Development and novel applications of hybrid pixel detectors

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LNF 2021/03/18

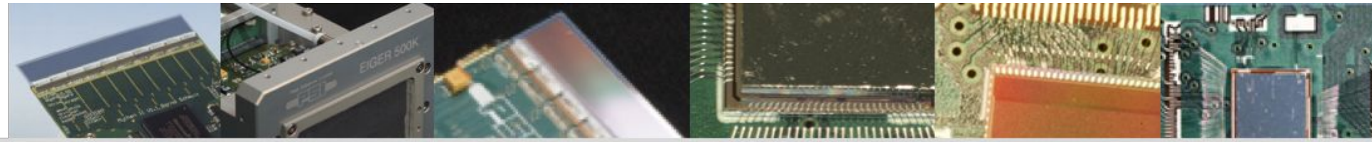
CMS group

- High Energy Physics

Photon science detector group

- Synchrotron Radiation
- Free-electron lasers
- Electron microscopes

Photon science detector group



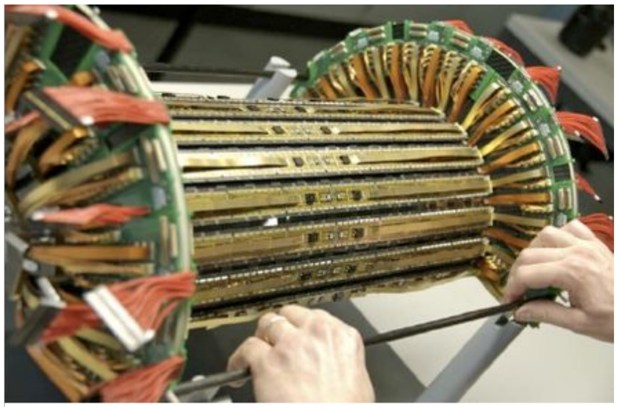
	MYTHEN II&III	EIGER	GOTTHARDI & II	JUNGFRAU	MÖNCH	AGIPD
1D/2D	Strip	Pixel	Strip	Pixel	Pixel	Pixel
Working Mechanism	Photon Counting	Photon Counting	Charge Integrating	Charge Integrating	Charge Integrating	Charge Integrating
Strip/Pixel size [µm]	50	75×75	25/50	75×75	25×25	200×200
Applications	Powder 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.

Pixel detectors for synchrotrons

Their development at PSI started 20 years ago

→ State of the art: CCD systems → bottleneck for science

Technology transferred from particle physics (CMS pixel detector at CERN) → PILATUS was developed



CMS

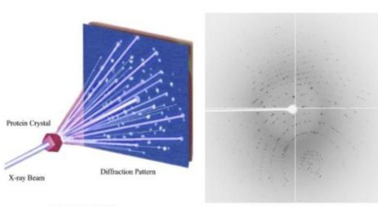
PILATUS

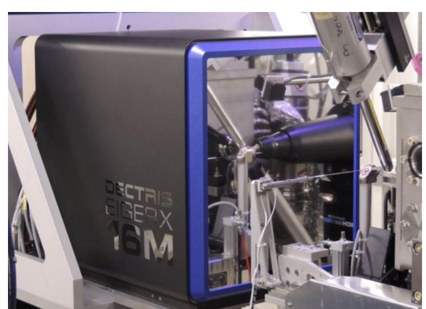
15 years ago, DECTRIS spin off company was founded

→ licensing of PILATUS, MYTHEN, EIGER..

Since then many PSI-technology detectors are contributing to science at every synchrotron

<5 years ago: extension to electron microscopy started



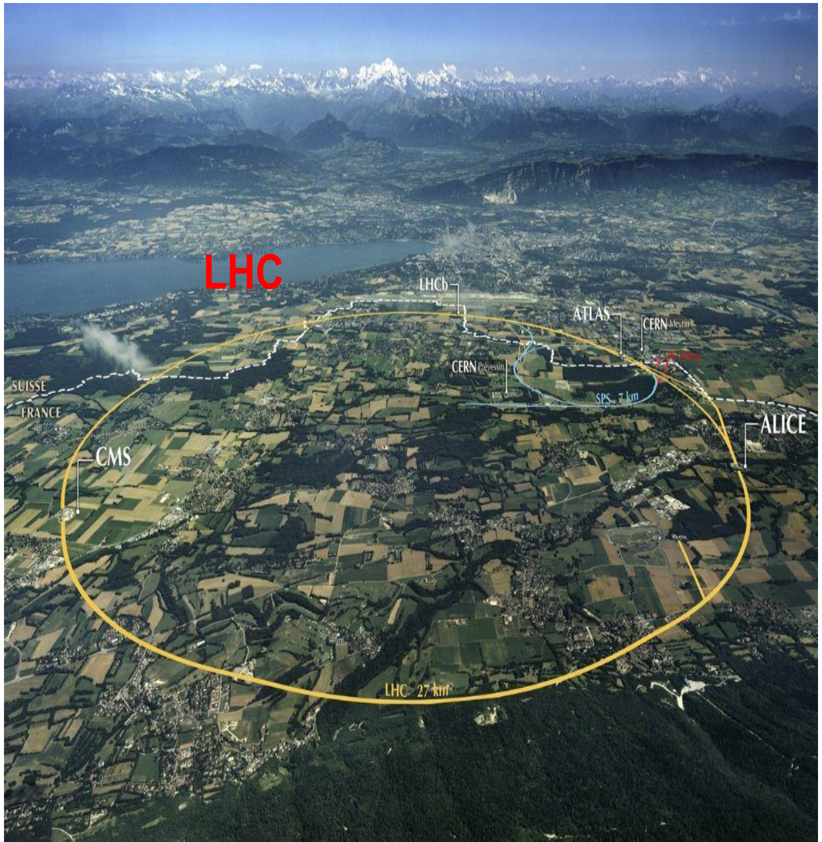


Protein structure of SARS-COV-2 was solved with crystallography @ Shanghai Synchrotron in March 2020 using an EIGER 16M

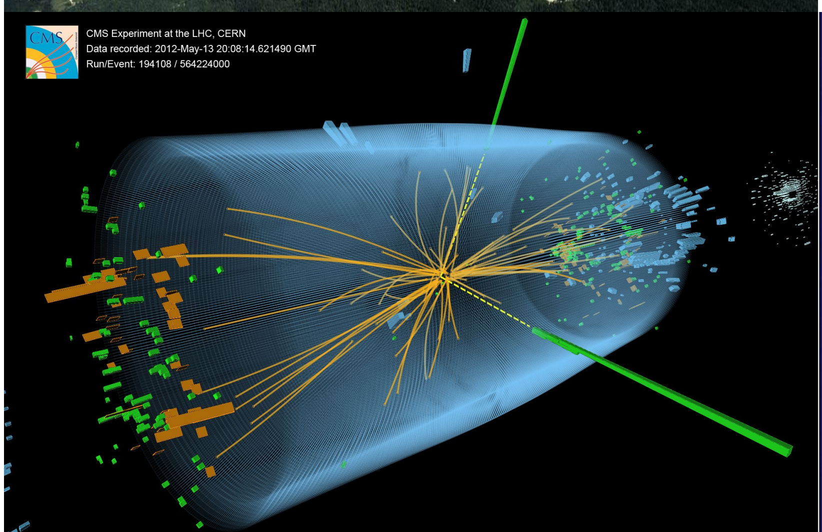
Outline

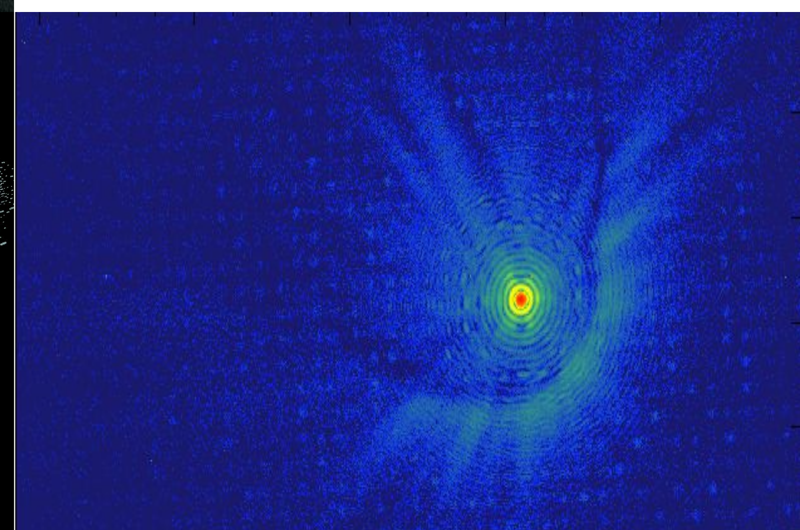
- Parallelism between CMS (HEP) and EIGER (Synchrotron)
  - Different subdetector components
  - Calibration
  - Rates
- Jungfrau specific implementation for FEL and synchrotron
- Electron microscopy
- Prospects for future developments

27 km
circumference
4 TeV p beams



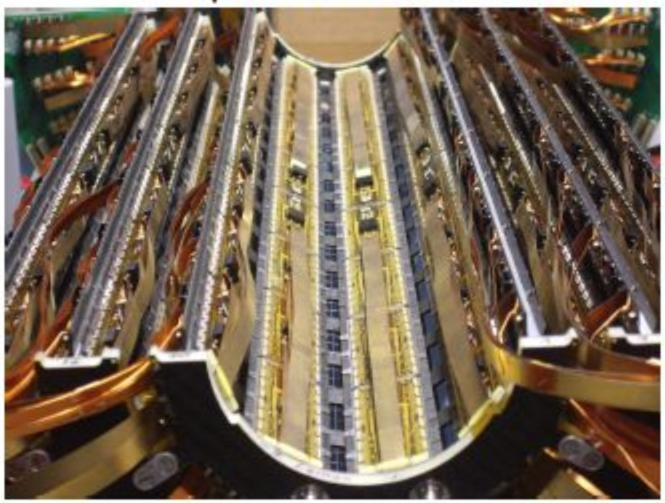
288 m circumference
2.4 GeV e beam
Xrays 3eV – 45 keV



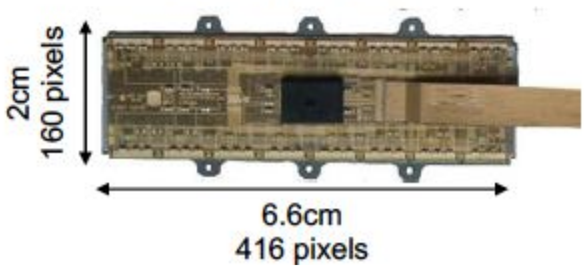


CMS pixel BARREL detectors

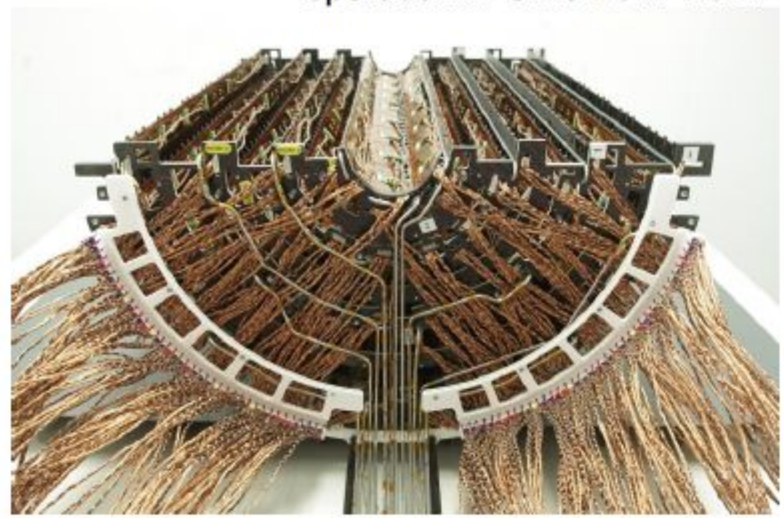
Original @PSI 2008
operated in CMS 2010-2016



1440 modules
66 M pixels



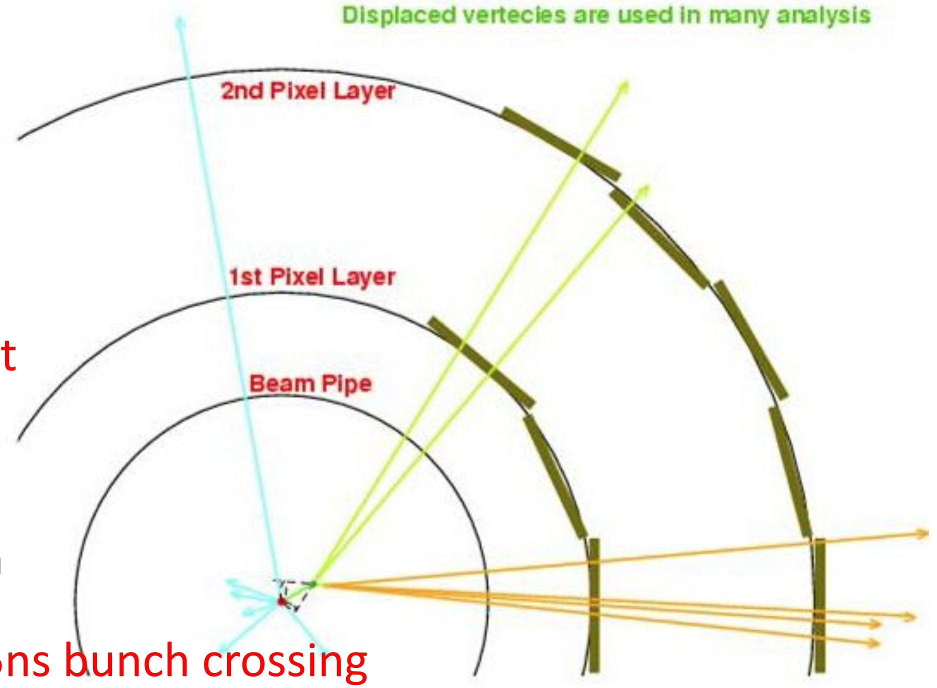
Phase-1 upgrade @PSI 2017
operation in CMS 2017-2024



1856 modules
124 M pixels

Pixel size is 100x150 μm^2

HEP pixel detector requirements



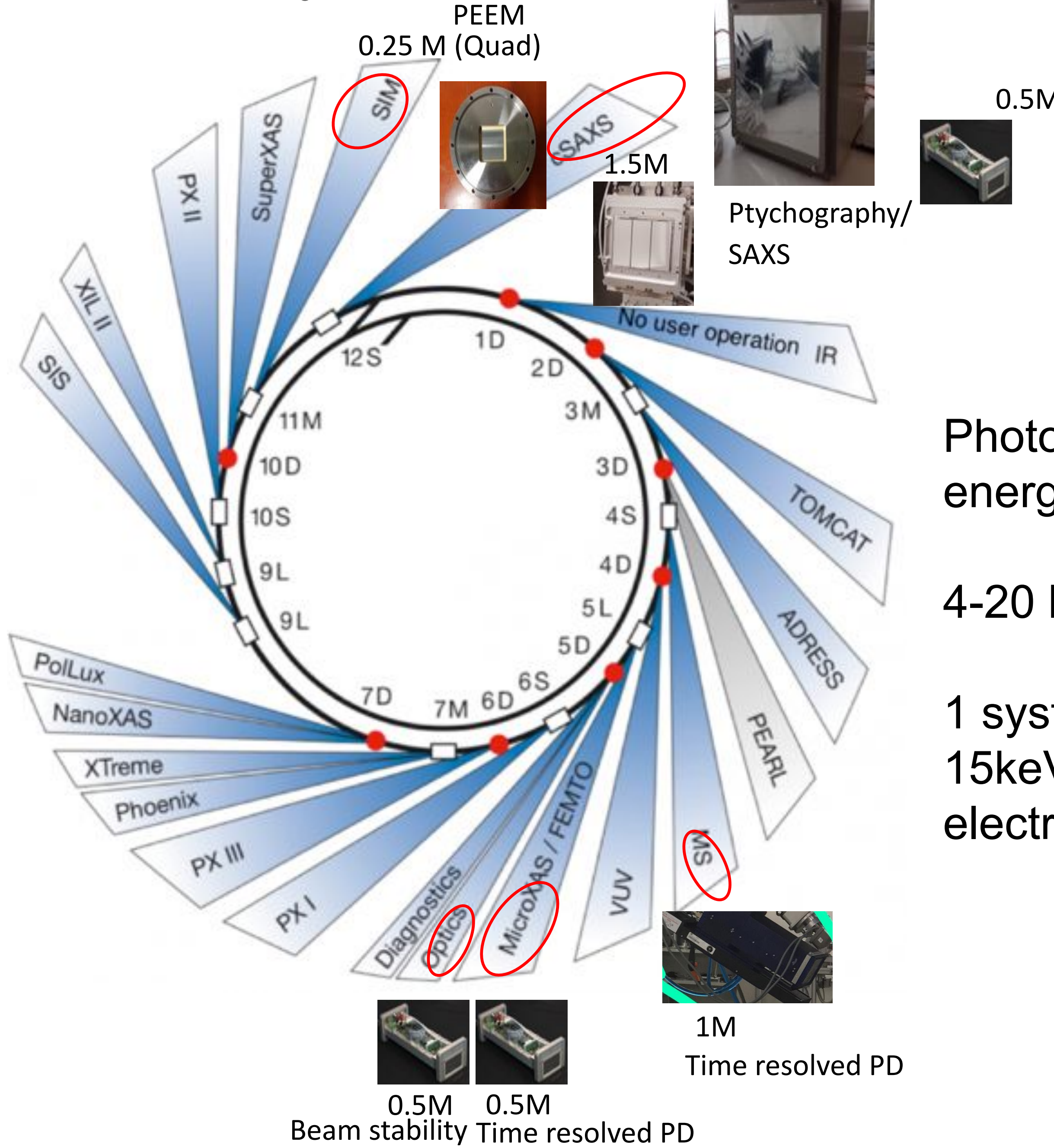
- Charged integrating detectors ➔ Pulse Height
- Readout of localized hits
- Highly granular detector ➔ spatial resolution
- Fast signal peaking time ➔ within the LHC 25ns bunch crossing
- Temporary hit storage during trigger latency: readout according to the CMS Level 1 trigger selection
- Low noise
- Low in-time threshold
- Very high radiation tolerance design ➔ charge particles
- Low material budget

EIGER systems at SLS

Only at SLS,

7 eiger detectors,

13M pixels

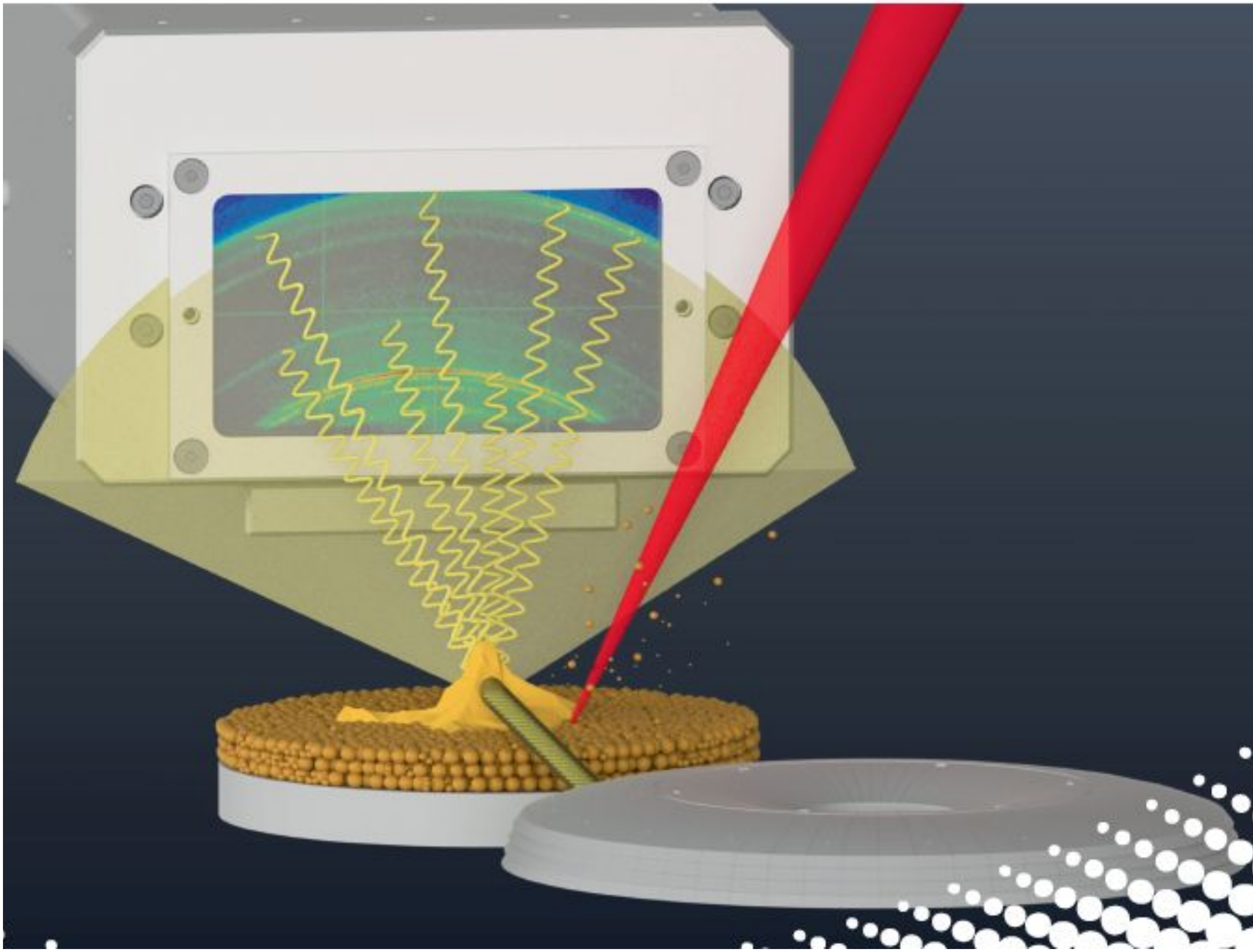


Photon energies:

4-20 keV

1 system @ 15keV electrons

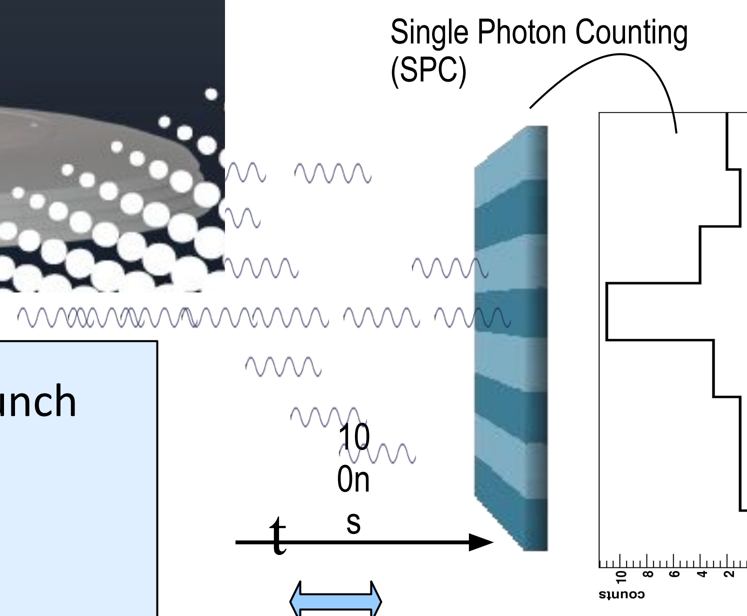
Pixel detectors at synchrotron



SLS at PSI 288 m circumference

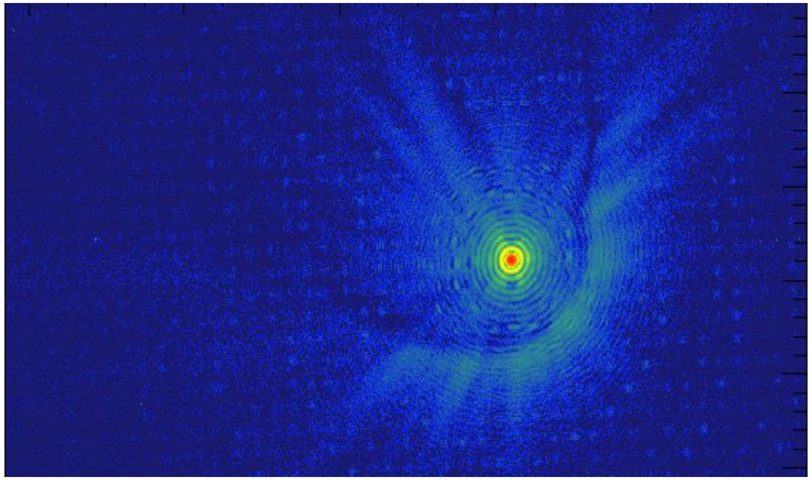
Xrays 3 keV – 20 keV

- Monochromatic beam
- Photons are 'continuous', time resolution given by the detector



