PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Gemma Tinti

Paul Scherrer Institut & ESRF

Similarities and differences of recent pixel detectors for X-ray and high energy physics

Outline

- Applications at particle collider experiments and at synchrotrons set requirements for the detectors

- Silicon hybrid pixel detector fulfill requirements – **psi46dig** / **EIGER**

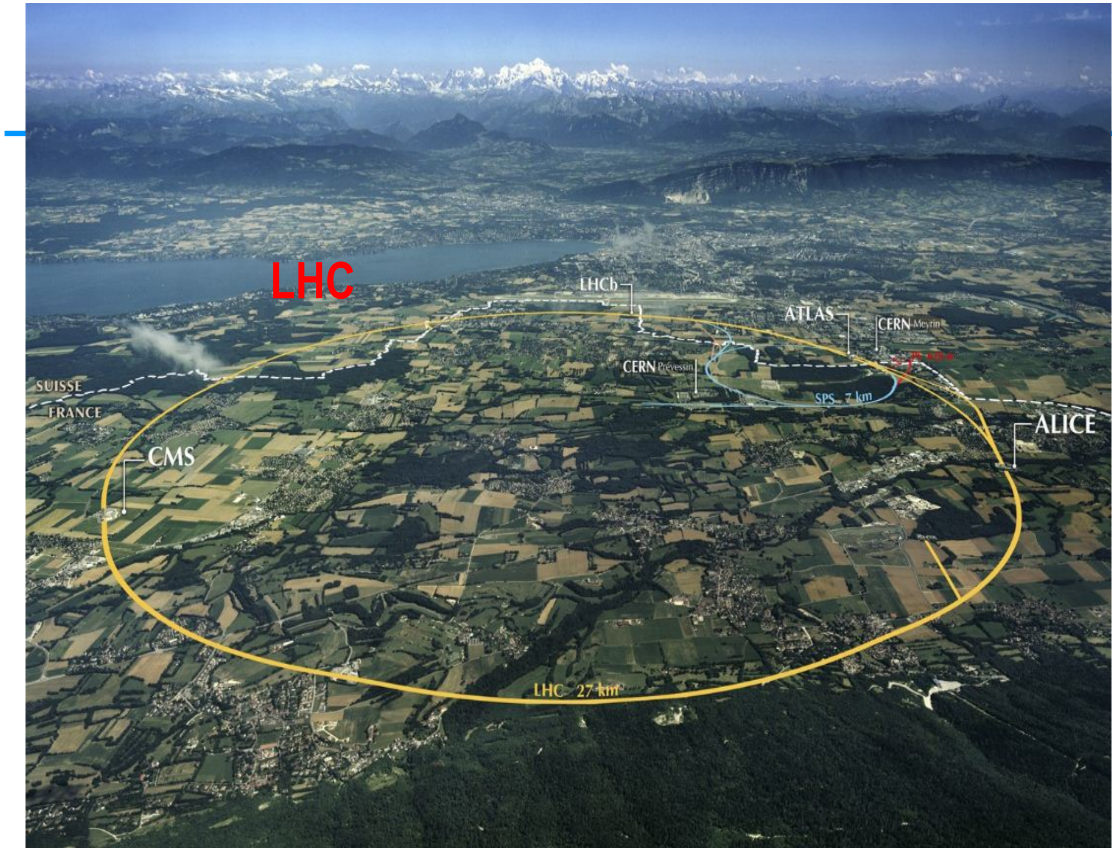
- Detector choices and integration

- Calibration and characterization: threshold, noise, rate capability…

- How limitations of current detectors can be overcome in the near future

27 km circumference

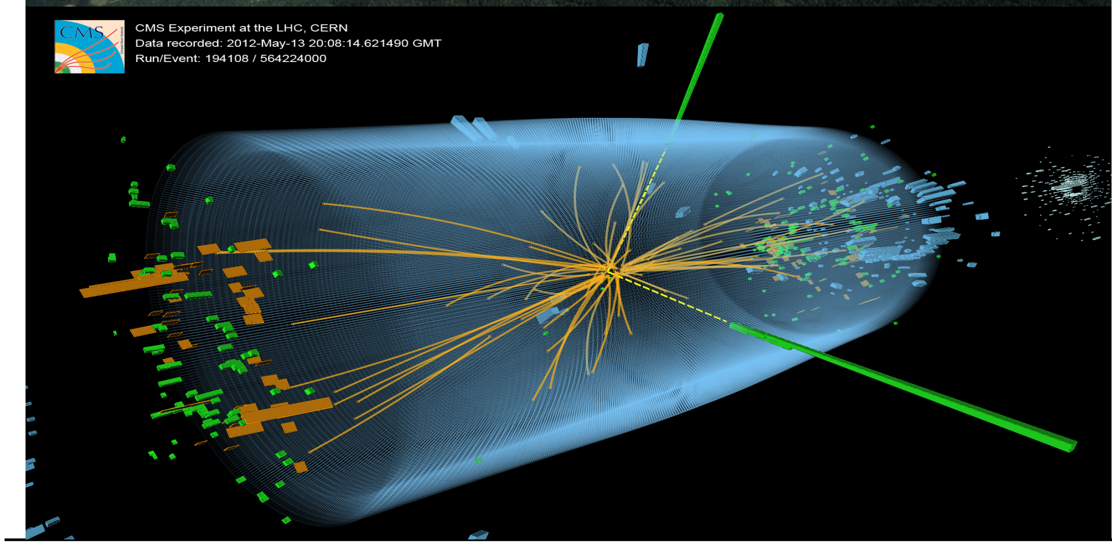
4 TeV p beams

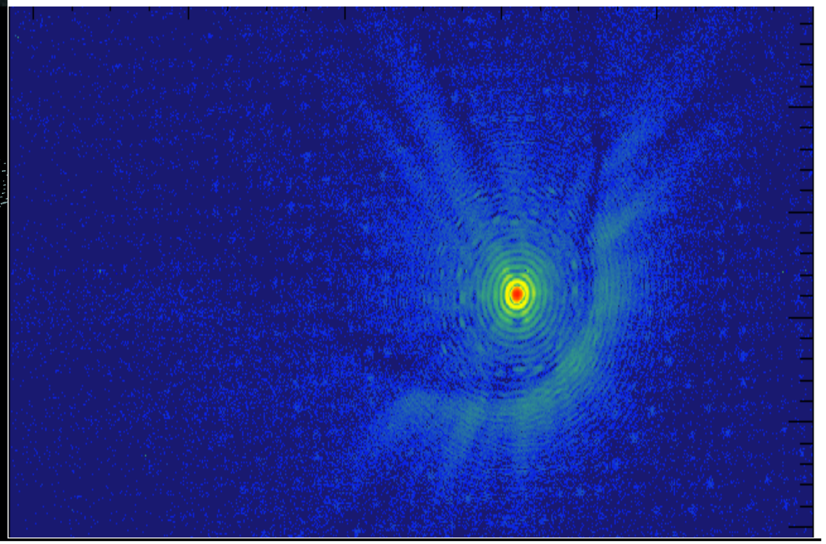


288 m circumference

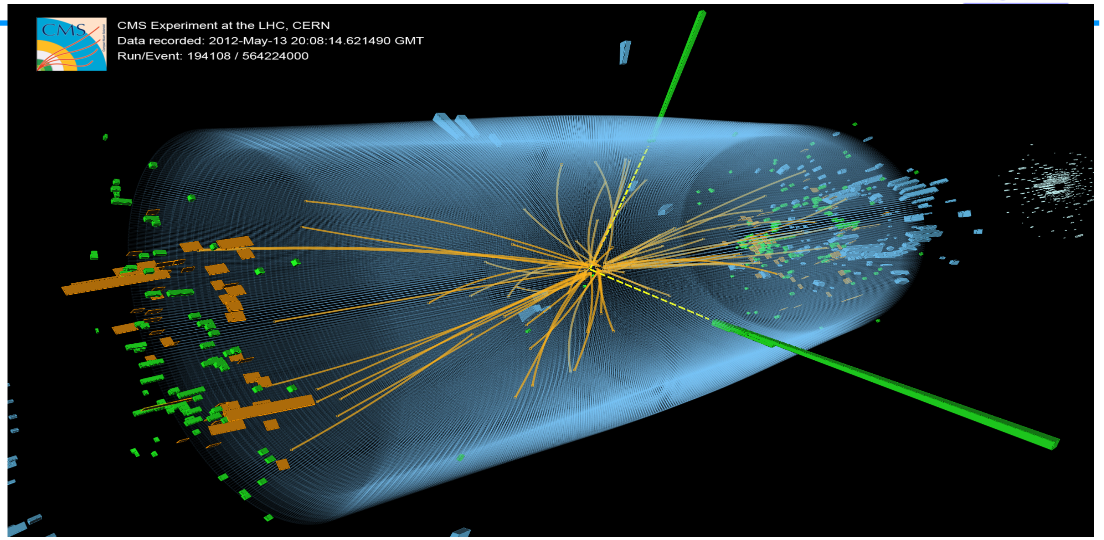
2.4 GeV e beam

Xrays 3eV – 45 keV



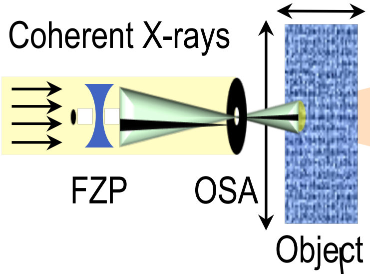


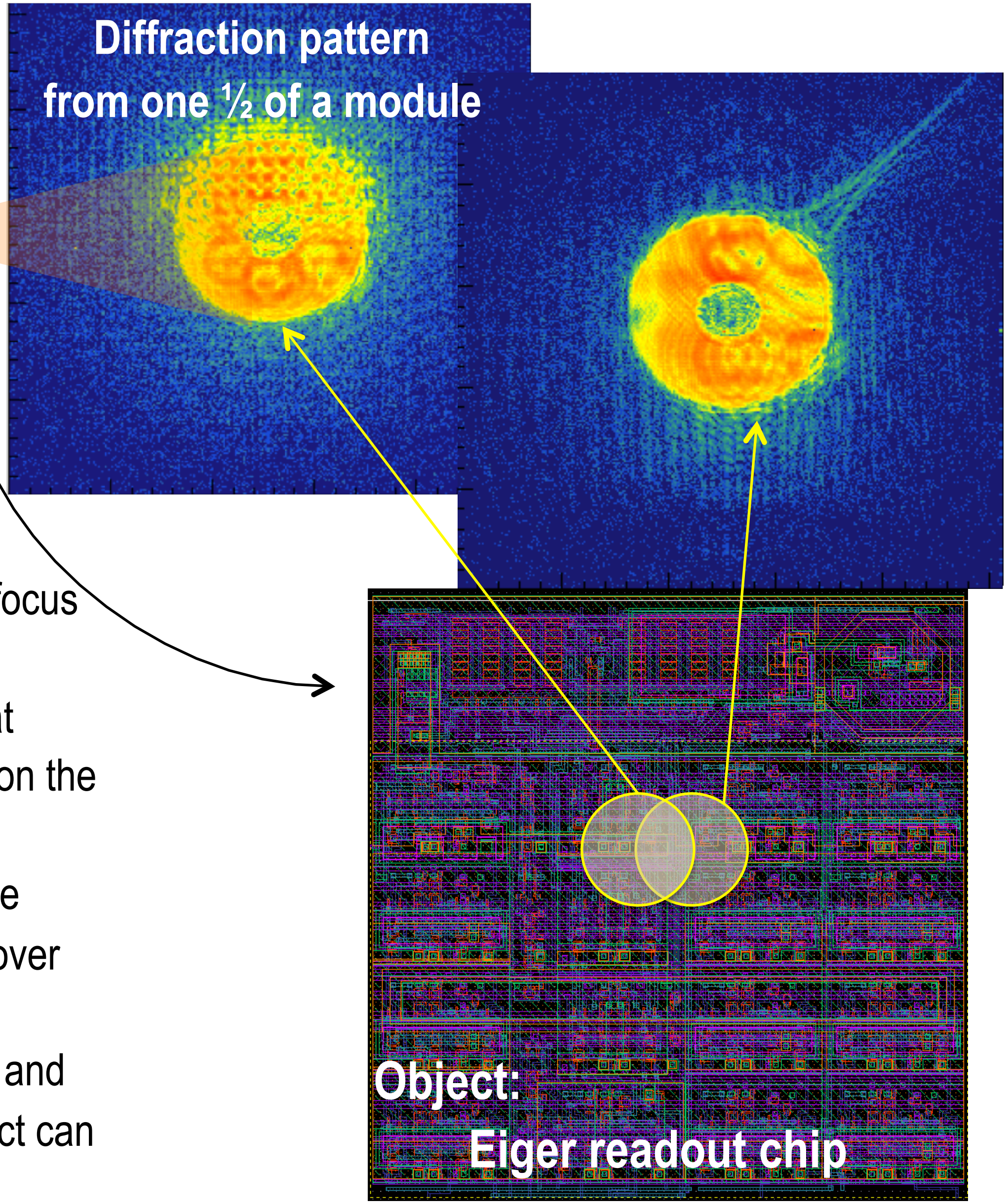
HEP pixel detector requirements



- Charged integrating detectors ➔ PH
- 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, 250 Mrad
- Low material budget

An EIGER 'selfie' (Ptychography)



