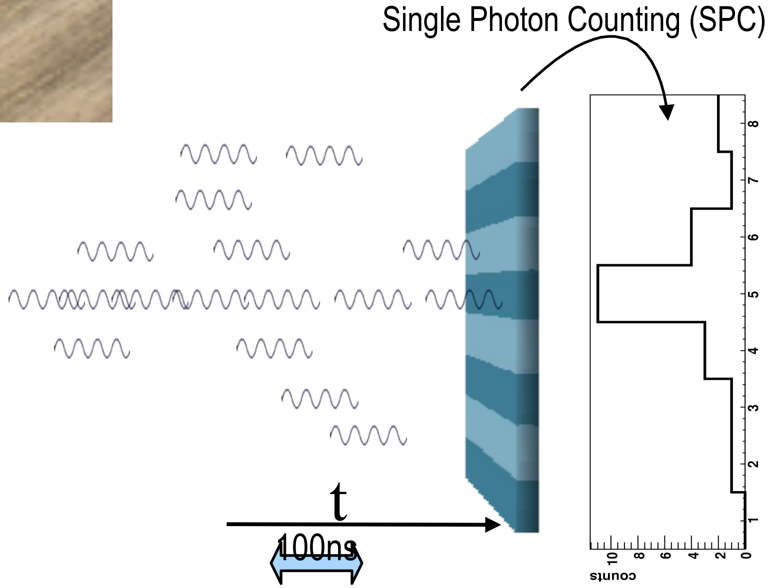
- Requirements for detectors
- Development of hybrid pixel detectors at PSI

- Outlook on upgrades of machines and requirements for future detectors

The Swiss Light Source

288 m circumference

Xrays 3 eV – 45 keV

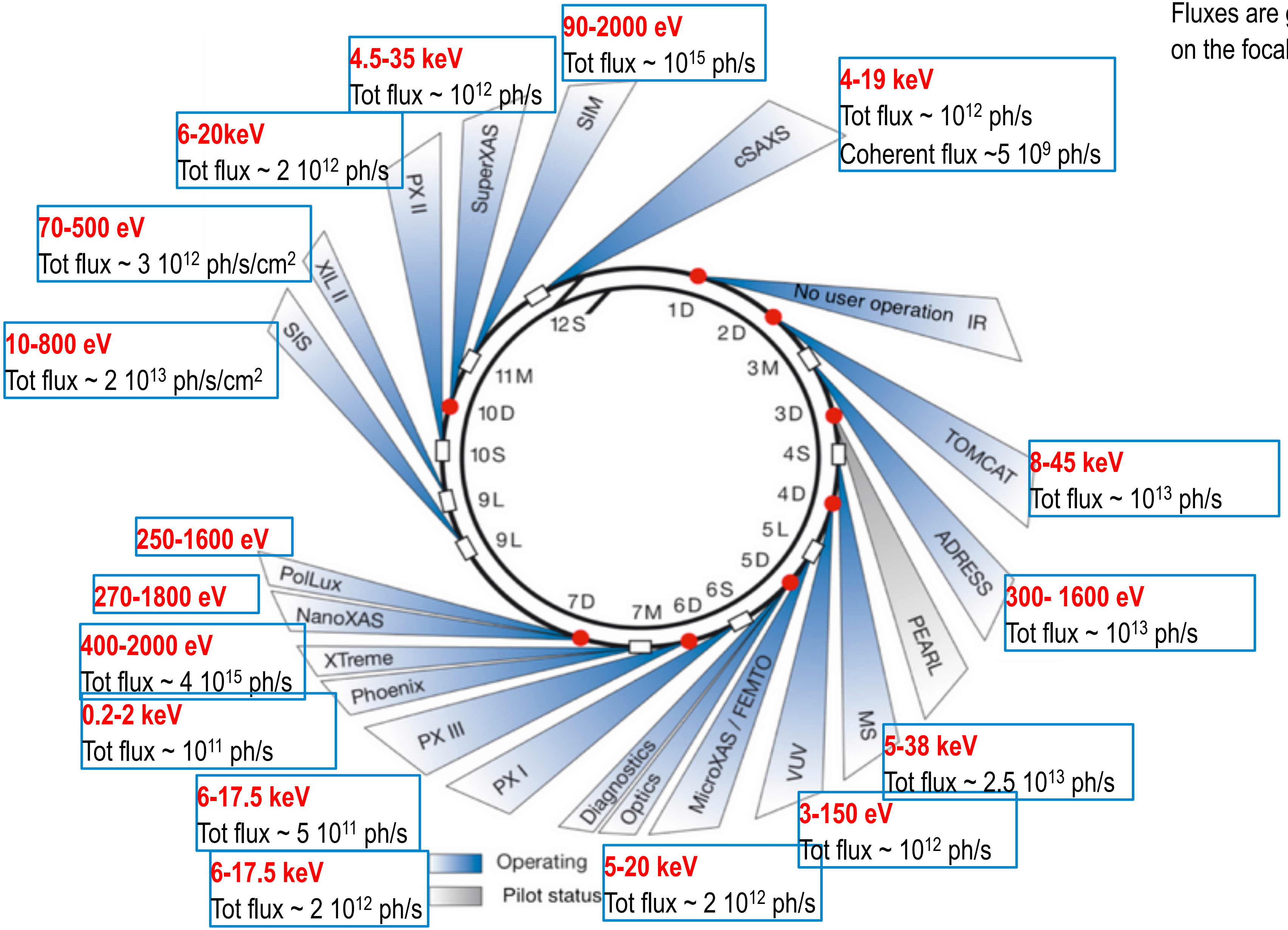


Synchrotron source:

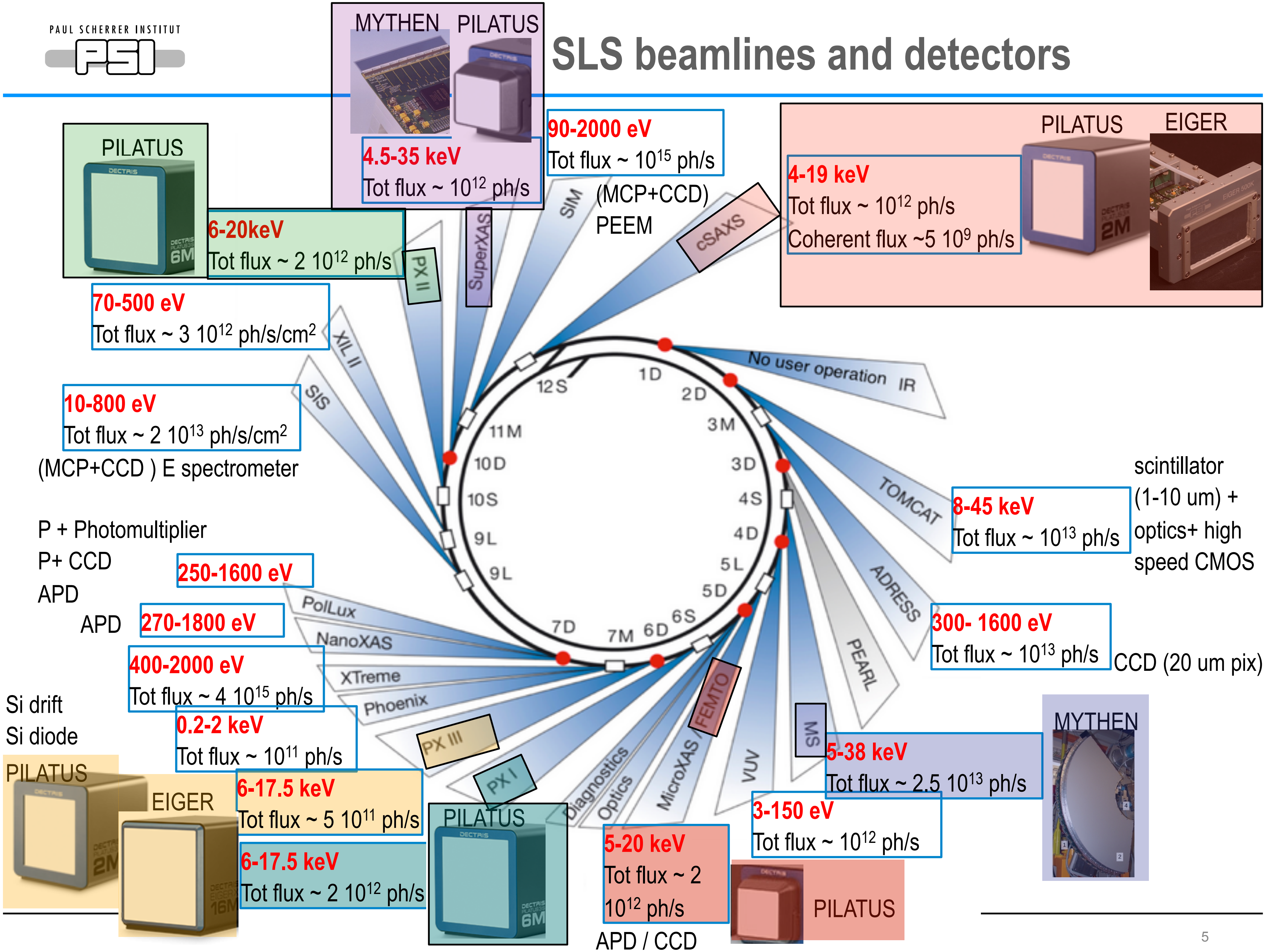
- Huge number of "weak" photon bunches (a bunch every 2 ns)
- Bunch length is 20 ps
- Photons impinge on the detector with a semi-continuous time distribution

SLS beamlines

Fluxes are given on the focal spot

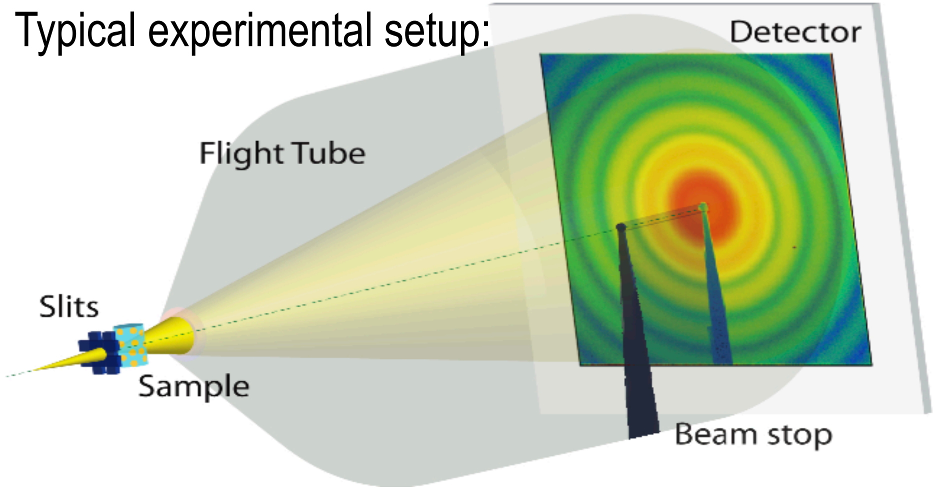


SLS beamlines and detectors



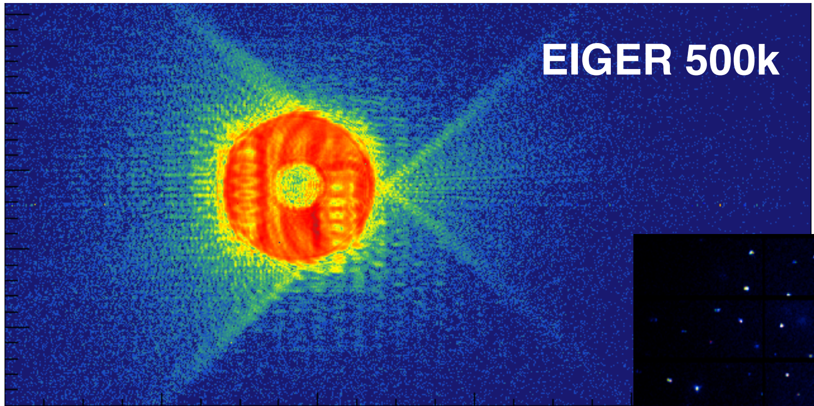
Diffraction experiments at synchrotrons

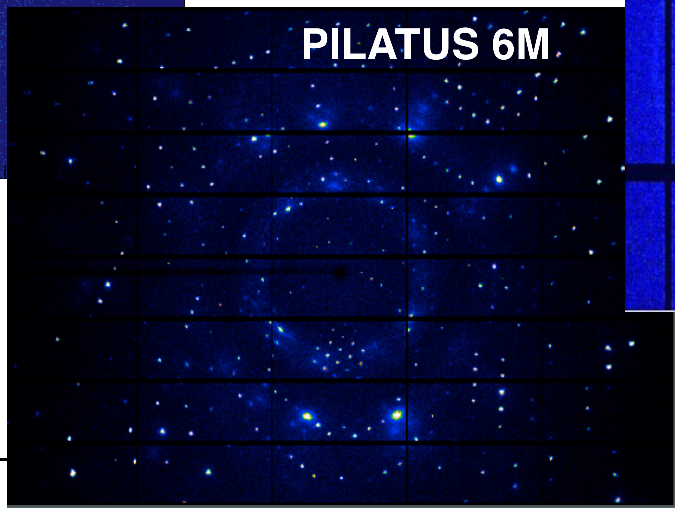
Typical experimental setup:

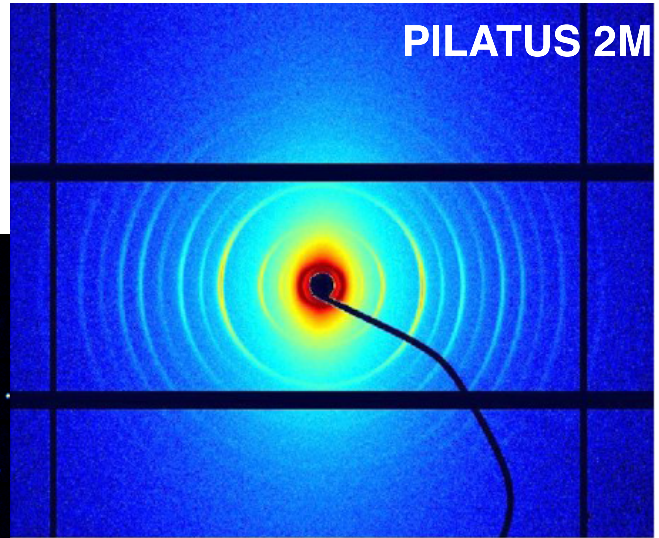


Typical applications:

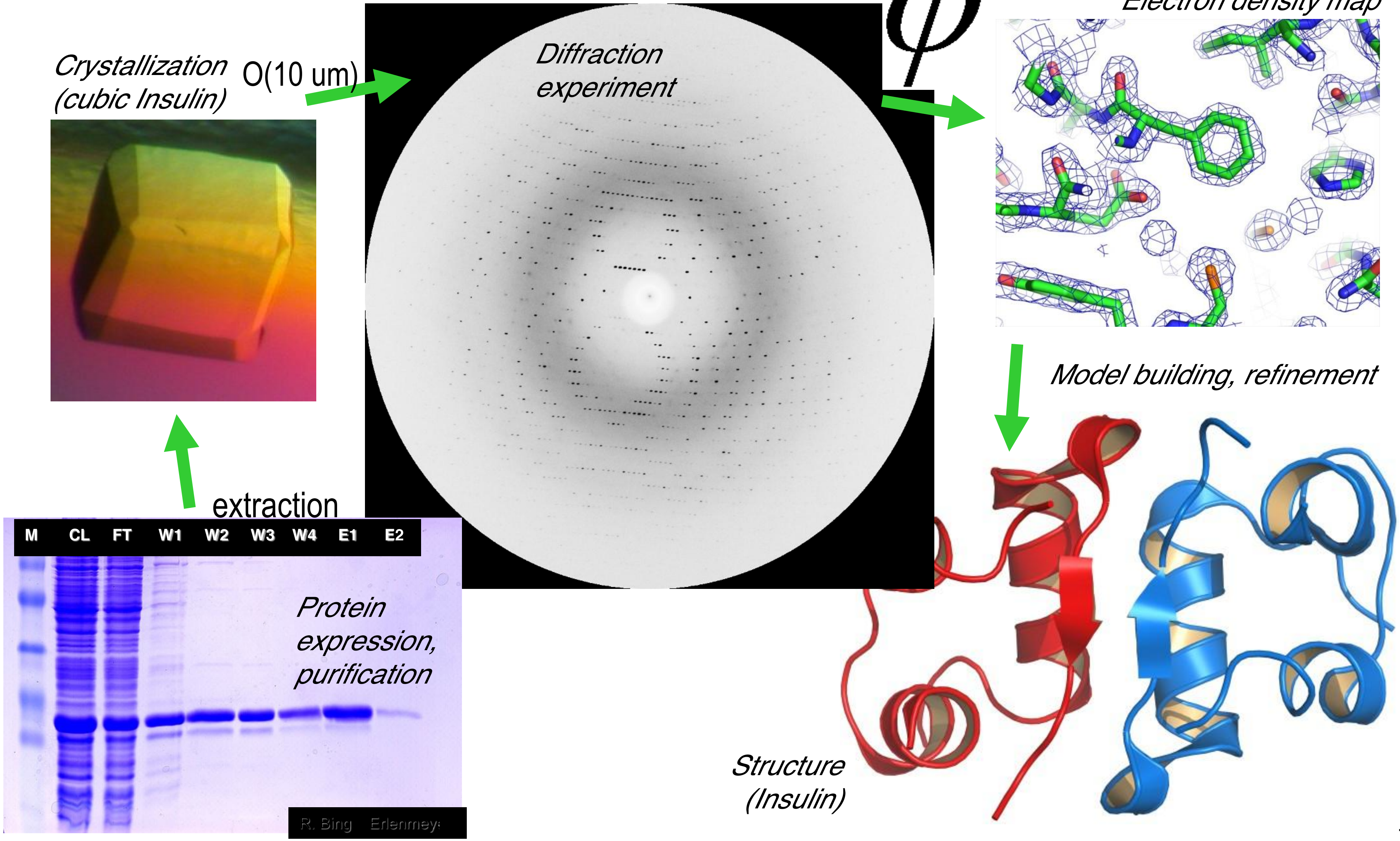
- Coherent Diffractive Imaging (CDI)
- Small Angle X-ray Scattering (SAXS)
- Scanning SAXS
- Protein Crystallography
- X-ray Photon Correlation Spectroscopy (XPCS)







From protein to structure



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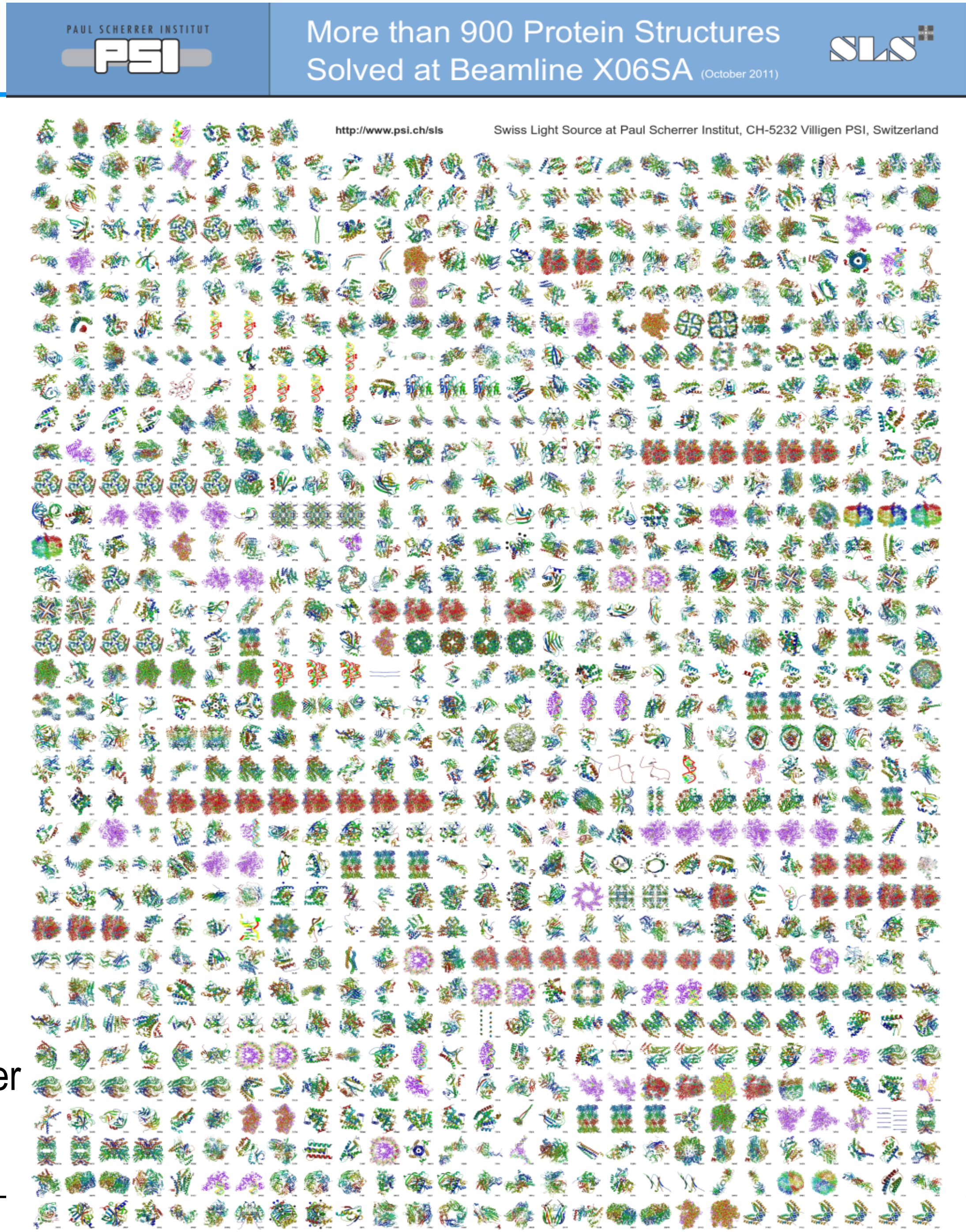
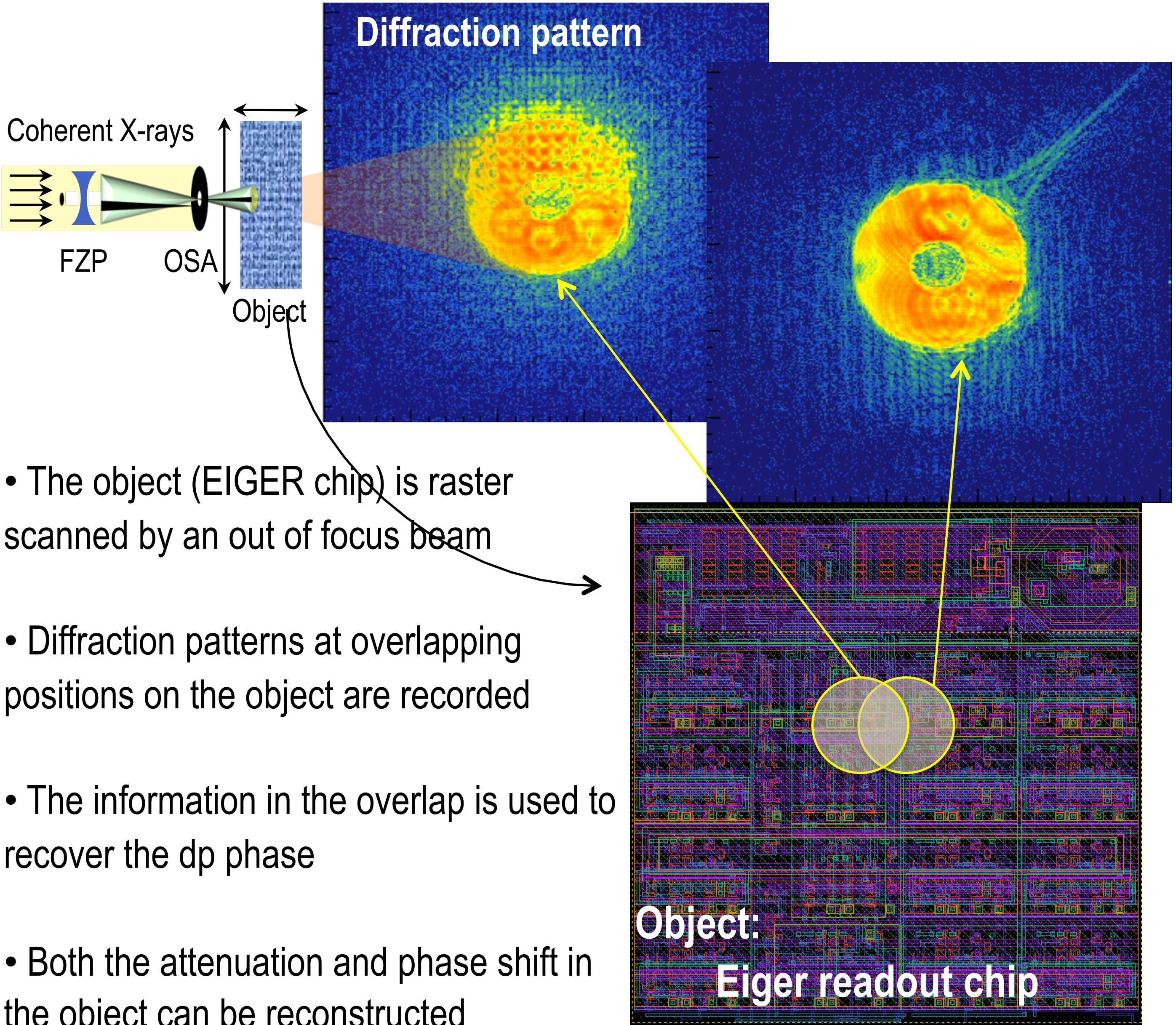


more than 900 protein structures solved at PXI beamline at SLS

~2/3 using Pilatus II 6M

compiled by Sandro Waltersperger
Oct 2011

Ptychography – Coherent imaging

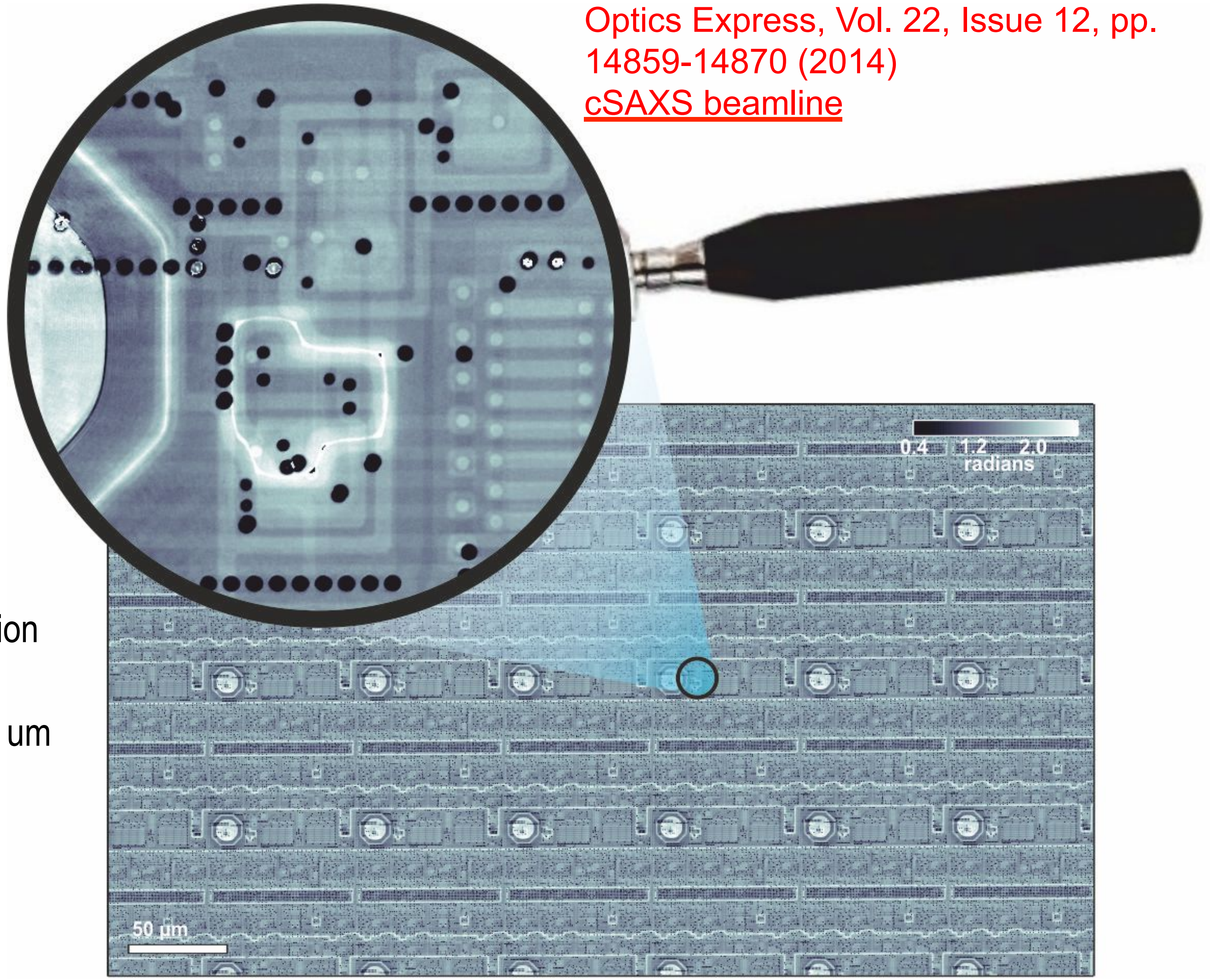


- The object (EIGER chip) is raster scanned by an out of focus beam
- Diffraction patterns at overlapping positions on the object are recorded
- The information in the overlap is used to recover the dp phase
- Both the attenuation and phase shift in the object can be reconstructed