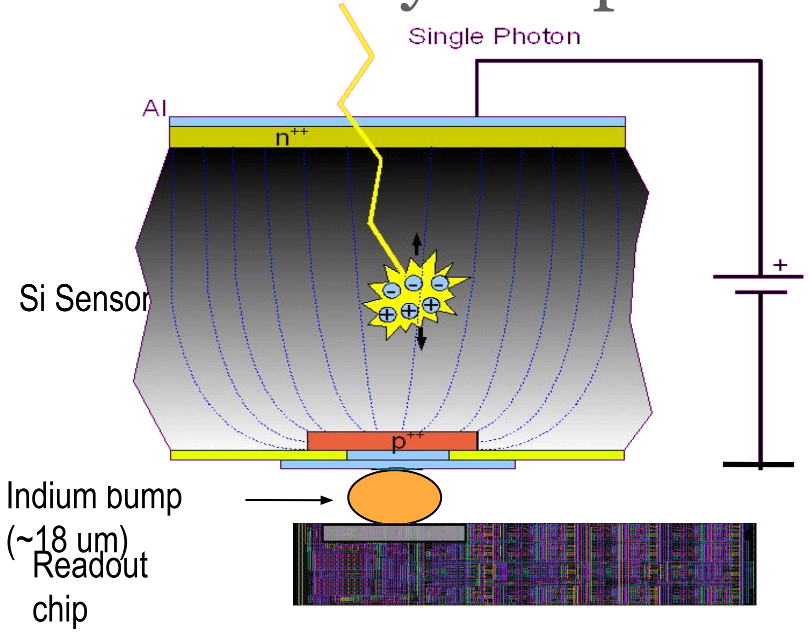
- Huge number of "weak" photon bunches (a bunch every 2 ns)
- Bunch length is 20 ps
- Photons impinge on the detector with a semi-continuous time distribution

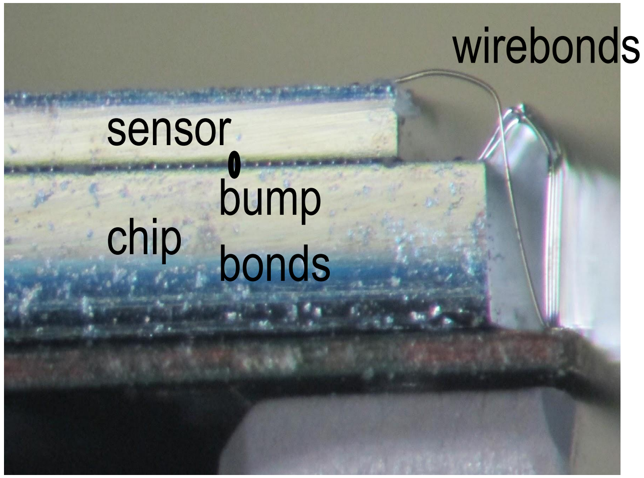
Synchrotron pixel detector requirements



- Energy range from a few to 25 keV
- Total frame readout
- Continuous beam, no trigger, high duty cycle
- High frame rate → tens of kHz
- Single photon sensitivity → low noise
- High dynamic range 1- 10^4 photons
- High count rate capability → 10^{10} photons/cm^2/s
- Spatial resolution <100 um
- High radiation tolerance → γ rays, 30MRad

Hybrid pixel detectors

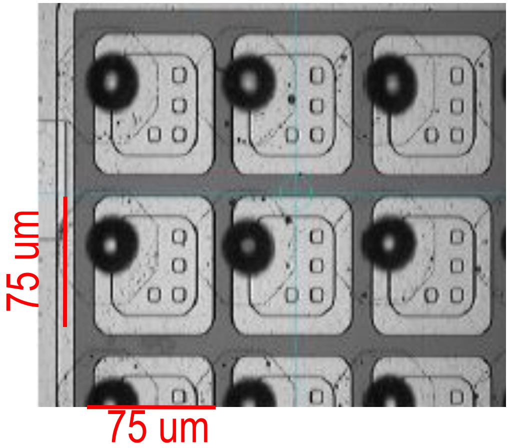




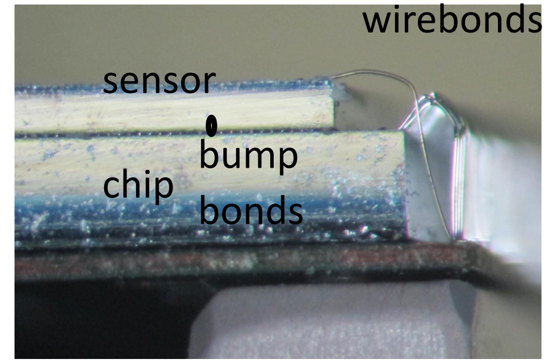
- The energy is converted into electric charge
- About 3.6 eV to generate an e-h pair in silicon

In our usual applications:

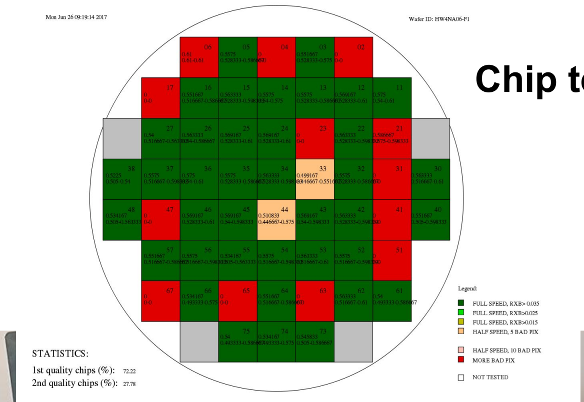
- 300 um thick Si sensor

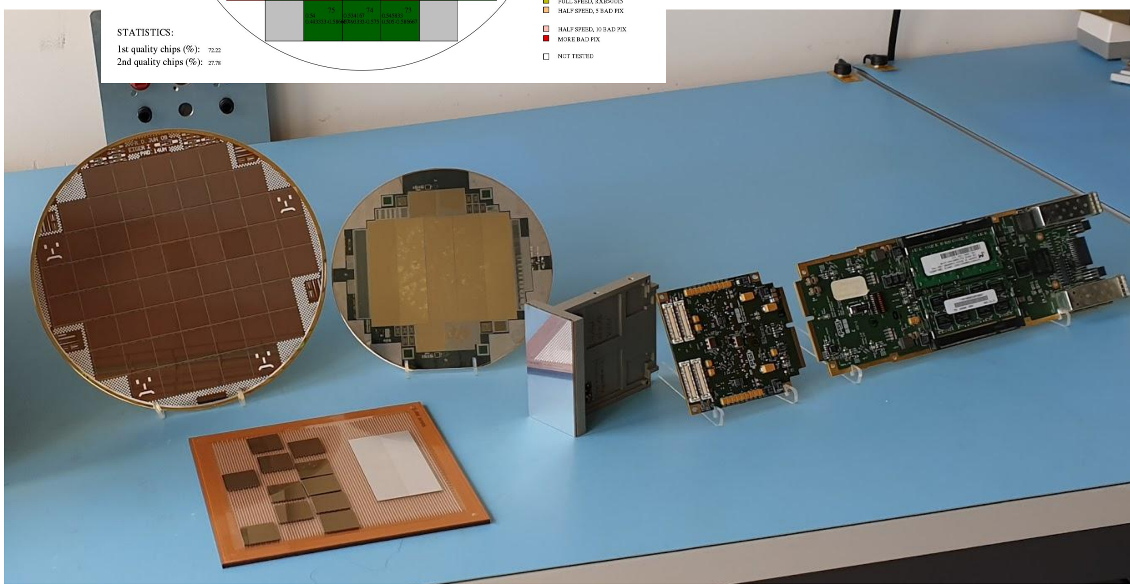


Hybrid pixel detectors

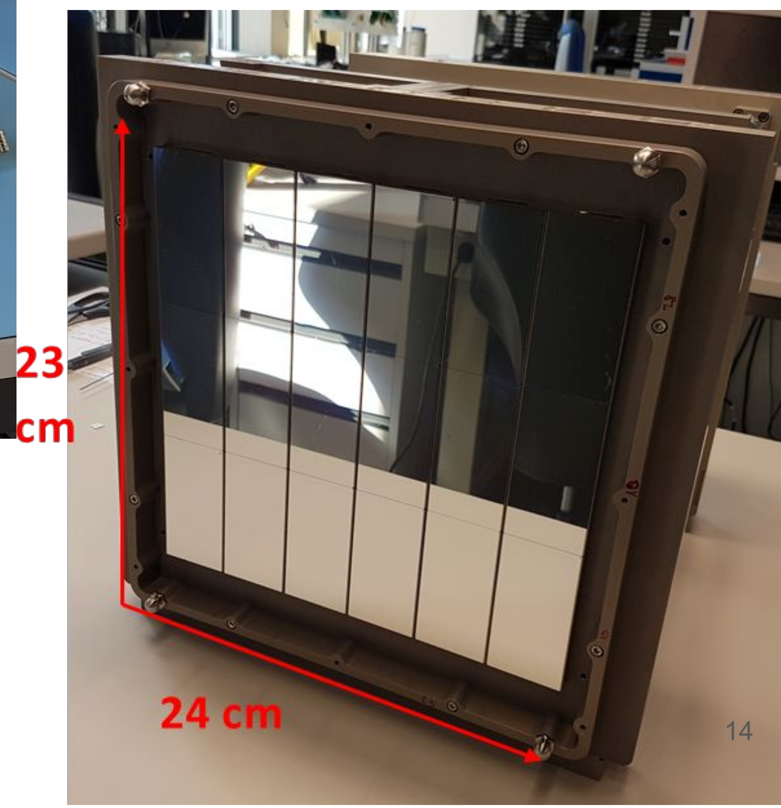


Chip tests on wafer

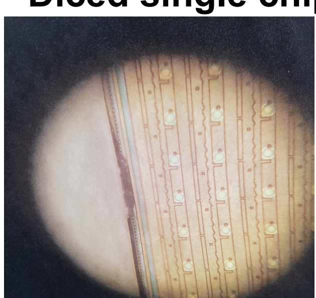




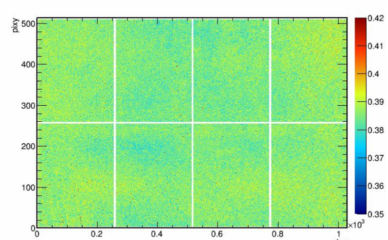
Full system test and calibration



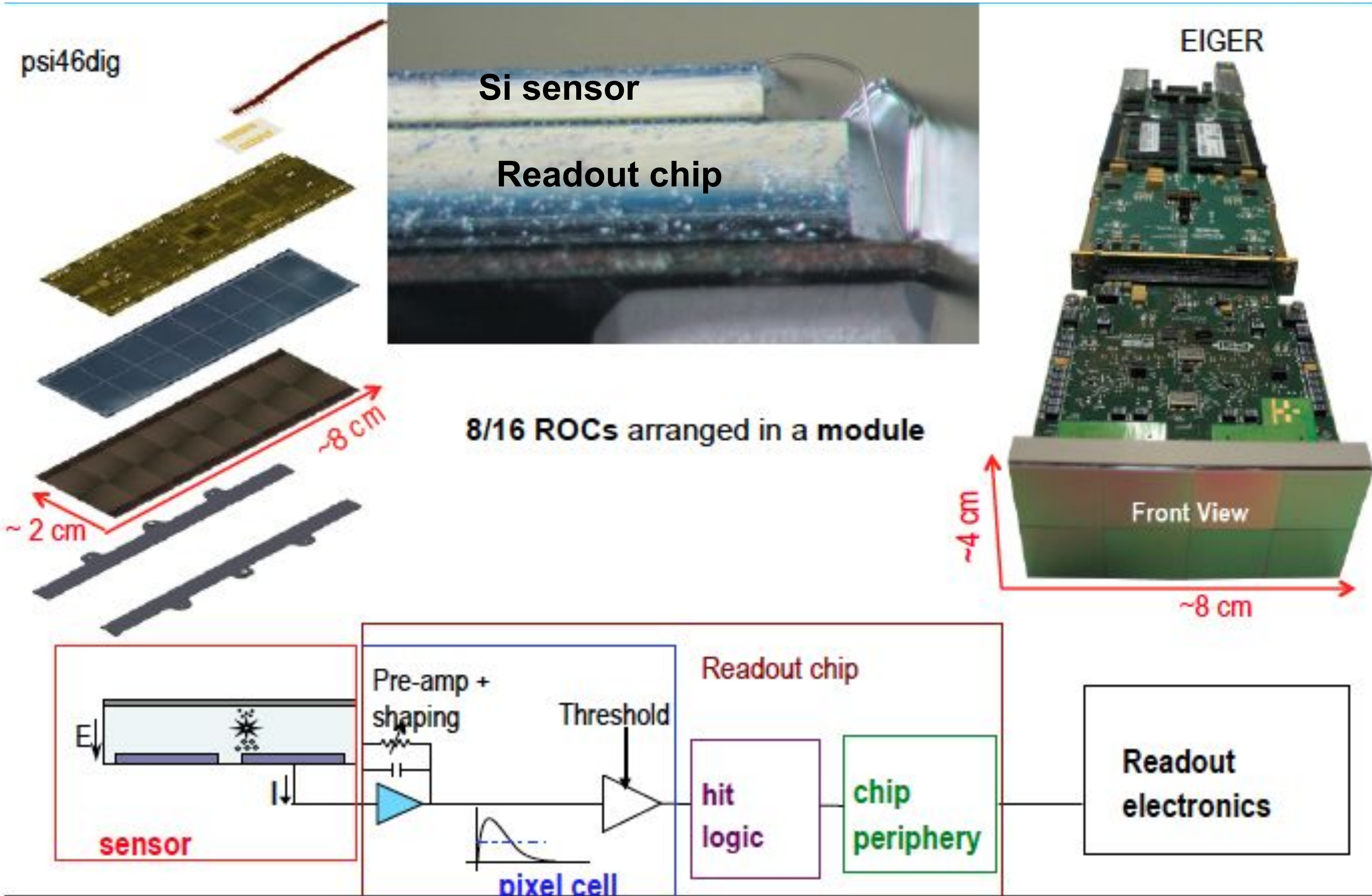
Diced single chip full tests



Module tests

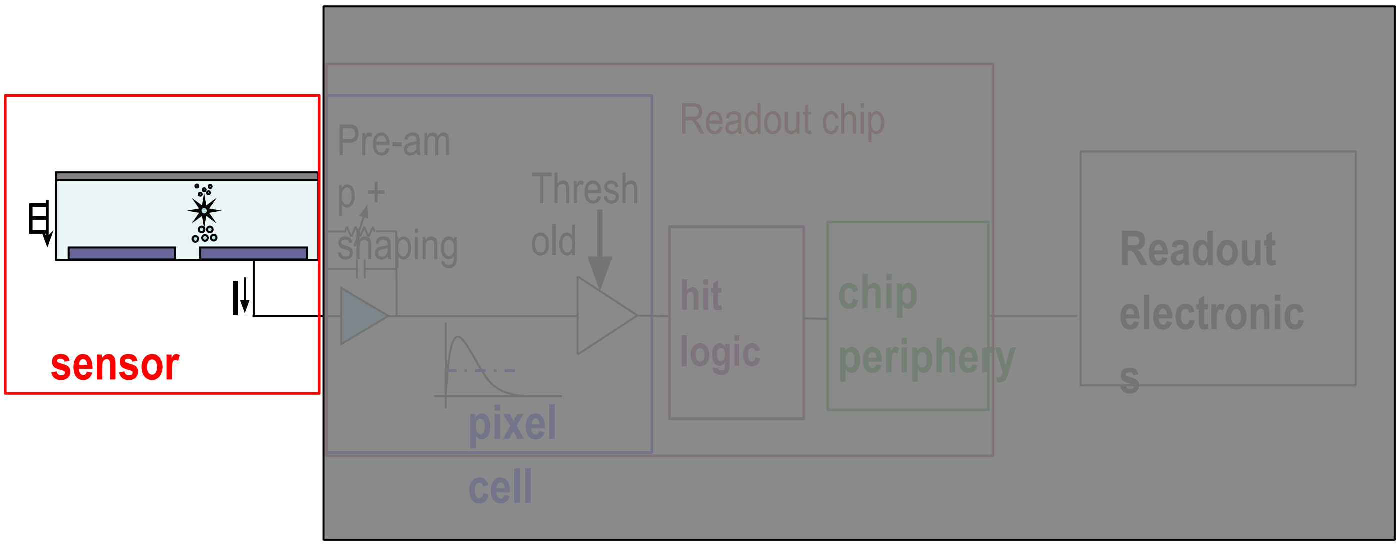


Hybrid pixel detectors

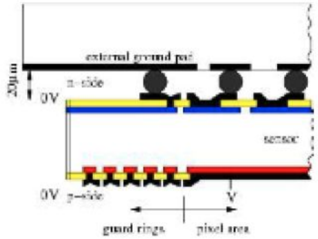


Sensor: particle interaction happens in sensor. Conversion to e/h pairs
Readout chip: comparison to a threshold. Counting or PH sampled

Sensor


sensor
Pre-am
p +
shaping
Thresh
old
pixel
cell
Readout chip
hit
logic
chip
periphery
Readout
electronic
s

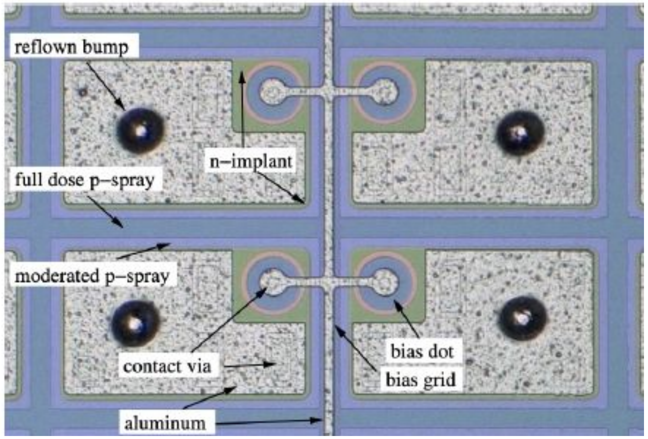
Sensor choice for HEP



n^+ - in - n 100 x 150 um^2
Sensor thickness: 280 um

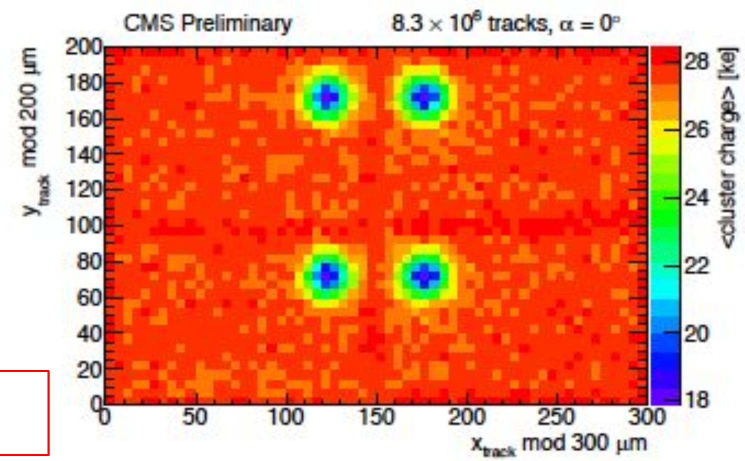
e^- collection motivated by:

- Higher mobility : timing requirements
- Less charge trapping: radiation requirements
- Higher Lorentz angle: charge sharing



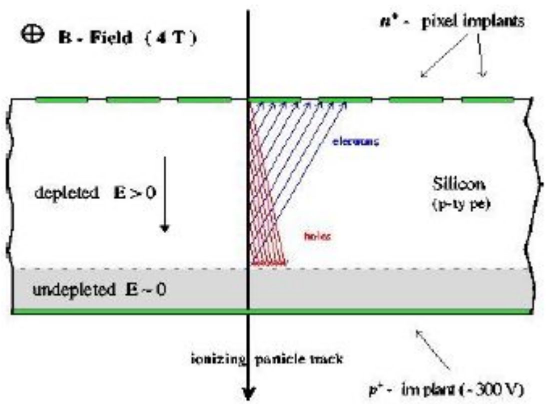
Ionization happens along the MIP track.
dE/dx = 3.87 MeV/cm

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87\cdot 10^6\,\mathrm{eV/cm}\cdot 0.03\mathrm{cm}}{3.62\mathrm{eV}} \approx 3.2\cdot 10^4\, e^- h^+\text{–pairs}$$



Spannagel et al., NIM A 2016 03 028

Spatial resolution and Lorentz angle

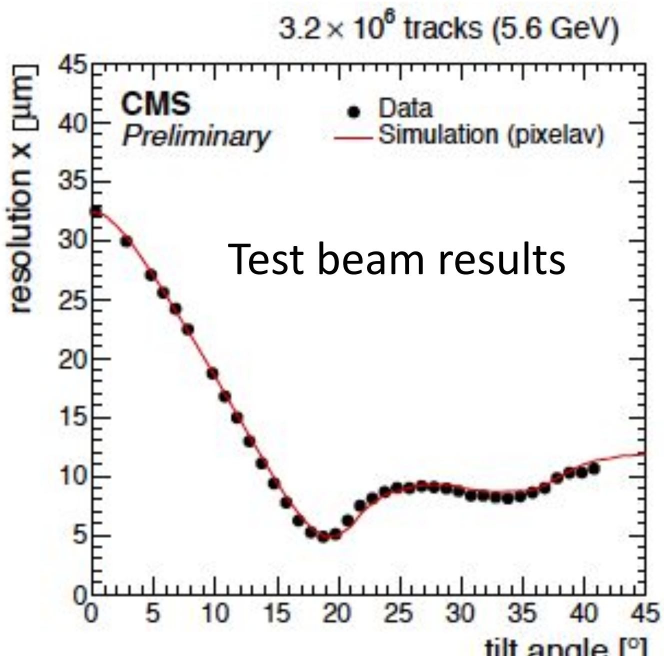


e^- collection motivated by:

- Higher Lorentz angle: charge sharing

CMS pixel resolution:

- 10.4 um transverse dir
- 20-45 um longitudinal direction depending on track angle



