PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut
Bernd Schmitt, Aldo Mozzanica

Charge integrating detectors for SWISSFEL

Outline

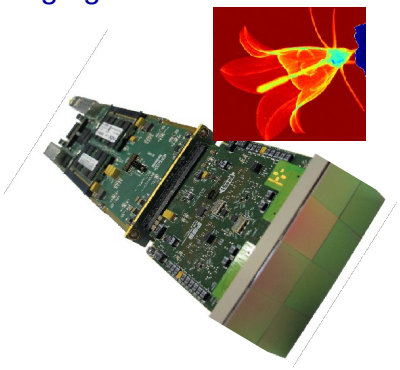
- From photon counting to charge integrating detectors
- Basic principles: preamplifier with automatic gain switching logic
- Requirements for a XFEL detector
- Read out chip development:
  - Prototype history
  - Design features of the GOTTHARD 1.0 ROC
- Summary of the GOTTHARD detector performances
- The AGIPD detector for E-XFEL
- The 2D detector for SWISSfel baseline concept
- Future 2D detectors: towards lower pitch and lower noise
- The image builder
- Conclusions.

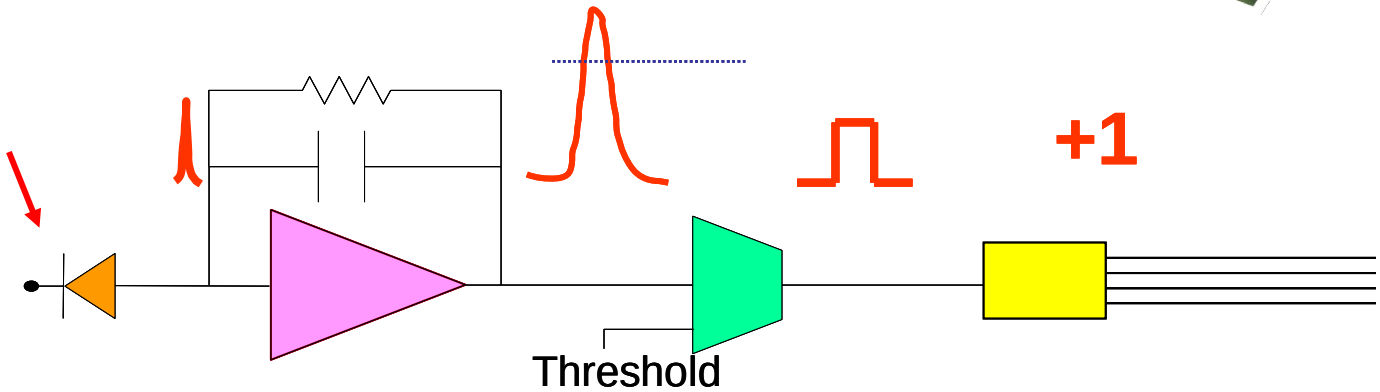
From photon counting detectors…

MYTHEN
1k to 30k 50µm strips for powder diffraction, small angle scattering, medical imaging…

PILATUS
100k to 6M 172µm pixels for protein crystallography, small angle scattering, imaging …

EIGER
500k to 9M 75µm pixels, small angle scattering, CDI, XPCS, for protein crystallography imaging ….





03/13/12

Sensor | Amplifier and shaper | Comparator | Counter | Digital output

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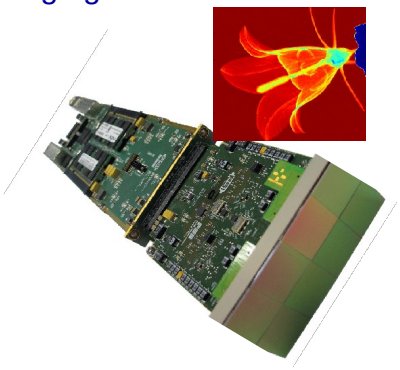

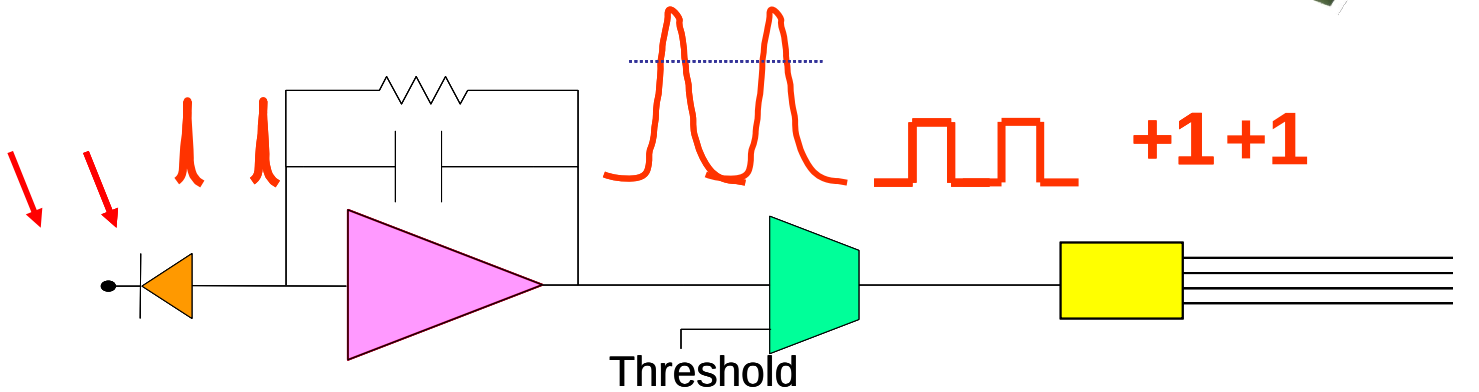

03/13/12

Sensor | Amplifier and shaper | Comparator | Counter | Digital output

From photon counting detectors…

10^{10-12} X-ray photons

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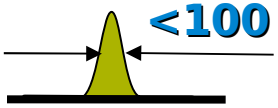