- Achieves imaging resolution of ~10 nm
- Can be combined with CT for 3D imaging

Large area, high resolution Ptychography

Optics Express, Vol. 22, Issue 12, pp. 14859-14870 (2014)
cSAXS beamline



- 45 nm resolution
- Large area:
  500 um x 290 um

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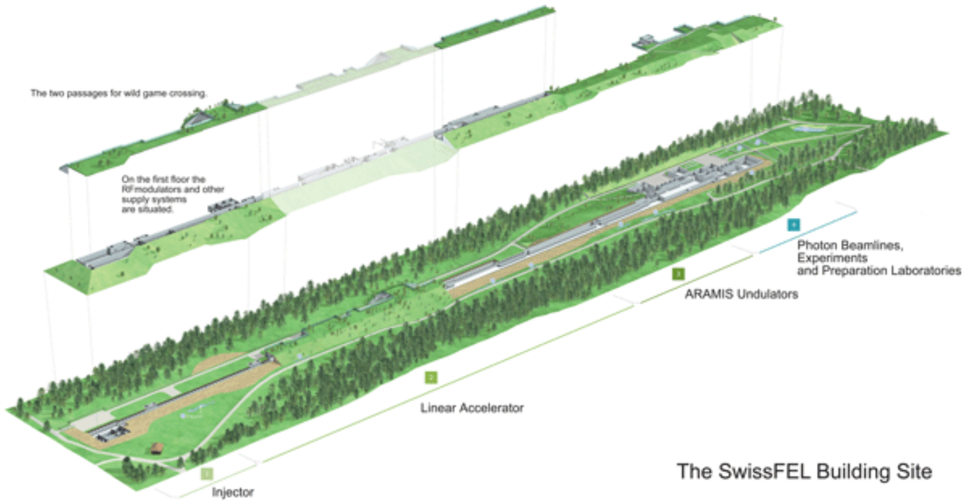
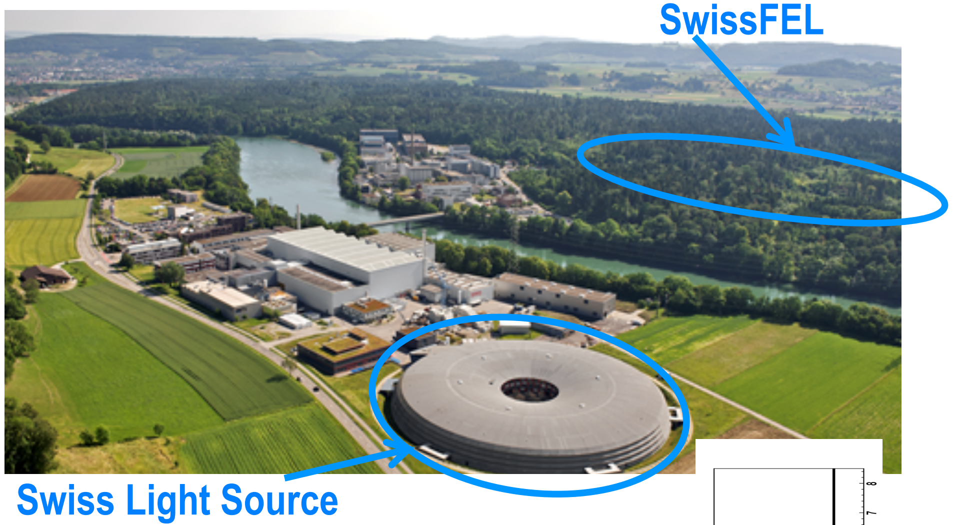
SwissFEL: New generation X-ray free electron laser

Light expected to users in 2016

Xrays 1.77 - 12.4 keV (7 to 1 Å)

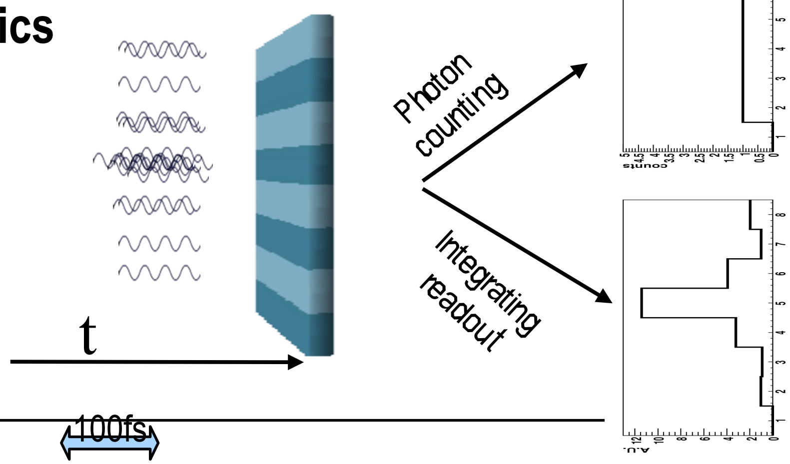
- 100 Hz repetition rate in two bunch charge modes (10 and 200 pC)
- 1.8 to 21 fs pulse lengths
- Pulse energies between 10 and 200 µJ → ≤ 10^{11} photons/pulse





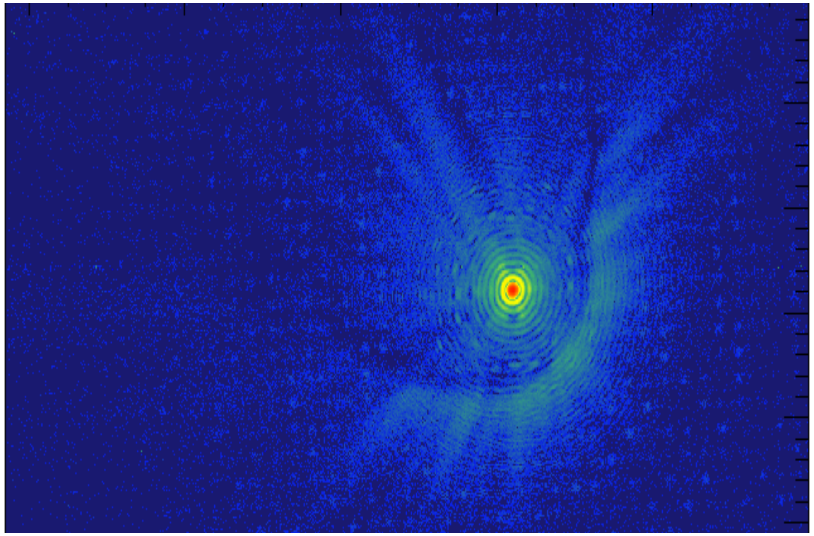
Higher brilliance than synchrotron and faster dynamics

FEL:
- Fewer intense bunches
- All photons in the bunch coming at once
- High number of particles/channel per bunch



Requirements for X-ray detectors at synchrotrons and FELs

- Energy range: 2 - 40 keV (@ SLS and SwissFEL), up to 150 keV (ESRF/Spring 8)
- Single photon sensitivity: noise << signal ~ O(100 e^-)
- Sufficient angular coverage: large area (40 x 40 cm^2)
- Spatial resolution: millions of pixels (75 x 75 um^2)
- High frame rates: Tens of kHz
- Ability to gate or synchronization to experimental machines



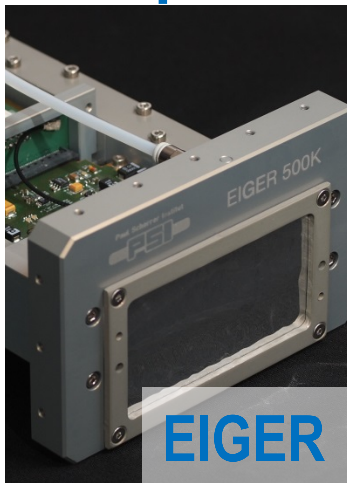
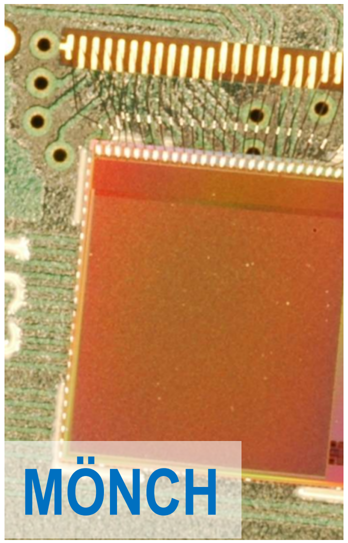
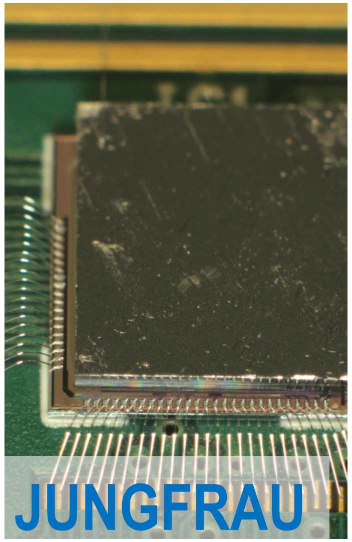
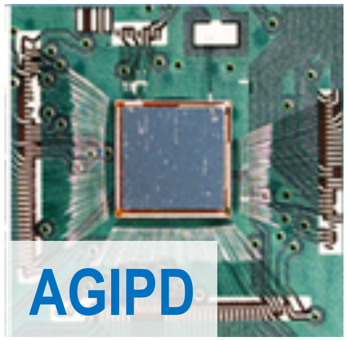
Synchrotrons:

- High count rate capability: count rates 1 MHz/pixel

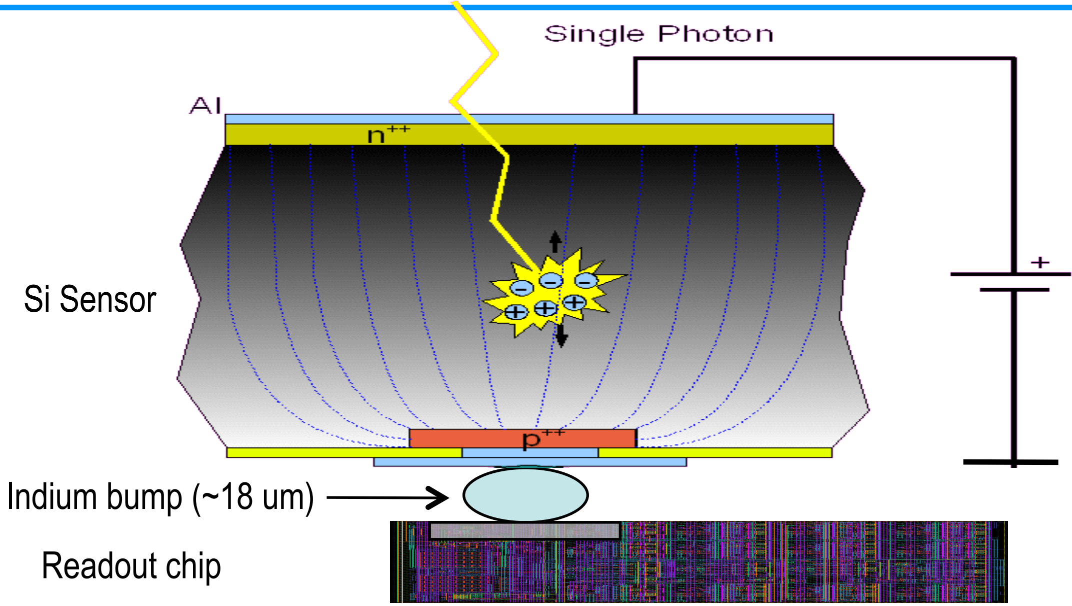
FELs:

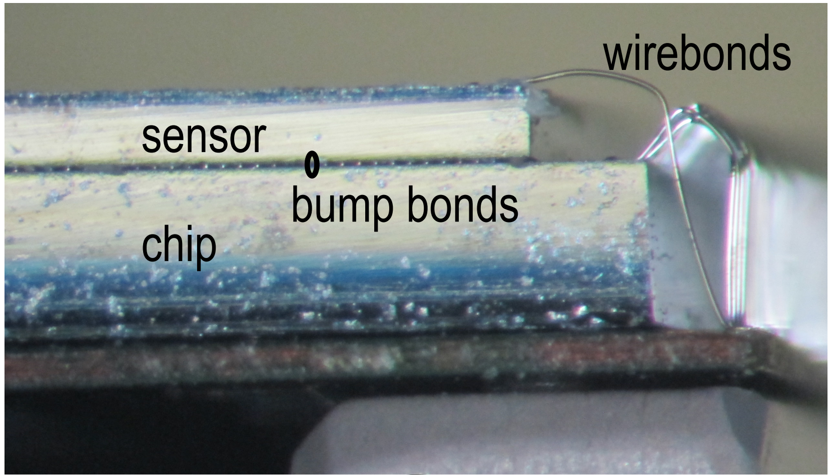
- High dynamic range: 10^4 12 keV photons/pixel/pulse

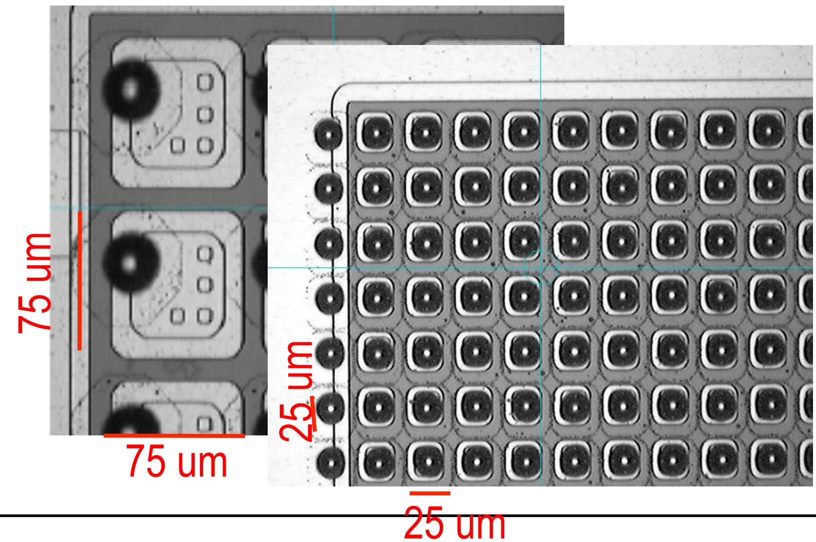
Swiss Light Source Detectors

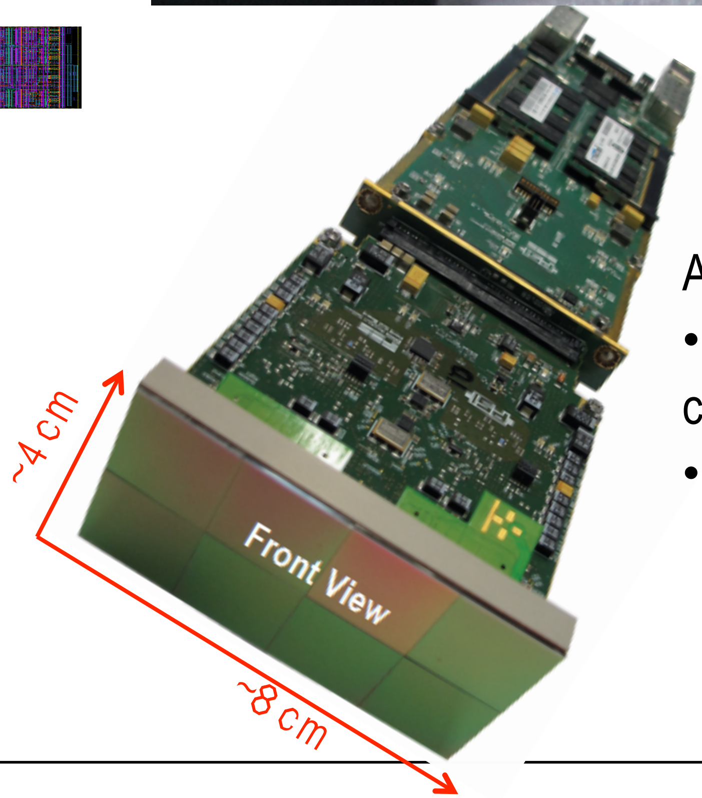
	Microstrips 50 um	Pixels 25 µm	Pixels 75 µm	Pixels ~200 µm
Single Photon Counting	 MYTHEN	✗	 EIGER	 PILATUS (DECTRIS)
Charge Integrating	 GOTTHARD	 MÖNCH	 JUNGFRAU	 AGIPD

Hybrid pixel detectors









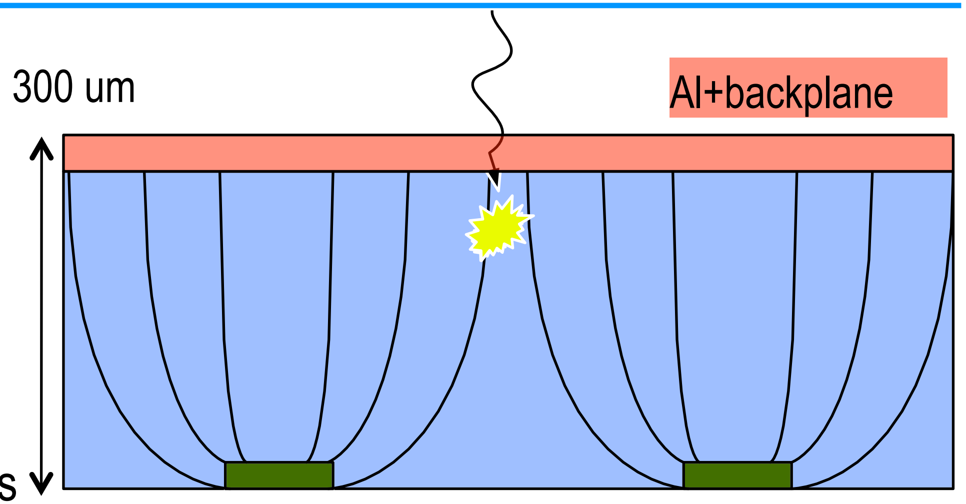
EIGER

A module:

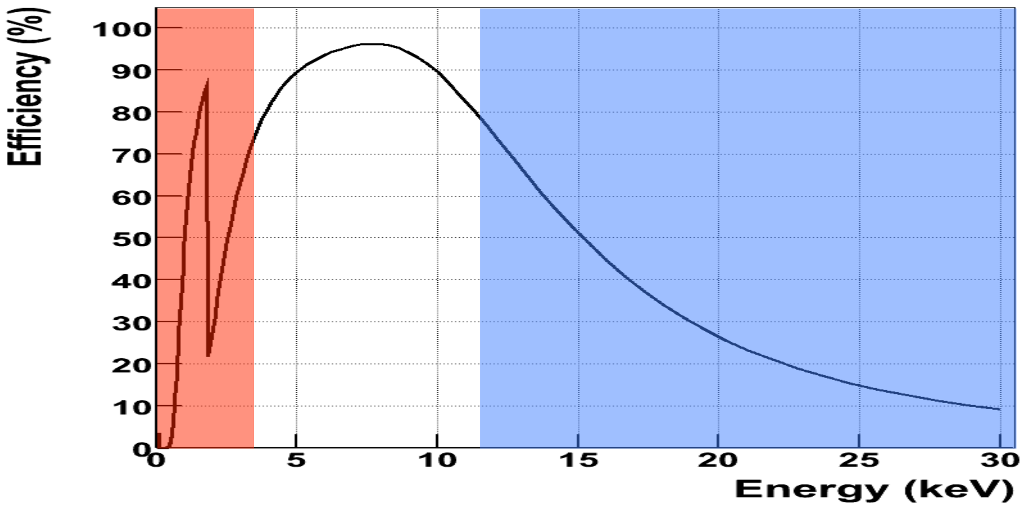
- many (8) chips
- 1 sensor

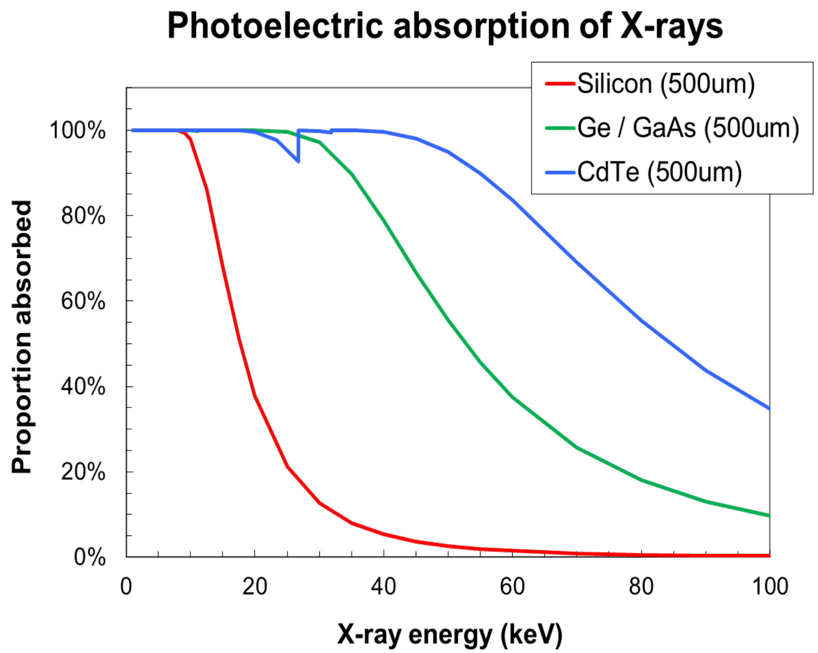
Sensor: Si and high Z materials

- Absorption of the X-rays in sensor: mainly photoelectric effect (<40 keV), 'pointlike'
- The energy is converted into electric charge
- About 3.6 eV to generate an e-h pair in silicon
- Signal is 1000 e^- for 3.6 keV photons
- Study of high Z materials (CdTe, GaAs) to extend the quantum efficiency at higher energies

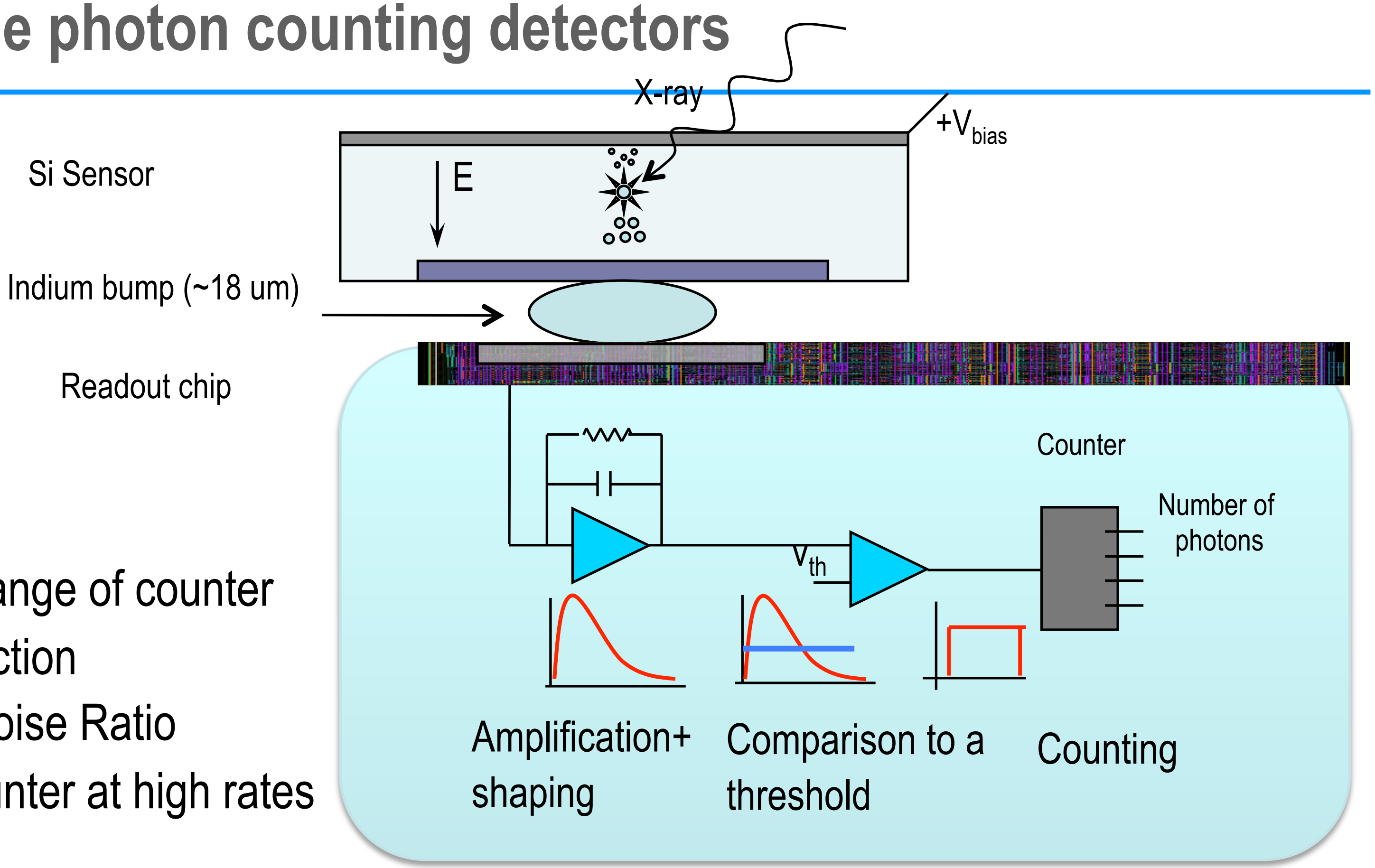


Standard silicon sensors:
300um thick, 2um backplane





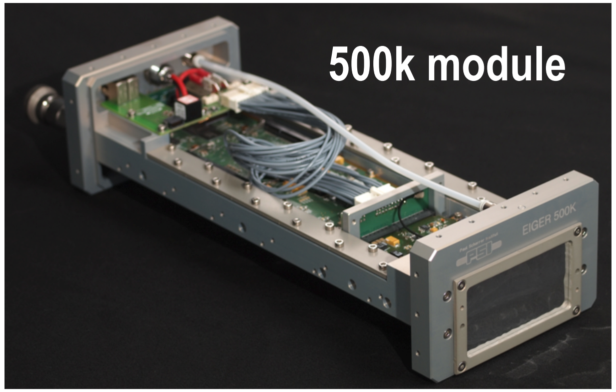
Single photon counting detectors

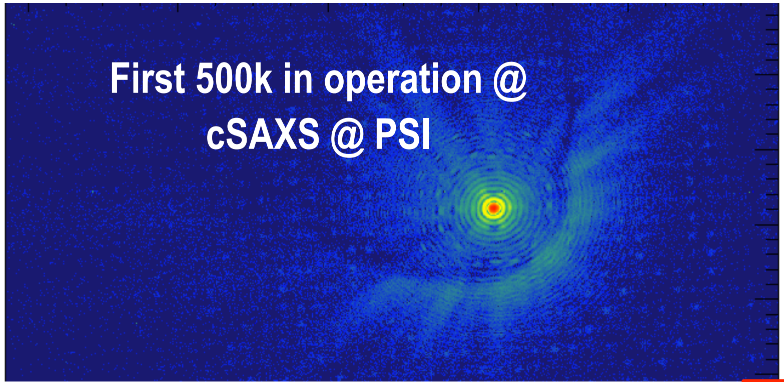


- Advantages:
  - Large dynamic range of counter
  - Background rejection
  - Ideal Signal to Noise Ratio
  - Gating of the counter at high rates
- Disadvantages:
  - Pile-up for high photon intensities
  - Minimum pixel size due to charge sharing between pixels
  - Minimum detectable energy

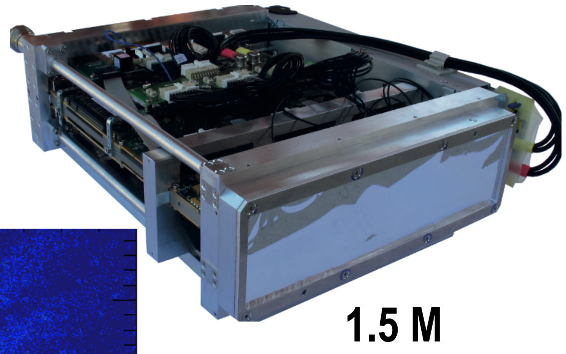
EIGER systems

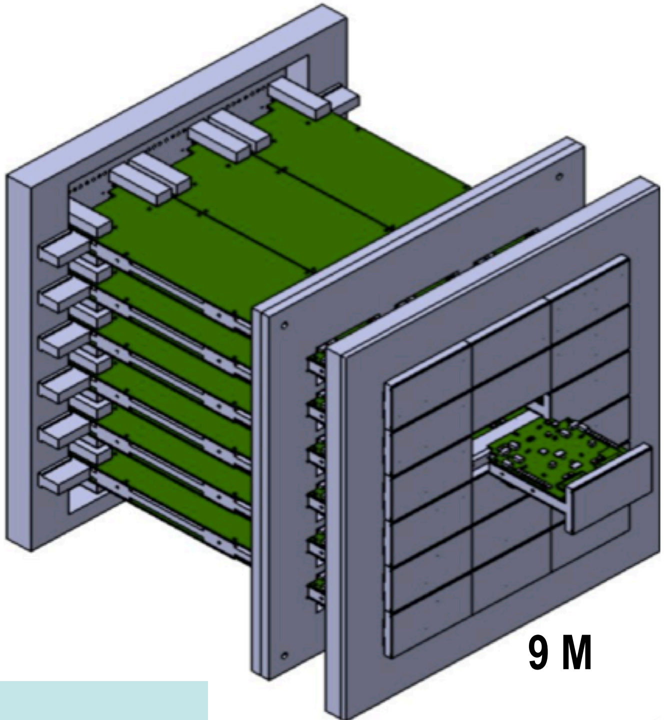
75 x 75 um^2 pixel size





Multi-module detectors





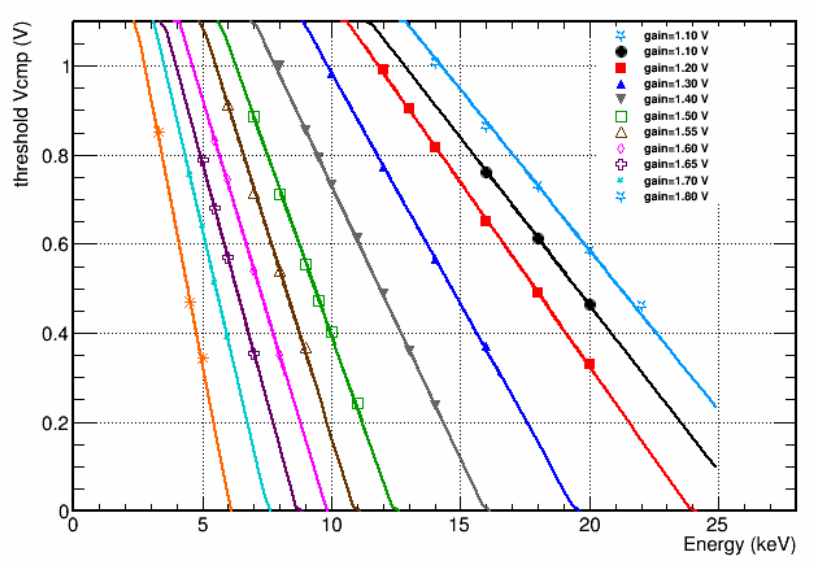
Tradeoff between frame rate and counter dynamic range

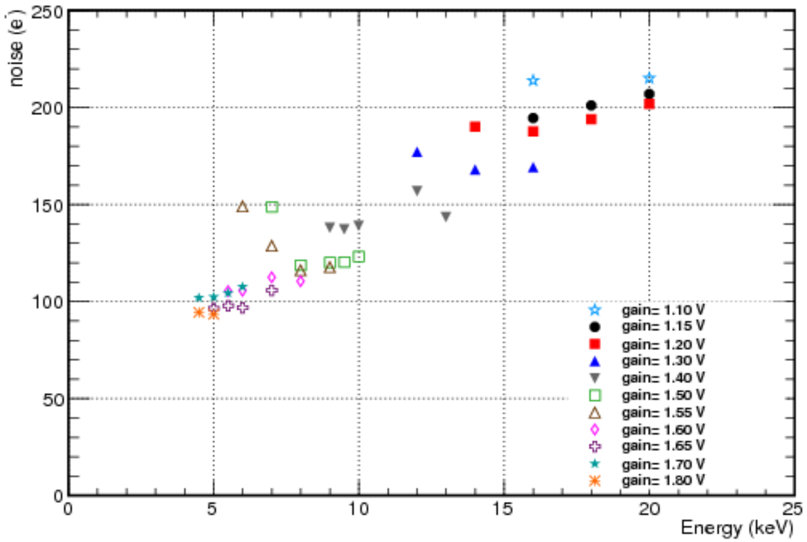
	Pixel array	Size	Frame rate @ 4b	Frame rate @ 8b	Frame rate @ 12b	Data rate @ 100Hz[1]
Module	512 x 1024	38x77 mm^2	23 kHz	12 kHz	8kHz	419 Mb/s
1.5M	512 x 3072	38x238 mm^2	23 kHz	12kHz	8kHz	1.26 Gb/s
9M	3072 x 3072	233x238 mm^2	23 kHz	12 kHz	8kHz	7.55 Gb/s