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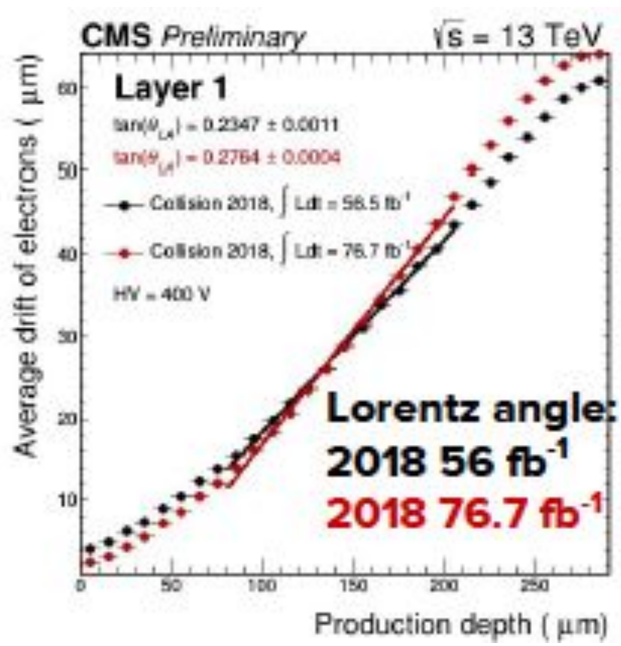
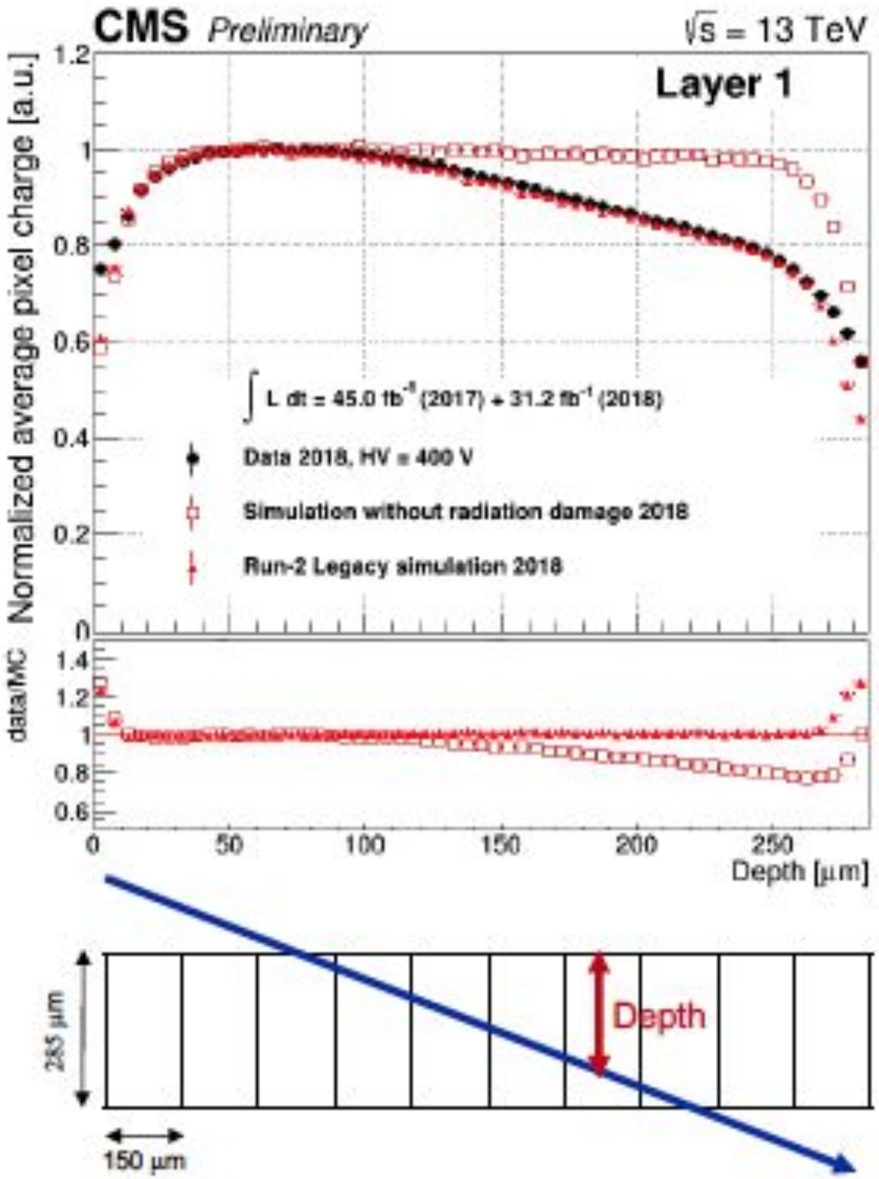


Charge trapping



e$^-$ collection motivated by:

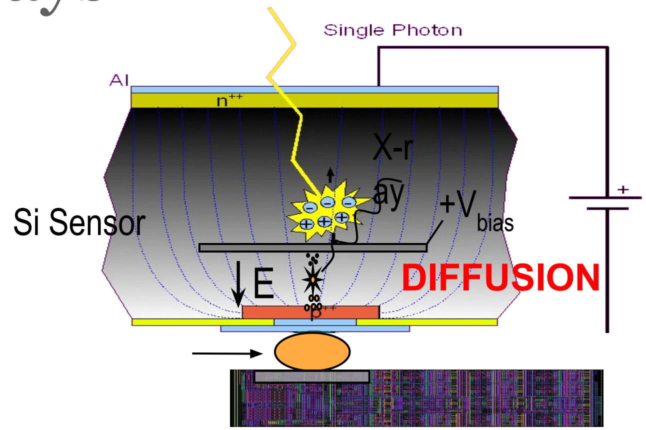
- Less charge trapping: radiation requirements

- Radiation damage causes defects in Si lattice
- Due to charge trapping: loss of signal charge
- Larger charge loss for larger (drift) depth for irradiated sensors
- Measured using inclined tracks
- Effect can be partially recovered by increasing the HV (450 V-800 V)

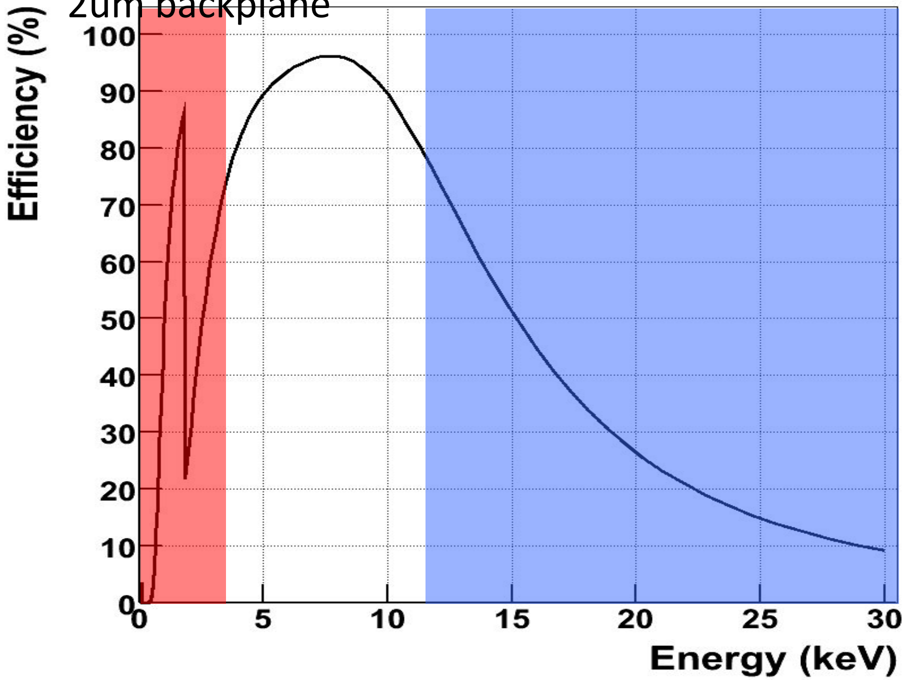
Affects the spatial resolution and needs to be taken into account in the reconstruction

Sensor: Si for X-rays

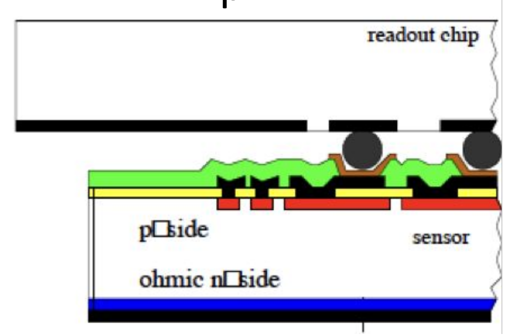
- Absorption of the X-rays in sensor: mainly photoelectric effect (<40 keV), ‘pointlike’
- No bulk damage caused by Xrays: hole collection
- Leakage current increase with dose expected
- The sensor (320um thick) ‘protects’ the readout chip up to 8 keV X-rays



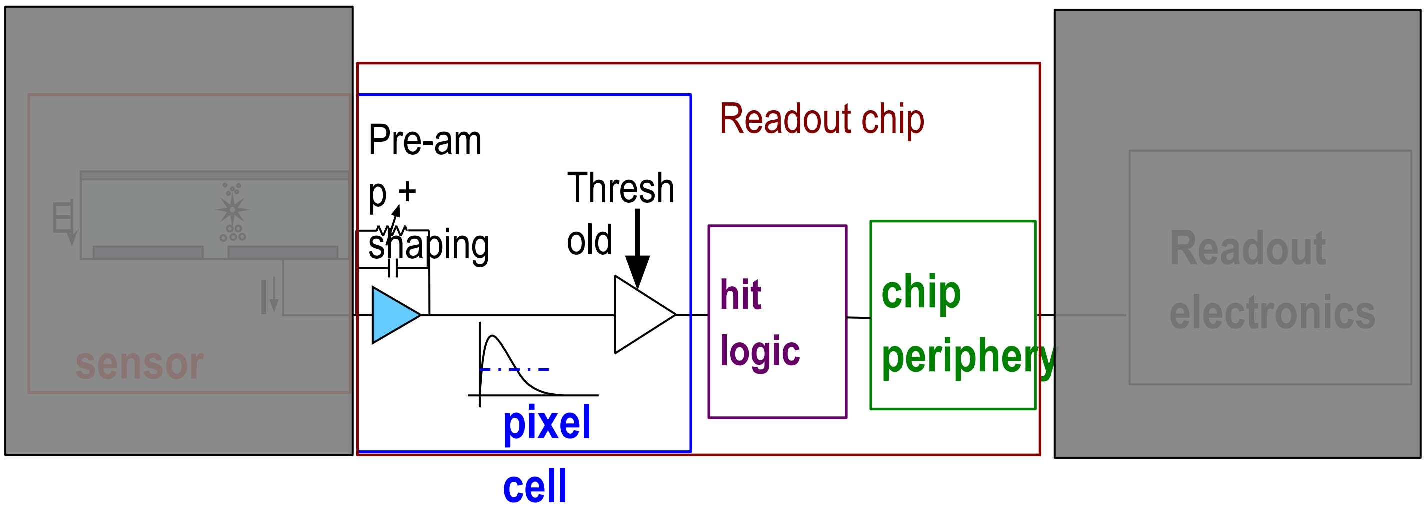
Standard silicon sensors: 320um thick, 2um backplane



p$^+$ in n

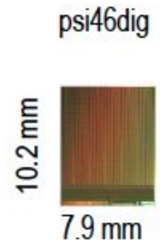


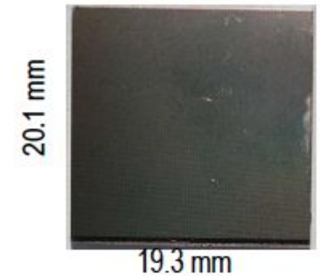
Readout chip



Readout chip characteristics

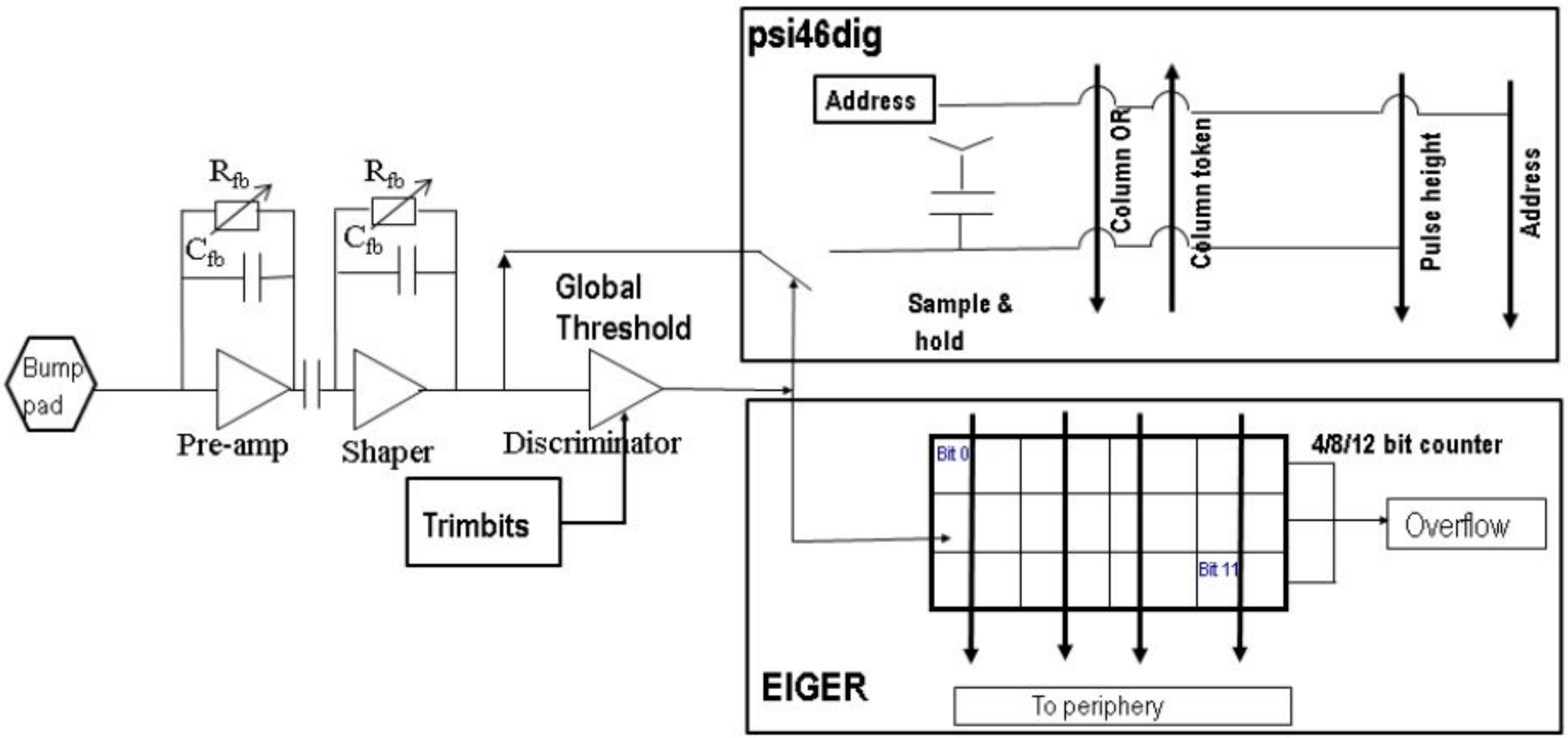
Layer 2-4 psi46dig
Layer 1 PROC 600
(optimed data rate sending
2x2 clusters)





property	*psi46dig*	EIGER
technology	IBM 250 nm Rad. tol. Design$>$250 Mrad	UMC 250 nm Rad. tol. Design$\approx$30 Mrad
pixel array	80×52=4160 pixels	256×256=65536 pixels
pixel size	$100\times150\ \mu m^2$	$75\times75\ \mu m^2$
count rate	$1.2\cdot10^8$ hits/cm^2/s	$1.8\cdot10^{10}$ hits/cm^2/s
data rate	160 Mb/s	6 Gb/s
analog power digital power total static power	11 μW/pixel 17 μW/pixel 0.12 W	10 μW/pixel 0.2 W (static periphery) 0.83 W

Readout chip analog part

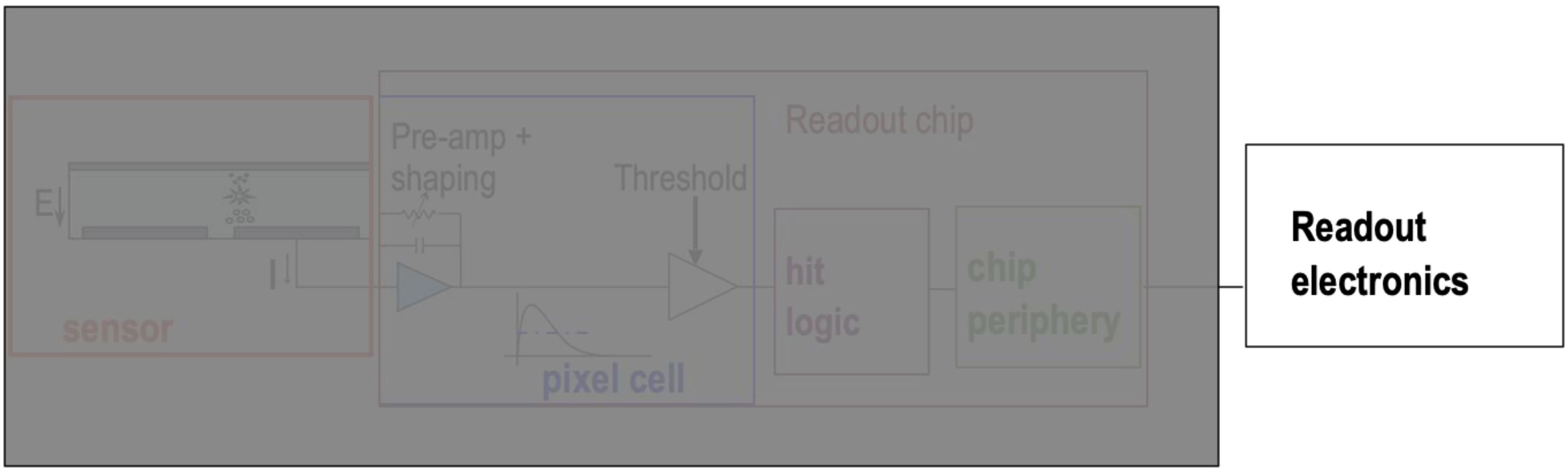


property	*psi46dig*	EIGER
output	event pulse height with timestamped hits	event counts with configurable integration time

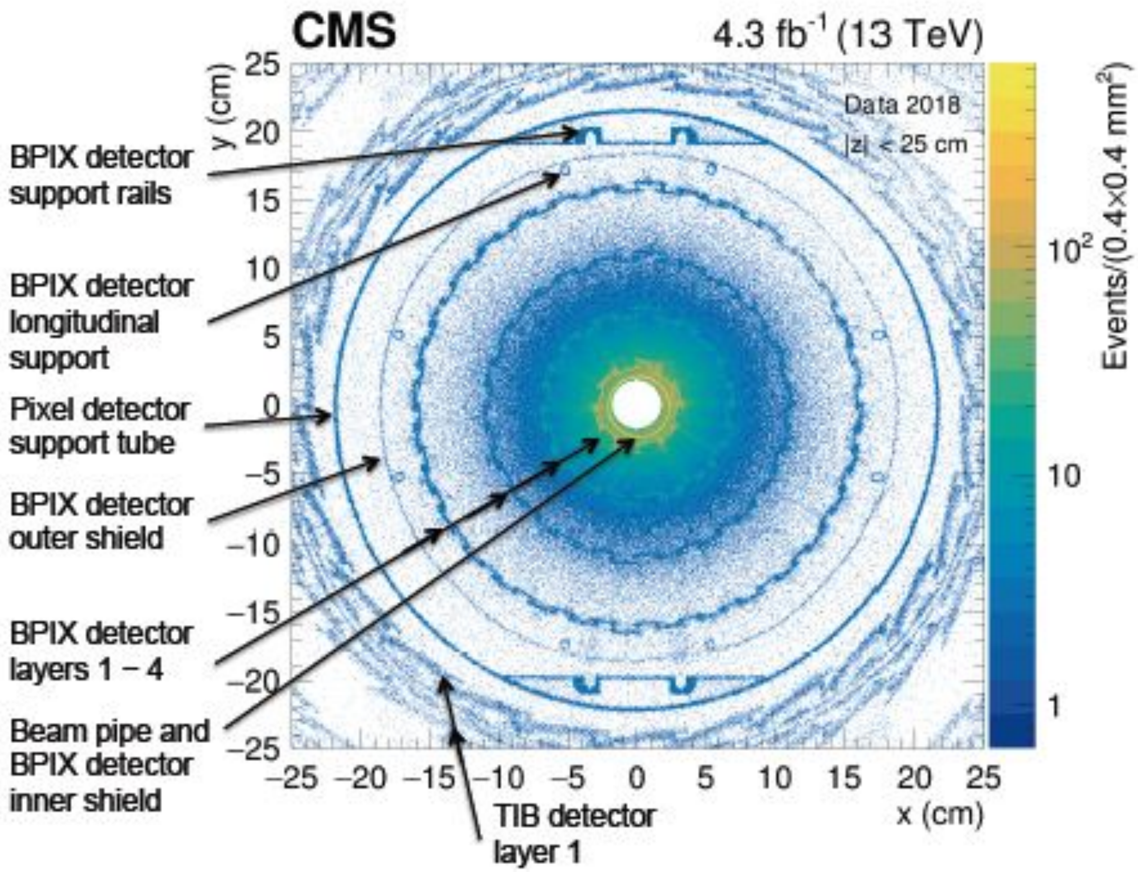
100 kHz

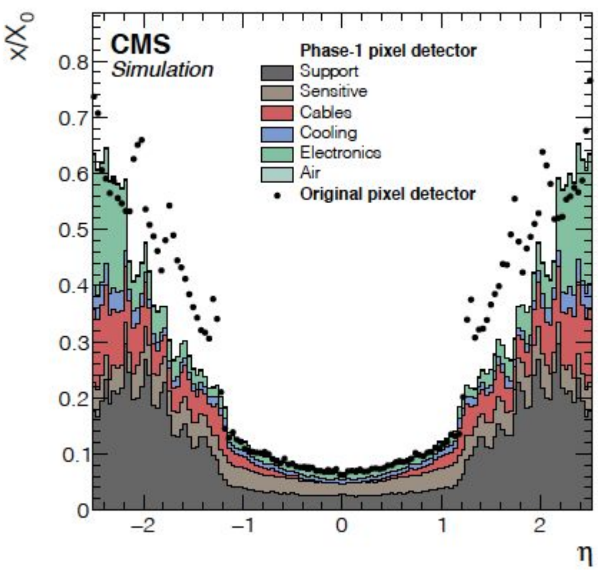
22kHz

Readout electronics



CMS: low material budget

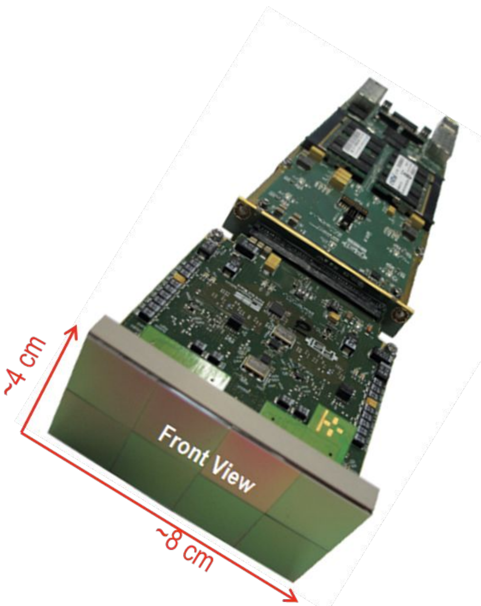




- Maintaining low material budget → CO_2 cooling with small pipes (-23℃)
- Data out of L1 trigger: 30-100 GB/s depending on Pile up