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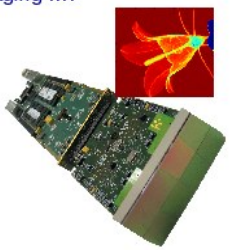

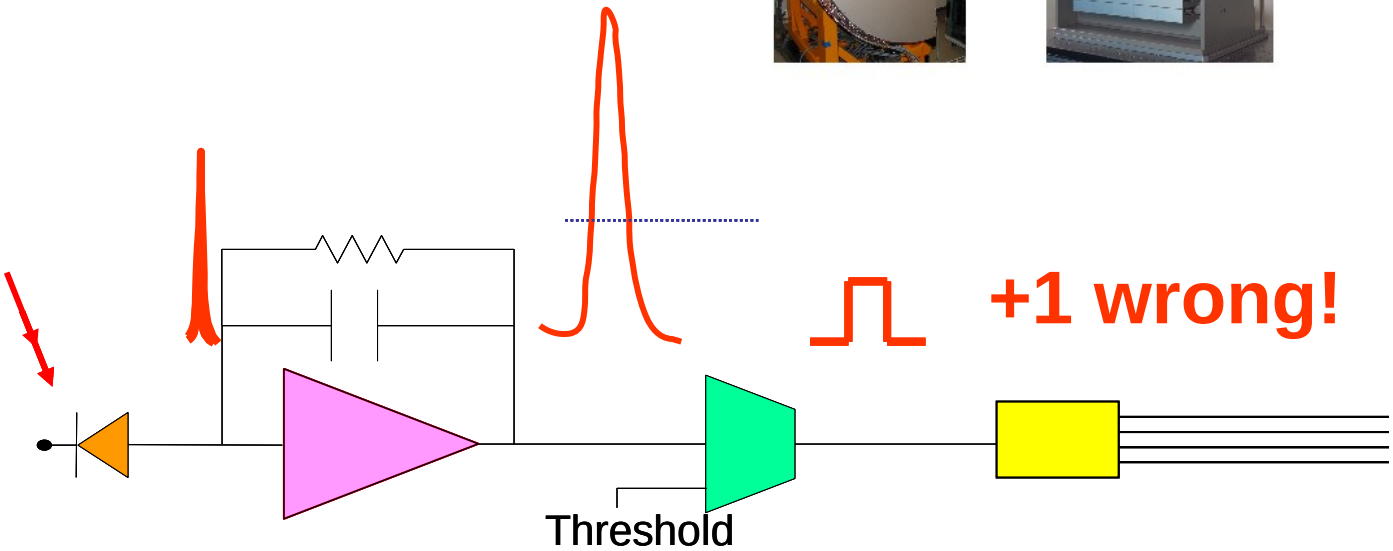

Sensor | Amplifier and shaper | Comparator | Counter | Digital output

… to charge integrating ones

10^{10-12} X-ray photons

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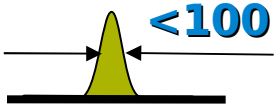

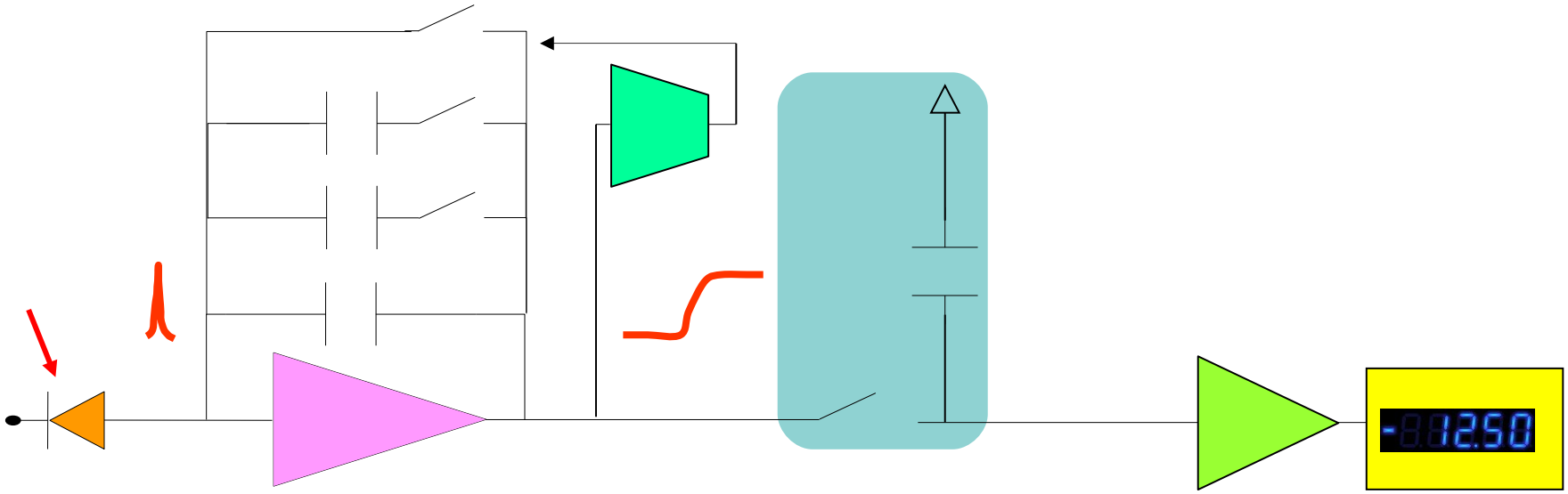

Sensor | Amplifier and reset | Gain switching | Sample and hold | Analog output | External ADC