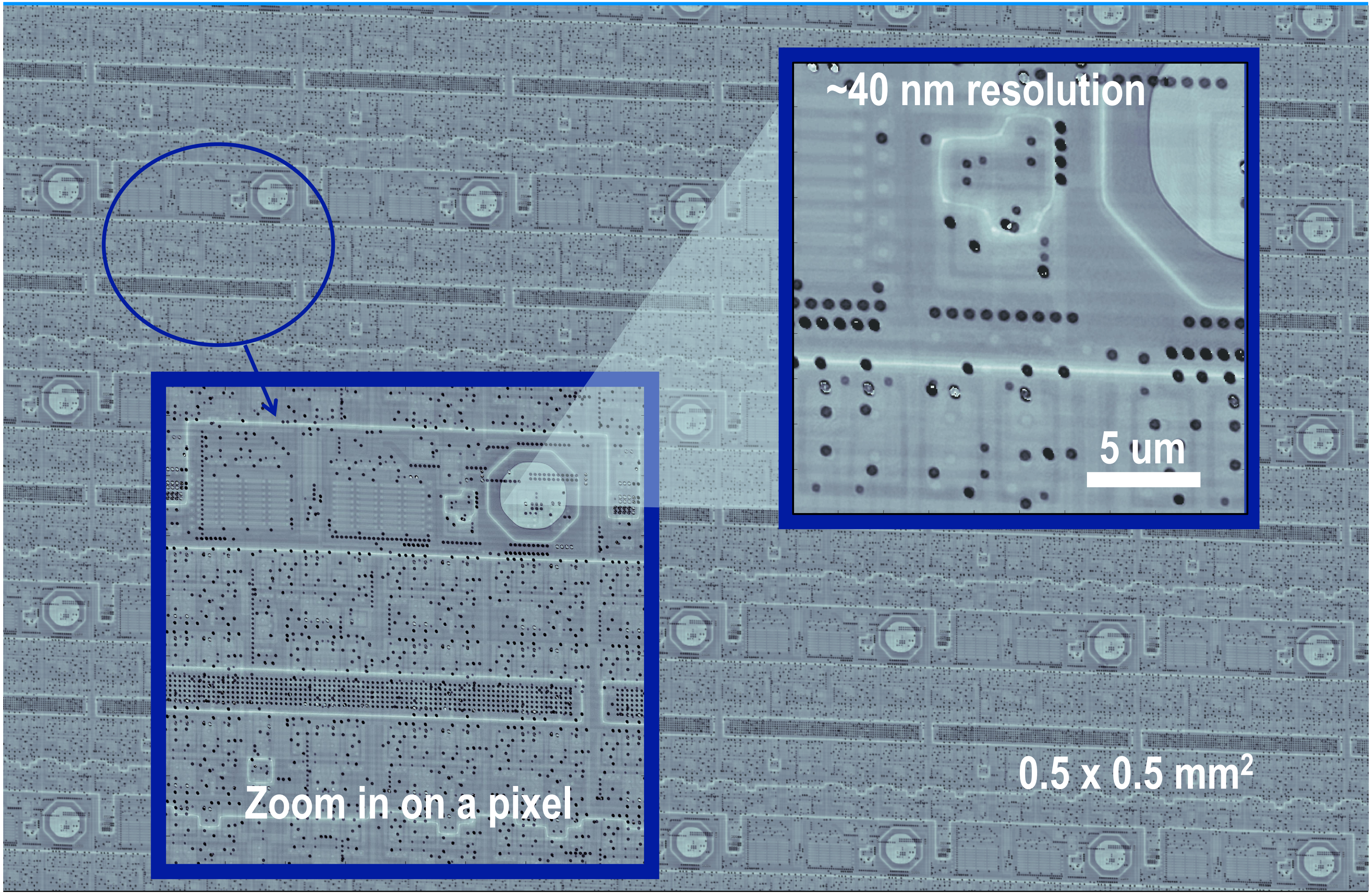


- The object is raster scanned by an out of focus beam
- Diffraction patterns at overlapping positions on the object are recorded
- The information in the overlap is used to recover the dp phase
- Both the attenuation and phase shift in the object can be reconstructed

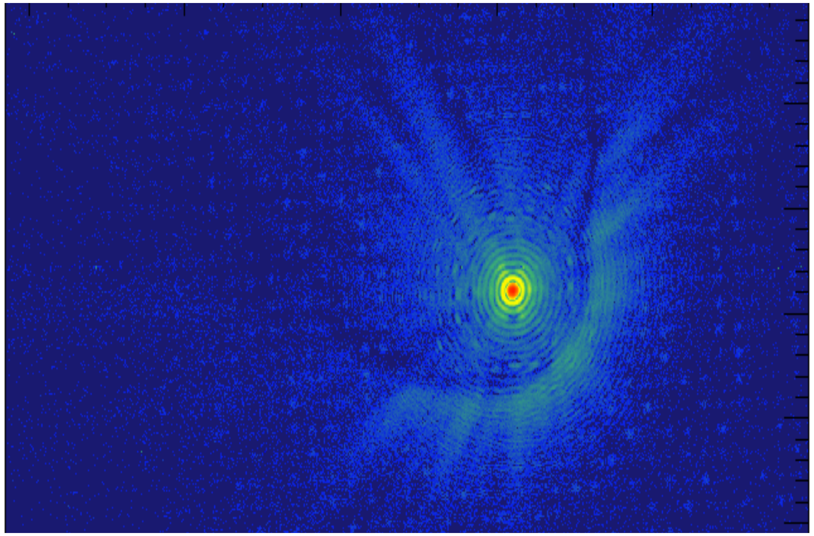
Optics Express, Vol. 22, Issue 12, pp. 14859-14870 (2014)

- large dynamic range
- small pixel size
- large area
- high frame rate

Large area, high resolution Ptychography



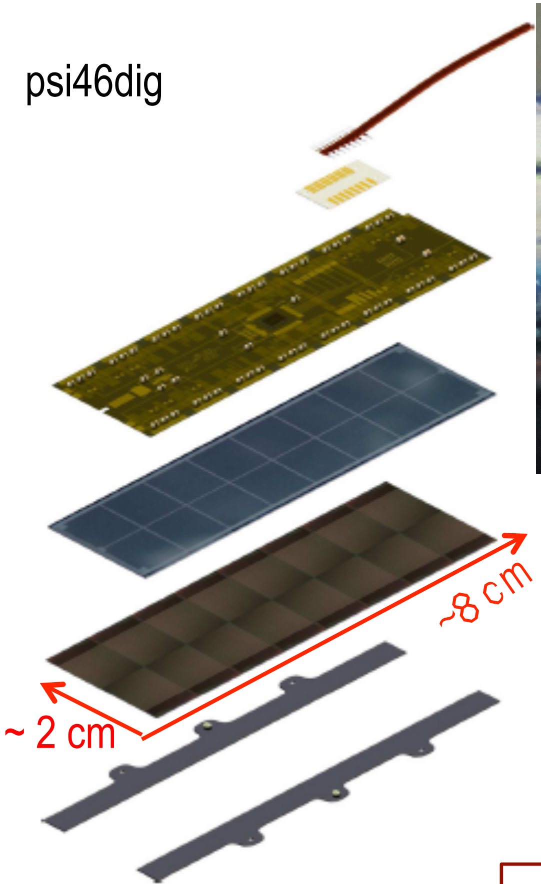
Synchrotron radiation detector requirements

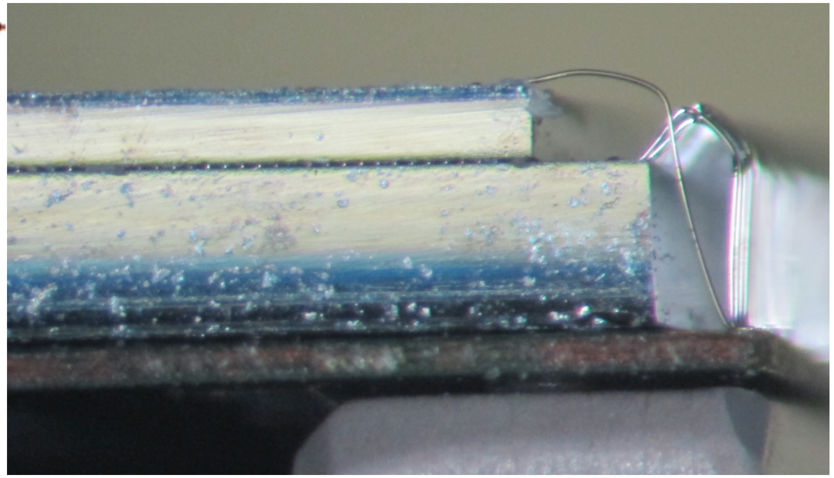


- Energy range from a few to 25 keV
- Continuous beam, no trigger
- Total frame readout
- Single photon sensitivity ➔ low noise
- High dynamic range 1- 10^4 photons
- High count rate capability ➔10^{10} photons/cm^2/s
- High frame rate ➔ tens of kHz
- Spatial resolution <100 um
- High radiation tolerance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

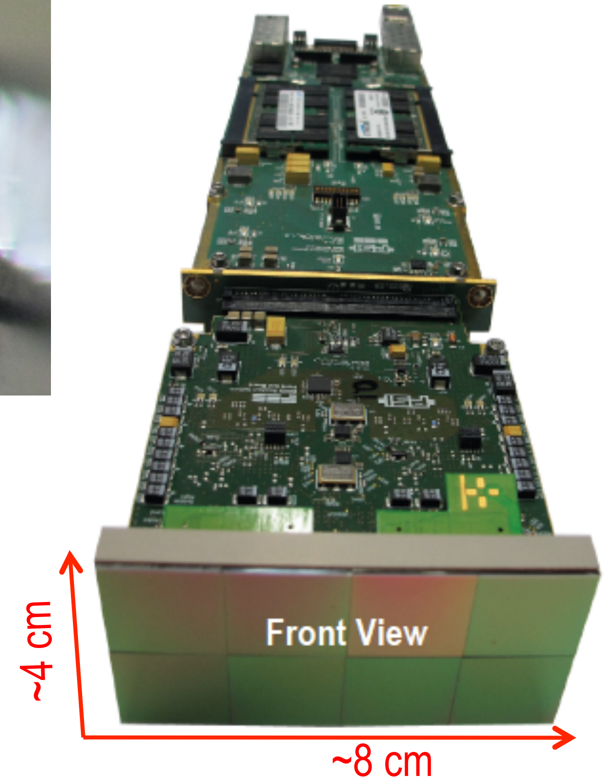
Silicon hybrid pixel detectors

psi46dig

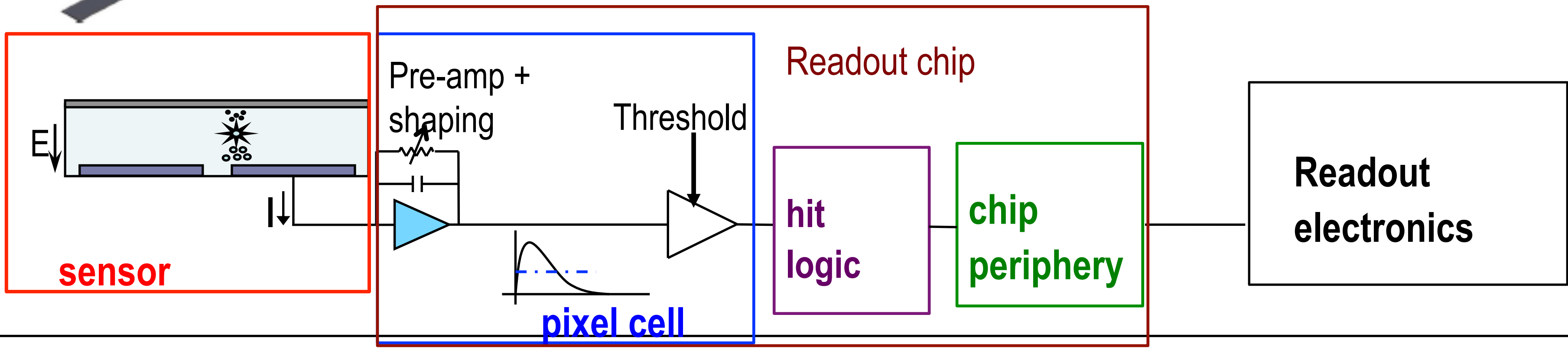




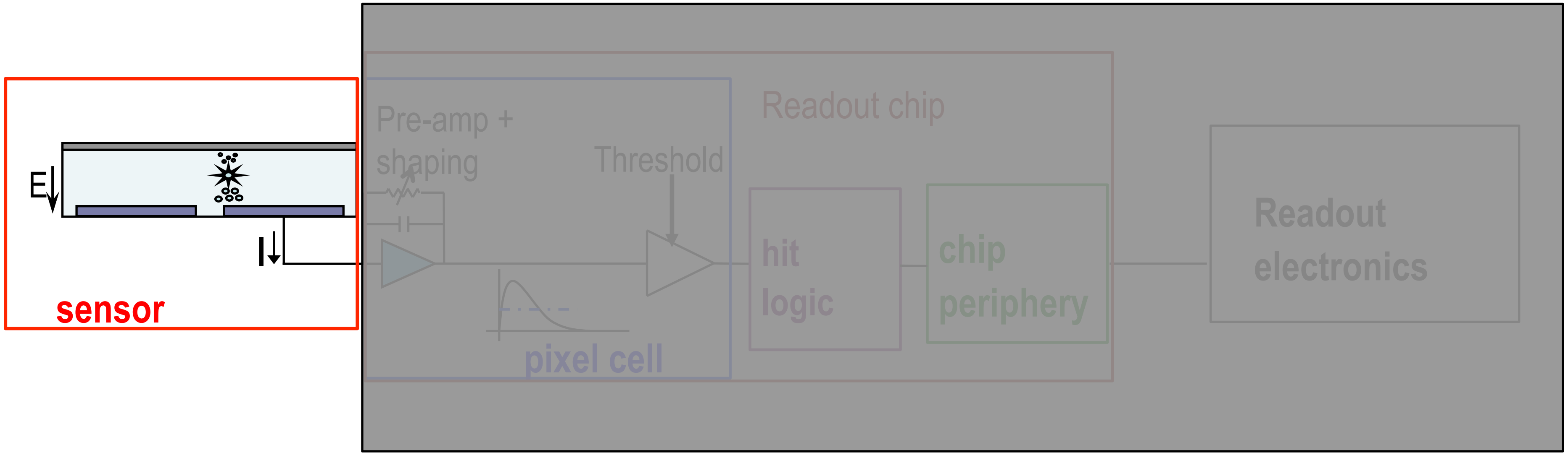
EIGER



8/16 ROCs arranged in a **module**



Sensor


E
I
sensor
Pre-amp +
shaping
Threshold
pixel cell
Readout chip
hit
logic
chip
periphery
Readout
electronics