CERN-CMS-NOTE-2020-005

EIGER: Very high frame rate

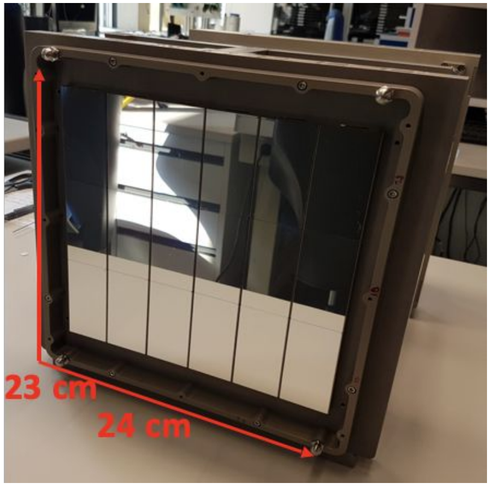


0.5M single module, 20Gb/s

2x10 Gb/s Ethernet connections are the bottleneck when running at maximum framerate

Thanks to large memory on board, we can buffer images

6 FPGAs per module
8 GB DDR2 per module



9M detector, up to 360Gb/s

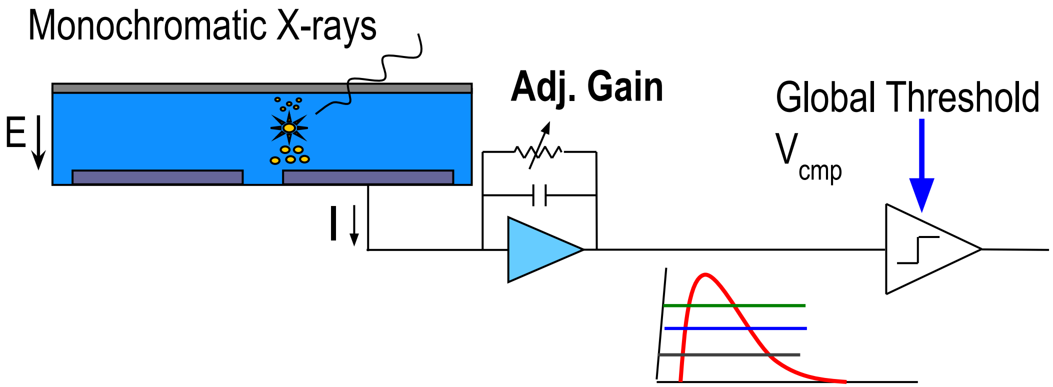
4 us dead time between frames
Time covered : 1.4 s

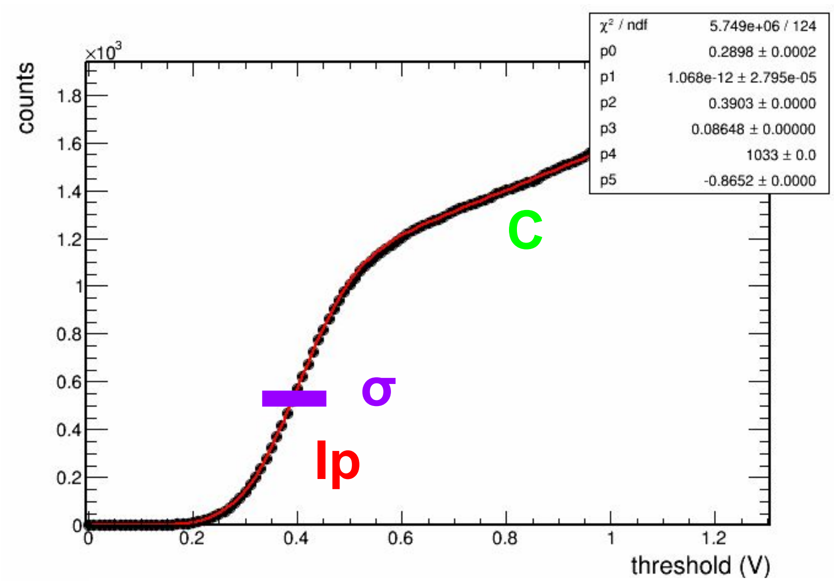
Water cooling at 20°C, mainly for FPGAs

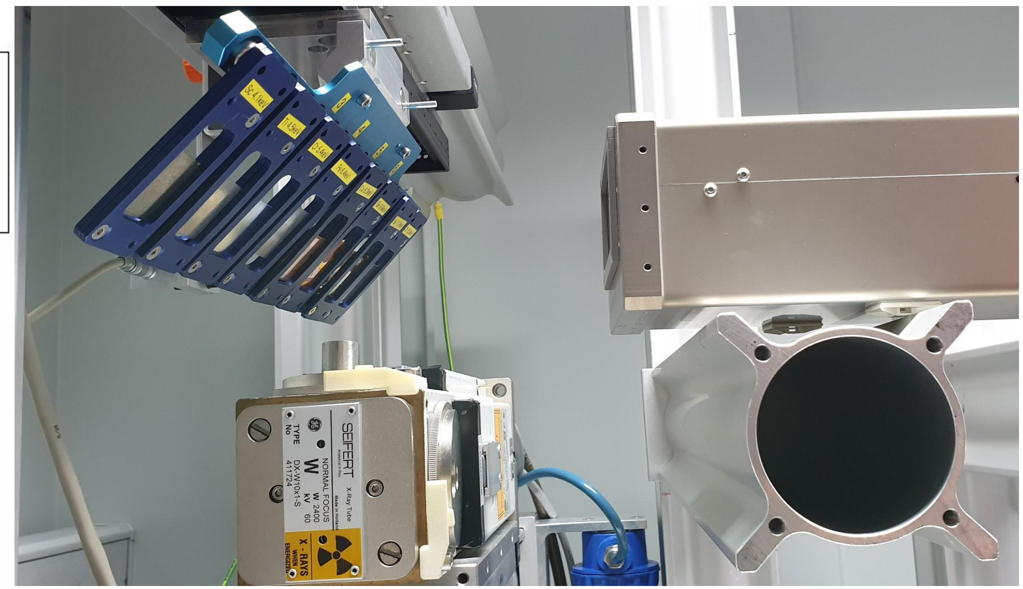
Dynamic range (bit)	Continuous frame rate @10 Gb (kHz)	Buffered max frame rate (kHz)	Images stored
4	10.2	22	30000
8	5.12	11	15000
12	2.56	6	7600
32	2 kHz internal	0.8	Online sum

- Parallelism between CMS (HEP) and EIGER (Synchrotron)
  - Different subdetector components
  - Calibration
  - Rates
- Jungfrau specific implementation for FEL and synchrotron
- Electron microscopy
- Prospects for future developments

Calibration: threshold scans







Amplitude

Inflection point

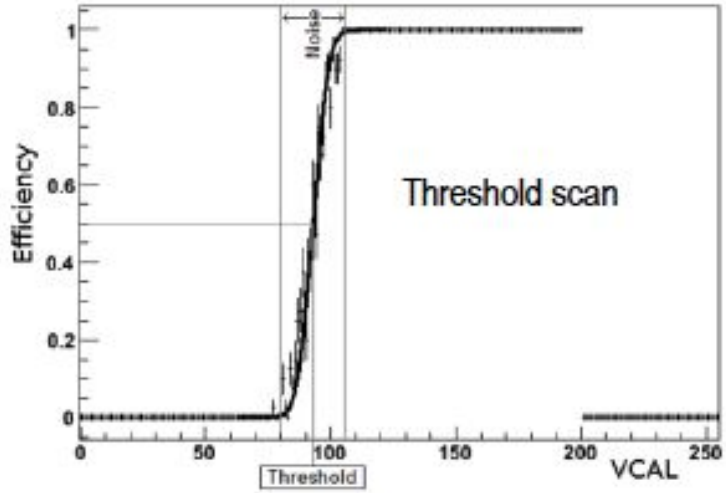
$$n(x) = \frac{A}{2} \cdot \left(1 + Erf\left(\frac{x - I_p}{\sqrt{2}\sigma}\right)\right) \cdot \left(1 + C \cdot (x - I_p)\right)$$

Noise

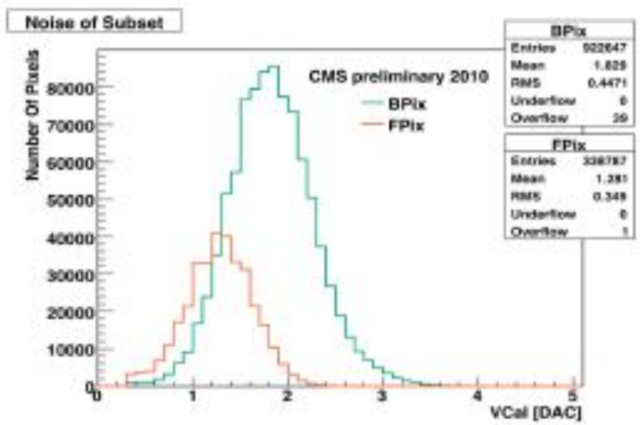
Charge sharing

CMS threshold and noise

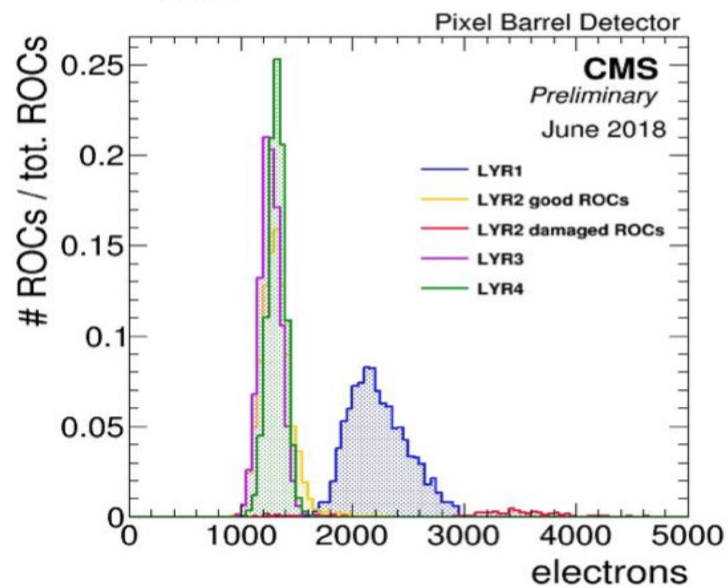
Calibrations similar to SPC ones

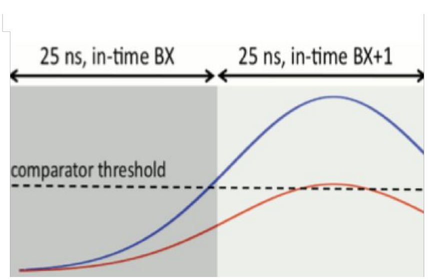


- Noise and thresholds determined with same Scurve method (but using calibration signal)
- Minimum threshold is higher than what achieved in pixel detectors for photon science



noise = 1.8 * 65 = 120 electrons

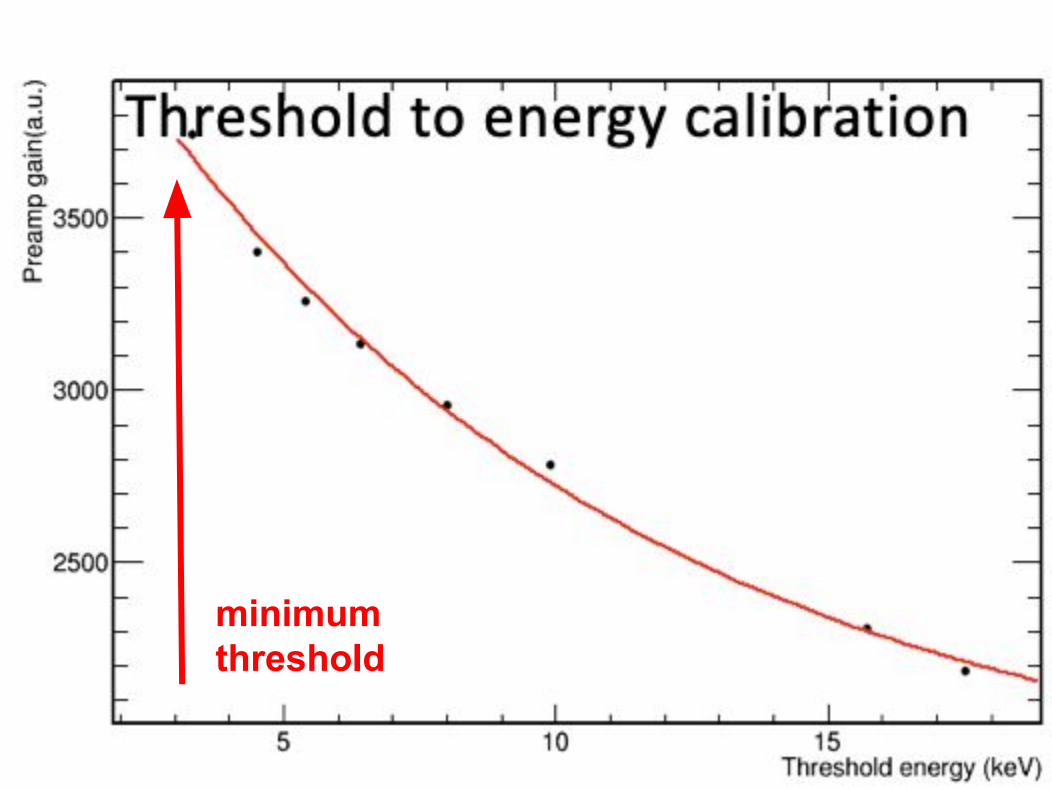


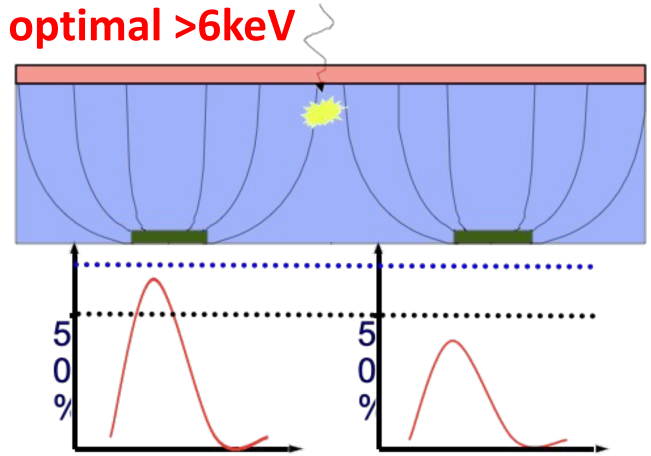


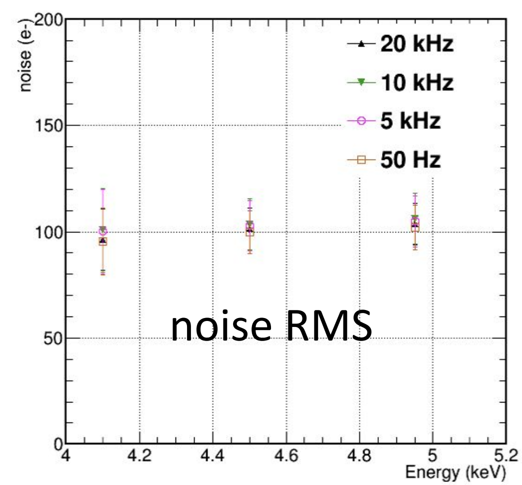
In-time threshold ~ 1500e$^-$

EIGER threshold and noise

- **Single photon counters**: compare the signal to threshold
- **Threshold** is normally set to **50% beam energy** to optimize for charge sharing between pixels
- Low noise <100 e^- RMS. Energy resolution 360-700 eV RMS at 3-15 keV
- Threshold can be set at > **3keV** → **beam energy optimal >6keV**





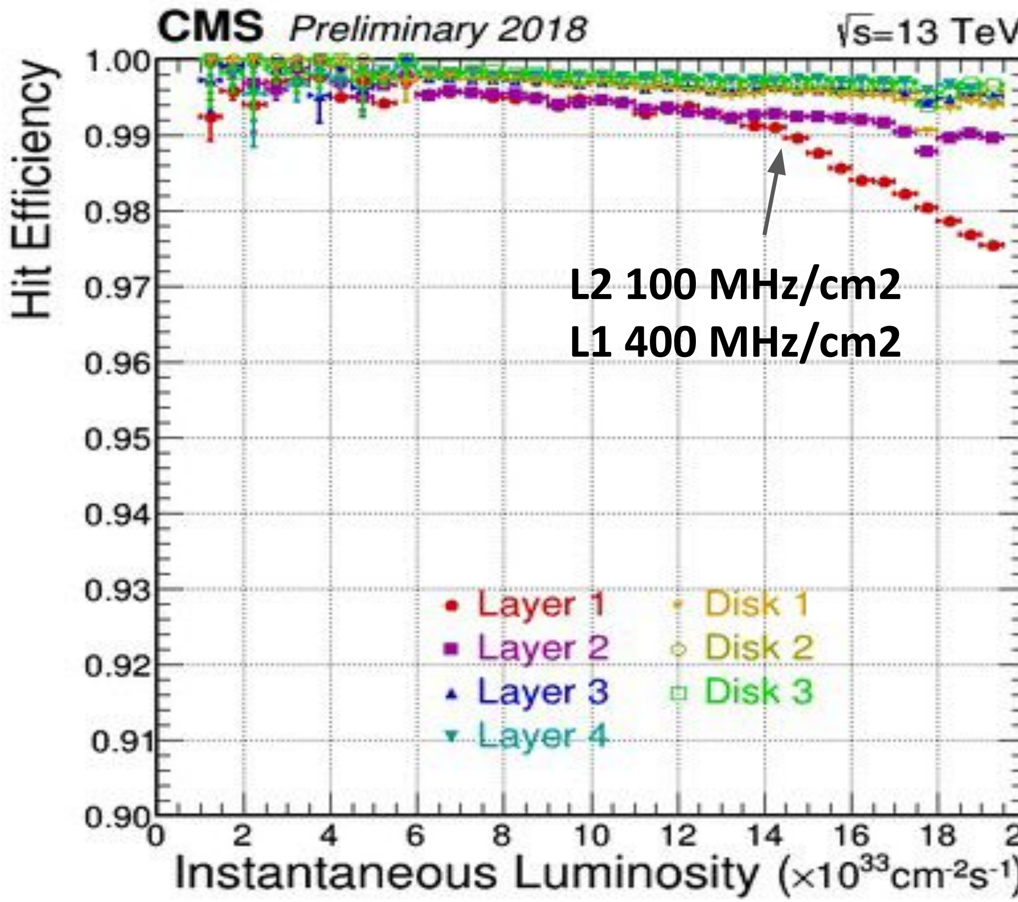


CMS hit rate and efficiency

	Pixel hit rate [MHz/cm^2]	Fluence [$10^{15} n_{eq}/cm^2$]	Dose [Mrad]
BPIX L1	580	2.2	100
BPIX L2	120	0.9	47
BPIX L3	58	0.4	22
BPIX L4	32	0.3	13
FPIX inner rings	56-260	0.4-2.0	21-106
FPIX outer rings	30-75	0.3-0.5	13-28

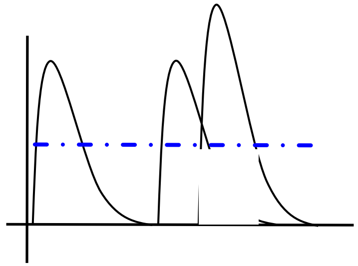
From simulation
Instantaneous luminosity 2 10^{34} cm^{-2} s^{-1}
Integrated luminosity 300 fb^{-1}

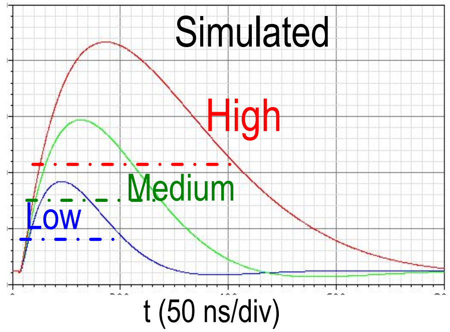
- Inefficiency <3 % till end run2
- PROC 600 designed to stand 600 MHz/cm2



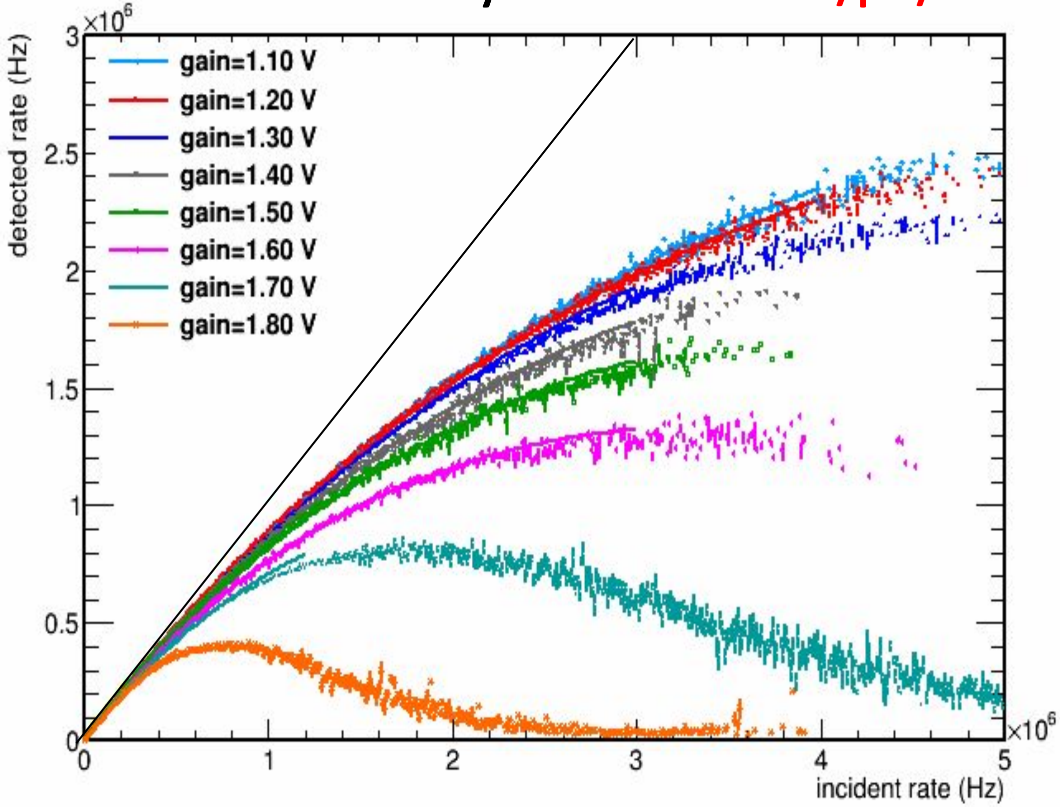
EIGER count rate characterization

PILE UP





90% non linearity 200-700 kcounts/pix/s



Paralizable counter model:

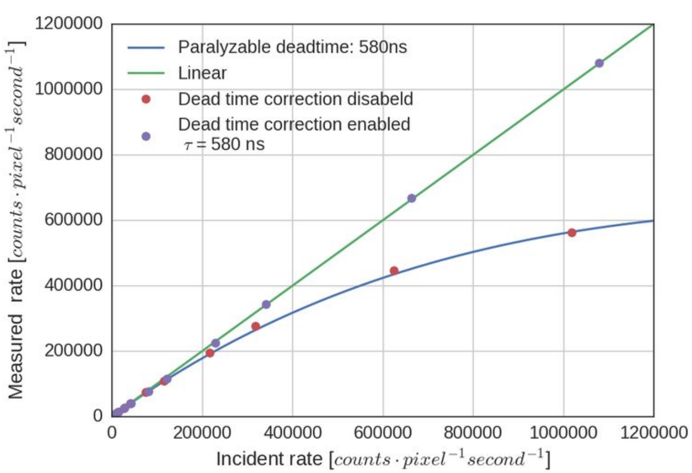
$$N_{det} = N_{inc} \cdot e^{-N_{inc} \cdot \tau}$$