… to charge integrating ones

10^{10-12} X-ray photons

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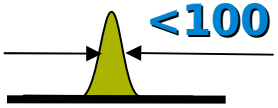
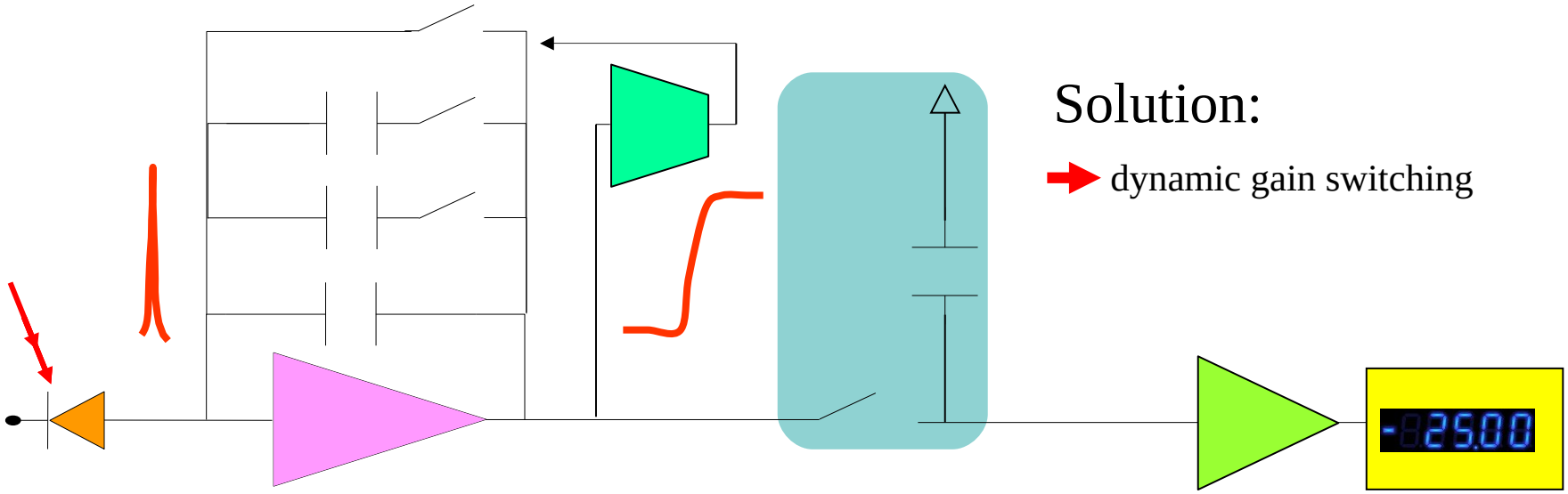


Dynamic range: 10000

- voltage swing usually ~1V
- noise usually ~mV

→ 1 photon ~10mV
100 photons dynamic range



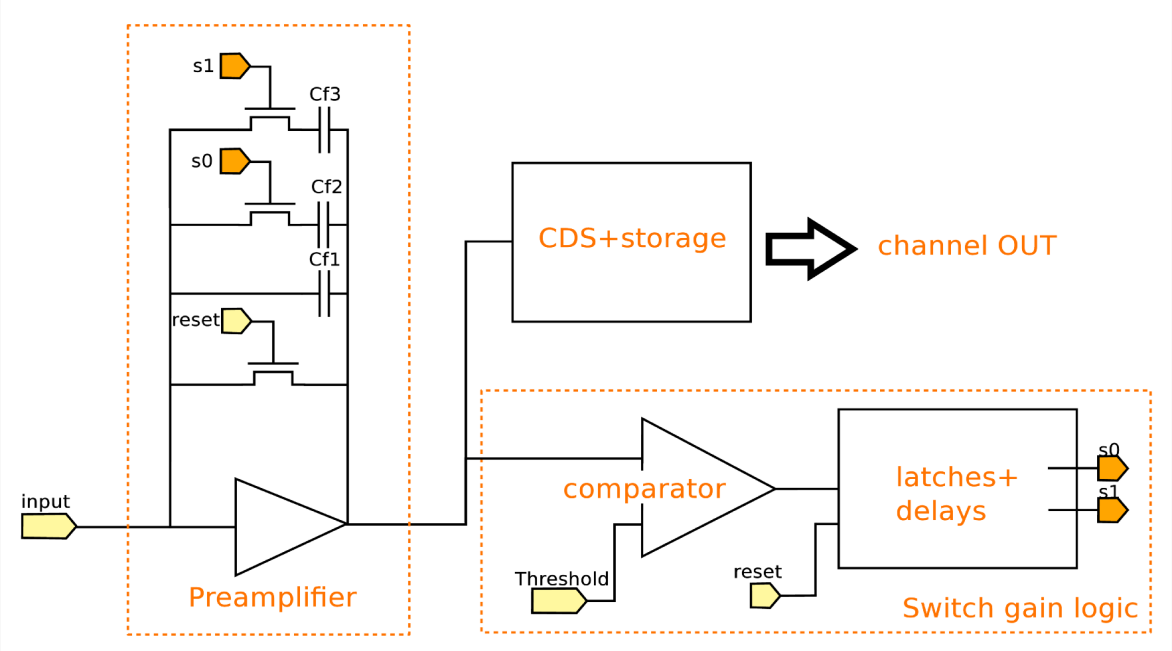
Solution:

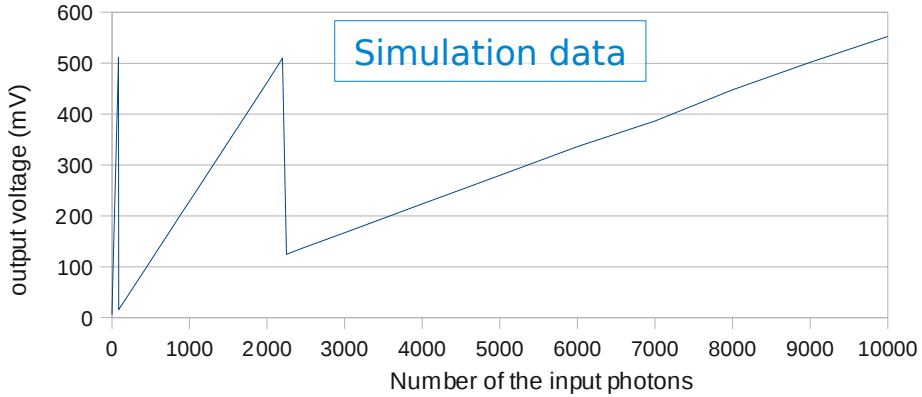
→ dynamic gain switching

Sensor | Amplifier and reset | Gain switching | Sample and hold | Analog output | External ADC