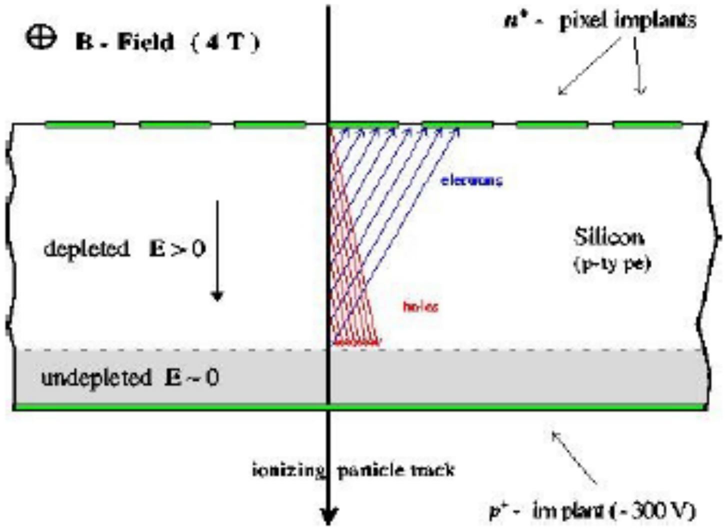
Sensor choice for HEP

- **Collecting electrons is motivated by:**
  - Higher mobility – timing requirements
  - Less charge trapping – radiation hardness
  - Higher Lorentz angle – charge sharing

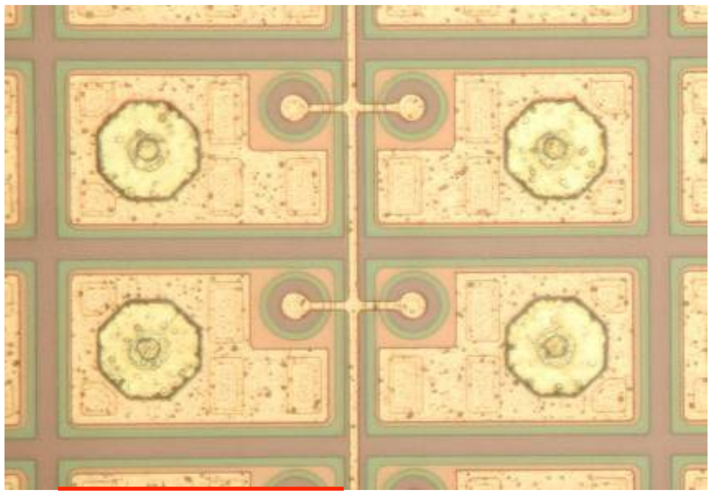
- Analog charge interpolation improves the spatial resolution

- Both surface and bulk damage with irradiation

- **n$^+$ implants on n substrate:** under depletion operation after irradiation



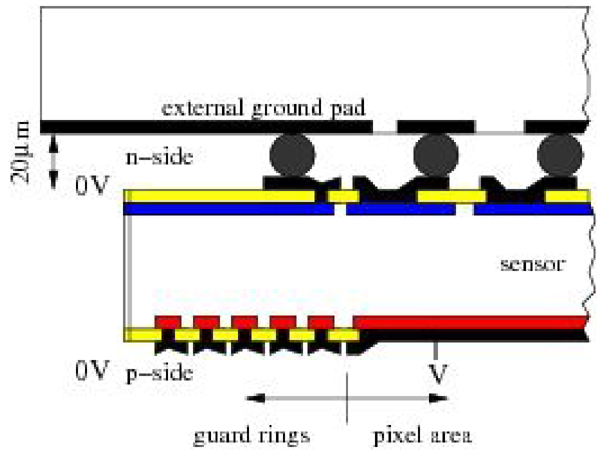
100 um



150 um

Moderated p-spray with bias grid

285 um thick



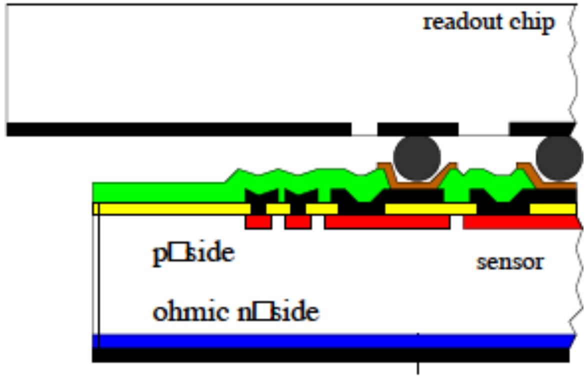
Sensor choice for synchrotron applications

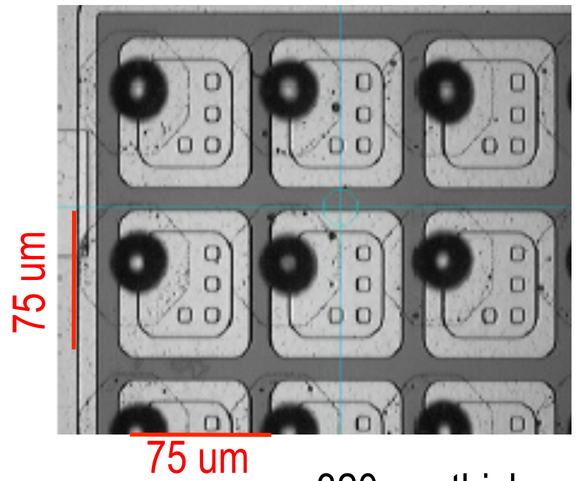
• **Photon detectors have less stringent requirements: collect holes**

• **p$^+$ implants on n substrate: cost effective approach** (single sided process)

• Photons interact with photoelectric effect ➔ almost 'pointlike' interaction, charge sharing only by diffusion