Effect can be partially corrected for

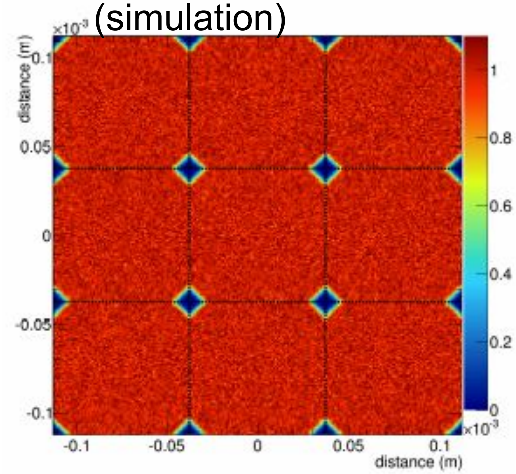
- Dependence on gain settings
- Correction only possible on the ascending part
- ***τ = 200-700 ns***

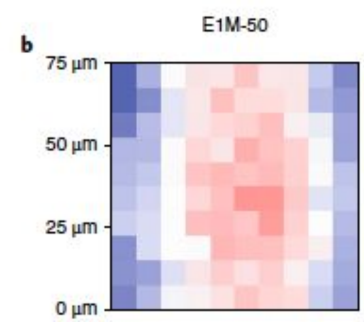
Protein crystallography

High rate capability: 1M counts/pix/s



Corner effect:
(simulation)





Leonarski et al.,
Nature methods 15 (2018)

- Parallelism between CMS (HEP) and EIGER (Synchrotron)
  - Different subdetector components
  - Calibration
  - Rates
- Jungfrau specific implementation for FEL and synchrotron
- Electron microscopy
- Prospects for future developments

Swiss Light Source and SwissFEL

Higher brilliance than synchrotron and faster dynamics

Xrays 250 eV - 12.4 keV (7 to 1 Å)

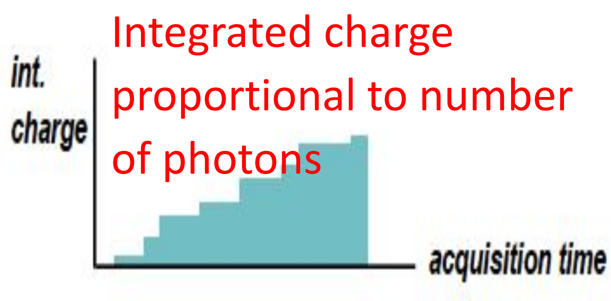
Synchrotron source:

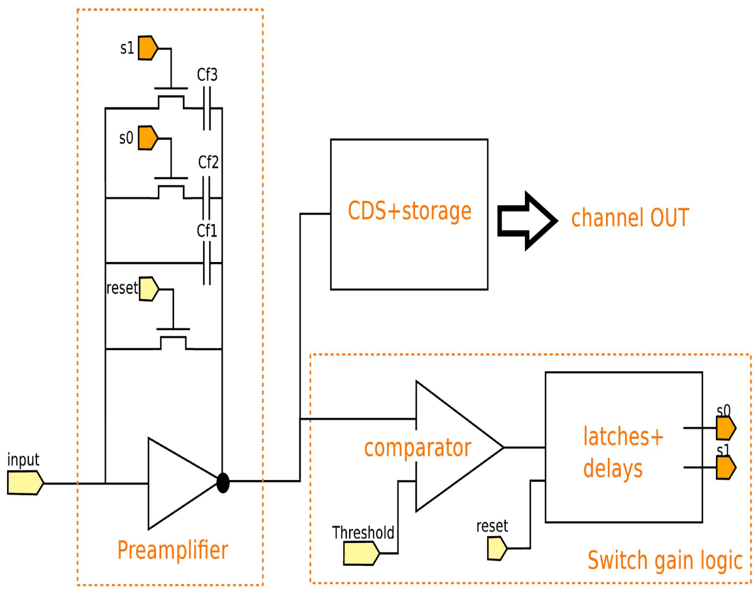
- Semi-continuous, a bunch every 2 ns
- “Weak” bunches → 10^3 photons/pulse
- Bunch length is 20 ps

FEL:

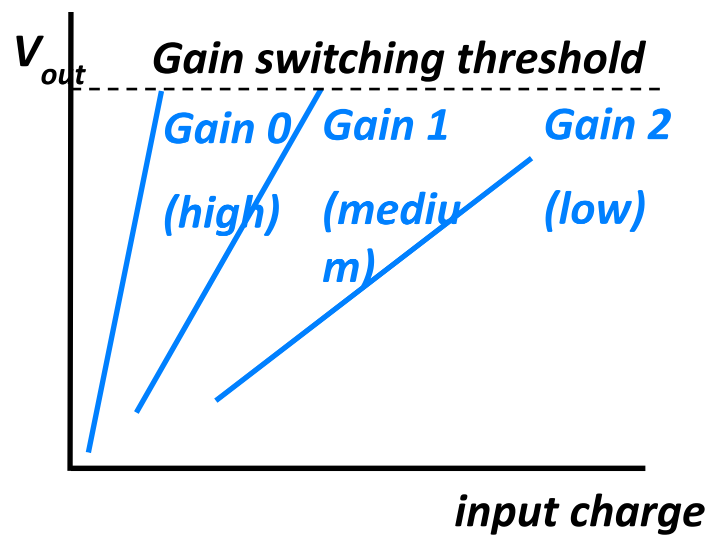
- 100 Hz repetition rate
- Fewer intense bunches → 10^{11} photons/pulse
- All photons in the bunch coming at once (1-60 fs pulse lengths)

CI detector + dynamic gain switching

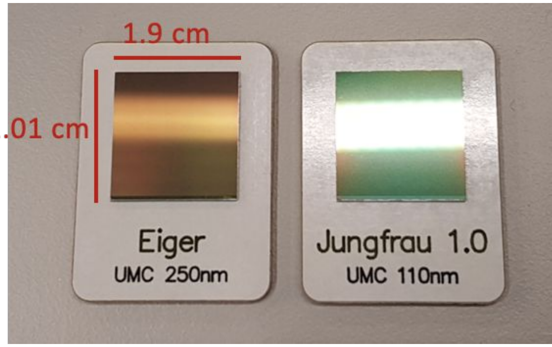


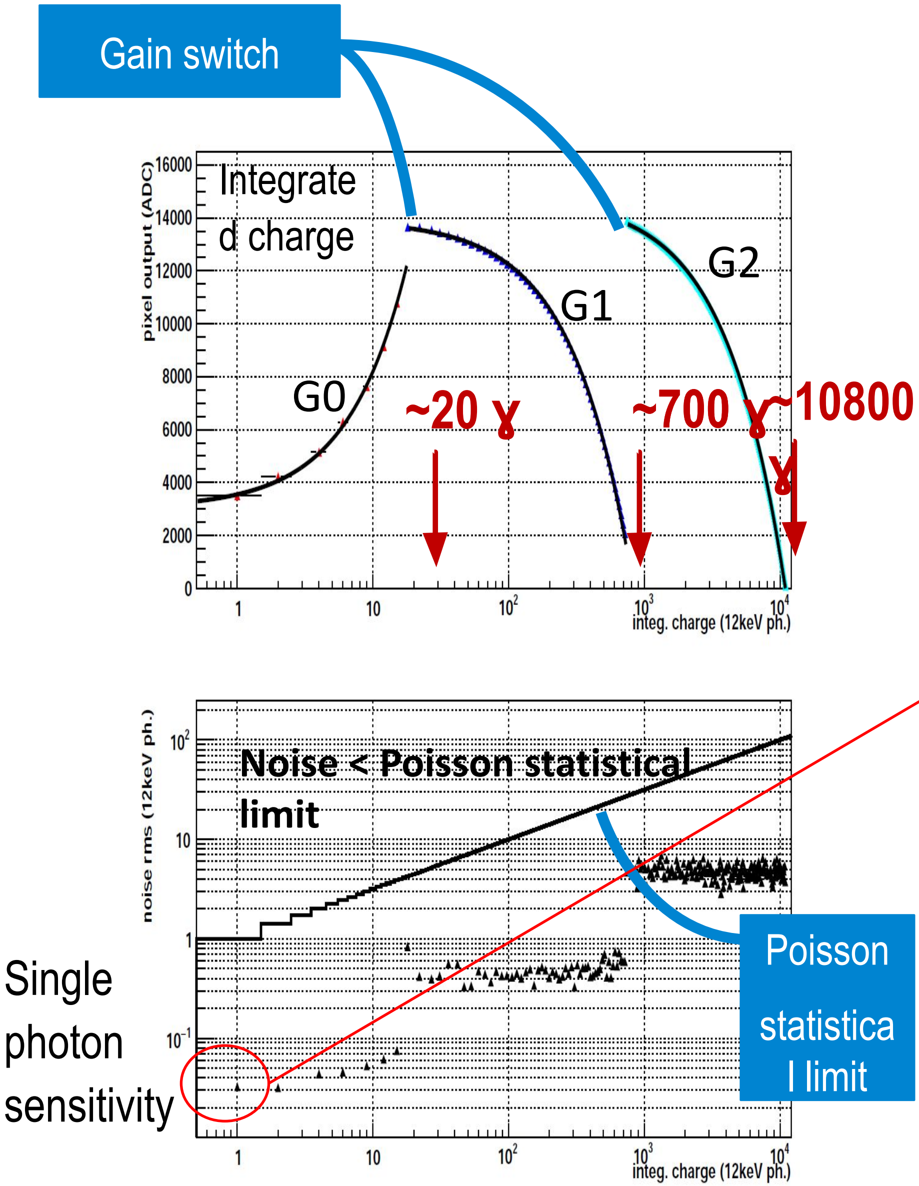


- For the detector the main challenges are:
    - Single photon resolution
    - Dynamic range of 10^4 12 keV photons per acquisition
- In exposure 'dynamic gain switching' is our solution

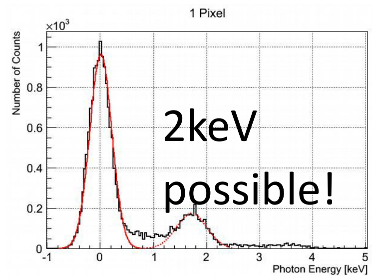


Gain switching and noise





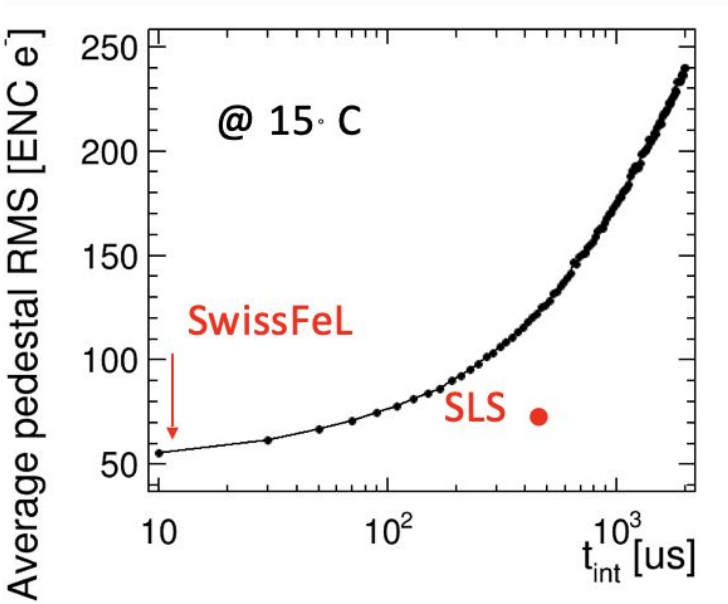
- Dynamic range is 10^4 12 keV photons



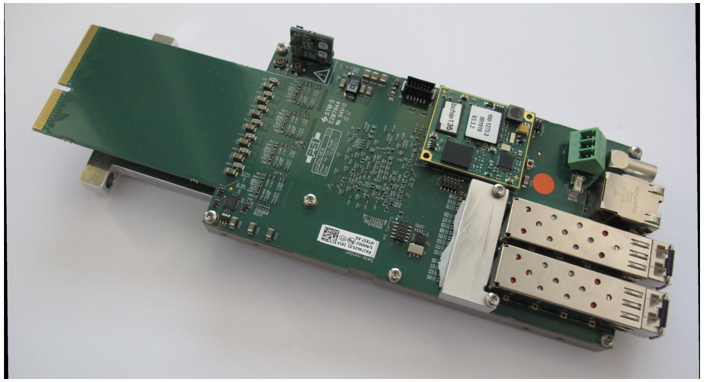
- Noise < statistical limit
- Single photon resolution at 2keV
- JF gives single photon counting equivalent data quality
- Large dynamic range ⟶ high rate capability
  - 1000 photons @ 12 keV
  - 12000 photons @ 1 keV

JUNGFRAU readout: FEL vs synchrotrons

	Integration t [µs]	Frame rate [Hz]	Data rate/module [Gbit/s]
SwissFEL	10	100	0.8
Synchrotron	400	2.2 k	18



New readout board (2019)

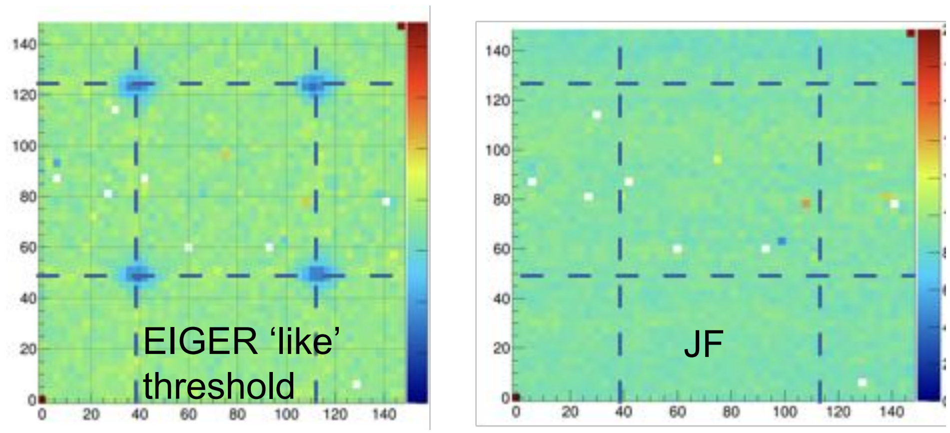


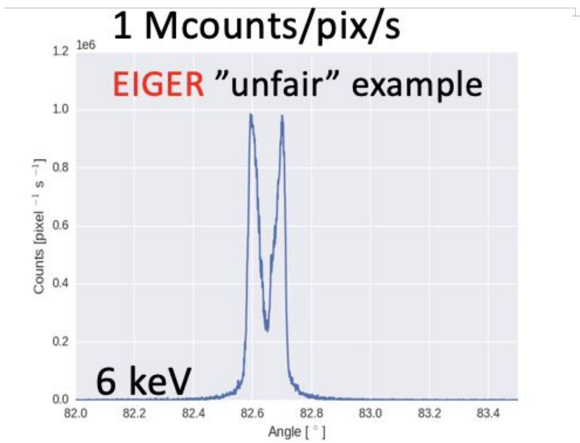
- Integrated charge from dark images: sensitive to leakage current
- The longer the exposure, the higher the integrated dark image charge
- Cooling of the sensor necessary (down to -12°C)

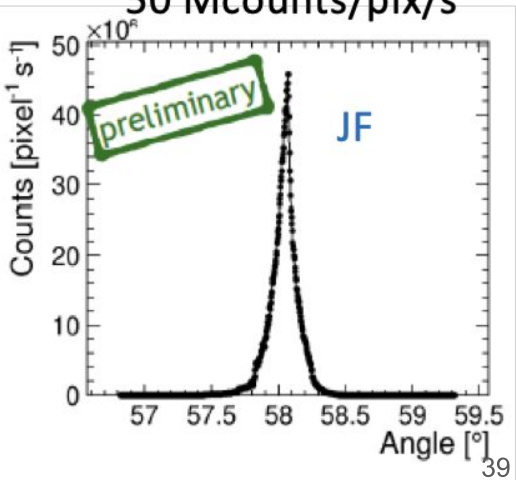
Advantages of JF at synchrotrons

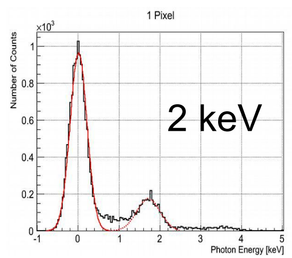
1. EIGER can loose small diffraction peaks between pixels in the case the events is at the corner of 4 pixels → JF provides better pixel uniformity
2. EIGER is limited by pile up → JF has much higher rate capability, fast data acquisition with higher transmission possible
3. EIGER has a lower threshold limit at 3 keV (ideal for 6keV beam). JF tested at synchrotrons at 3.75 keV

Pencil beam scan, 20 keV









- Parallelism between CMS (HEP) and EIGER (Synchrotron)
    - Different subdetector components
    - Calibration
    - Rates

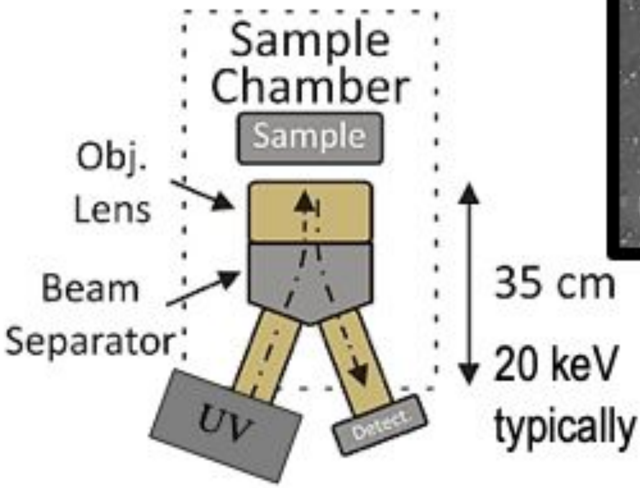
- Jungfrau specific implementation for FEL and synchrotron

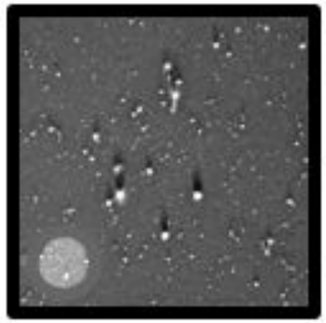
- Electron microscopy

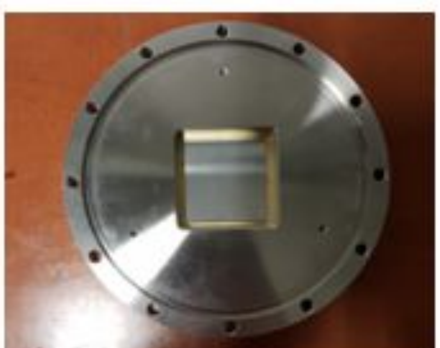
- Prospects for future developments

EIGER in electron microscopy

- **PEEM - Photo Emission Electron Microscopy - Imaging**
  - ELMITEC, SIM Beamline SLS
  - 20keV Electrons

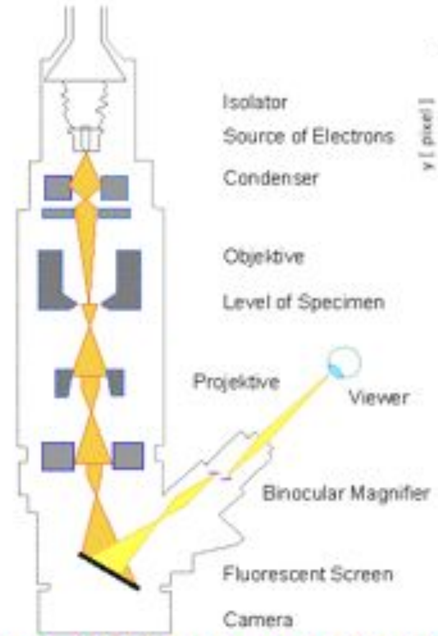


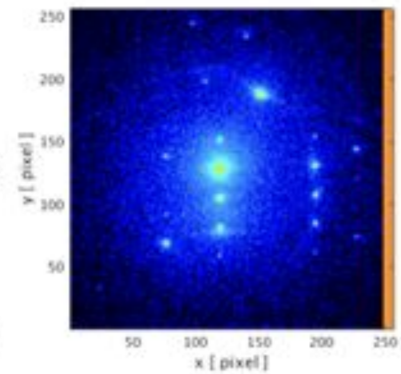




- Quad: active area 4x4 cm^2
- In vacuum

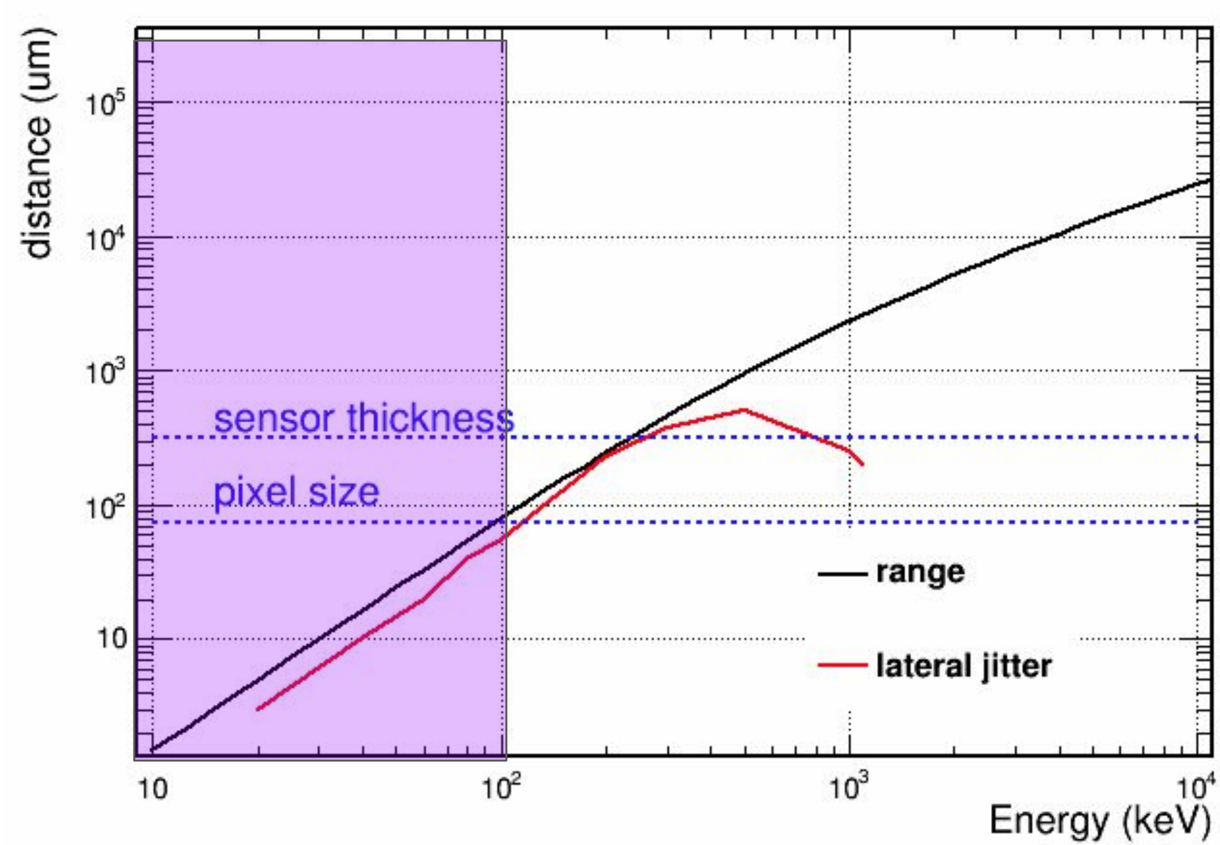
- **TEM - Transmission electron microscopy - Electron Diffraction/(Imaging)**
  - Prof. Jan Pieter Abrahams C-CINA/PSI
  - 100 – 300 keV