Preamplifier with gain switching

- Common for 1D and 2D
- CSA in charge integrating configuration
- 3 feedback capacitors:
  - C_{f1}=50-100fF
  - C_{f2}~20xC_{f1}
  - C_{f3}~100xC_{f1}





- Logic after comparator to:
  - Switch a 2nd time if 1st switch not enough
  - Avoid a 2nd switch on spikes due to the 1st one
- Switching has to be FAST (<10ns)

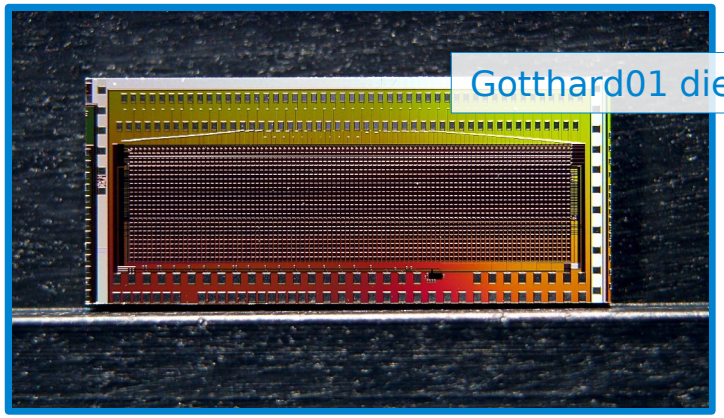
E-XFEL Detector requirements

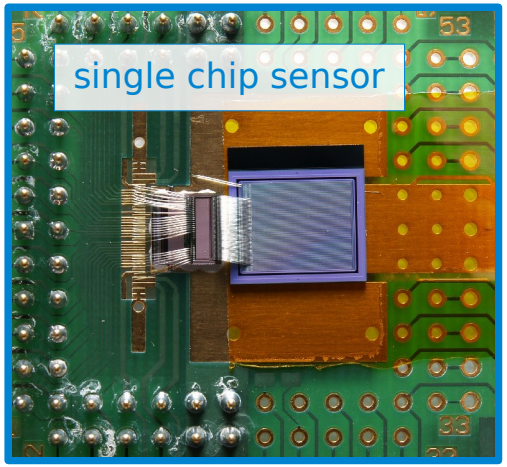
- High dynamic range (in the 10^4 γ/ch. range)
- Single photon resolution (@12keV γ energy): same performance as a photon counting device at low rate (low signal regions)
- Electronic noise negligible with respect to Poisson fluctuations at high rate (high signal regions)
- High Linearity (~1%)
- Small pitch (50μm or smaller for strips)
- Fast front-end: integration-store-reset cycle in <220 ns
- 4.5 MHz frame rate:
  - Ability to record as many frames per bunch train as possible
- Radiation tolerant design: >>MRad dose on the sensor