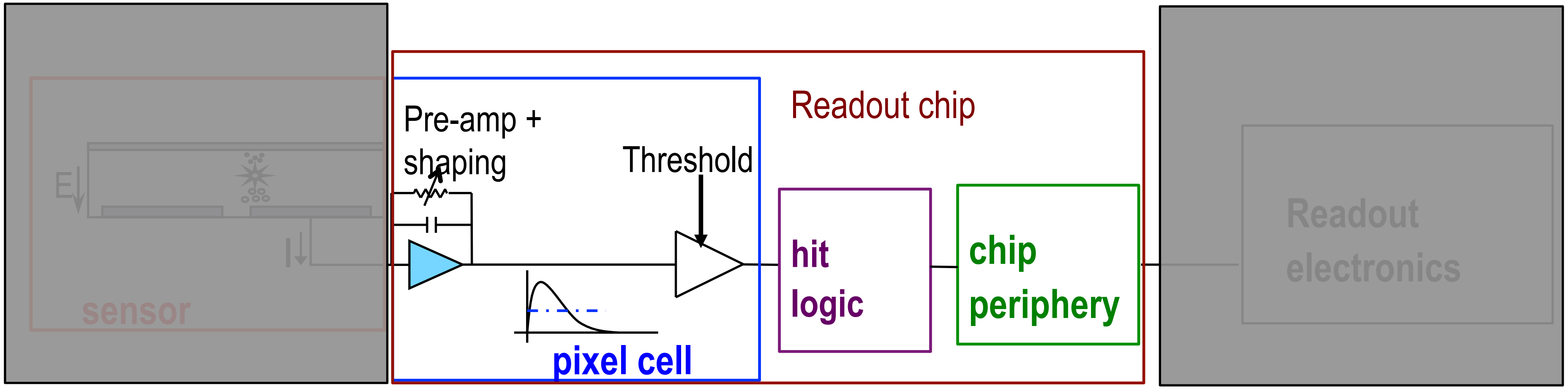
• Only surface damage with irradiation





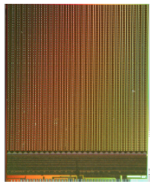
320 um thick

Readout chip

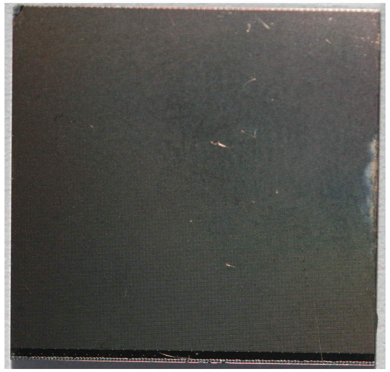


Chip characteristics: psi46dig and EIGER

psi46dig

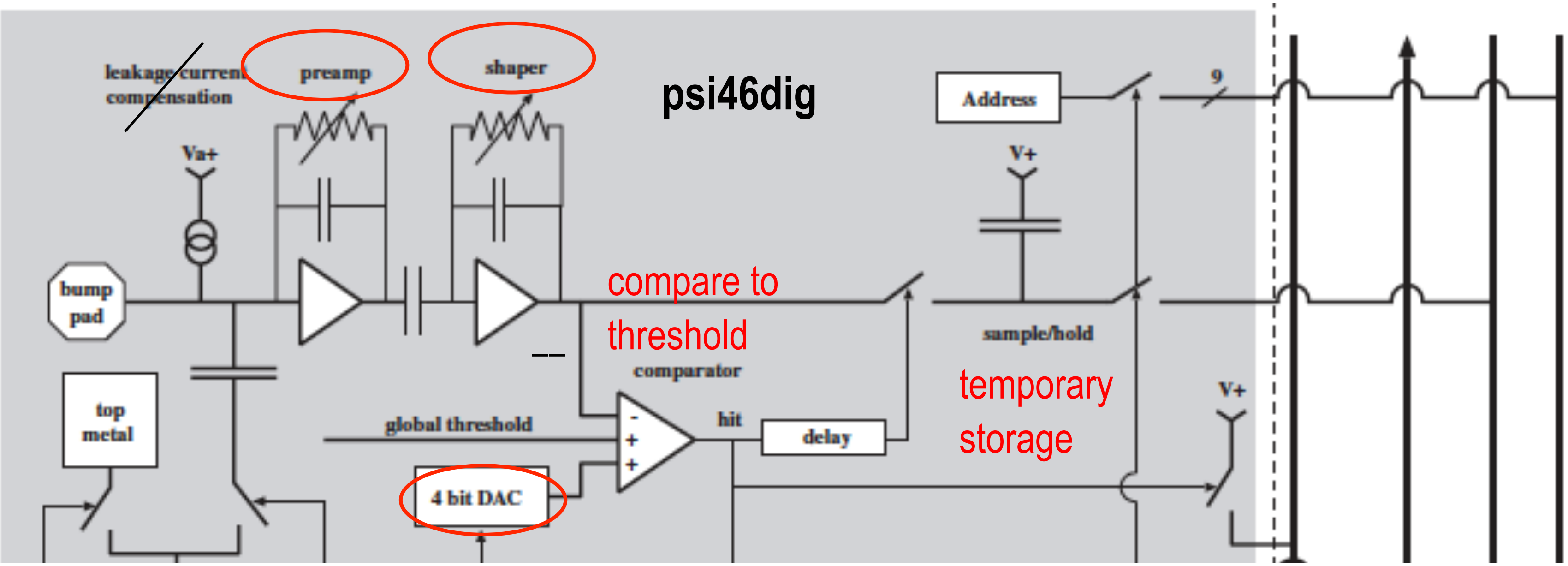


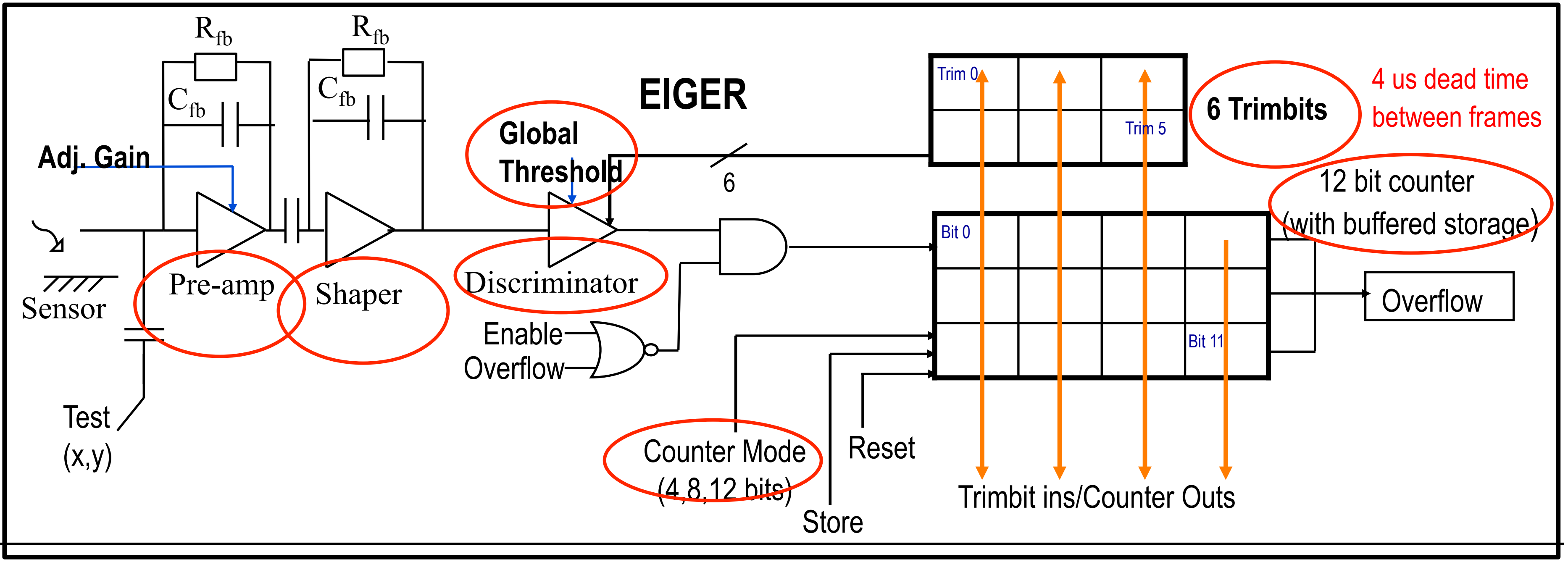
EIGER



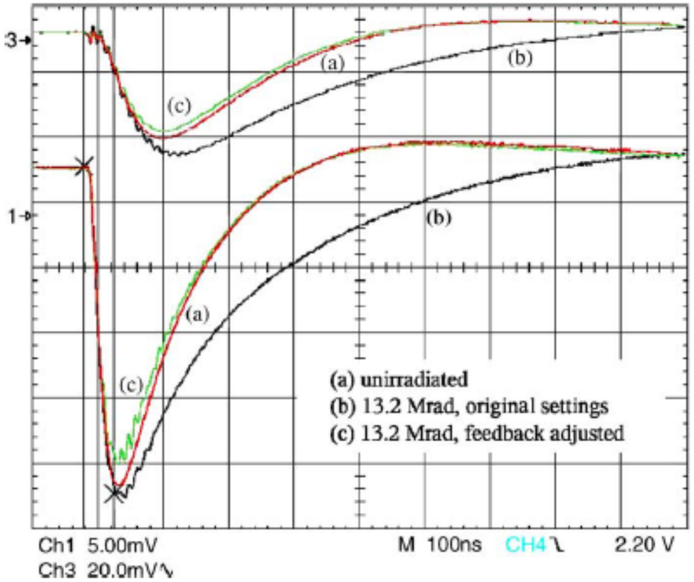
Technological process	IBM 0.25 µm Rad tol Design> 250 Mrad	UMC 0.25 µm; Rad tol. Design > 4 Mrad
Pixel array	80 x 52 = 4160 pixels	256 x 256 = 65536 pixels
Pixel size	100 x 150 μm^2	75 x 75 μm^2
Count rate	1.2 10^8 hits/cm^2/s	1.8 10^{10} photons/cm^2/s
Data rate	160 Mb/s	6 Gb/s
Transistors matrix Periphery Transistor density	1.26 M (304/pixel) 575 000 2.2 10^6/cm^2	28.44 M (430/pixel) 120 000 7.6 10^6/cm^2

Analog functionality in a pixel cell





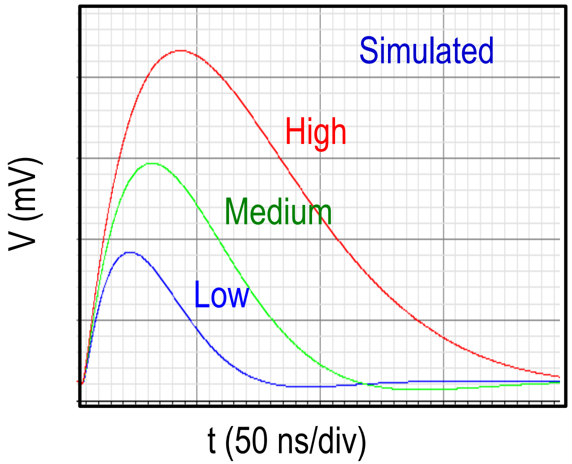
Analog signal



psi46

- 'Leading' edge of the signal has to be fast ➔ within 25ns bunch crossing at the LHC
- Return to zero has more relaxed requirements
- Analog signal from the previous psi46v2 chip
- Analog signal from psi46dig even improved
- Gain adjusted for irradiated chips

Adjustable Preamp/Shaper

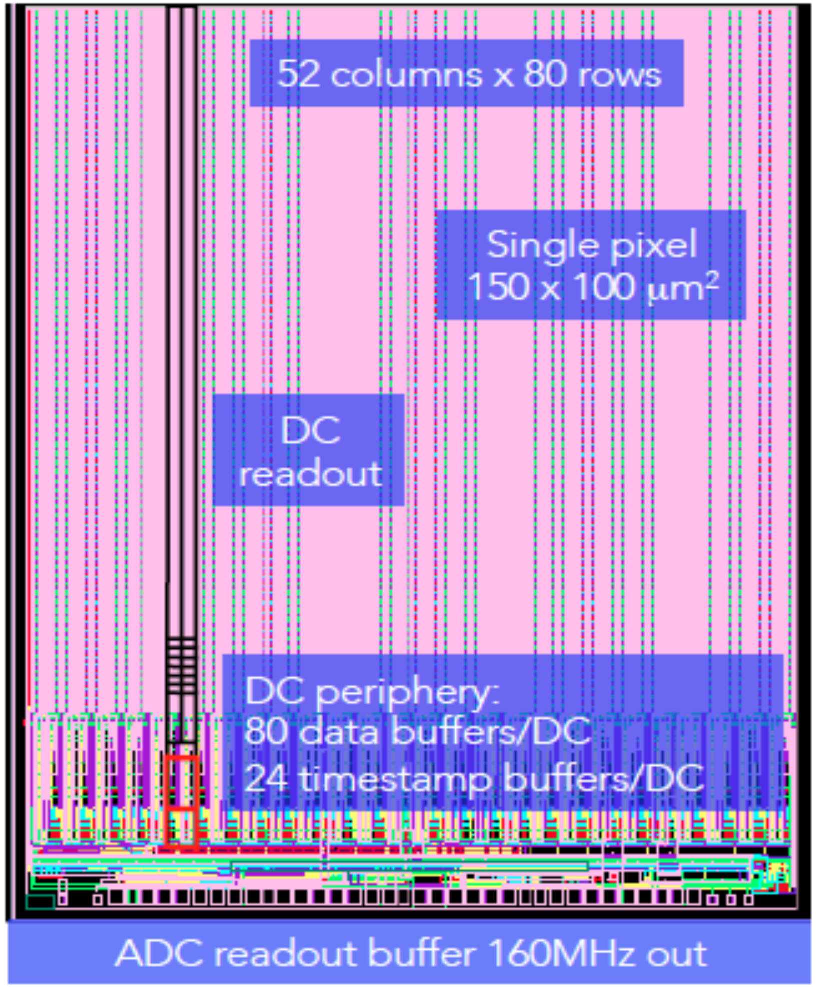


EIGER

- User configurable gain
- No stringent requirements on the peaking time of the signal
- Fast return to zero of the signal is important to limit the pileup
- Higher gains will have lower noise, but lower count rates

Readout architecture of psi46dig: column drain

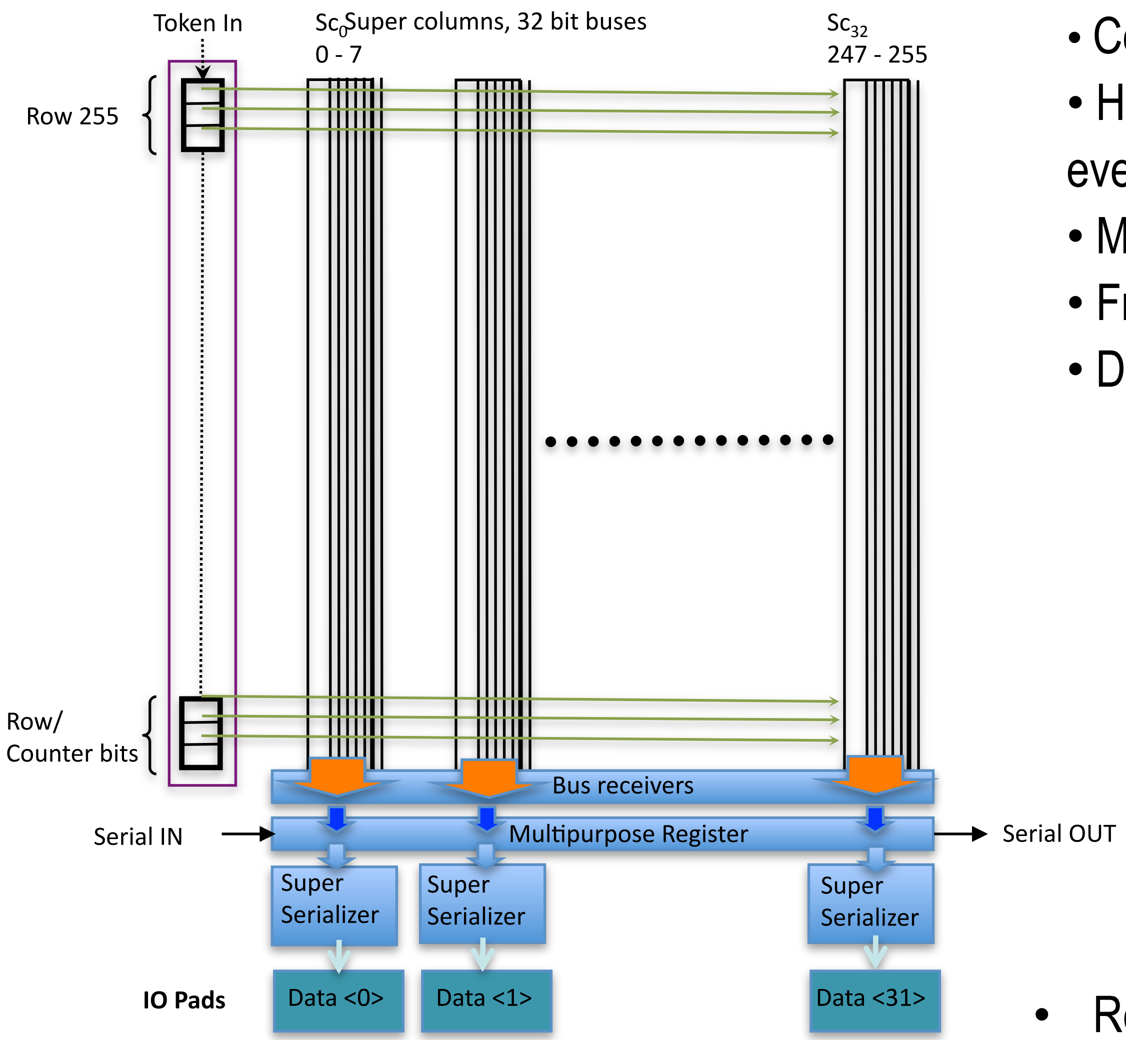
The hits have to be stored inside the ROC during the CMS level 1 trigger decision time (4 µs)



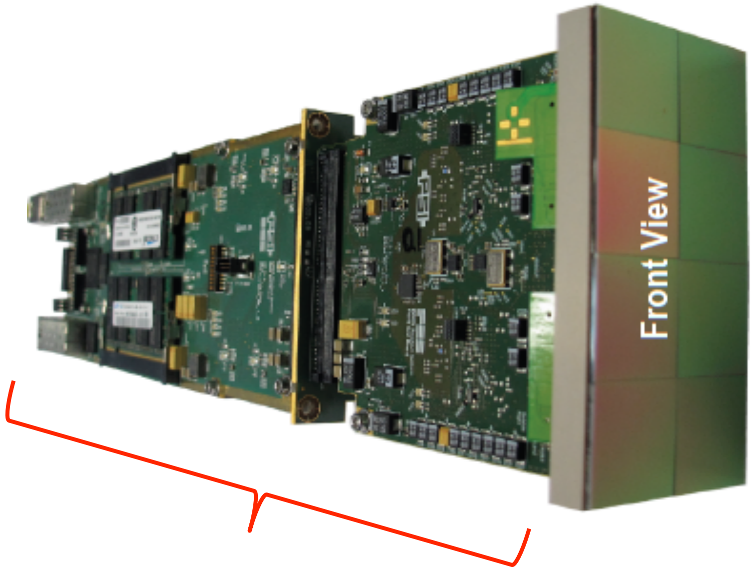
- 'Hit based' readout
- The periphery is shared between Double Columns (DC)
- When a pixel has a signal above threshold: latch into a time stamp buffer in DC periphery
- A column drain is initiated ➔ PH information transferred to data buffer in DC periphery
- When the CMS L1 trigger validation happens, data is read out
- Validated data are moved to a readout buffer to prevent inefficiencies during the 26 DC readout