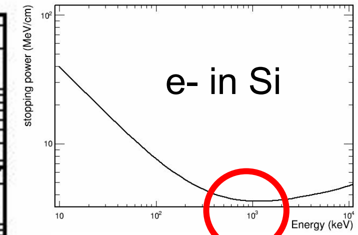




- **For energies <=100 keV, hybrid pixels are an "ideal detector"**
- **At higher energies, EIGER is appealing thanks to frame rate: scanning/rotation techniques, imaging single electrons, reducing sample drift**

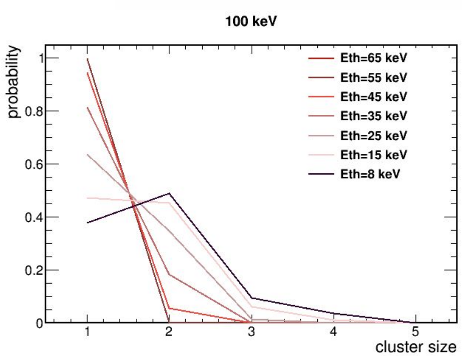
EIGER as a detector for low energy electrons

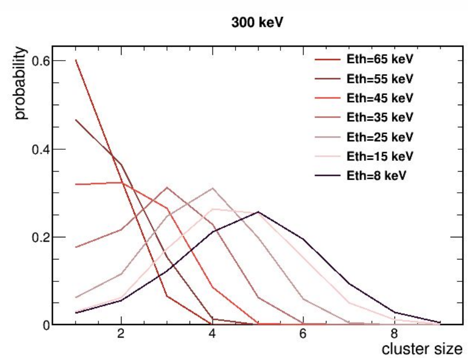


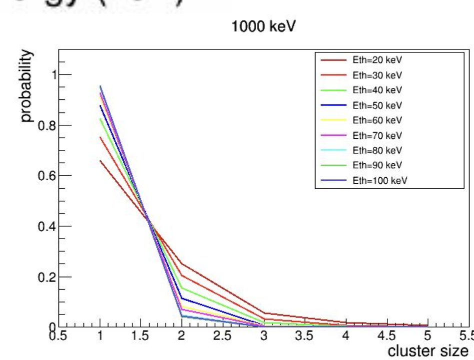


MIP @ 1 MeV

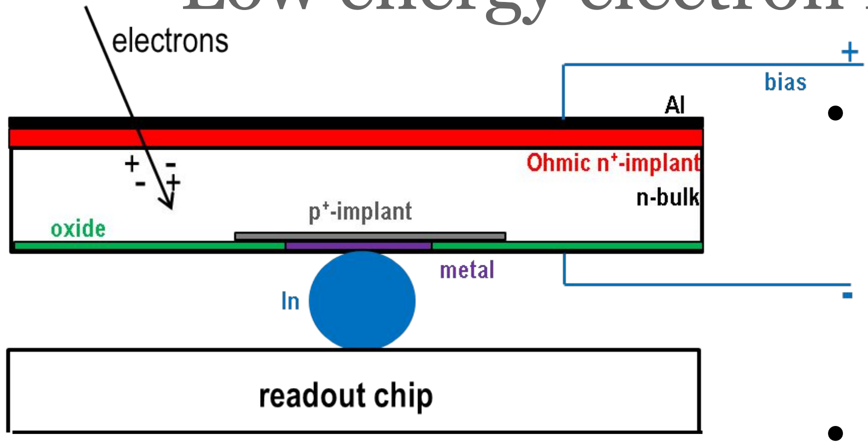
75 x 75 um2





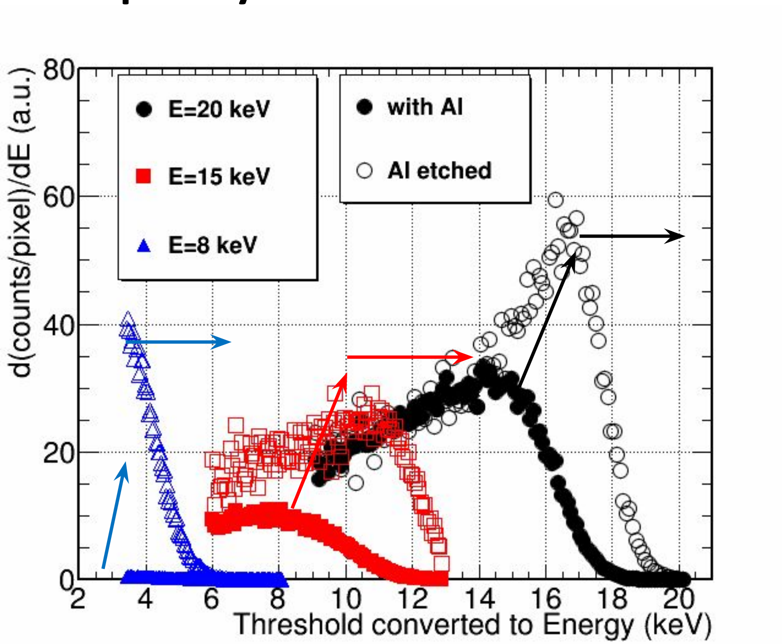


Low energy electron interaction



- e^- interaction:
  - lose energy due to multiple collisions with atomic electrons
  - Deposit energy in multiple points due to multiple scattering
- Al layer can be etched away
- e^- lose part of their energy in Si backplane

Completely rad hard for 8-20 keV e^-



Tinti et al., JSR 5 2017

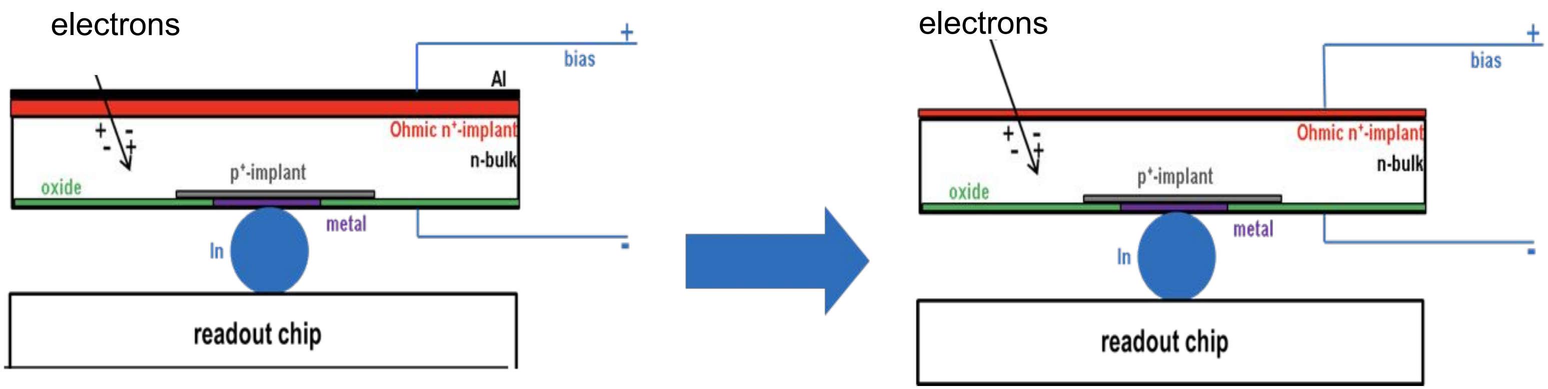
Standard entrance window

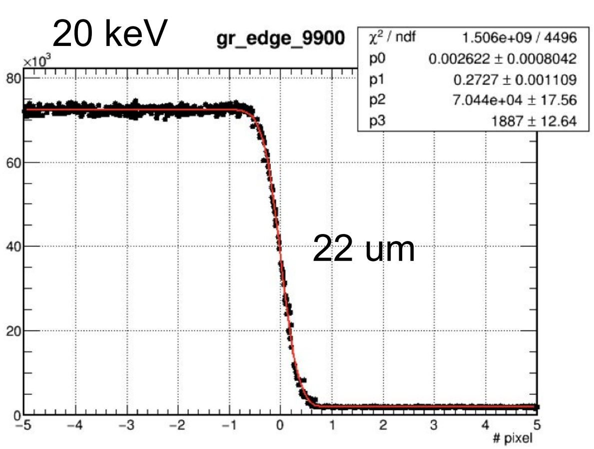
Material crossed	20 keV e^-	10 keV e^-
Al 1µm	2.6 keV	5 keV
Si 1.5µm	3 keV	4 keV
Si 200 nm	**0.5keV**	**0.9keV**

Sensor designed:
Plans to measure DQE

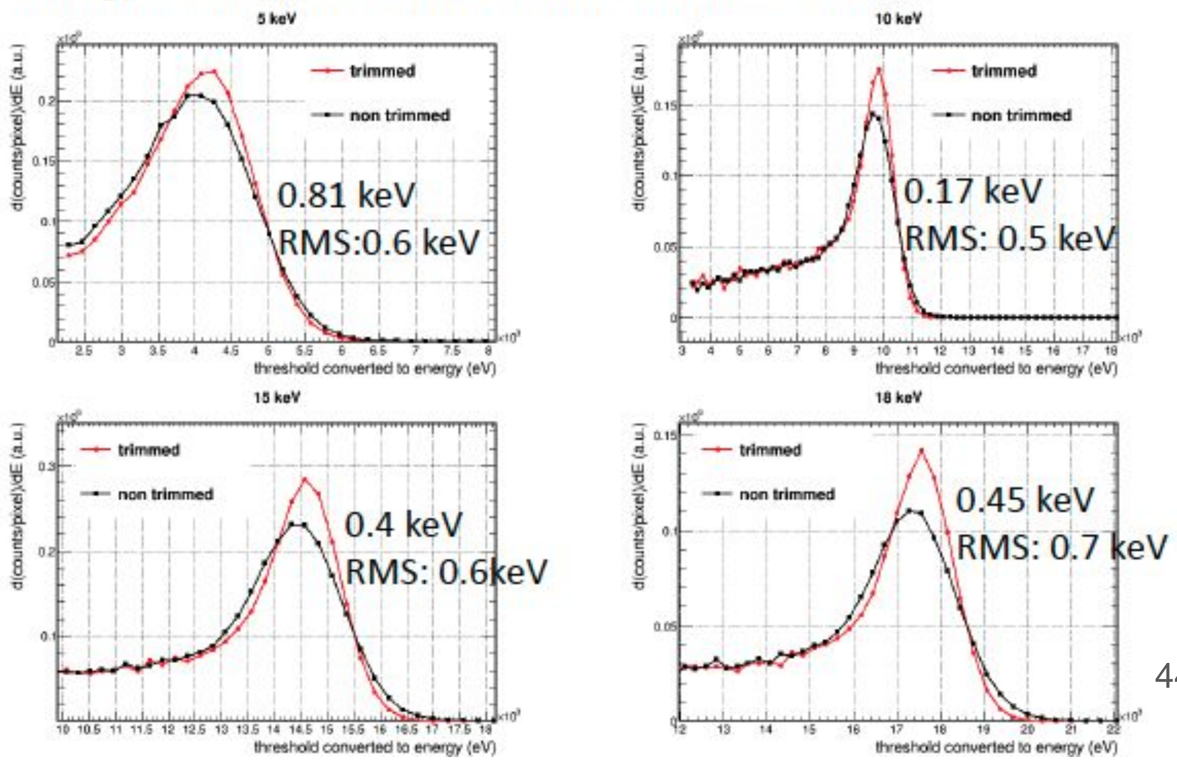
Thin entrance window sensors

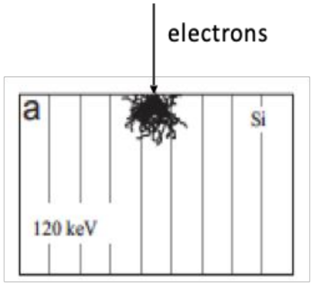
FBK



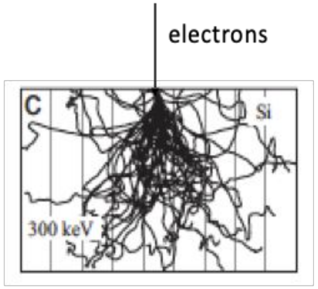


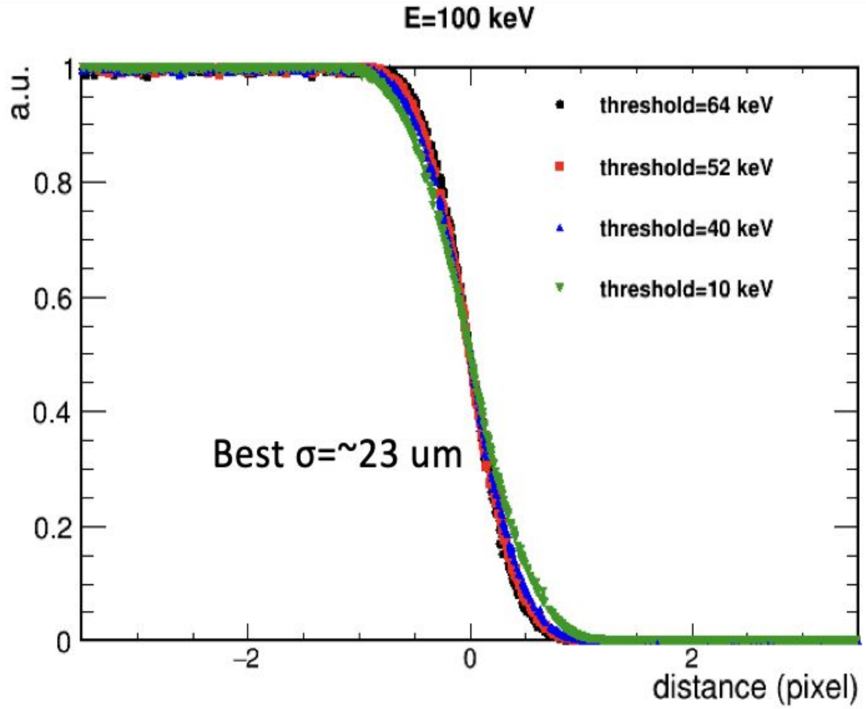
Energy lost in the new thin entrance window sensors:

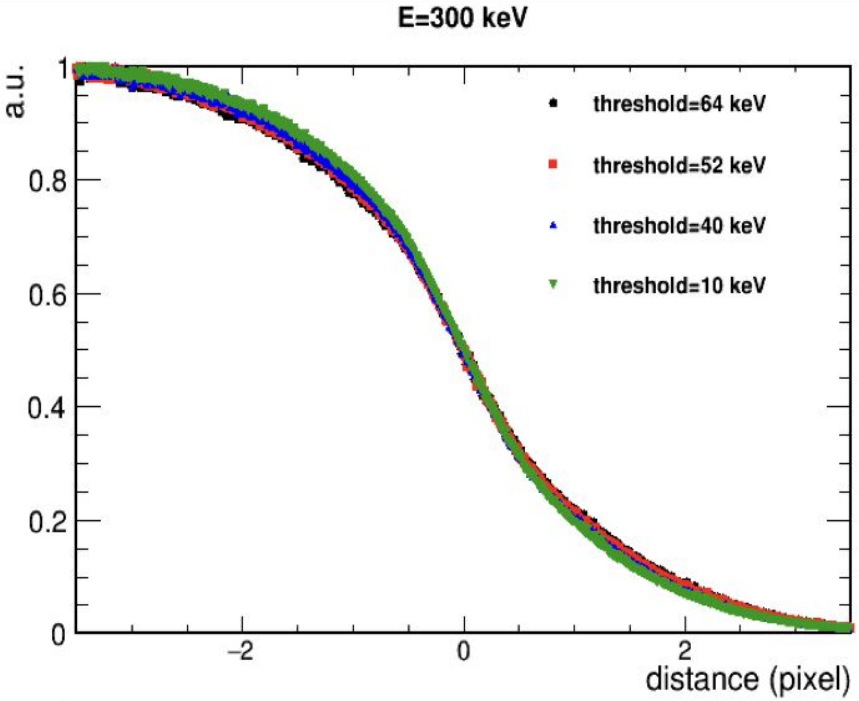




e- deposit energy in multiple points due to multiple scattering



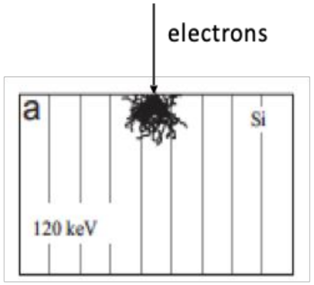




100keV: Single pixel resolution, good for imaging and diffraction

200-300keV: Good for diffraction

Tinti el al., IUCrJ 2018 5(2)



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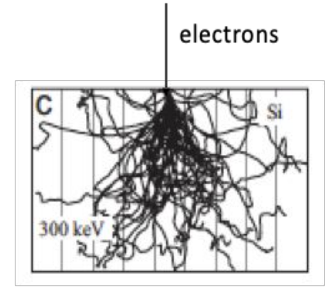
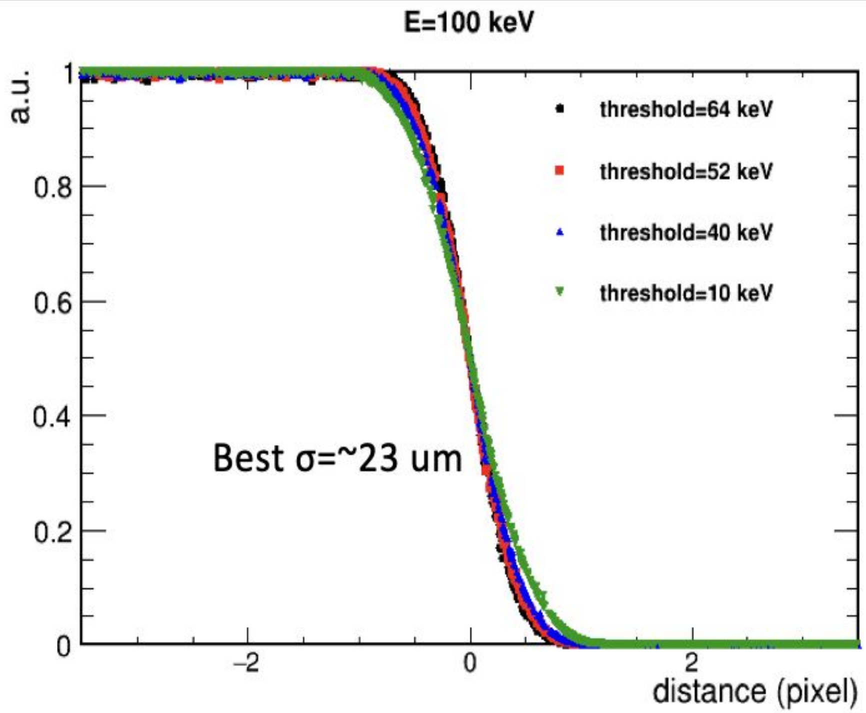
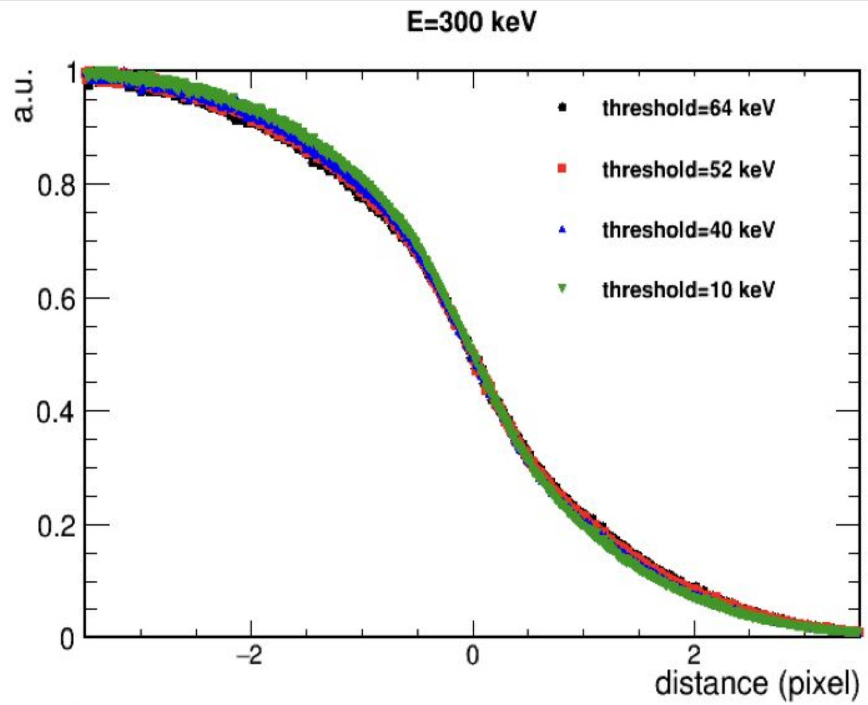






- High-Z sensors for 300 keV electrons
- Smaller pixels (same sensor height) : ONLY useful with TIMING info → TIMEPIX
- THIN MONOLITHIC pixel detectors for E>100 keV but RADIATION HARNESS

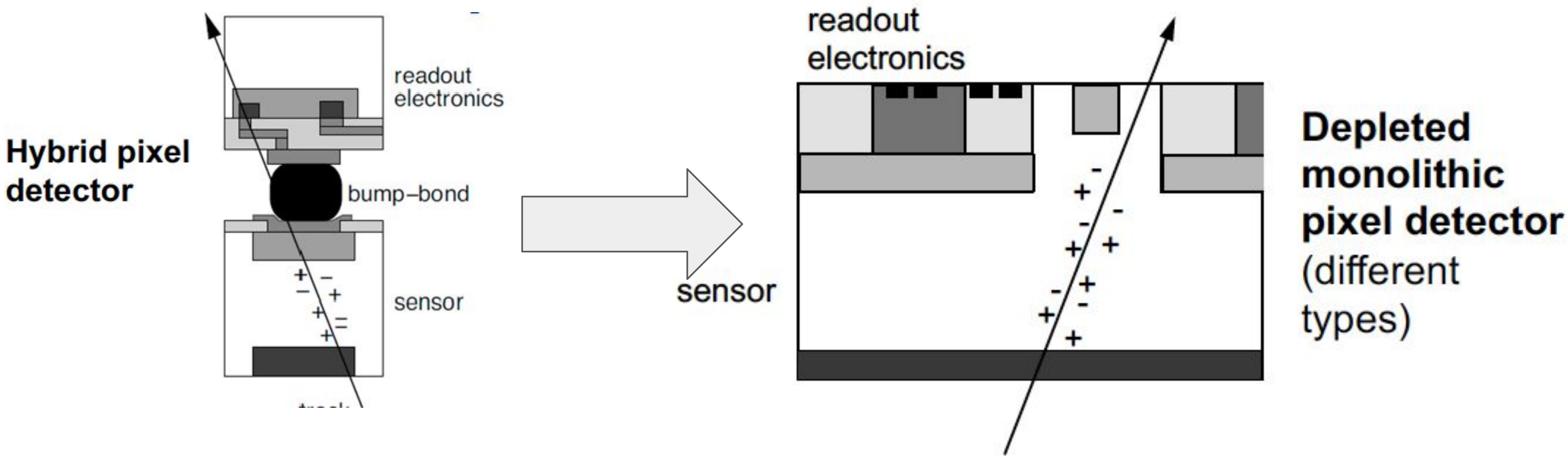
- Parallelism between CMS (HEP) and EIGER (Synchrotron)
  - Different subdetector components
  - Calibration
  - Rates