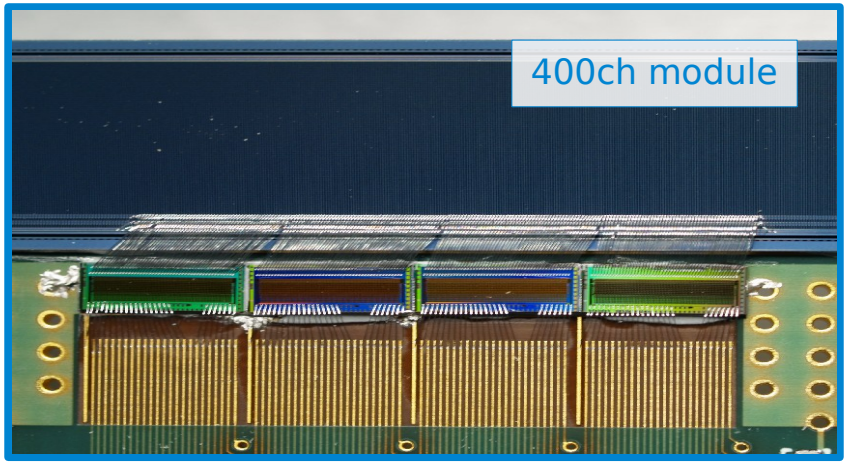
GOTTHARD 0.1 – the starting point

GOTTHARD:
Gain Optimizing microsTrip sysTem witH Analog ReaDout

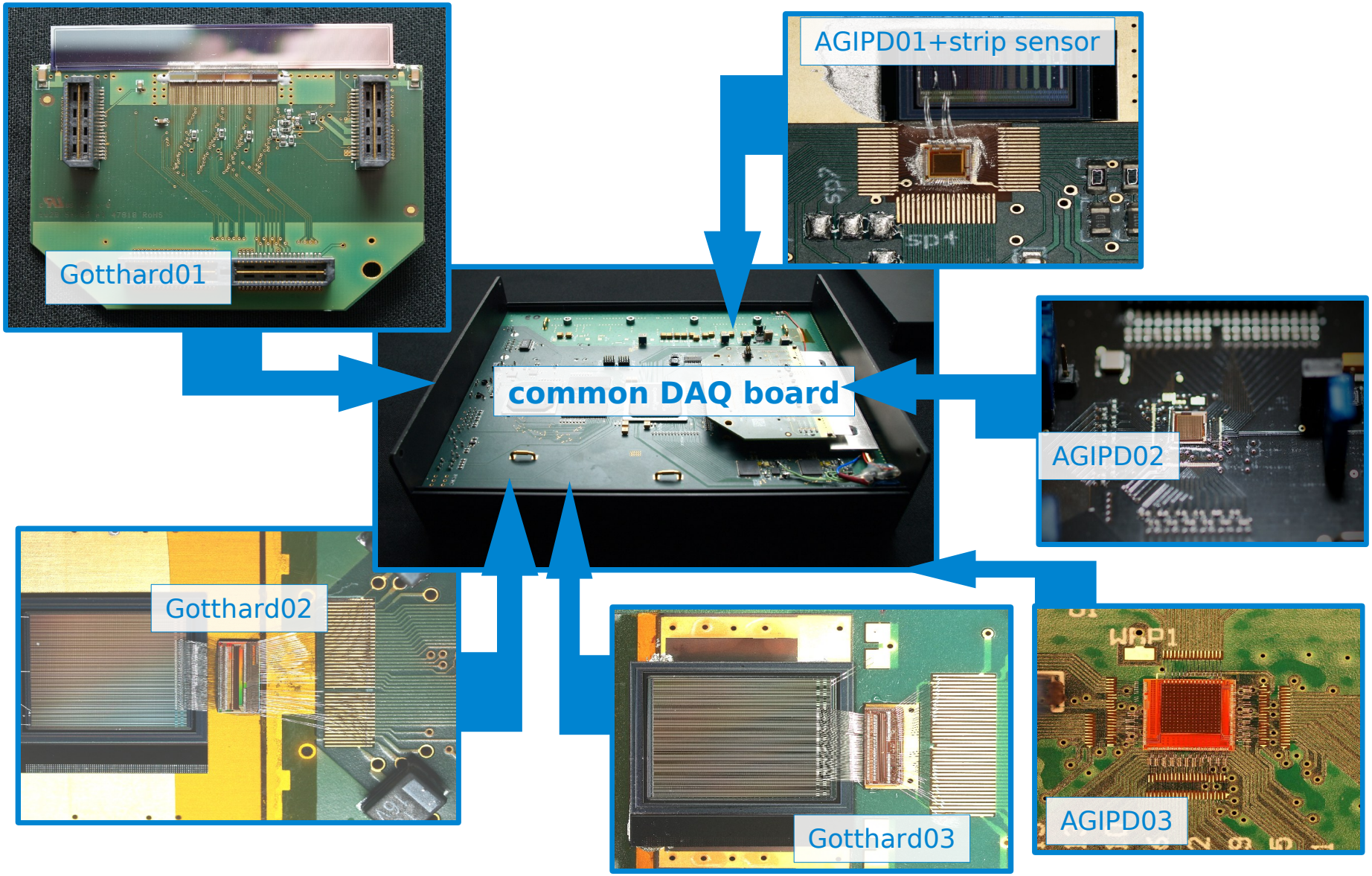
- designed in 2004 in UMC0.25µm technology
- 100 channels
- 4 gain stages with automatic gain switching
- double sample and hold circuit to perform offline CDS
- source follower based output bus
- single ended output





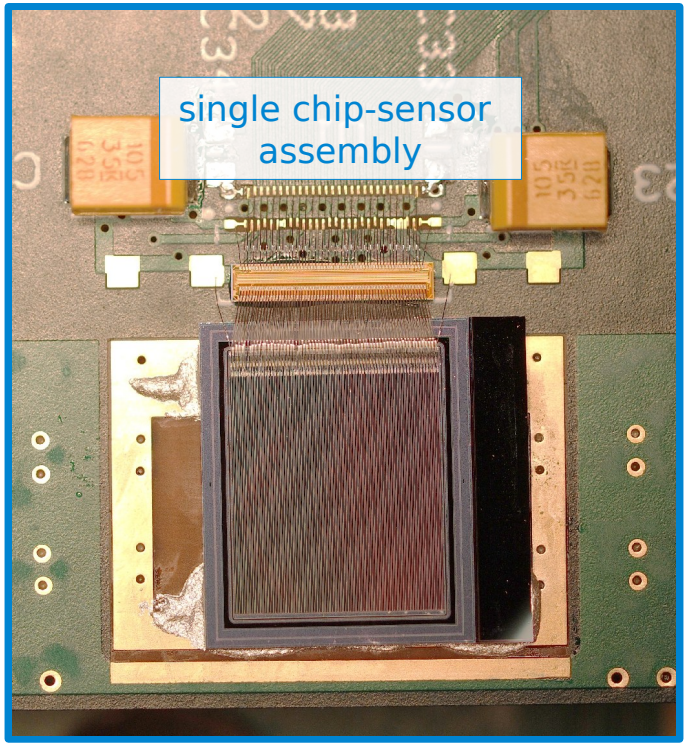


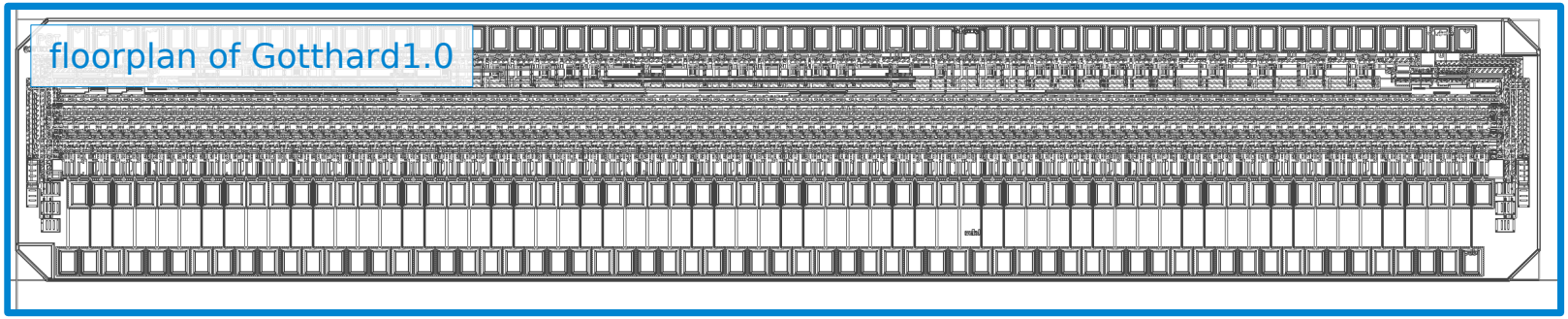
Prototypes (2008-2010)