- Output data rate at 160 Mb/s per chip, serial

Readout architecture of EIGER: high parallelism



- Complete pixel matrix readout
- Highly parallel readout: a serializer every 8 columns ➔ 32 output pads/chip
- Main clock is 100MHz Double Data Rate
- Frame rate @ 12bit: 7.9kHz
- Data rate per chip: 6Gb/s



- Readout electronics behind sensitive part
- No radiation tolerance requirements on the electronics

Power consumption and radiation tolerance

Psi46dig:

- Analog power 11uW/pixel
- Digital power 17uW/pixel
- Total static 0.12 W/chip, 2 W/module
- Fluence dependence contribution 0.12 uW/pixel*fluence (MHz/cm^2)

- Radiation tolerance tested up to 250 Mrad
- Pre-amp can tolerate leakage current > 100nA/pixel
- Minor adjustment to voltages and threshold equalization necessary
- Single Event Upset: change of state in memory elements due to the passage of heavy ionizing particles ➔ chip design
- DACs generated in the chip through reference bandgap voltage ➔ rad and T hardness

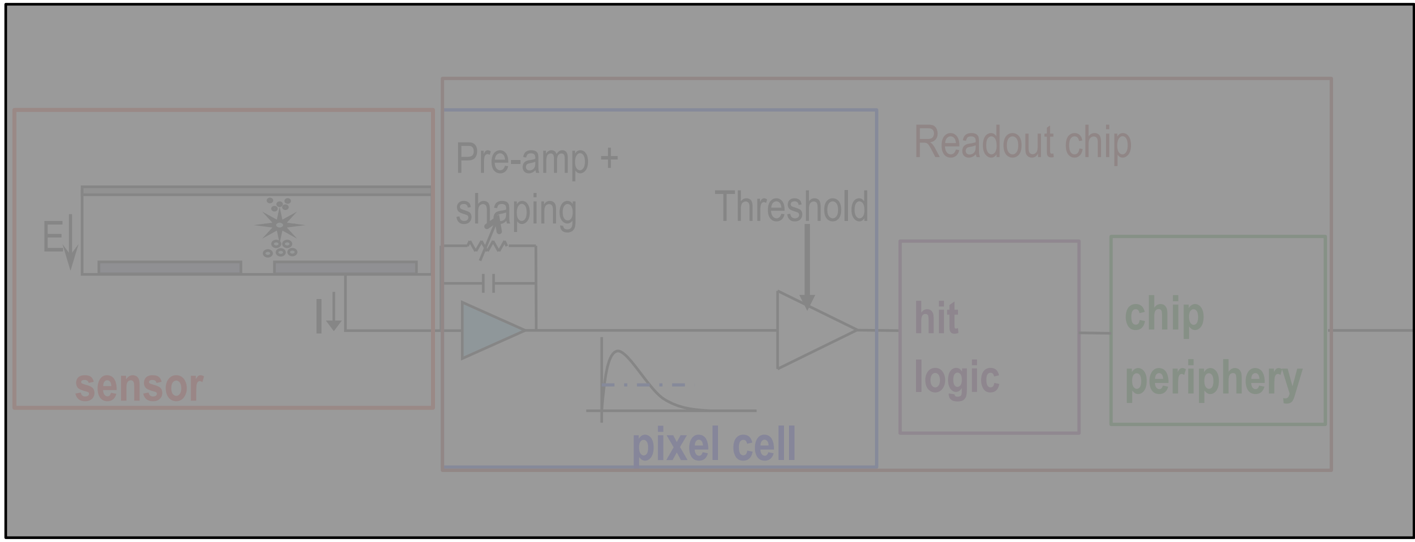
EIGER:

- Analog power 9.58 uW/pixel
- Digital power 0.2 W (static-periphery)
- Total Static 0.83 W/chip, 6.63 W/module

- Radiation tolerance tested ~ 30 Mrad
- Pre-amp can tolerate leakage current > than 100nA/pixel
- Minor adjustment to voltages and threshold equalization necessary
- No SEU

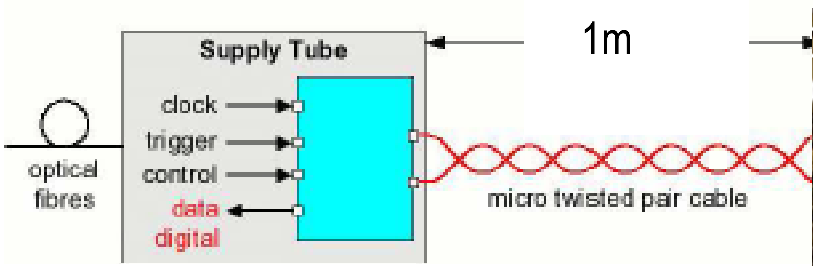
- DACs from readout electronics

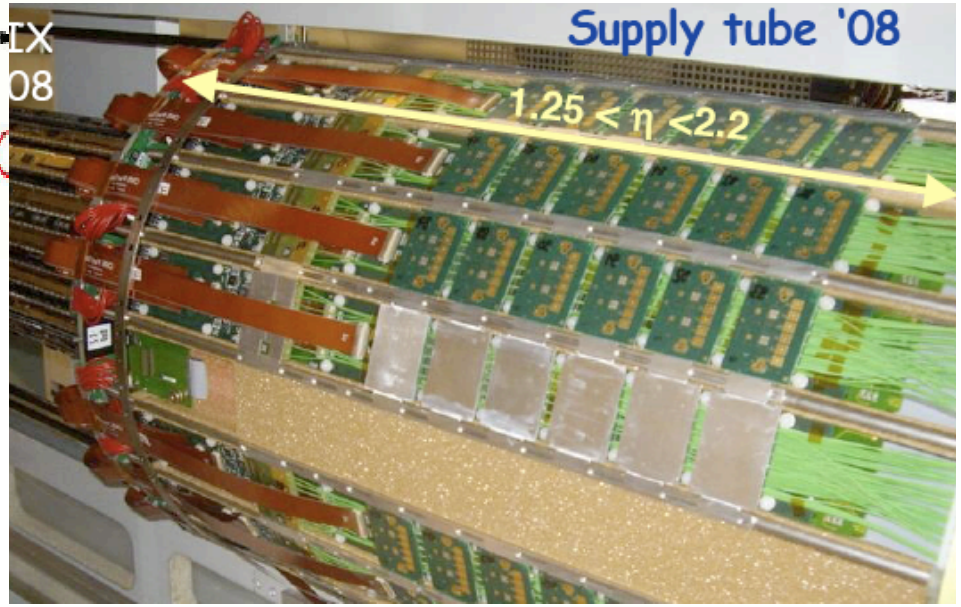
Readout electronics



Readout
electronics

Readout electronics for HEP

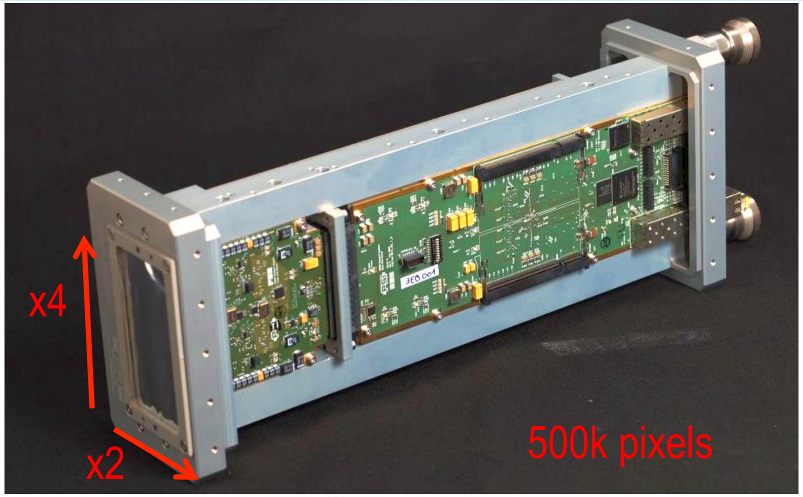


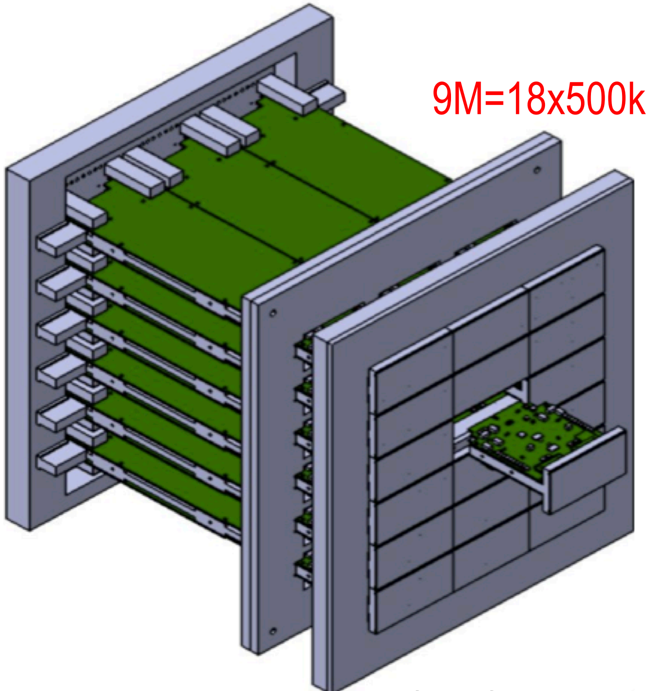


4 barrel layers: 79 Mpixels
3 disks: 45 Mpixels

- Token Bit Manager (module controller) is placed over the module
- Microtwisted pair cables move the supply tube away: less material budget in the forward direction
- Ultra light mechanics
- CO_2 cooling, low density, small diameter steel pipes ➔ target -20°C: limits leakage current after irradiation

The EIGER Systems: 500k and 9M



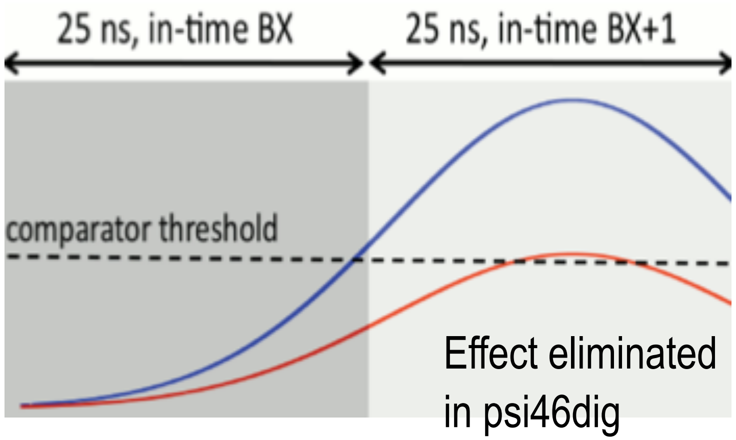


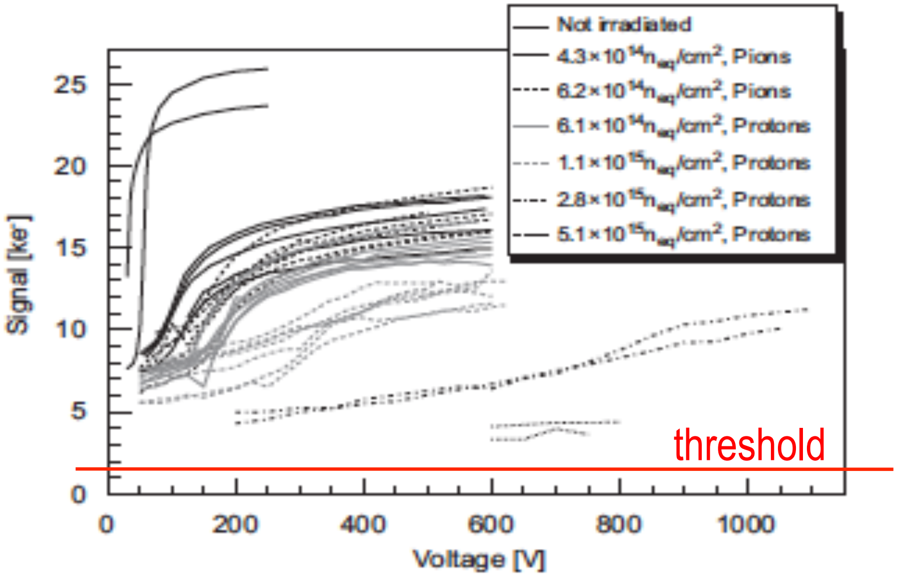
- 48 Gb/s per module (burst mode)
- High speed data transfer: 2x 1 /10 GbE connections per module
- Need of data buffering: 8 GB of on board memory per module
- Image summation if firmware
  - **extends the dynamic range from 4096 (12 bits) to $4x10^9$ (32 bits)**
  - **exploits parallel exposure and readout properties of the chip**
- Water cooling (23 °C) dissipates FPGA heat (85W, <10W from chips)
- Data processing is fully parallel on multi module systems
  - On board storage and frame rate independent of system size
- Simple integration and synchronization with users' experimental setup