- Jungfrau specific implementation for FEL and synchrotron

- Electron microscopy

- Prospects for future developments

R&D fur future HEP pixel detectors

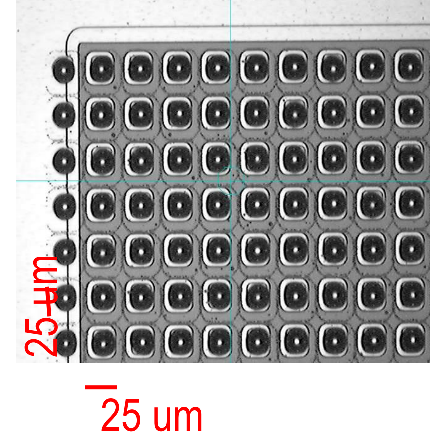


Exploit potential offered by depleted monolithic pixel detector technology:

- less material → less multiple scattering
- smaller pixels → improved spatial resolution
- lower costs → large area pixel detector

High radiation tolerance extension needs R&D studies

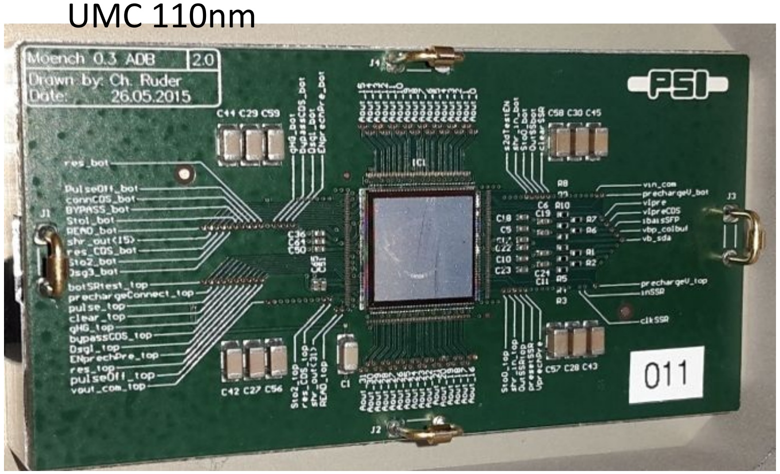
MÖNCH



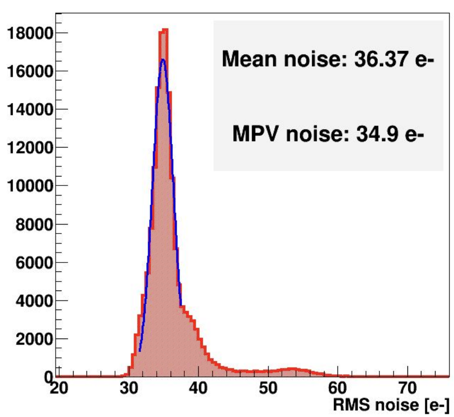
Small pixels + charge sharing → spatial resolution
Low noise → low energy

25 x 25 μm^2 pixel size

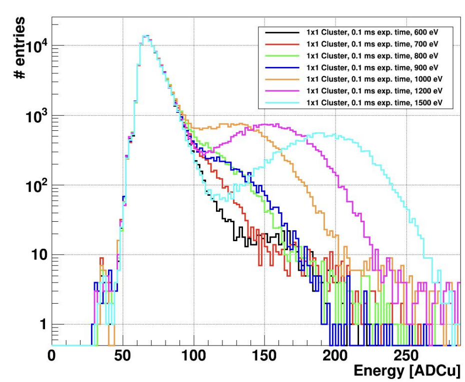
UMC 110nm



- Area 1x1 cm^2
- Charge integrating
- Pixel architecture optimized for low noise
  - No dynamic gain switching
- 2-3 kHz frame rate (10 Gb port)
  - Up to 6 kHz by design



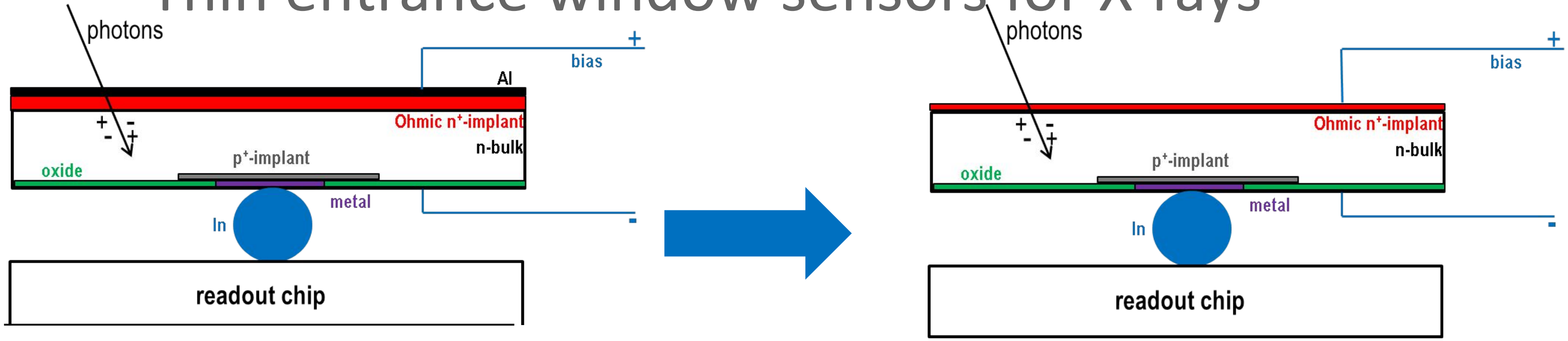
requiring > 5 σ noise RMS



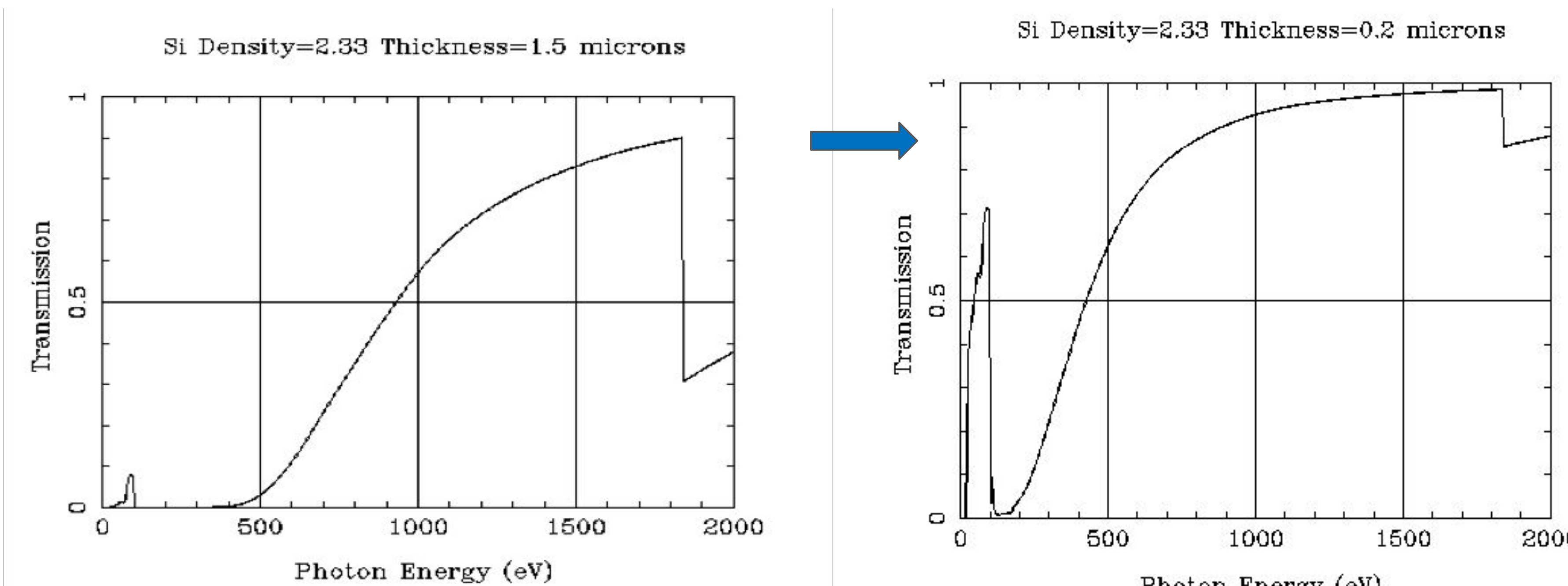
Single photon resolution down to about 800 eV (220e-)

Thin entrance window sensors for X-rays

FBK

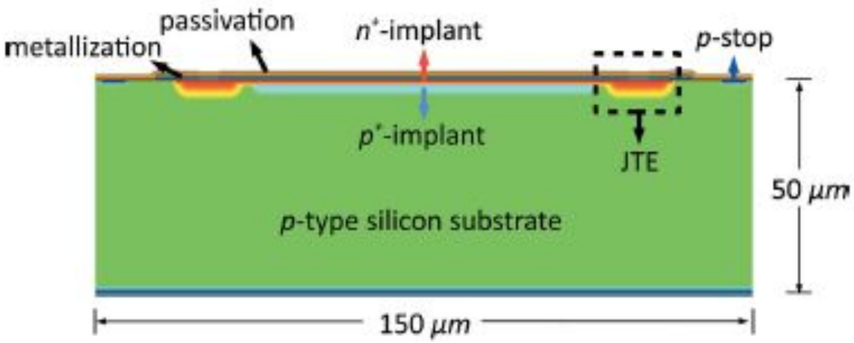


- 200nm thin backplane sensors are being tested now for JUNGFRAU and MOENCH
- Extend the transmission> 600eV and in the ultra violet region



Low Gain Avalanche Detectors (LGAD)

Collaboration with FBK to design optimal sensors



Charge multiplication

Amplify signal in the sensor

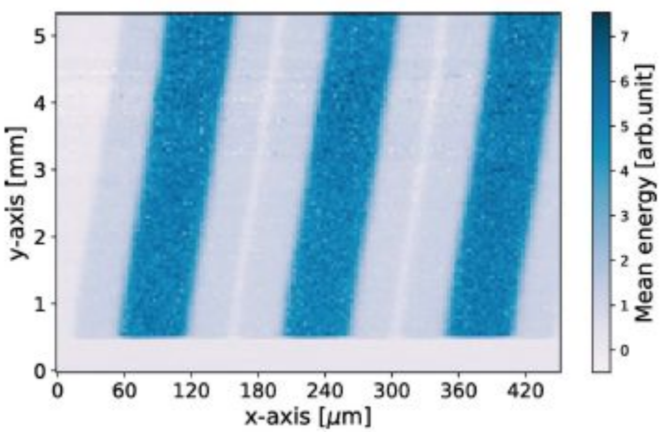
Moderate gain (5-20)

No dark counts

Andrae et al, JSR 2019 26

Same technology used in HEP to improve timing

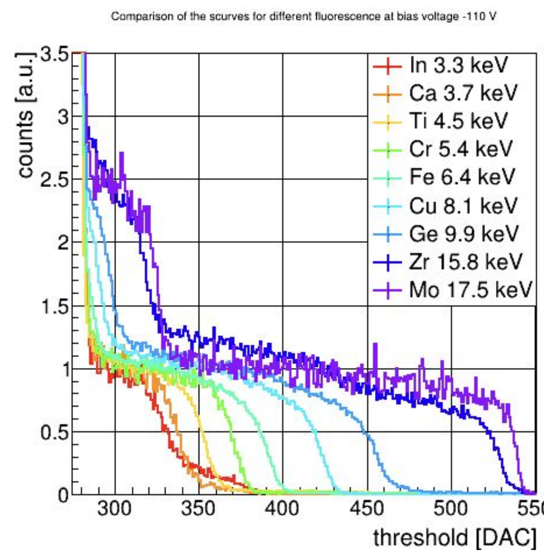
By amplifying the signal already in the sensor, one can detect energies that are not possible with a standard sensor: >3 keV can be easily seen vs 8 keV of the standard detector



150 μm strip-pitch, 50 μm thick on substrate, 4 mm long

High input capacitance (~2.5 pF) → higher noise

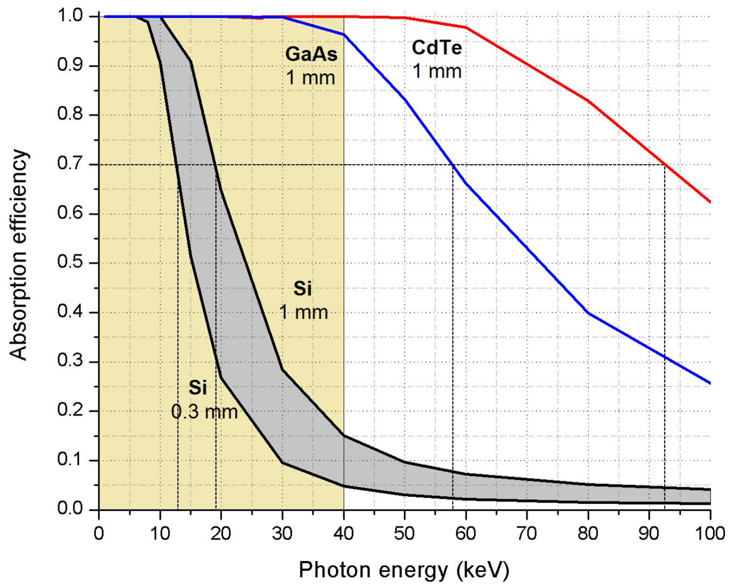
Region without multiplication between strips: fill factor ~45%



Only strip detectors tested so far, pixel planned in the future, but fill factor and segmentation need to be improved

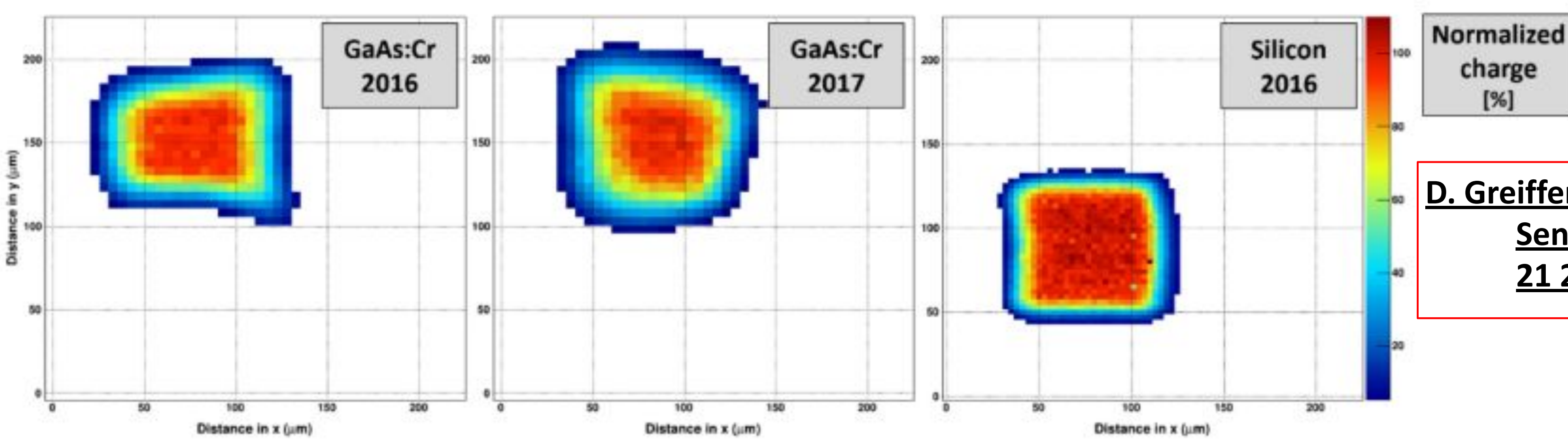
R&D towards pixelated LGADs with thin entrance window: goal extend EIGER use to 1keV

High-Z sensors for higher energies



- Extend efficiency for higher energy X-rays
- Ideally use for electron microscopy >100keV
- Extensive R&D program needed to achieve same quality as Si

Pencil beam scan of the charge collected by a single pixel (20keV):



D. Greiffenberg at al, Sensors 21 2021

Conclusions

- HEP:
  - Operation of phase I CMS
  - Involvement in HL-LHC forward region acceptance extension TEPX Phase II (2027)
  - Extension of radiation tolerance and monolithic

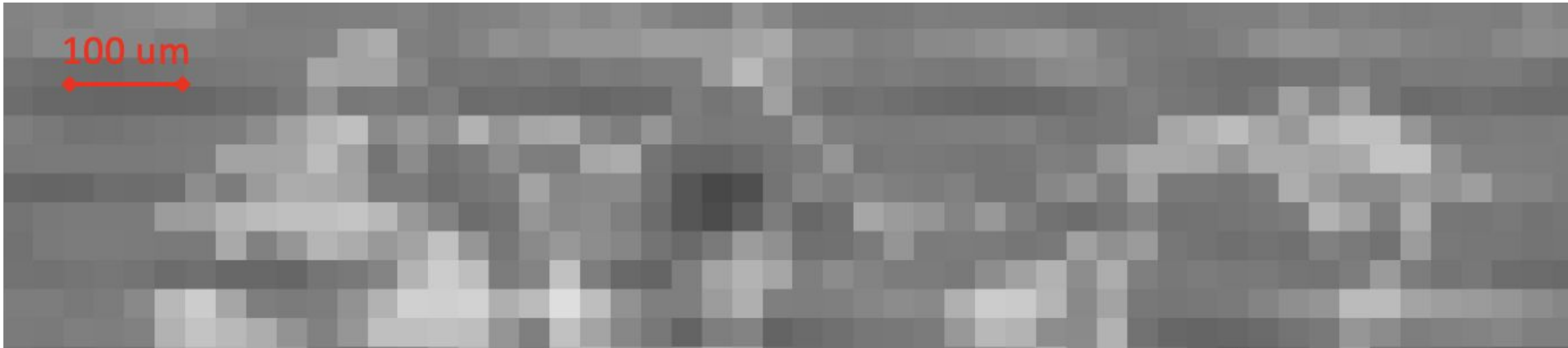
- Synchrotron:
  - Maintaining single photon counting technology as advantages of data reduction compared to charge integrating detectors
  - count rate capability (1M counts/pix/s) $\longrightarrow$ 20 Mcounts/pix/s in view of SLS2 (2024)
  - Extension of use >1keV through special sensors

- FEL:
  - Large data handling to be further developed
  - Even lower noise readout chips for single photon resolution at >700eV (90eV) with special sensors

- Electron microscopy:
  - High count rates in diffraction require use of charge integrating technology
  - Monolithic pixel detectors to limit multiple scattering

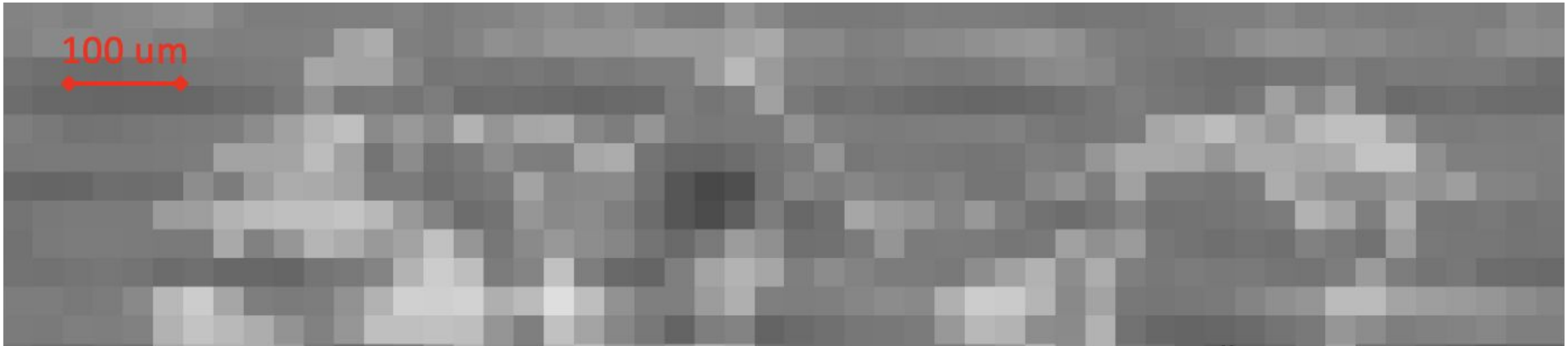
SUCH A COMPREHENSIVE RESEARCH PLAN CAN BE DEVELOPED ONLY IN A RESEARCH CENTER

Spatial interpolation with MÖNCH



Gold on Silicon sample, MS beamline (SLS), 8keV, with MÖNCH

Spatial interpolation with MÖNCH



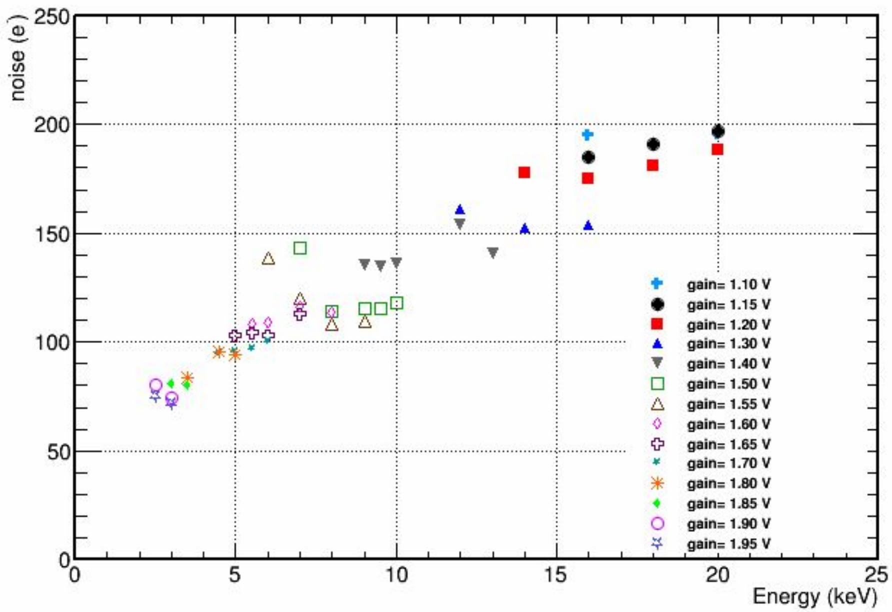
Gold on Silicon sample, MS beamline (SLS), 8keV, with MÖNCH

Eiger Mönch Jungfrau

Thanks for the attention!