GOTTHARD 1.0

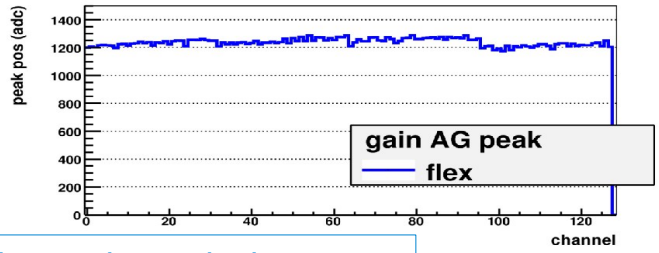
- 6.3x1.4mm^2 - 128 channels - 50µm pitch
- 3 automatic gain stages + 1 High Gain mode
- fast off pixel buffers, to sustain 32MHz readout with no cross-talk
- 4 diff. analog outputs, 8 digital (gain) outputs
- ~ 1mW/ch.
- Produced in a MPW run, shared engineering run foreseen



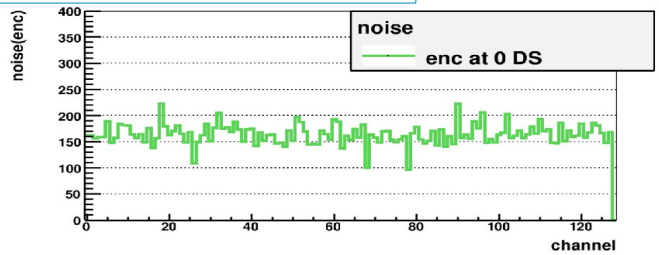


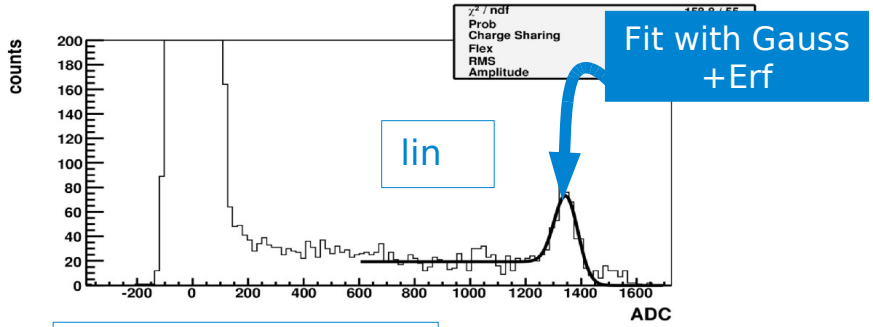
Noise – very high gain mode

- measured with X-ray tube and Ag fluorescence light (22 keV)
- 120 V detector bias
- ~ 1 us integration time
- Energies as low as 4keV can be used

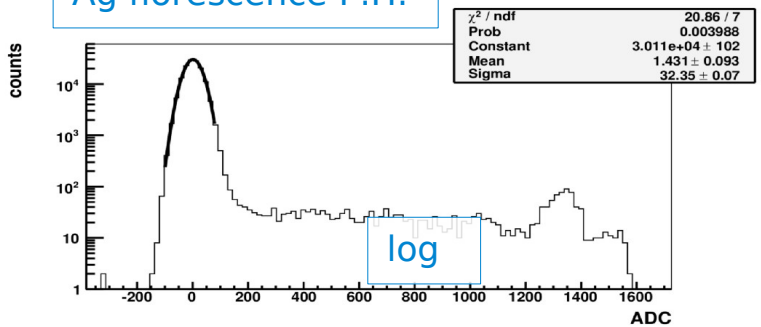


ch. to ch. variations

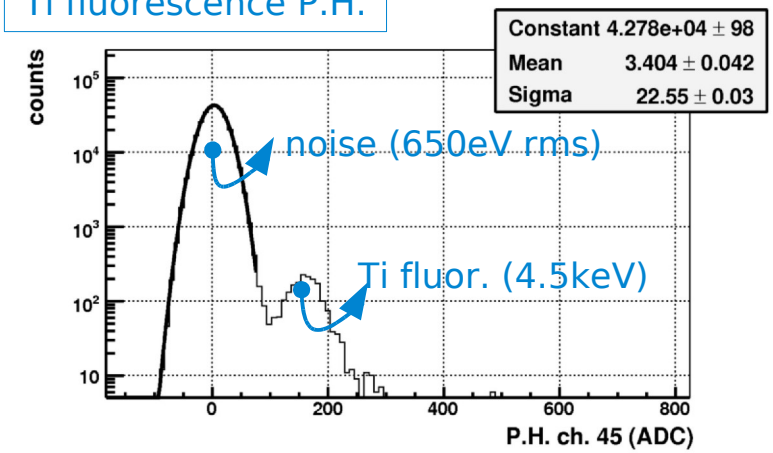




Ag florescence P.H.

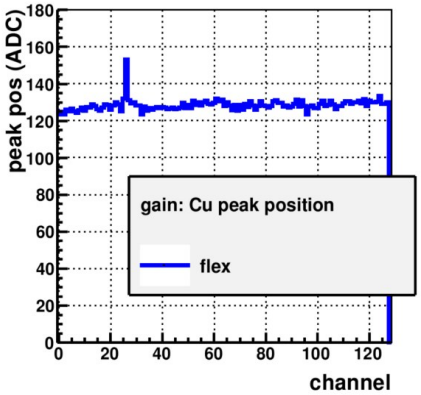


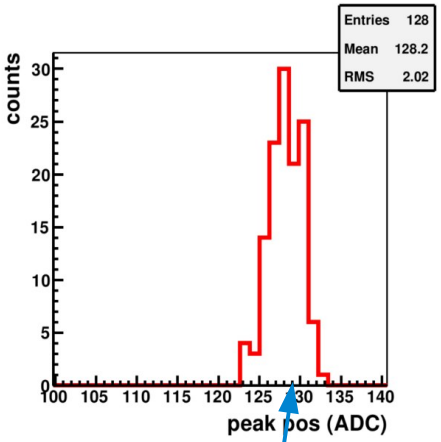
Ti fluorescence P.H.