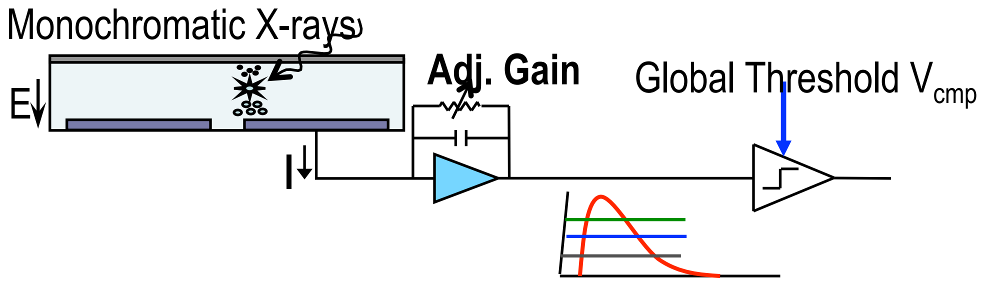
- Almost dead time free detector
- High frame rate independent on size
- Data rate grows with size

1) 8 bit

Threshold calibration and noise



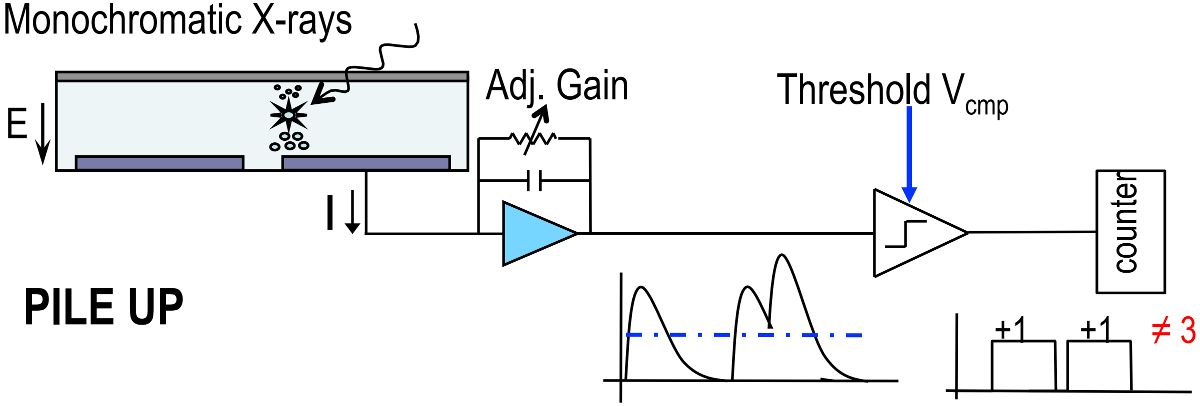


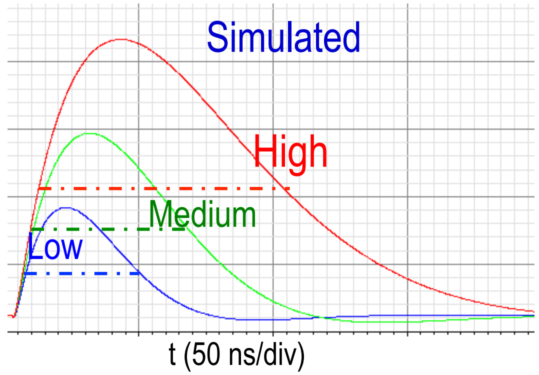


- The **preamplifier gain** in EIGER is user configurable to scan a different range of photon energies
- The **threshold setting** can be calibrated into photon energy
- Threshold is calibrated to be uniform in the detector and its dispersion is negligible (20 e^-) in respect to noise

- Noise decreases with higher pre-amp gain
- As the noise at high gain is ~100 e^-, we see photons >3 keV

Rate correction as a function of energy



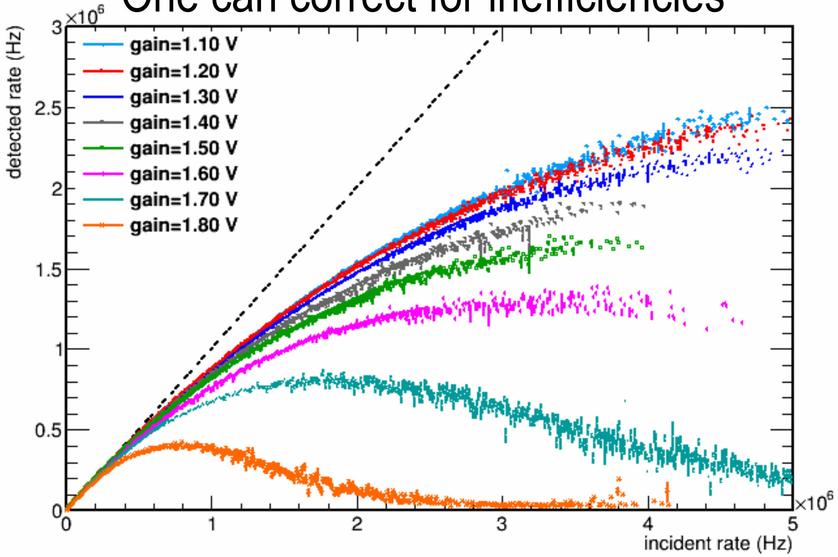


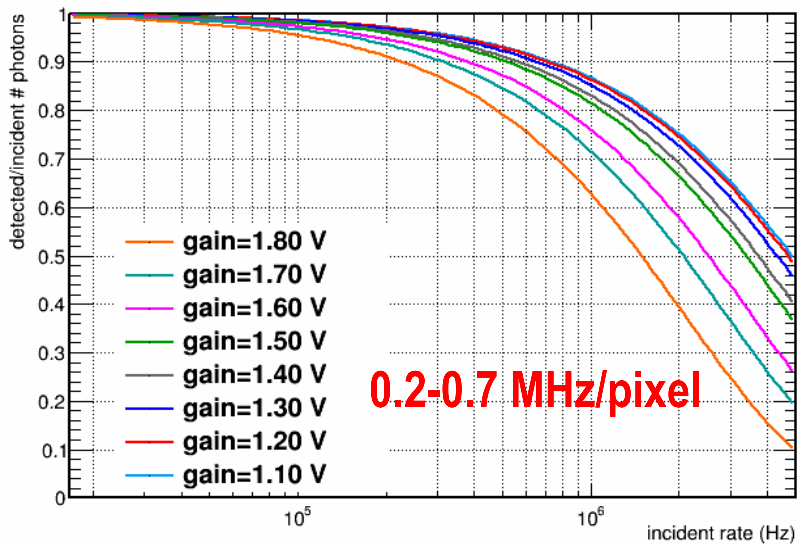
Paralizable counter model:

$$N_{det} = N_{inc} \cdot e^{-N_{inc} \cdot \tau}$$

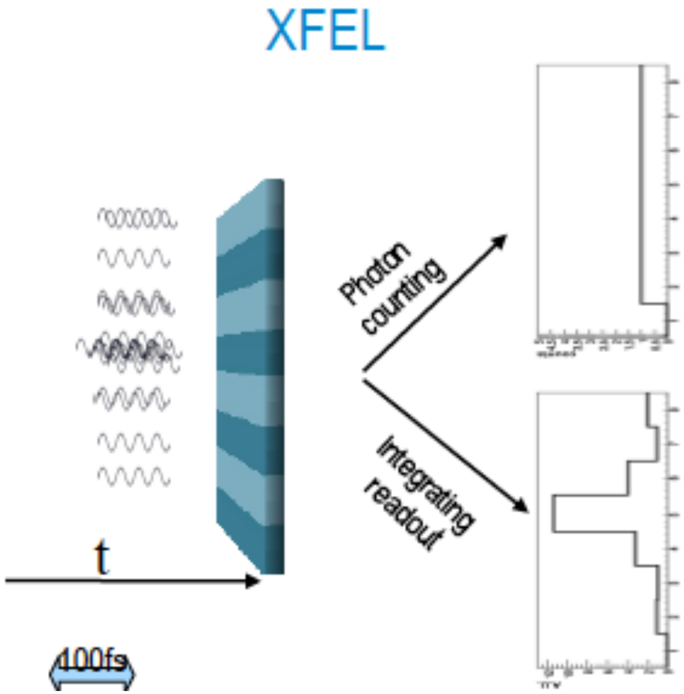
One can correct for inefficiencies

For the same energy, lower gain optimizes for rate capabilities

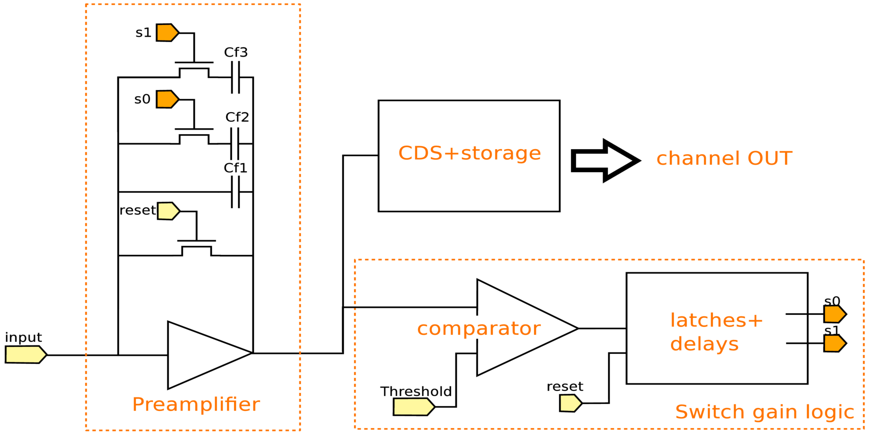


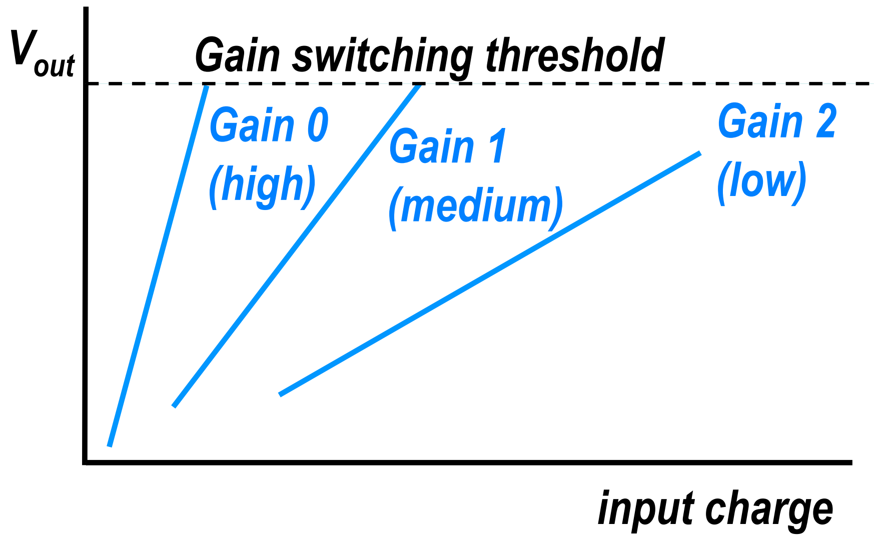


The future: charge integrating detectors for FELs



- Swiss-FEL will deliver 10^{11} photons/pulse in ~hundreds of fs
- Photon counters cannot be used
- Development of charge integrating detectors with charge information
- For the detector the main challenges are:
  - Single photon resolution
  - Dynamic range of 10^4 photons
- In exposure 'dynamic gain switching' is the solution





JUNGFRAU at ESA @ SwissFEL

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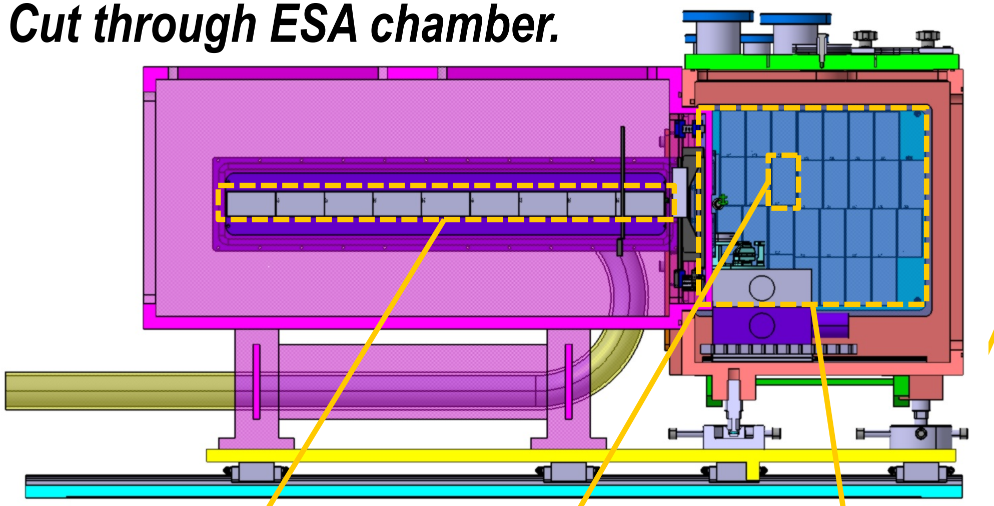
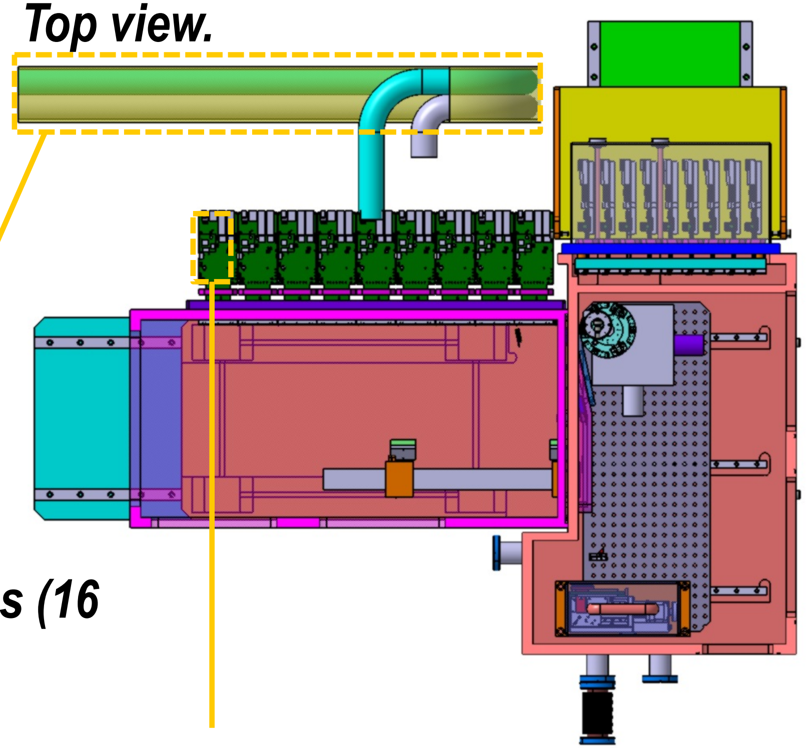
Cut through ESA chamber.



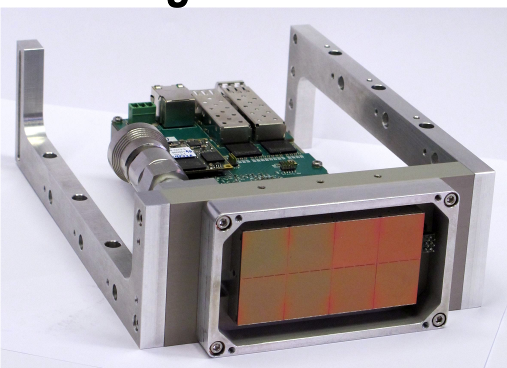
Top view.



9 JUNGFRAU modules (4.5 Mpixel).

32 JUNGFRAU modules (16 Mpixel).

Single module.