Threshold energy calibration

Tinti et al., Performance of the EIGER single photon counting detector, JINST 10 C03011 (2015)

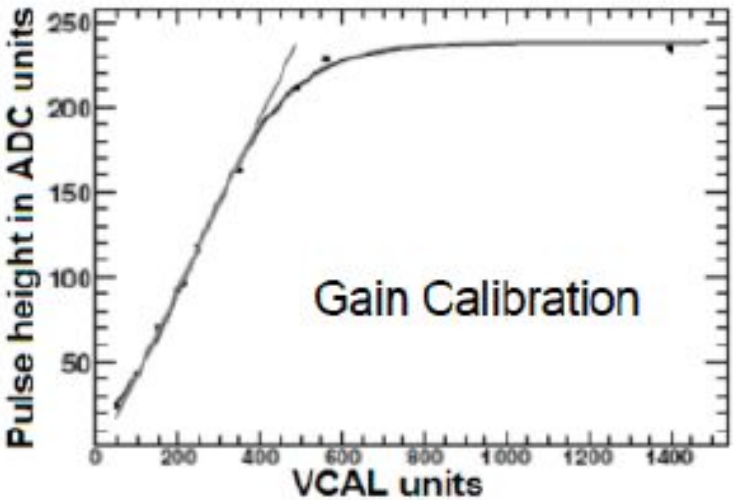


$$RMS_{tot} = \sqrt{RMS^2_{noise} + RMS^2_{th}}$$

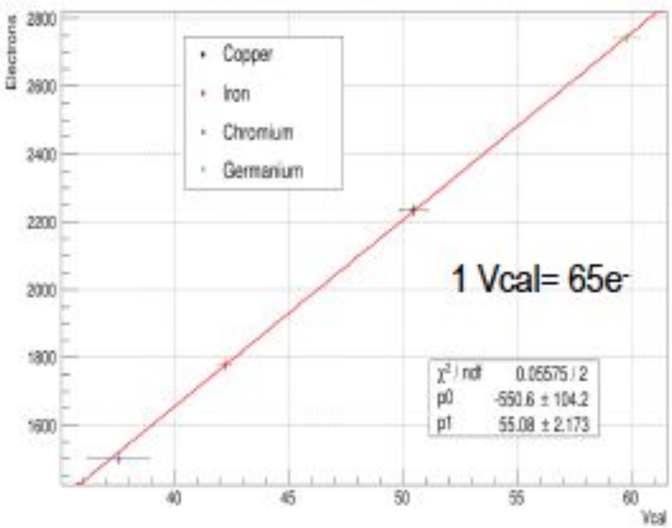
- Noise RMS: 100 - 200 e- depending on preamp gain:
- 360 - 720 eV Noise RMS

Gain calibration

Calibrated conversion from ADC units to deposited charge units:



Cal signal calibration

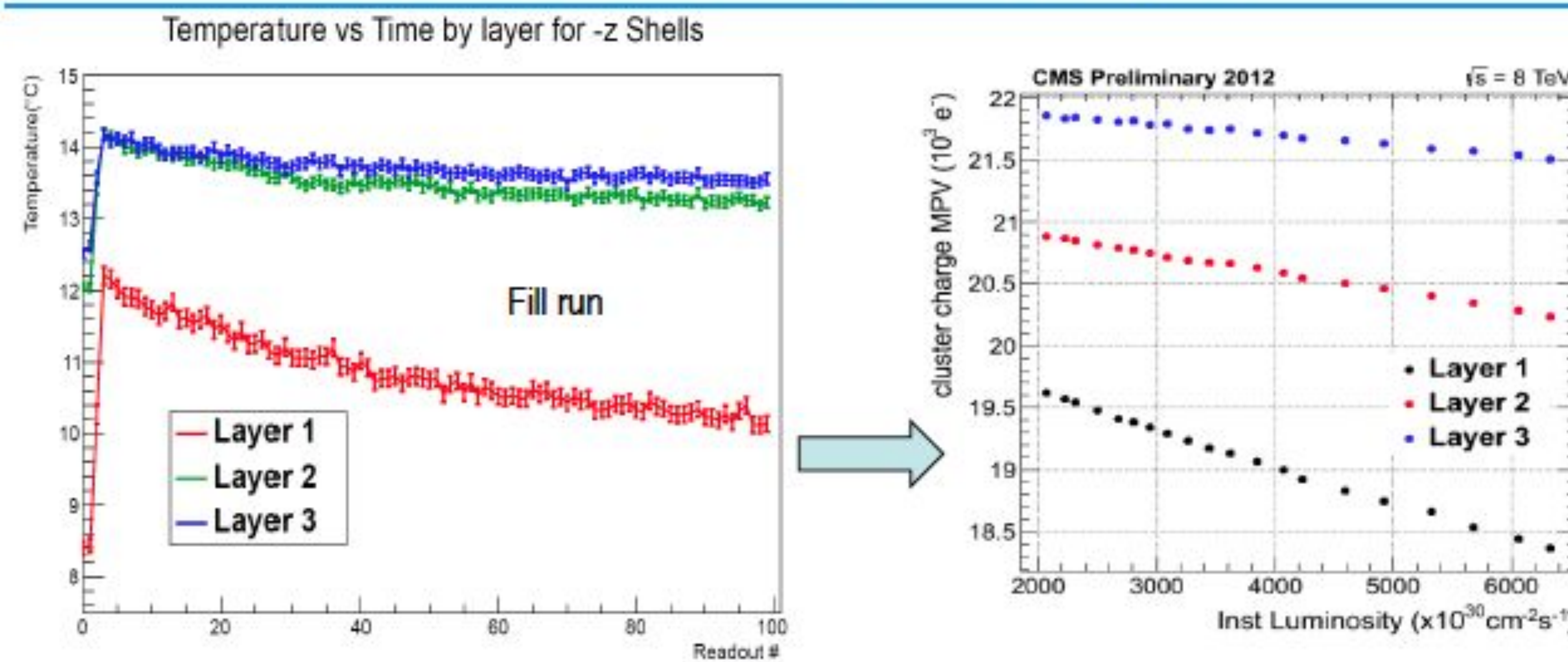


Gain calibration is dependent from:

- temperature
- radiation
- analog voltage setting

Calibration similar to the one required by charge integrating detectors with analog readout for photon science

Gain calibration as function of occupancy



- Temperature sensor on the readout chip. Calibration performed offline.
- **Higher occupancy ➔ higher digital activity ➔ higher temperature**
- During fill, the temperature decays exponentially following instantaneous luminosity
- Effect visible in the cluster charge: **Occupancy dependent gain calibration**

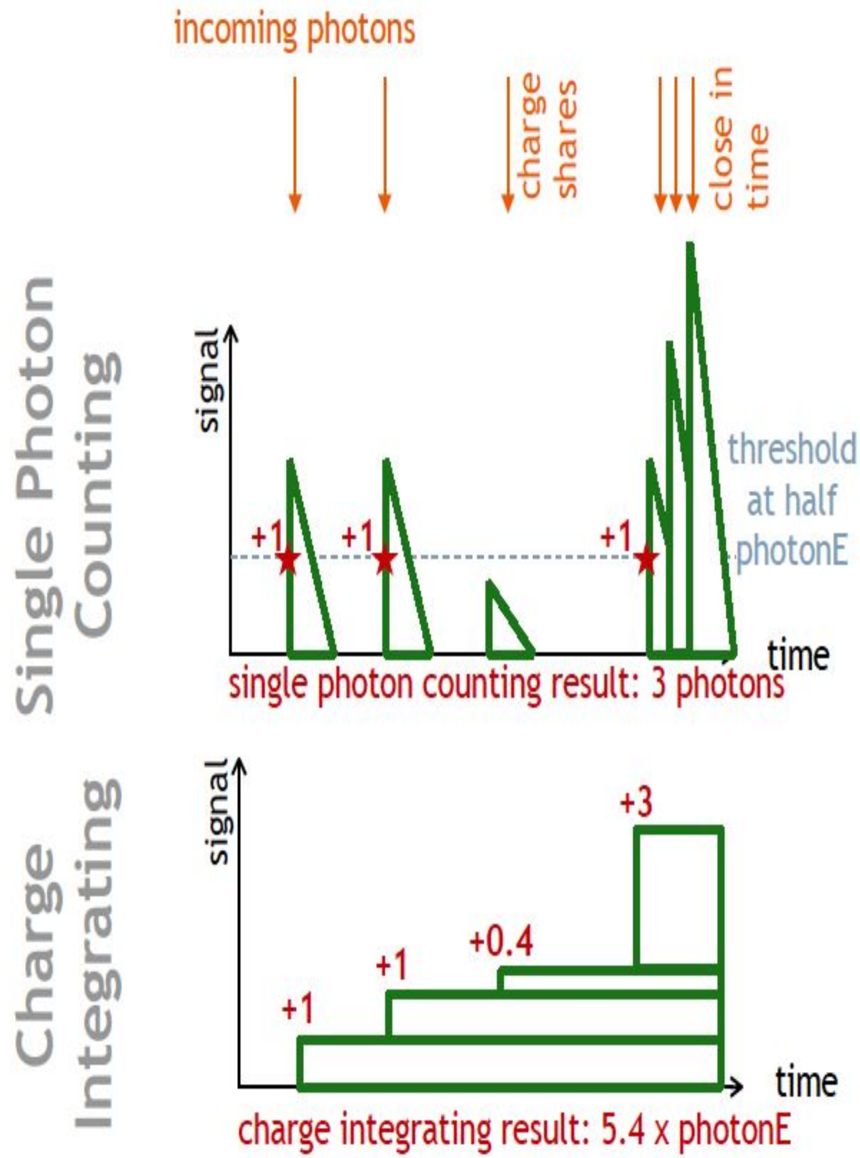
Single Photon Counting vs Charge integrating detectors

SINGLE PHOTON COUNTERS:

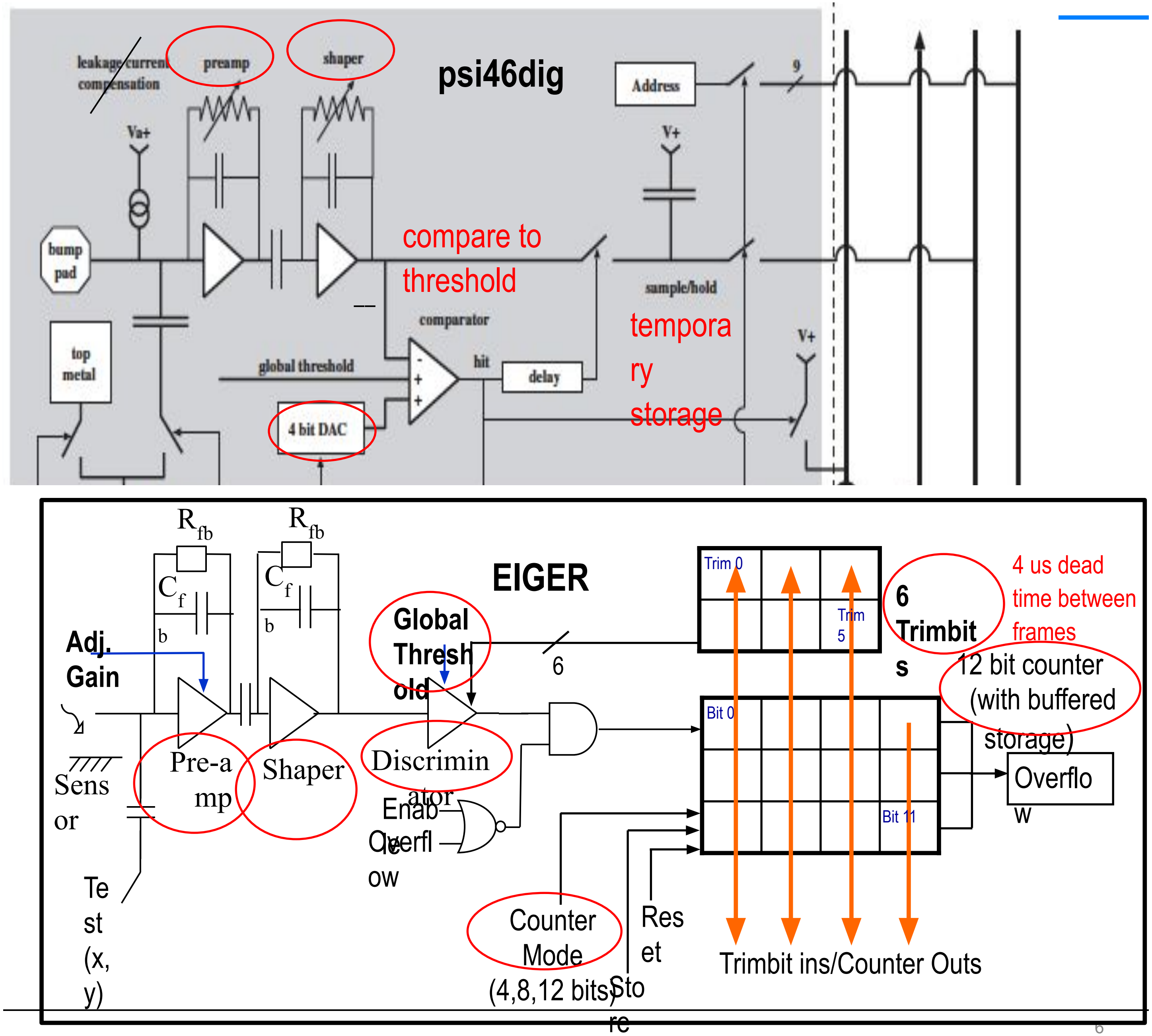
- Count a photon every time the signal is above a threshold
- Dynamic range limited by counter depth
- Ideal signal over noise ratio
- The threshold allows for fluorescence rejection
- Time required by the signal to return under threshold ~100ns → synchrotrons

CHARGE INTEGRATING DETECTORS:

- Integrate charge during acquisition window
- Necessary at FELs
- No minimum photon energy, but the noise is measured
- For monochromatic beam,



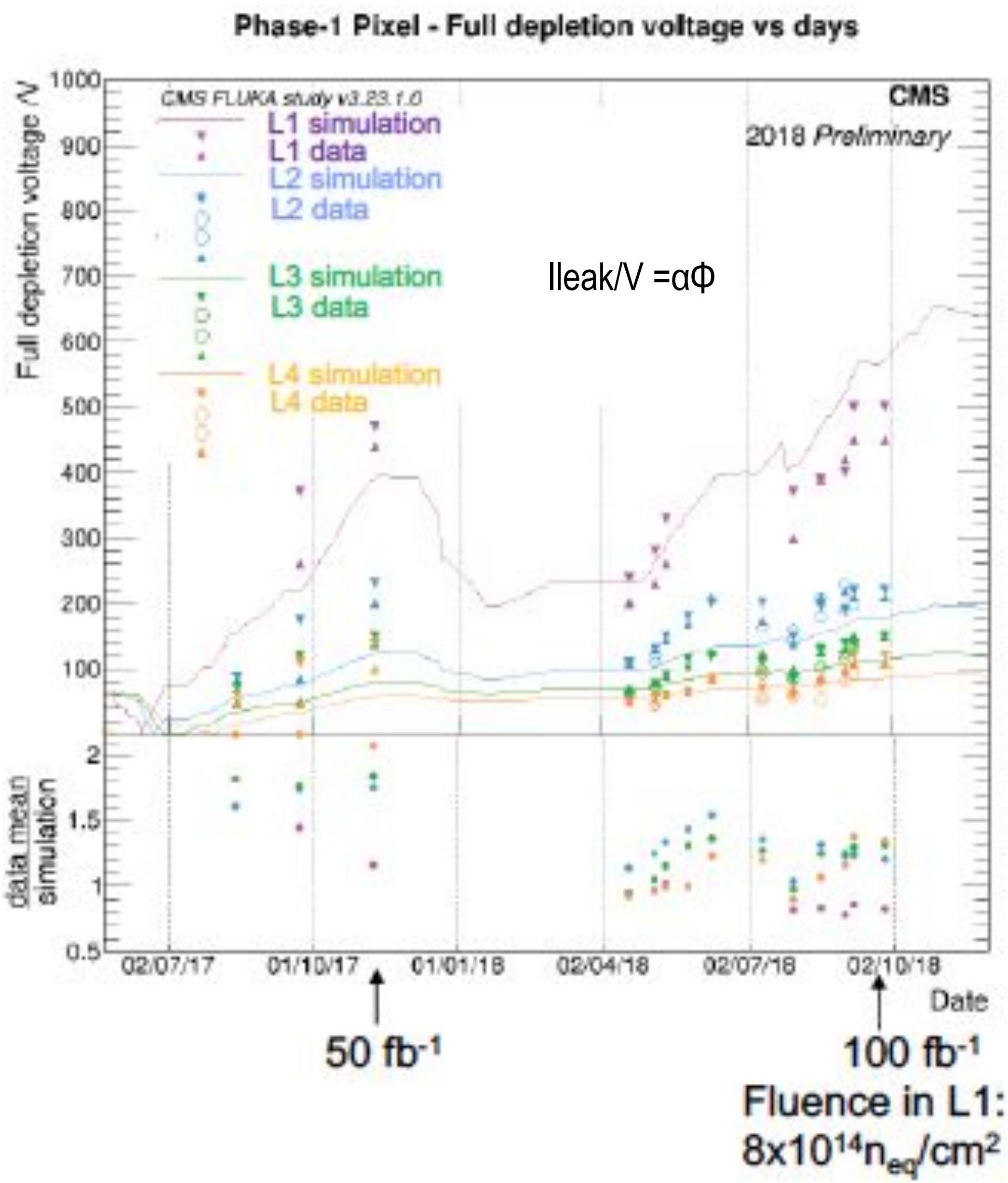
Analog functionality in a pixel cell



Pixel detector development at the Paul Scherrer Institut (CH):

- High Energy Physics
- Synchrotron Radiation
- Free-electron lasers
- Electron microscopes

Leakage current



- Radiation effects due to surface sensor damage
- Increase in i_leak proportional to fluence
- Depends on T and annealing

- Expect to collect 300 fb^{-1} in LHC Run 3 (2021-2024)

Detector integration concept

Detector: 18 modules

36x10GbE

TCP
x36

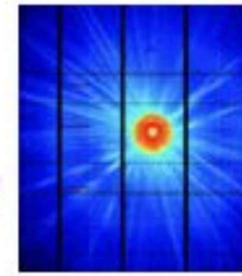
Control PC
beamline

UDP
stream
x36

Receiver

x72
receivers
on a server

PREVIEW



zmq

- Independent half modules
- Parallel data processing/ transmission
- 9 M with 36 half modules (18 modules) 360Gb/ s

Limited to 2GB/ s

zmq

writer

data (metadata added from client)

38 MB/image

Storage
(GPFS)

Limited to 1.6GB/s
currently

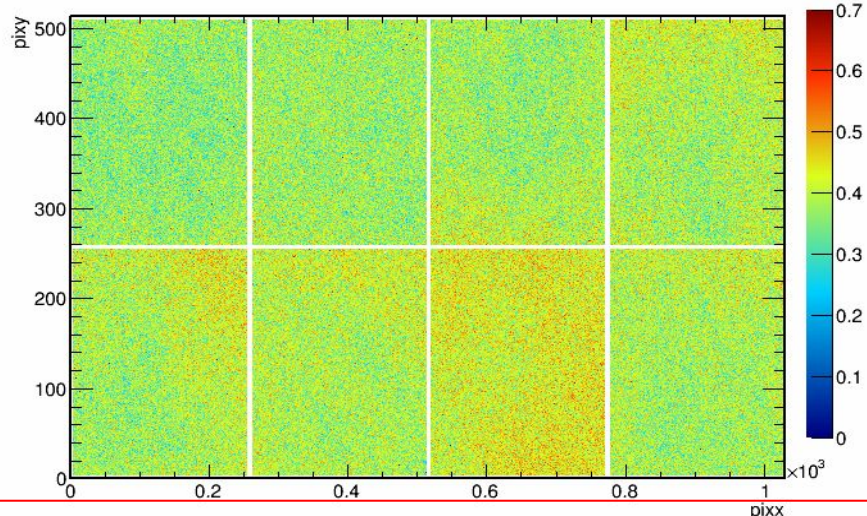
infiniband

Phase I: User operation at minimum 25 Hz for 32-bit starting from Feb 2019

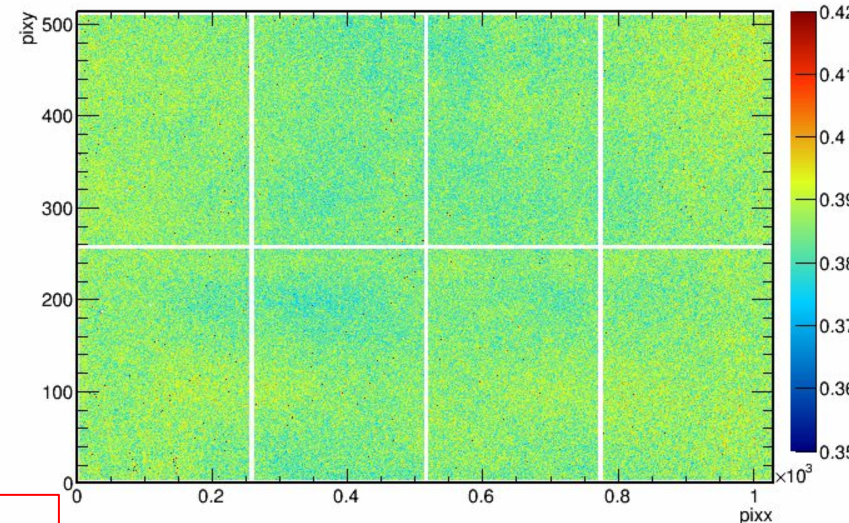
Expected: 42 Hz, 1.6GB/s.   The detector can send out up to 45 GB/s

Threshold dispersion: threshold equalization

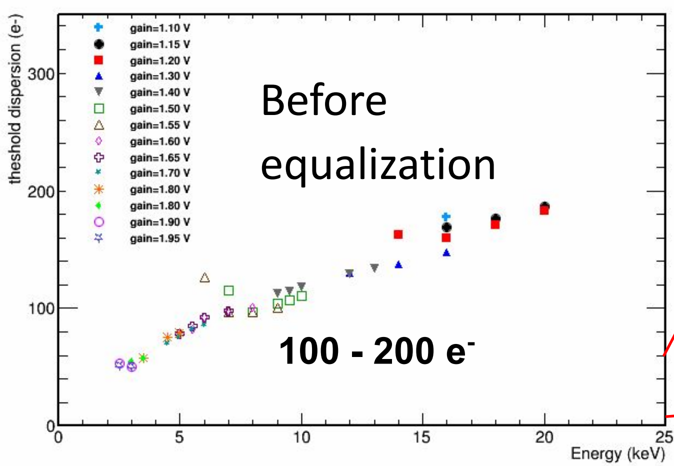
500k pixels in a single module

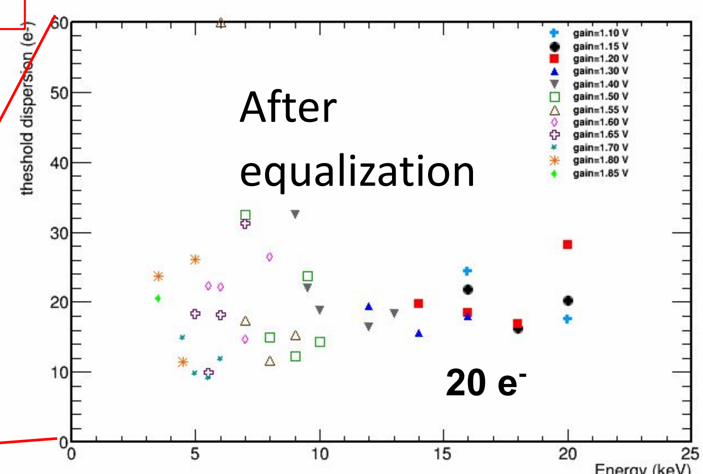


Possibility to activate pixel to pixel corrections



Tinti et al., **Performance of the EIGER single photon counting detector,** JINST 10 C03011 (2015)





x 5-10 improvement

- Gain variation
- Offset in comparator

After equalization threshold dispersion small compared to noise

CMS hit rate

Layer radius	3 cm		7 cm	11 cm	16 cm
Pixel fluence [MHz/cm^2]	$\boxed{520}$		119	52	27
Hits / trigger / module	190		40	18	8.4
MBit/link/sec	435		118	66	45

From simulation

- Inefficiency <3 % till end run2
- PROC 600 designed to stand 600 MHz/cm2