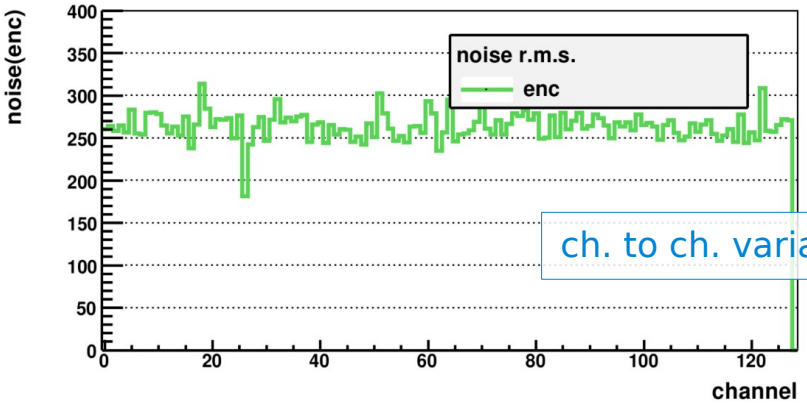
Noise – Gain 1

- Gain1 is the starting gain for the switching mode
- measured with Cu fluorescence light (8 keV)
- 120 V detector bias
- ~us integration time
- Average noise is 260 e.n.c.
- SNR=13 (for a 12 keV photon signal)
- Gain1 total range ~ 80 ph. --> Dynamic range in excess of 10bit with one gain only

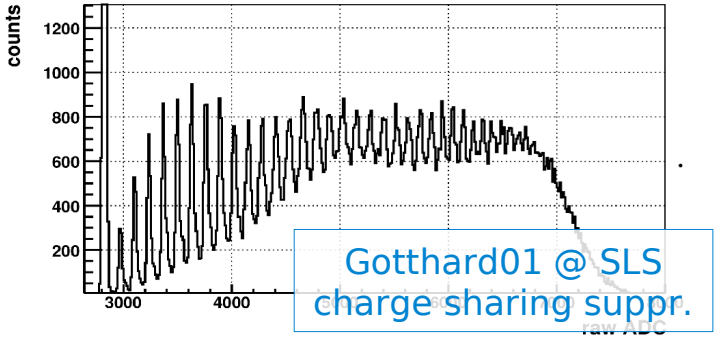




gain dispersion 1.5%

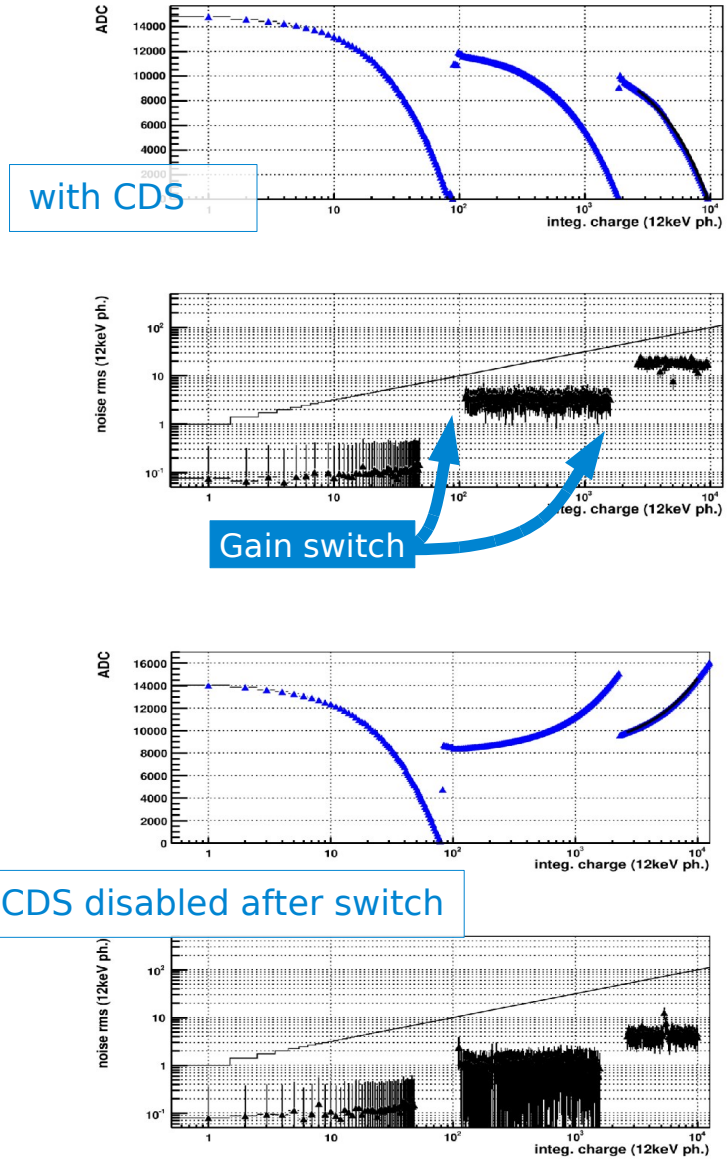


ch. to ch. variations



Gotthard01 @ SLS
charge sharing suppr.