Detector infrastructure:
Power, cooling, data, controls.

Readout board.

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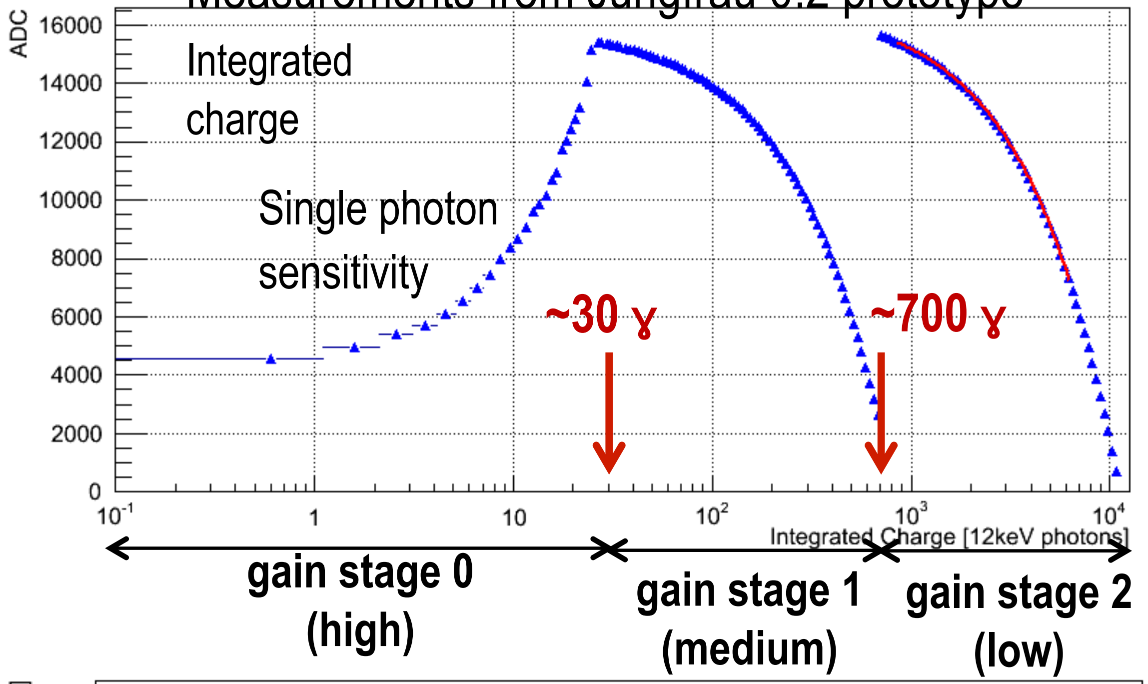
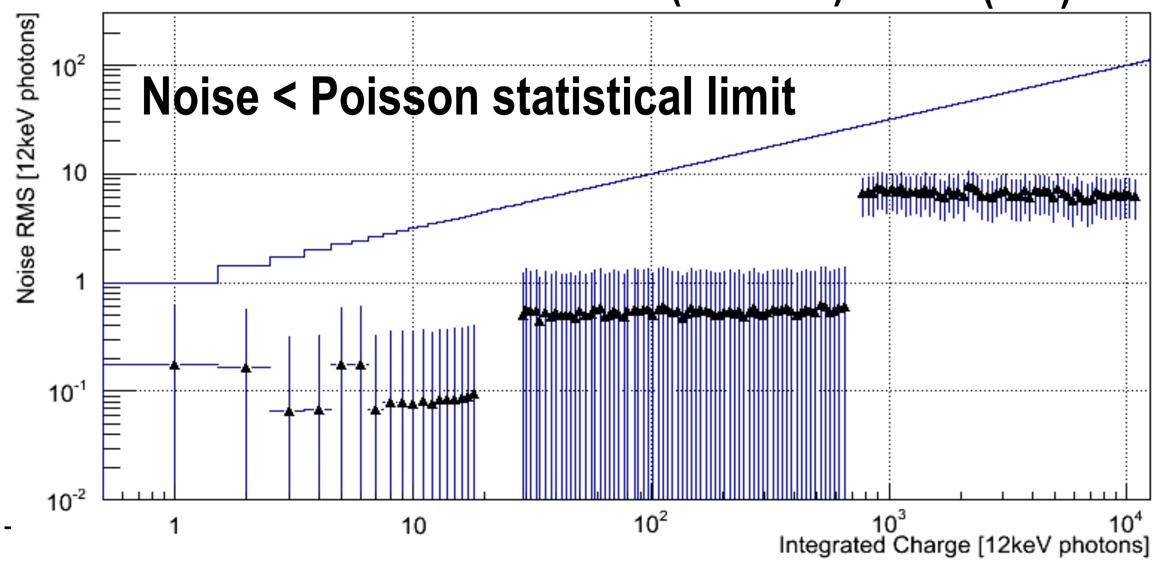
JUNGFRAU

J.H. Jungmann-Smith et al, JINST 9, P12013

Measurements from Jungfrau 0.2 prototype





Detector returns the charge info (ADC) and the gain used

Automatic gain switching:

- White visible light illumination
- Increasing integration time

→ Covers ***dynamic range*** of ***> 4 orders of magnitude*** !

Calibration of the **integrated charge vs number of photons** needs to be studied and applied

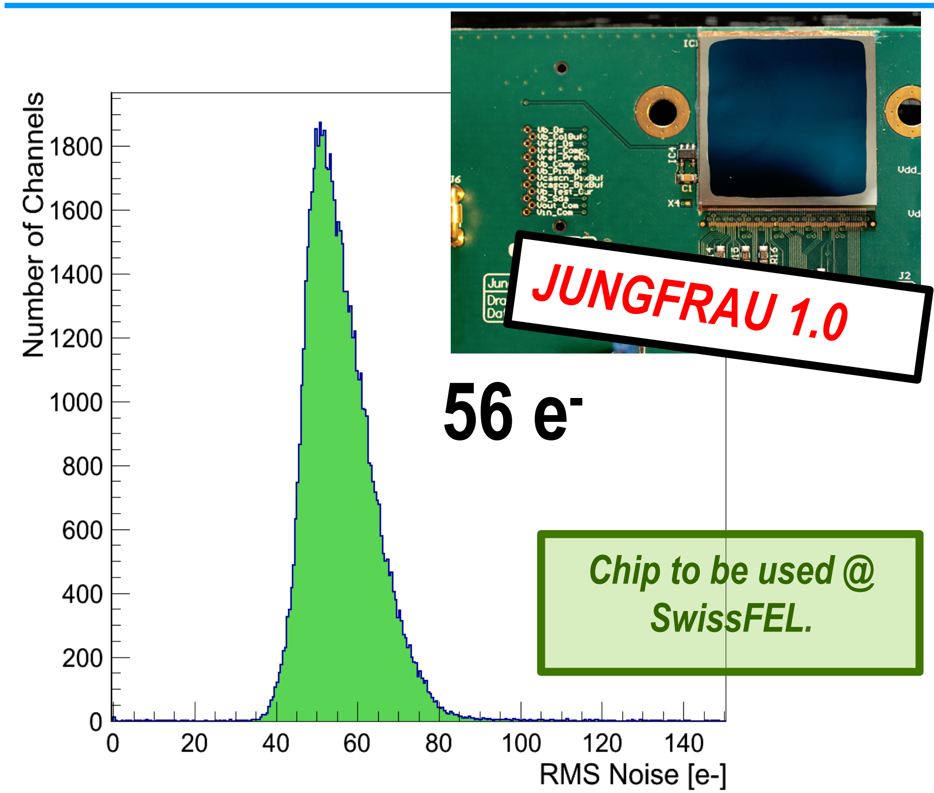
Targeted **frame rate** of **2 kHz**:

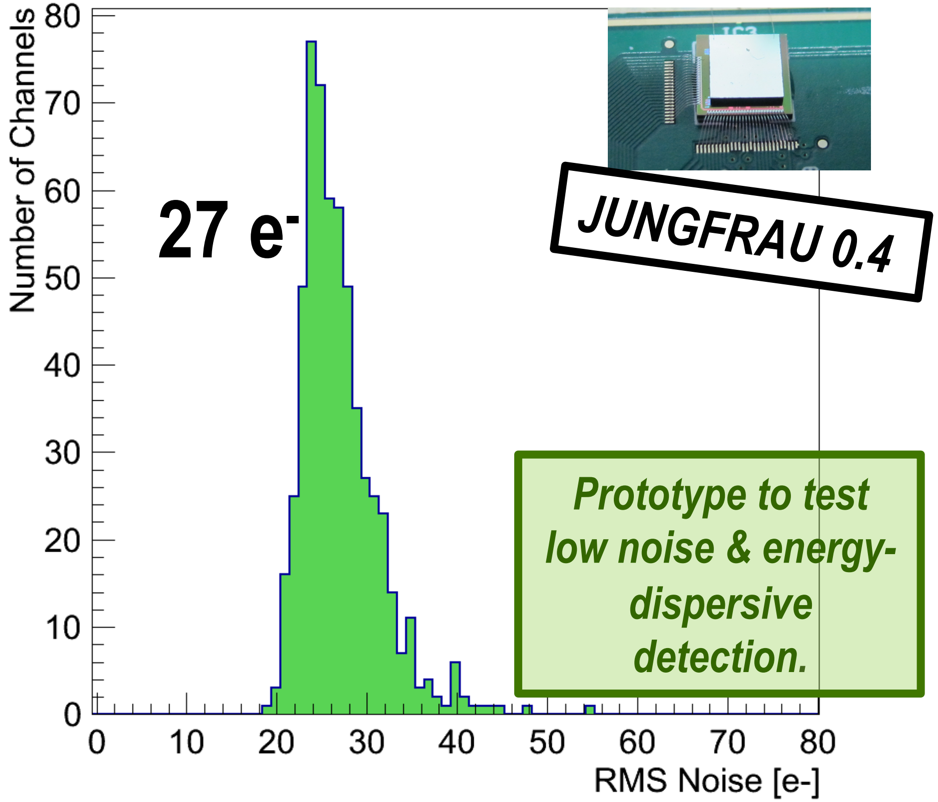
Count rate of 20 MHz/pixel

Factor 20 better than EIGER!

Use at synchrotrons is under study!

Noise of JUNGFRAU

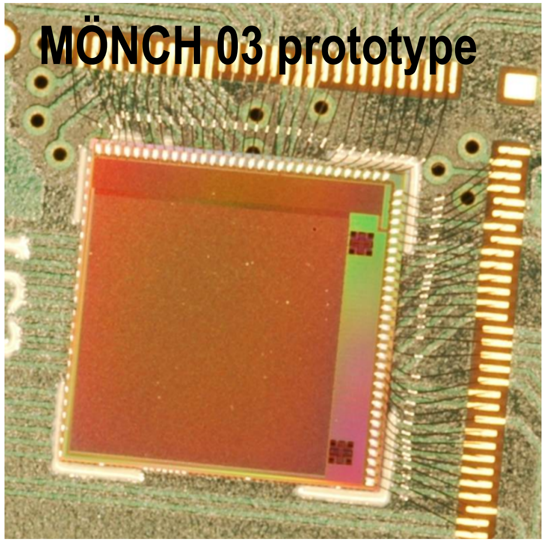




	JUNGFRAU 0.4	JUNGFRAU 1.0
RMS Noise [e-]	27	56
RMS Noise [eV]	< 100	< 210
5σ RMS Noise [eV]	< 500	< 1050

- SwissFEL will provide Xrays with energy as low as 2 keV
- Extend the use of hybrid pixel detectors to lower photon energies

Small pixels: the MÖNCH detector

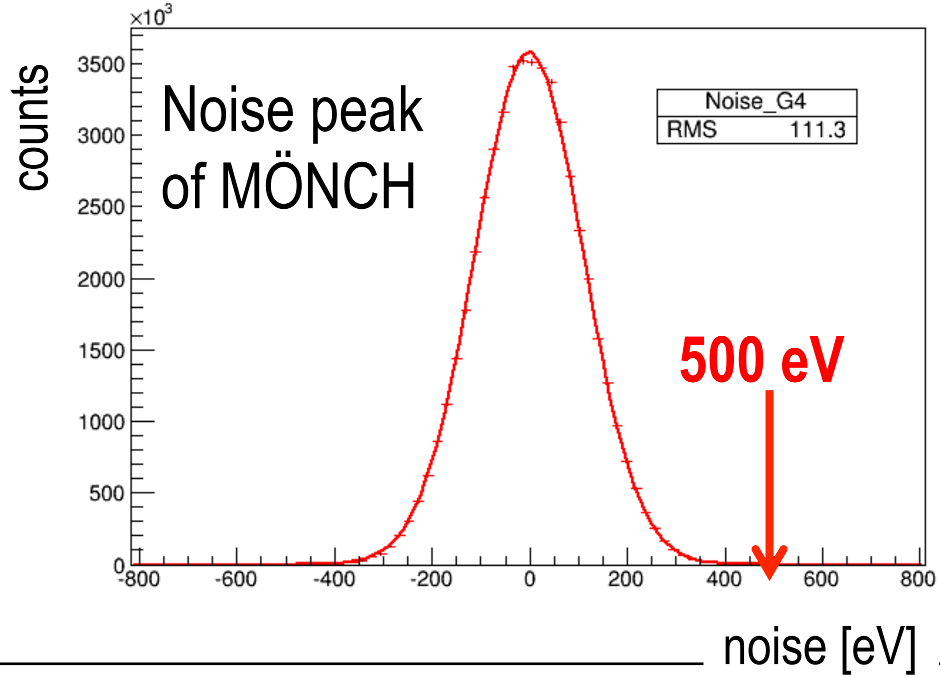


- 25 x 25 um^2 pixel size
- Active area: 4x4 mm^2
- 160 x160 pixels

- Active area 1x1 cm^2
- 400 x 400 pixels
- Frame rate foreseen up to 6 kHz

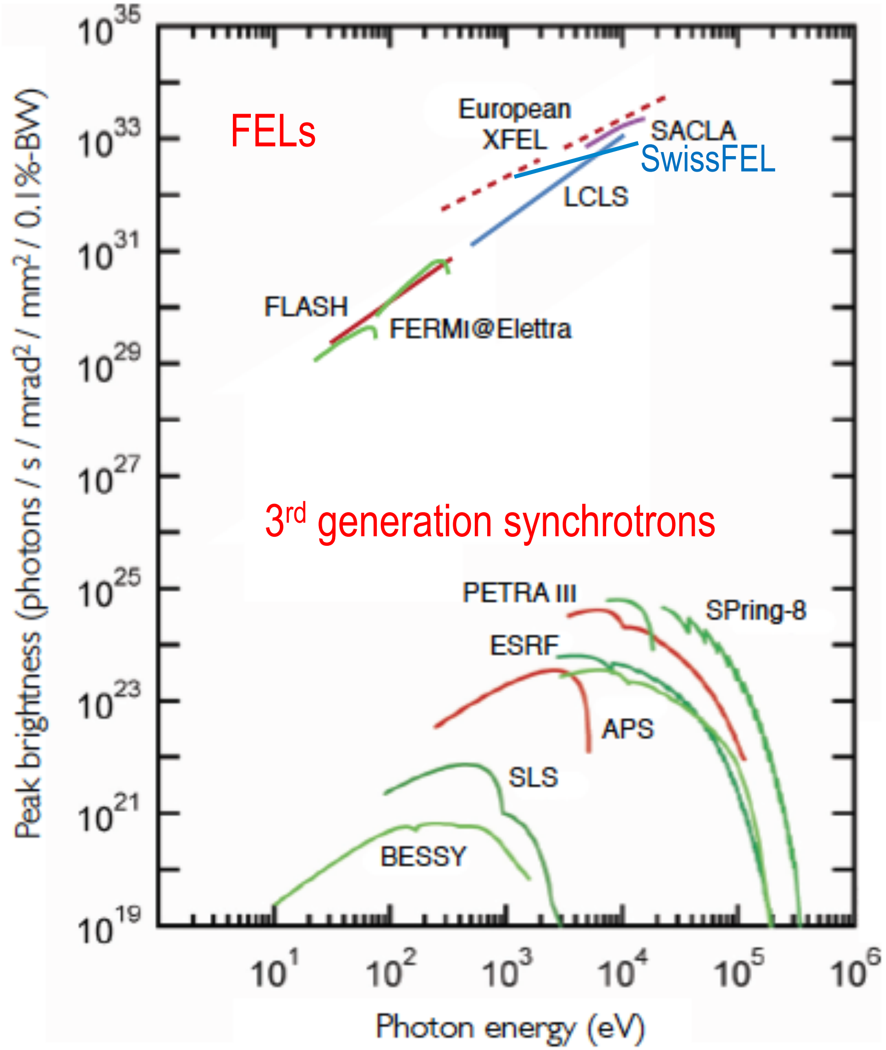
- Goal 2 x 3 cm^2 chip

- Smallest pixel size of hybrid pix detectors: bump bonding yield is >99.9%
- Low noise detector 30 e^- noise RMS : minimum photon energy 500 eV!
- Plan larger systems as a low energy detector
- High spatial resolution: algorithm to exploit the charge shared between more pixels allow for 1um spatial resolution