Foreseen in operation at cSAXS beamline at SLS beginning 2015

Calibration and characterization

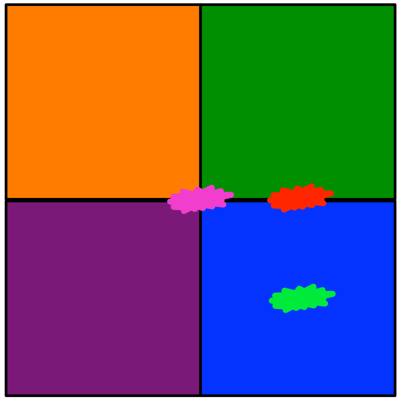
Threshold and noise for HEP detectors



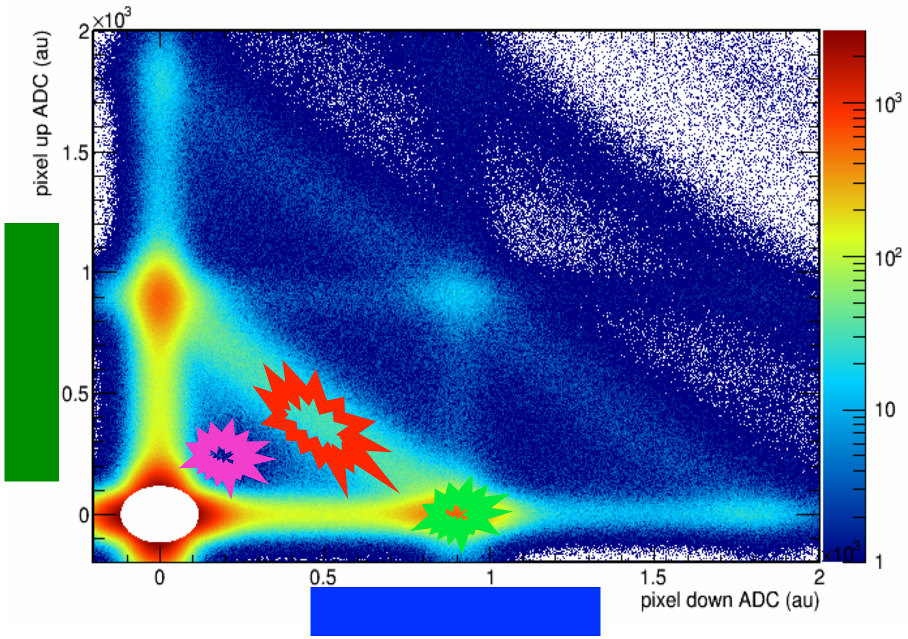


- Noise is 150 e$^-$ RMS: pixel detectors are practically noiseless
- Typically the value of the minimum threshold is much higher than the noise level
- Minimum in time threshold is < 1800 e$^-$
- Low threshold is essential to improve spatial resolution and prolong sensor efficiency after irradiation

Threshold and charge sharing for photon counters

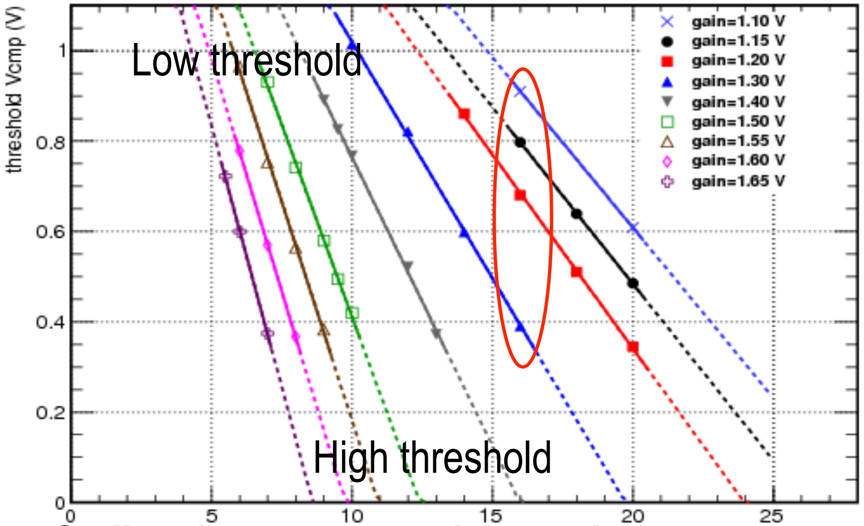


Analog readout, same sensor as EIGER

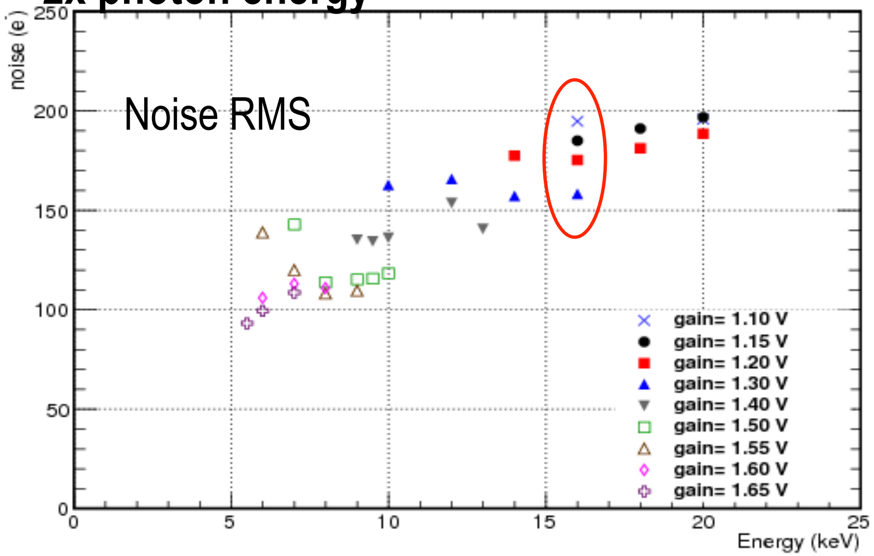


- Signal is 1000e⁻ for 3.6 keV photons
- Want to be efficient and count photons uniquely
- Setting the threshold to 50% of the incoming photon energy allows to count a photon uniquely
- EIGER has >95% efficiency
- Limits to the minimum size of pixels for photon counters
- Threshold could be set to higher value to cut on fluorescence of the sample

Threshold and noise for photon counters



Calibration curves to be applied at 2x photon energy



- Threshold is set at 50% photon energy
- Provide the user with calibration curves of the threshold vs Energy
- For the same energy more than one gain setting is possible
- Choosing a lower gain (lower threshold) optimizes the rate capabilities
- Choosing a higher gain (higher threshold) gives a low noise configuration
- Noise reduces with higher gain

Rate limits in psi46dig

Data Rate Estimations

- Simulation with Pythia Z2 tune and GEANT4
- Assuming 24 bits per hit, 100 kHz level 1 trigger rate
- Peak luminosity = $2x10^{34} cm^{-2}s^{-1}$, σ_{tot}=80mb, σ_{signal}=1.5mb, 25 ns BC

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

1 ROC = 0.65 cm^2

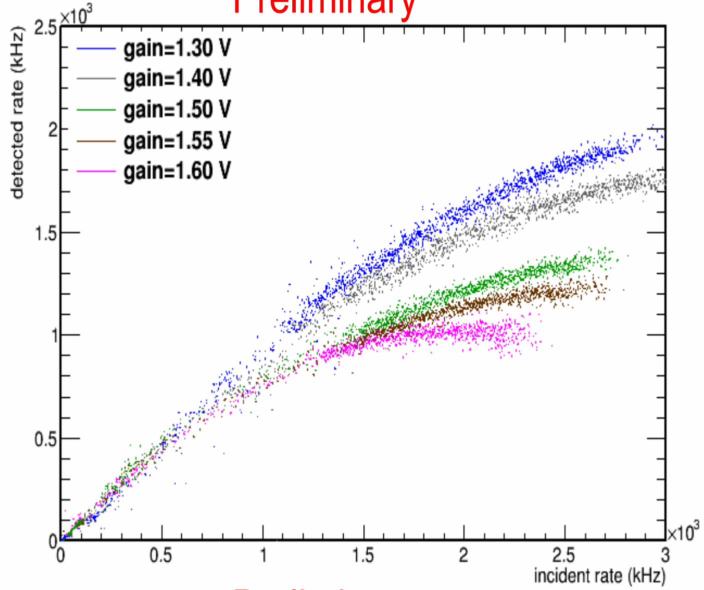
See talk ‘The CMS readout chip for the Phase I Upgrade’ for more details

- psi46dig fulfill rate requirements for Layer 2,3,4 with inefficiencies up to **2%**
- The rate requirement at Layer 1 would cause **~30%** inefficiencies

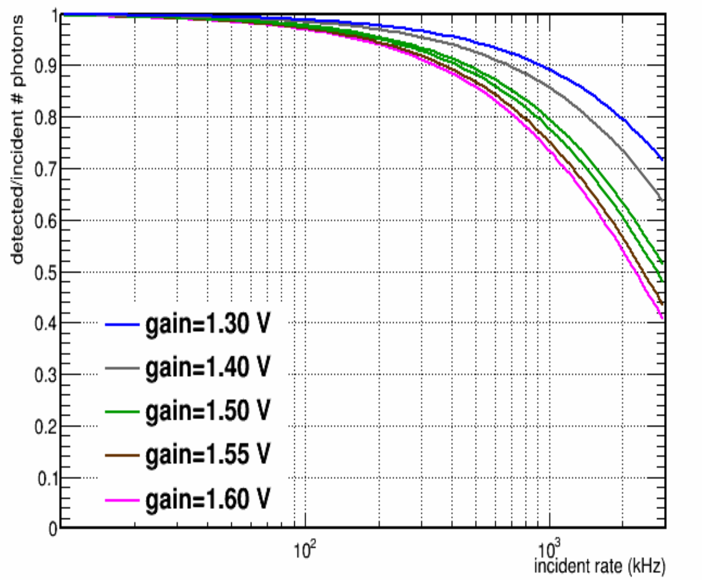
- ‘Dynamic cluster’ column drain reduces the double column bandwidth
- A new chip will be submitted by the end of this year

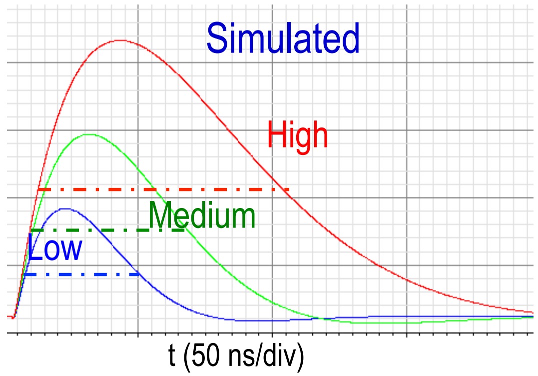
Rate limits for photon counter detectors

Preliminary



Preliminary





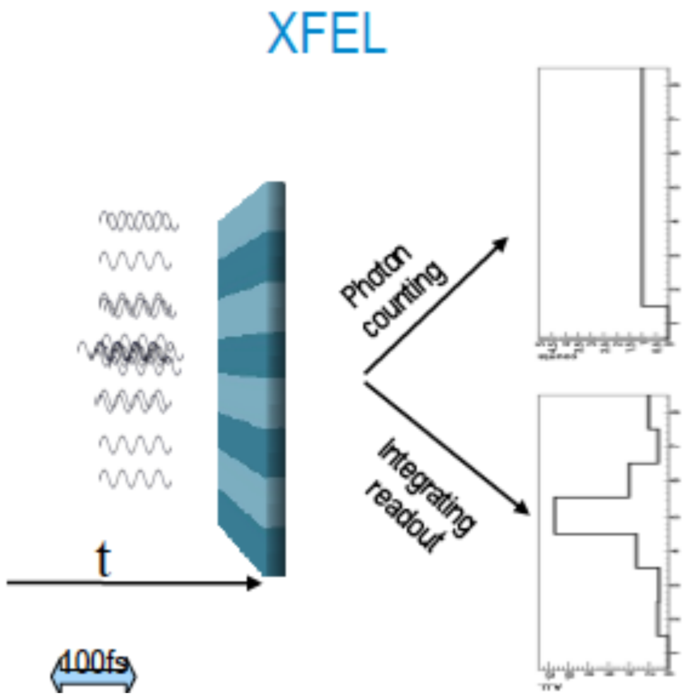
$$N_{det} = N_{inc} \cdot e^{-N_{inc} \cdot \tau}$$

Preliminary

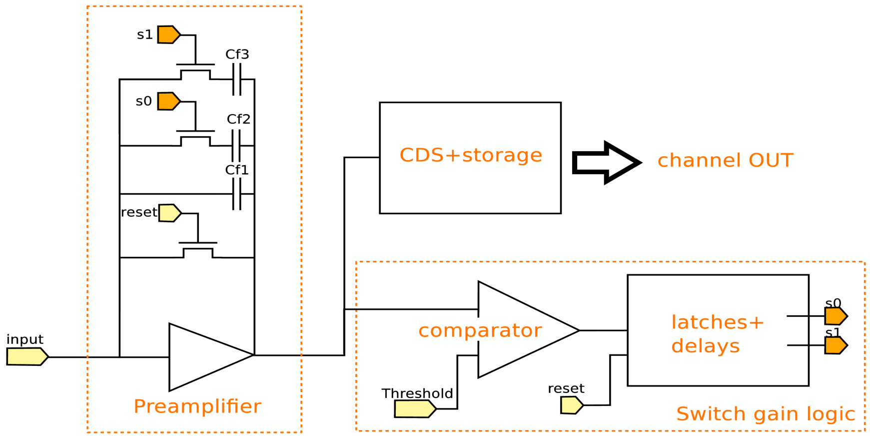
gain (V)	τ (ns)
1.30	115
1.40	155
1.50	230
1.55	285
1.60	307