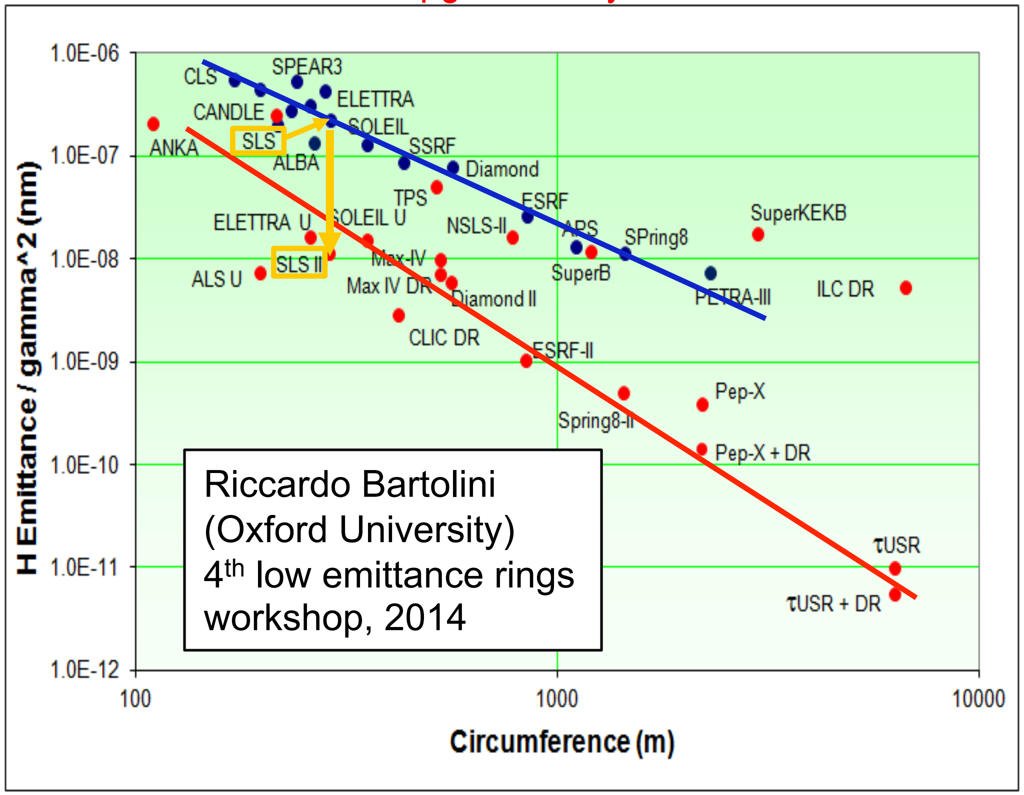


Perspective for the future accelerators

FELs are getting into operation now and plans to upgrade many synchrotrons to diffraction limited light sources:



Upgrade at synchrotrons:



- A factor 10-100 lower horizontal emittance
- MAX IV (2015), SIRIUS (2016), ESRF-2 (2019), SLSII (>2021?) etc…

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Perspective for the future detectors

Applications like **ptychography** and **protein crystallography** are hungry for **brightness** and **coherence**

- High flux ptychography due to increased coherent flux-> higher rate capabilities (100-1000 MHz/pixel) needed for the detector.
- Protein crystallography beamlines will increase the flux O(10-100) by using a multilayer monochromator instead of Si monocrometor to allow higher flux PX -> higher rate capabilities needed for the detector.
- Study of dynamics -> deadtime free detector operation at very fast frame rates (50-100 kHz)
- Angular coverage and a good spatial resolution (when increasing the detector distance from the sample) will be needed -> large area detectors (49 Mpixels ~ 60 x 60 cm^2…).
- The coherent flux increase at some synchrotrons will be at higher photon energies -> high quantum efficiency up to 30/40 keV
- Spatial resolution is improved by smaller pixel sizes with interpolation of the charge shared between pixels ->replacement of CCDs with pixel detectors
- Development towards low energies (~0.5 keV) will be favored ->replacement of CCDs

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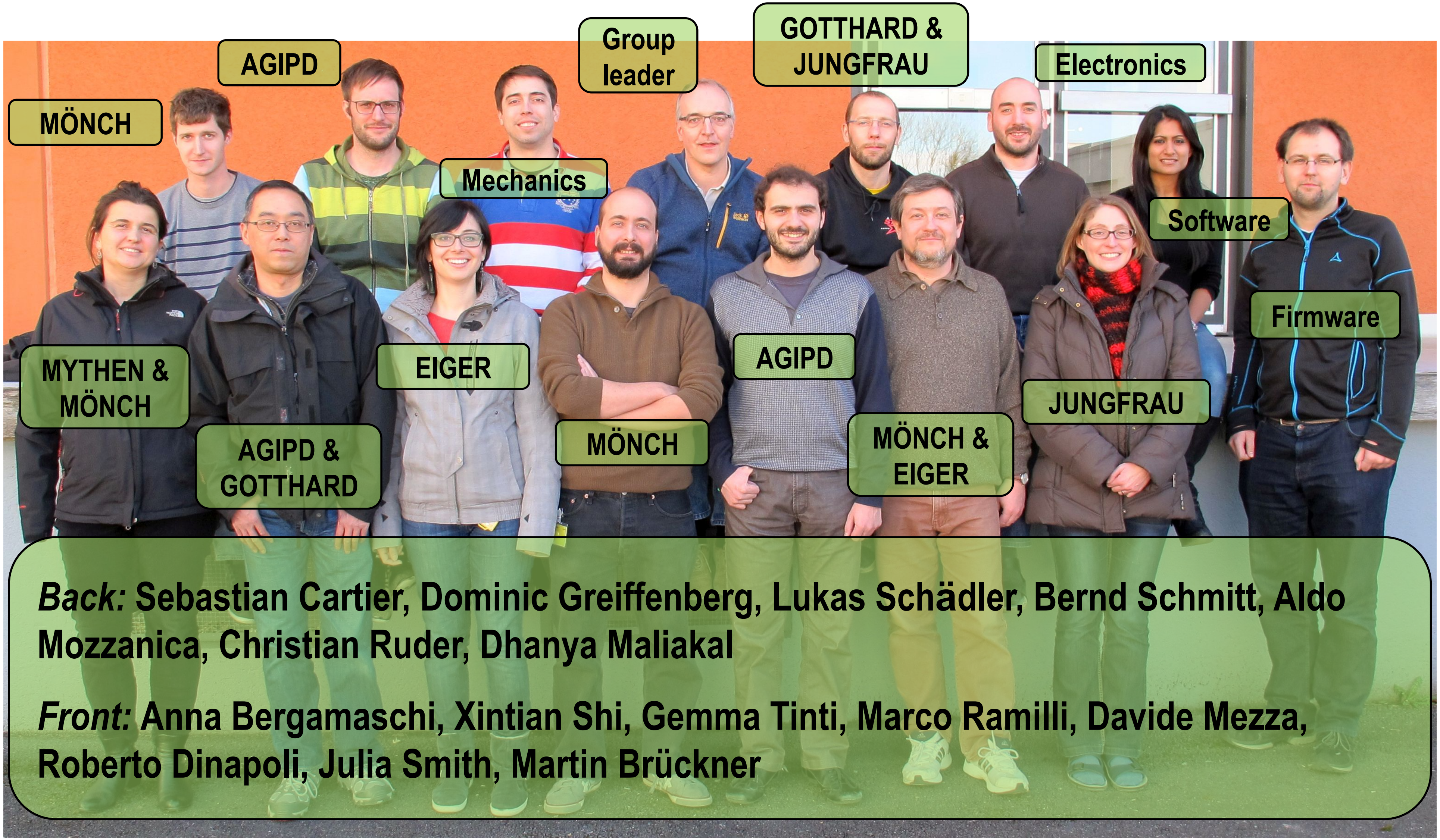
Swiss Light Source Detector Group



Back: Sebastian Cartier, Dominic Greiffenberg, Lukas Schädler, Bernd Schmitt, Aldo Mozzanica, Christian Ruder, Dhanya Maliakal

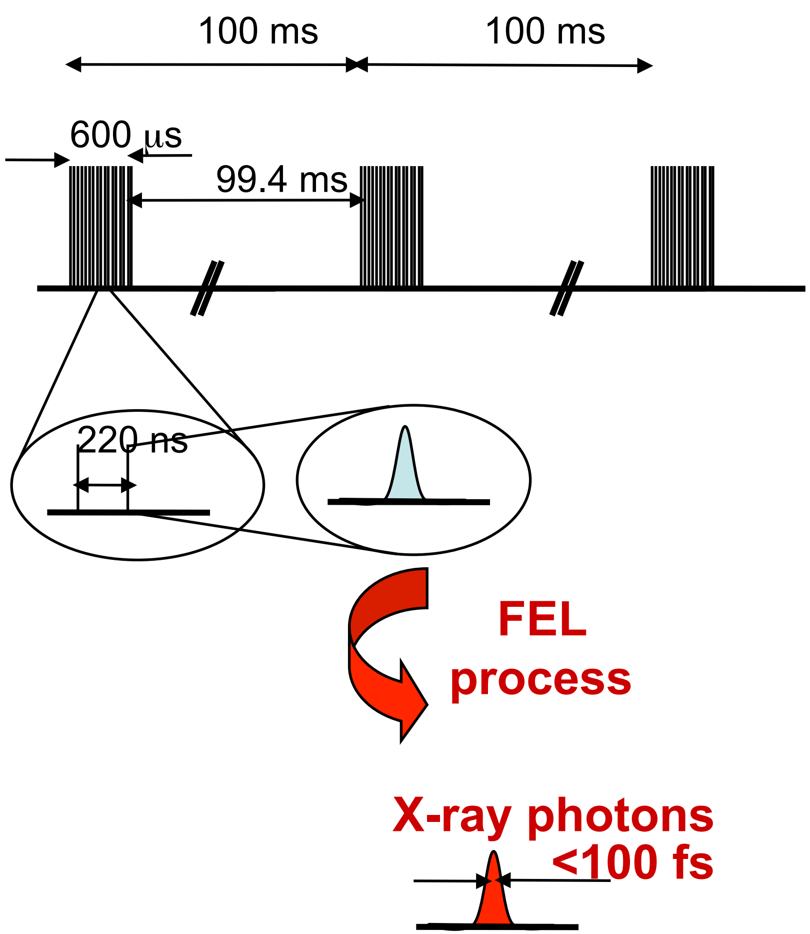
Front: Anna Bergamaschi, Xintian Shi, Gemma Tinti, Marco Ramilli, Davide Mezza, Roberto Dinapoli, Julia Smith, Martin Brückner

www.psi.ch/detectors/detectors-group

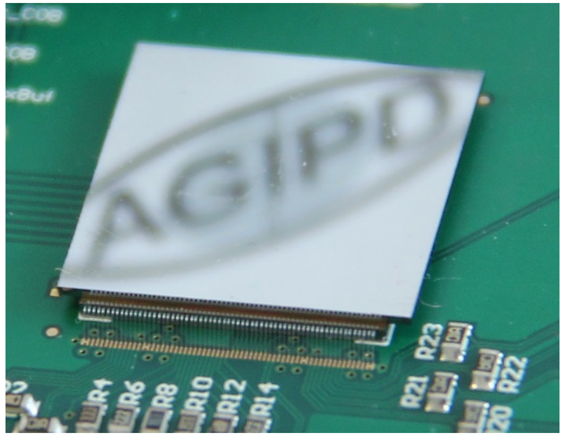
More Information.

http://www.psi.ch/detectors/detectors-group

The European XFEL challenge & AGIPD



200 x 200 um^2
pixel size

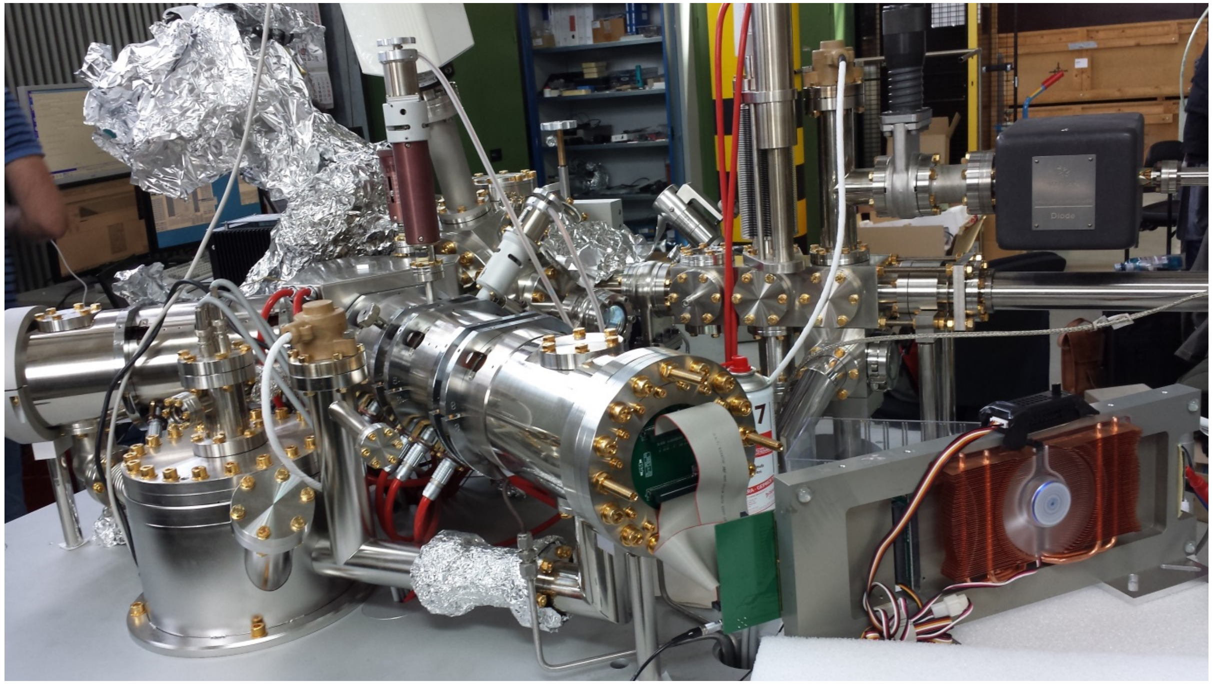


- Single photon sensitivity
- Dynamic range >10^4
- Low noise
- High radiation tolerance (100 MGy)
- 5 MHz frame rate:

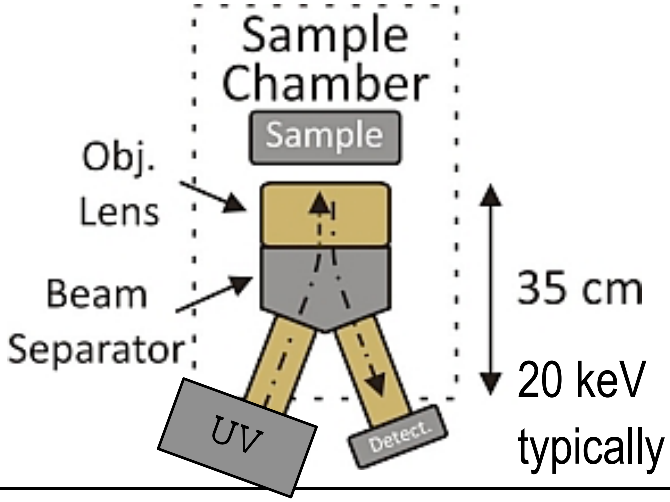
  Storage of 352 images
  on pixel cells and
  readout in the idle time

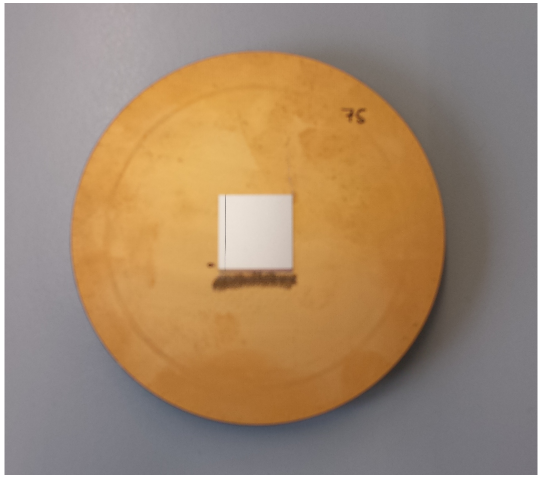
27 000 bunches/s with 4.5 MHz repetition rate

Study of performance of EIGER as a PEEM detector



- Photo emission microscope from ELMITEC
- Feasibility studies
- Source UV lamp/ synchrotron beam
- Vacuum achieved: $5x10^{-9}$ mbar
- Ongoing efforts to reach 10^{-10} mbar



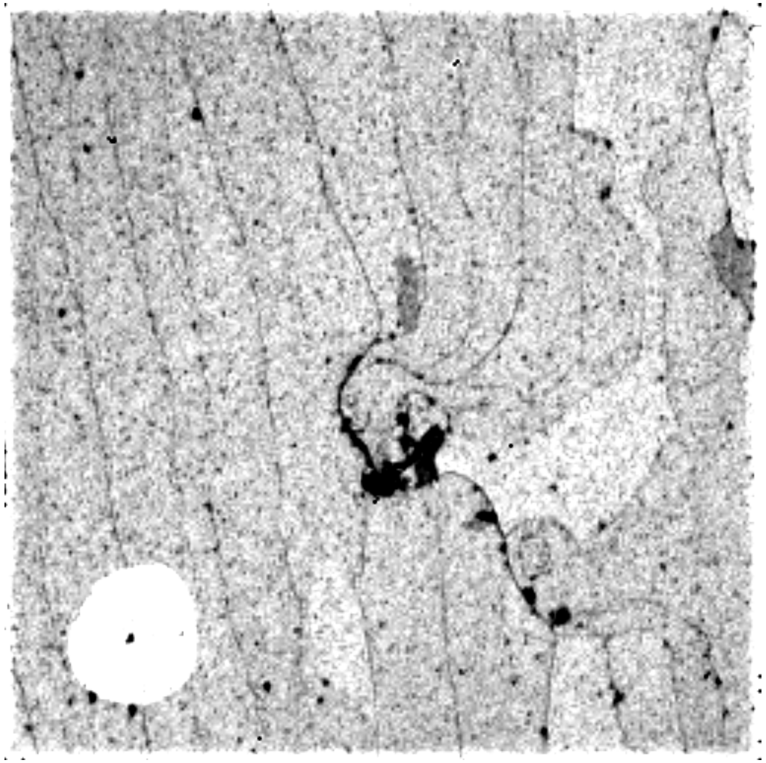


- Single chip: active area 1.92 x1.92 cm^2
- Round board is vacuum barrier

PEEM with EIGER

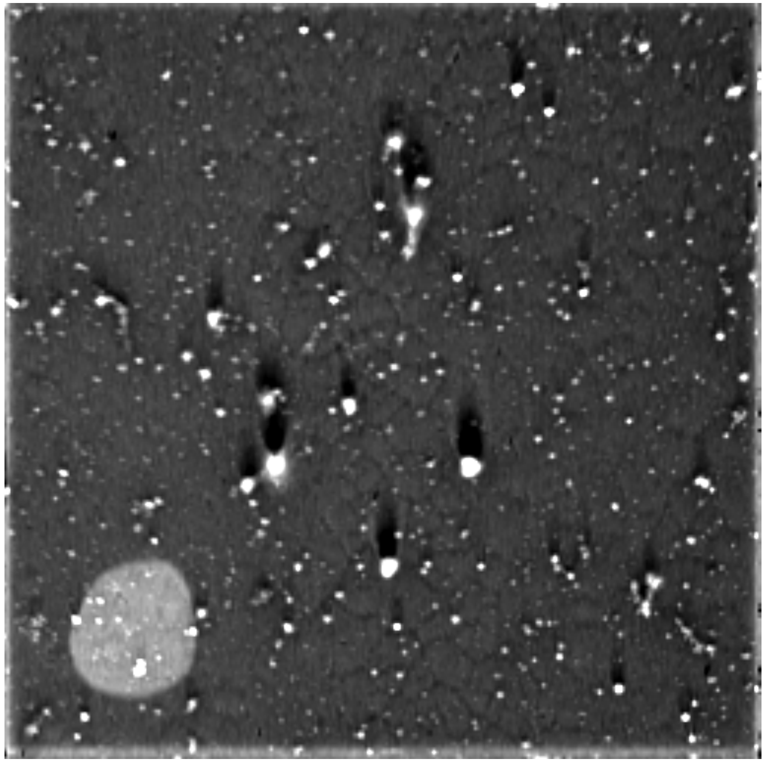
H. Marchetto

FoV=25 μm, 10 sec, 5 avg



Graphene/SiC

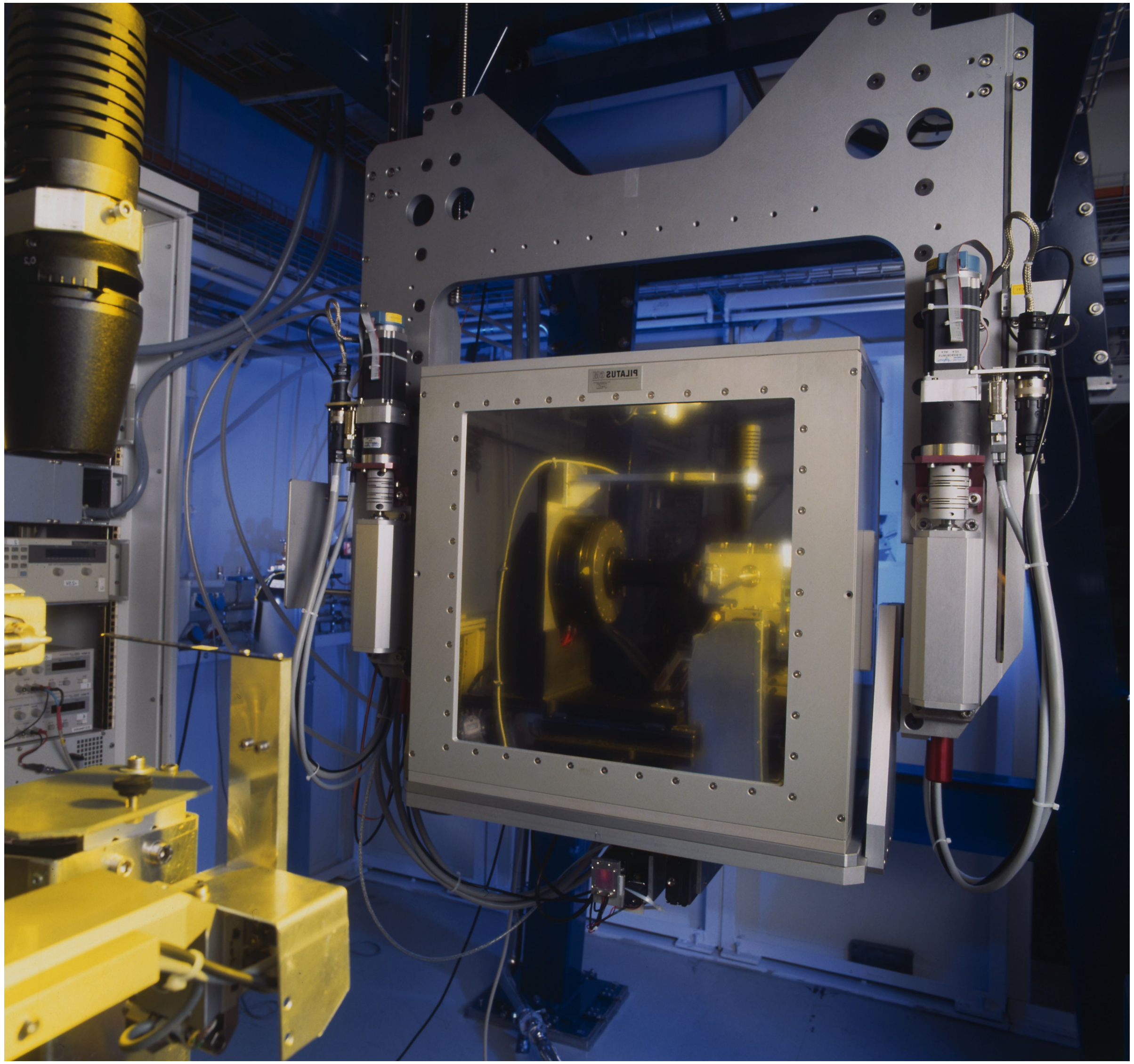
FoV=50 μm, 5 sec, 200 avg



Pb/Si(111)

PilatusII6M at the Protein Crystallography Station

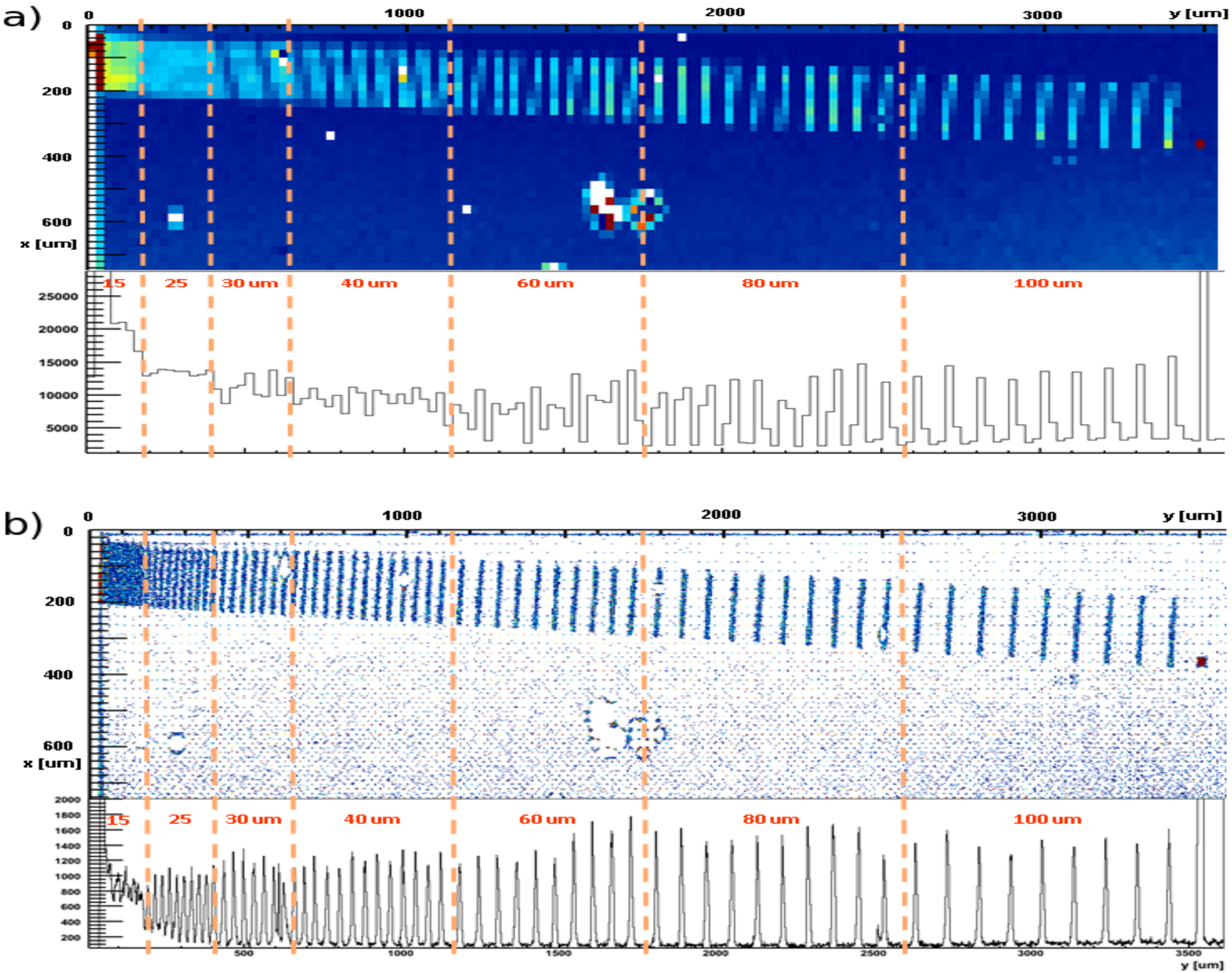
No of Modules	60, 12 x 5
Detector Size [mm]	431 x 448
Format	6'224'001 pixels
Pixel size	172 x 172 μm^2
Dynamic range/pixel	20bits
Count rate/pixel	~ 1-3 MHz
Readout time	3.5 ms
Frame rate	12.5 Hz



made continuous shutter-less operation possible at PX

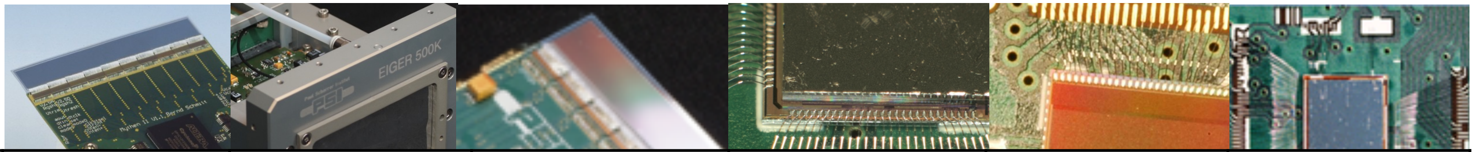
Sold and further developed By Dectris

Small pixels: the MOENCH detector



PAUL SCHERRER INSTITUT

Hybrid SLS detectors



	MYTHEN	EIGER	GOTTHARD	JUNGFRAU	MÖNCH	AGIPD
1D/2D	Strip	Pixel	Strip	Pixel	Pixel	Pixel
Working Mechanism	Photon Counting	Photon Counting	Charge Integrating	Charge Integrating	Charge Integrating	Charge Integrating
Strip/Pixel size [μm]	50	75×75	50	75×75	25×25	200×200
Maximum frame rate [kHz]	1 (4 bit)	23 (4 bit)	40	2 (14 bit)	6 (not final)	4500
Minimum Energy [keV]	5	<3.5	<3.5	2	0.4	<6
Applications	Powder diffraction, energy-dispersive spectrometers, beam position.	Ptychography, coherent imaging, protein crystallography.	@ FLASH, main energy-dispersive detector for EU-XFEL.	Spectroscopic applications, high count rate applications at XFELs & synchrotrons.	(Biological) imaging & tomography, RIXS, spectroscopy, Laue diffraction.	Development for the EU-XFEL.
Status Project	At beam lines.	Moving to beam line.	At beam lines.	Prototype.	Experimental /Prototype.	Moving to beam line.