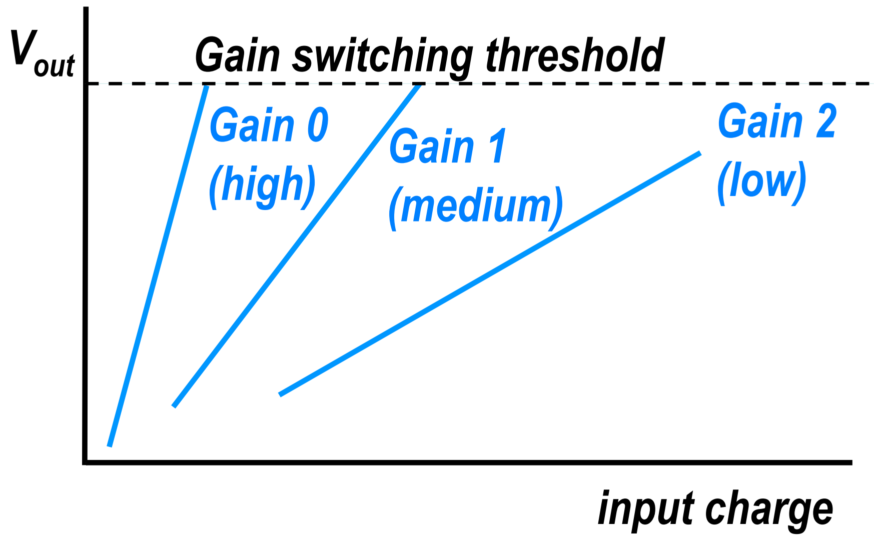
- Rate non linearity is one of the major limitations of photon counters
- 300 kHz – 1MHz (at 90%)

The future: charge integrating detectors for FELs



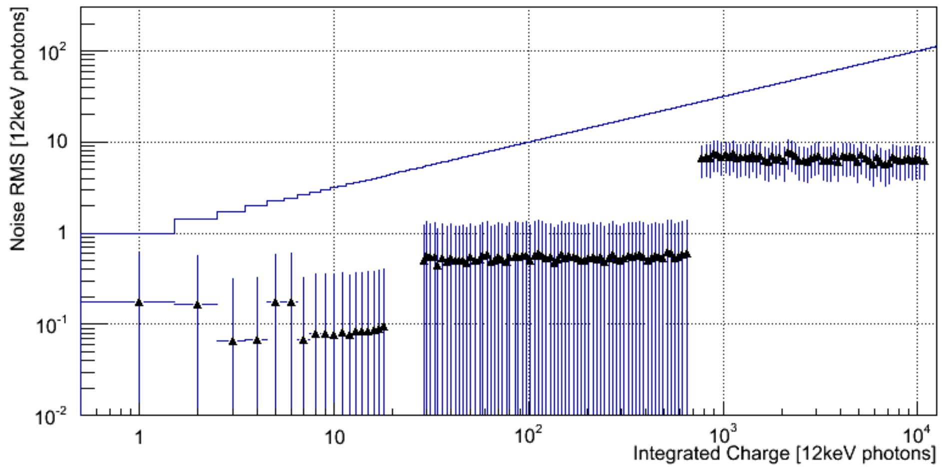
- Free Electron Lasers deliver 10^4 photons in ~hundreds of fs
- Photon counters cannot be used
- Development of charge integrating detectors with charge information
- For the detector the main challenges are:
  - Dynamic range of 10^4 photons
  - Single photon resolution
- In exposure 'dynamic gain switching' is the solution





The future: charge integrating detectors for synchrotrons

- **JUNGFRAU: adJUstiNg Gain detector FoR the Aramis User station at Swiss-FEL at PSI**
- High dynamic range with up to 10^4 photons/pulse/pixel achieved through dynamic gain switching (3 gains)
- Single photon sensitivity (higher gain)
- Low noise (~100 e^-), below the Poisson statistic limit
- Good linearity (1%)



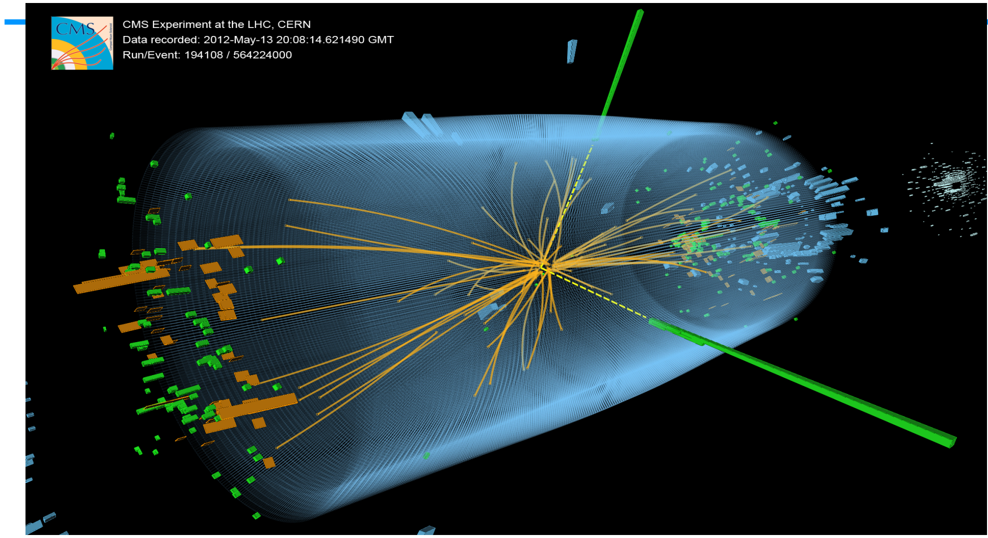
- Calibration from charge to photon number required
- Target frame rate: 2 kHz with 10Gb/s data link (allows use at synchrotrons)

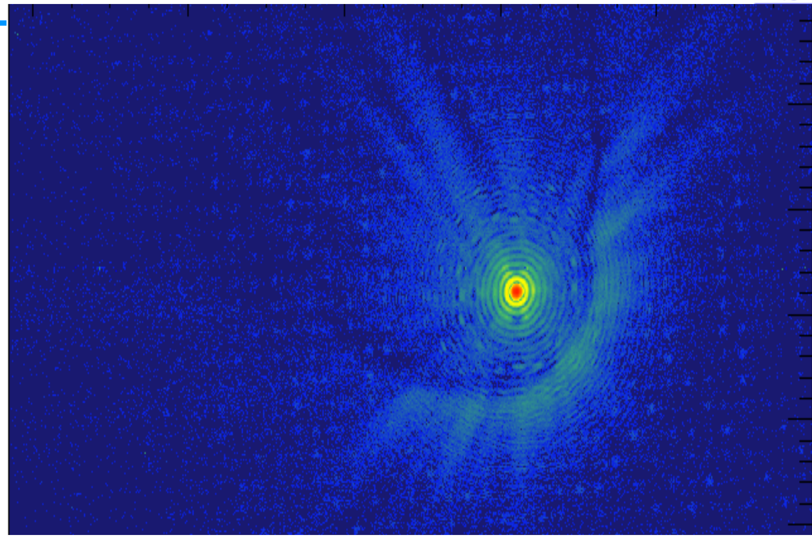
Count rate of 4.3 10^{11} photons/cm^2/s

Factor 20 better than EIGER

Other use of charge integrating detectors is to improve spatial resolution ➔ see Roberto Dinapoli's talk in this session

Conclusions



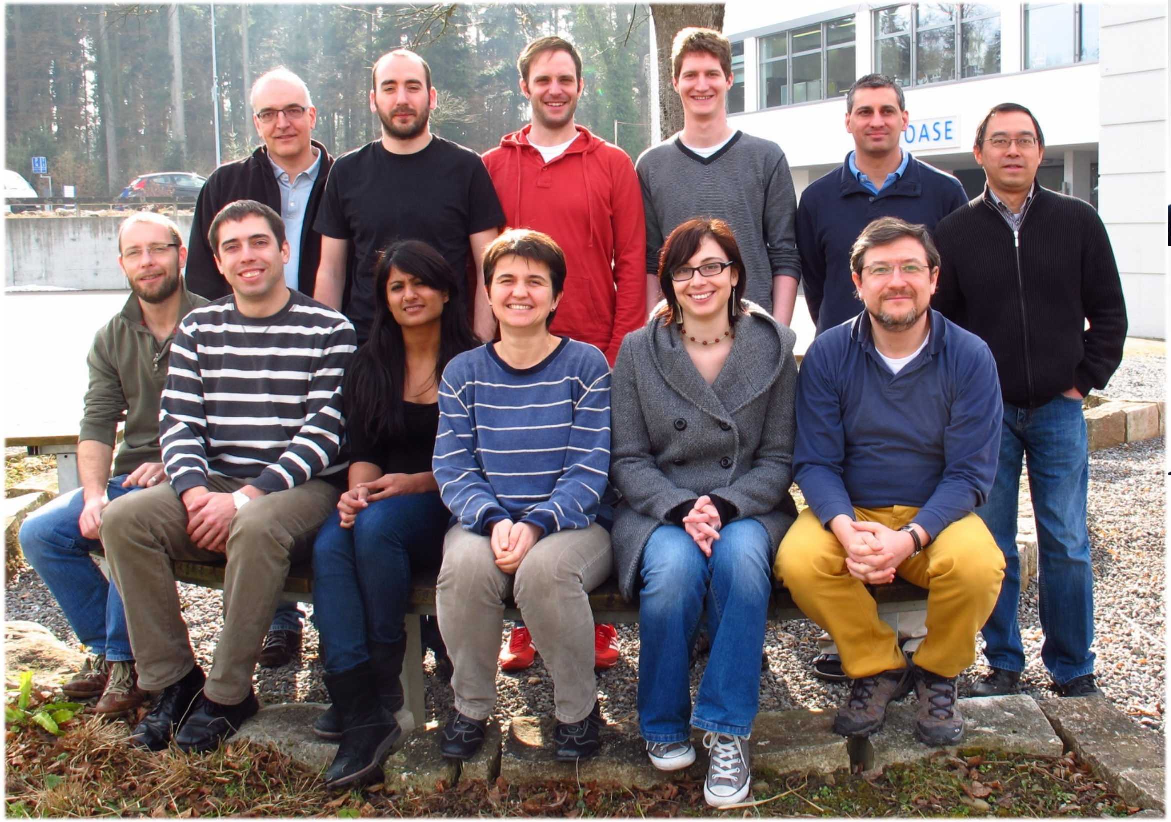


- Charge integrating detectors ➔ PH
- Readout of localized hits
- Fast signal peaking time ➔ within the LHC 25ns bunch crossing
- Temporary hit storage during trigger latency: readout according to the CMS Level 1 trigger selection
- Low noise
- Low in-time threshold

- Energy range from a few to 25 keV
- Continuous beam, no trigger
- Total frame readout
- Single photon sensitivity ➔ low noise
- High dynamic range 1- 10^4 photons
- High count rate capability ➔ 10^{10} photons/cm^2/s
- High frame rate ➔ tens of kHz

➔Next generation of pixel detector for FELs will re-introduce charge integration with PH readout

Thanks



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

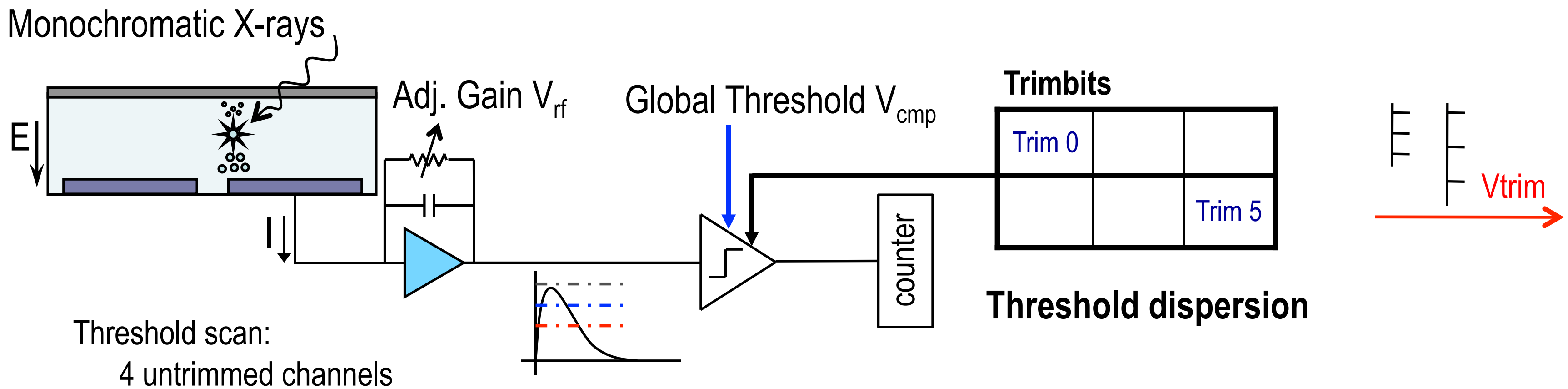
B. Schmitt, C. Ruder, D. Greiffenberg, S. Cartier, I. Johnson, X. Shi, J. Jungmann-Smith
A. Mozzanica, L. Schaedler, D. Maliakal, A. Bergamaschi, G. Tinti, R. Dinapoli, D. Mezza

W. Erdmann, R. Horisberger,
H-Ch. Kaestli, B. Meier

PAUL SCHERRER INSTITUT

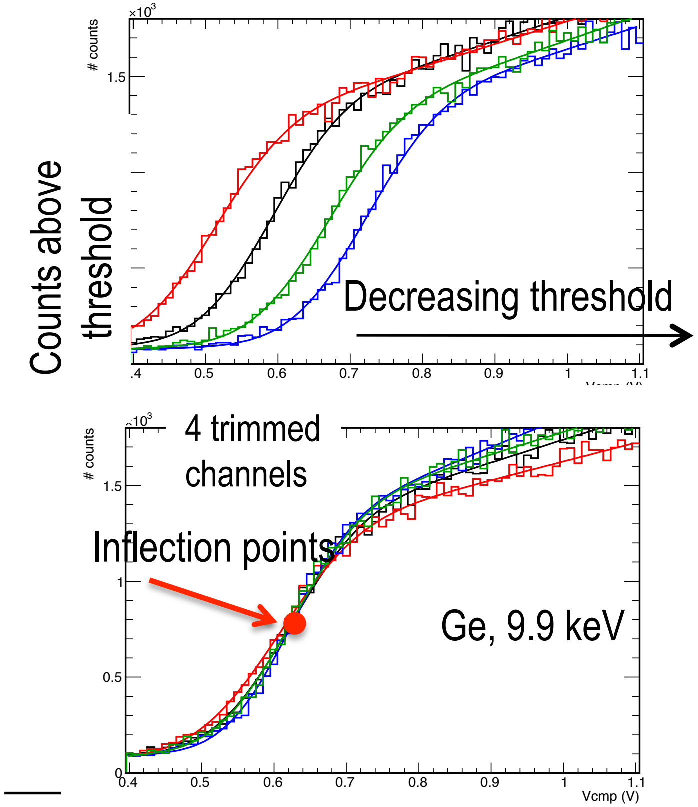
Spare slides

Module Trimming and Threshold dispersion

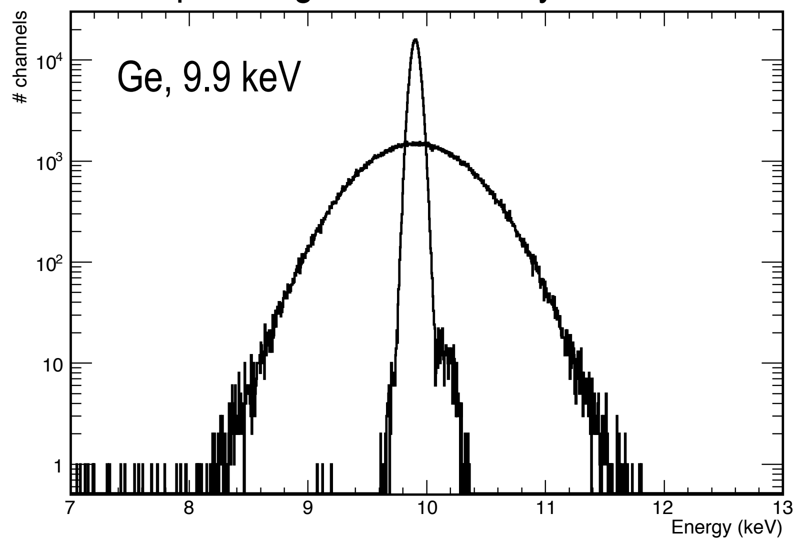


Vtrim changes strength of trimbits

Threshold scan:
4 untrimmed channels



5 chips using the module system

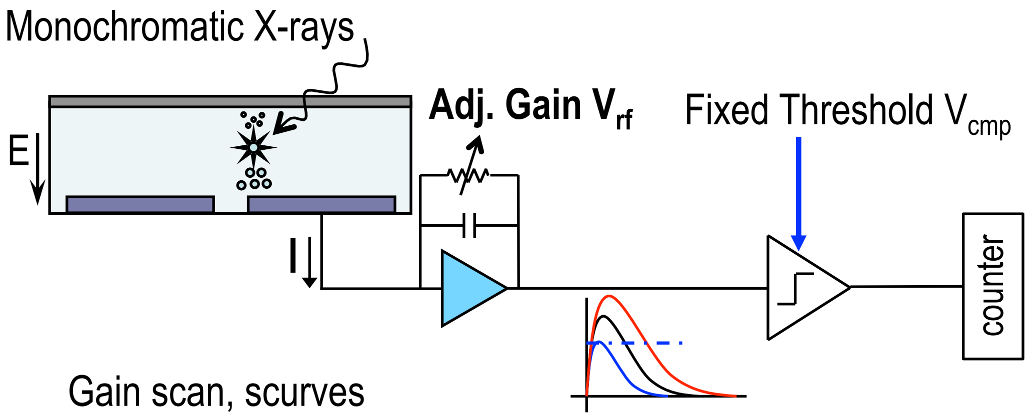


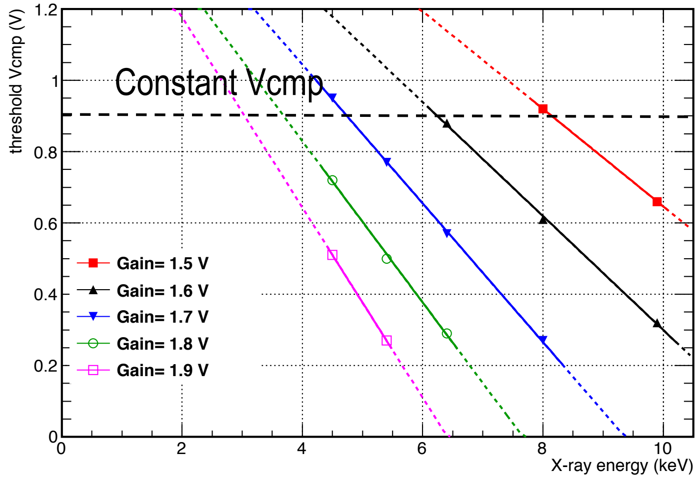
Trimmed
σ= 40 eV

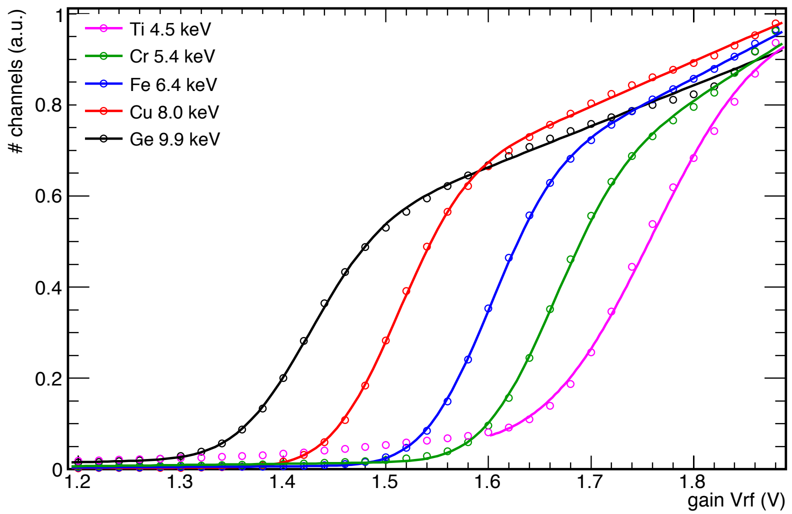
Untrimmed
σ= 420 eV

- Threshold dispersion ~ 11 e^-
- Noise: 200 e^- RMS

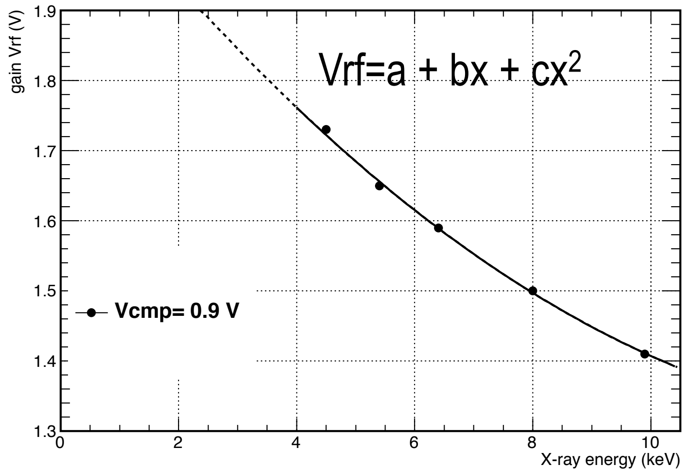
Energy calibration along the Gain axis







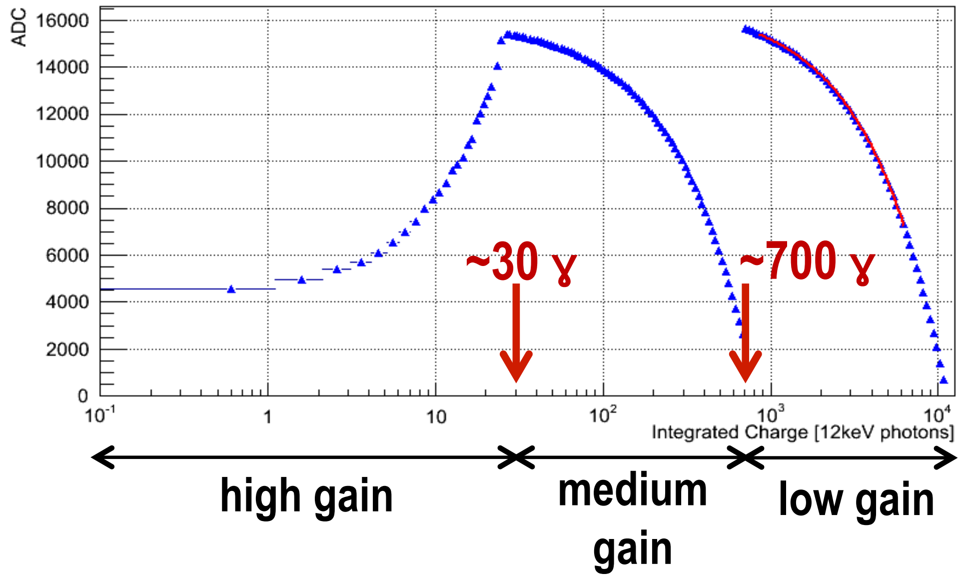
T= 23°C



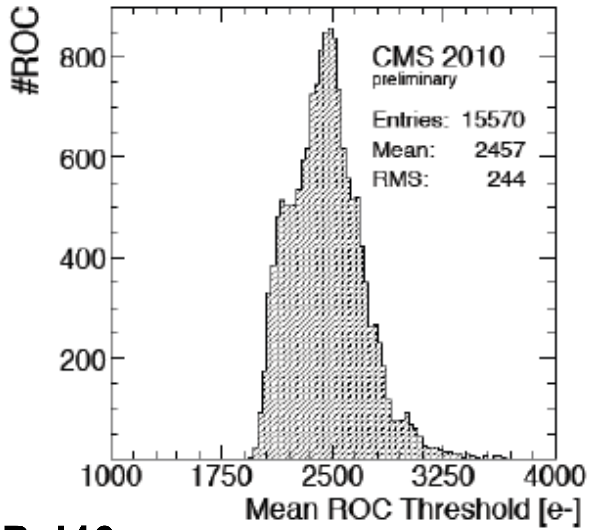
- A low threshold means the fastest settings and an optimization rate capabilities at all energies
- As Vtrim is primarily a function of Vcmp, it can be kept constant

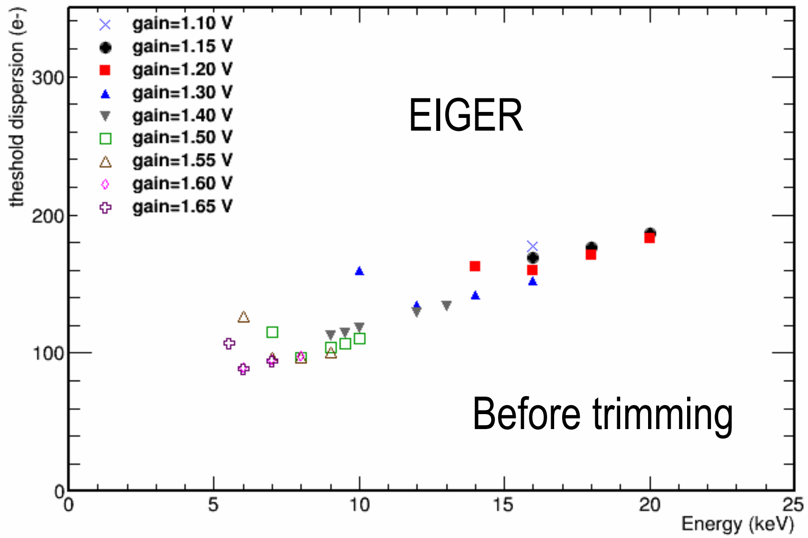
The future: charge integrating detectors for synchrotrons

- **JUNGFRAU: adJUstiNg Gain detector FoR the Aramis User station at Swiss-FEL at PSI**
- High dynamic range with up to 10^4 photons/pulse/pixel achieved through dynamic gain switching (3 gains)
- Single photon sensitivity (higher gain)



Threshold dispersion and trimming





Psi46:

• Each ROC to lowest possible threshold, but trimmed within a ROC

• 70e⁻ threshold dispersion

EIGER:

• After trimming, threshold dispersion has to be <30 e⁻ in all Energy, threshold settings

• Important to assure same threshold everywhere to assure same counting capabilities for every pixel and reject fluorescence