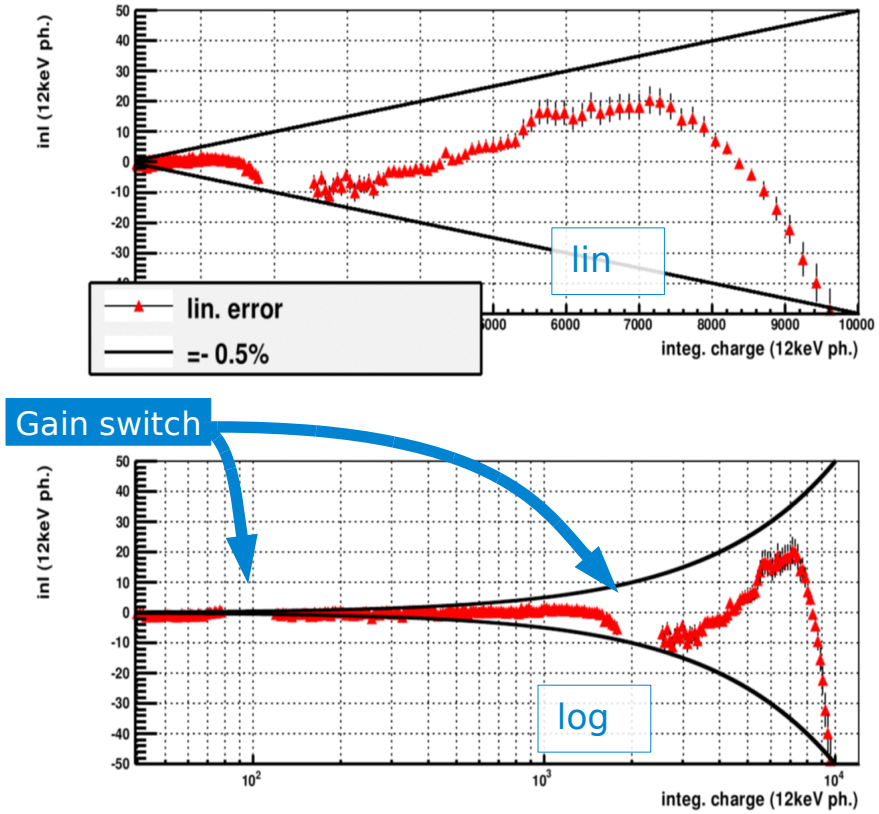
Noise – many photons



- an integration time scan at constant input current (visible light) was used to evaluate the noise at low gains
- CDS increases the noise of gain 2 and 3: a circuit to disable CDS after switch is present
- at all gains the electronic noise is well below the Poisson level
- “terminal” saturation at 10^4 ph.

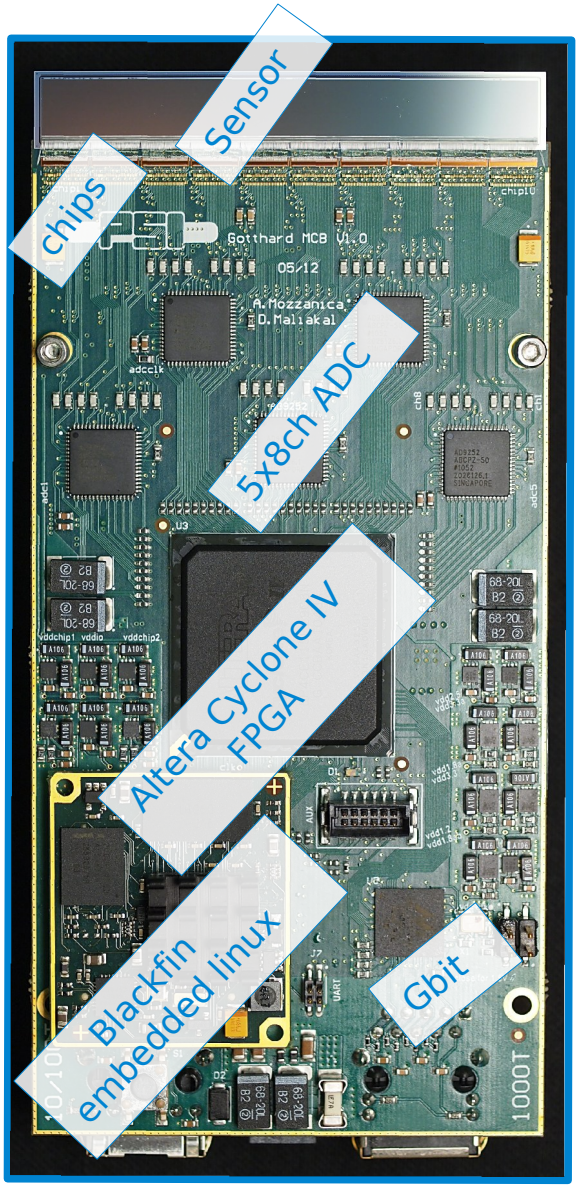
Linearity

CDS disabled after switch



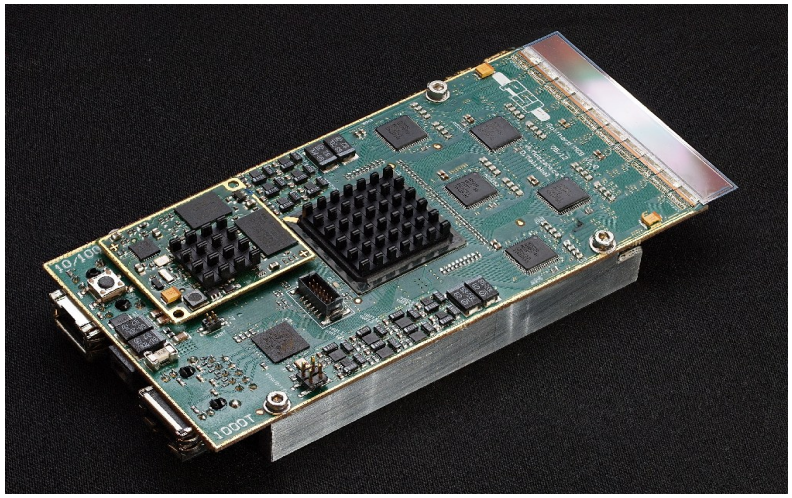
- for each stage a linear fit is performed
- for each intensity the difference between the line and the measured ADC value is plotted
- linearity errors within +- 0.5% (source effects included) in the design input range (0-10^4 ph.)
- On smaller ranges better linearity can be achieved

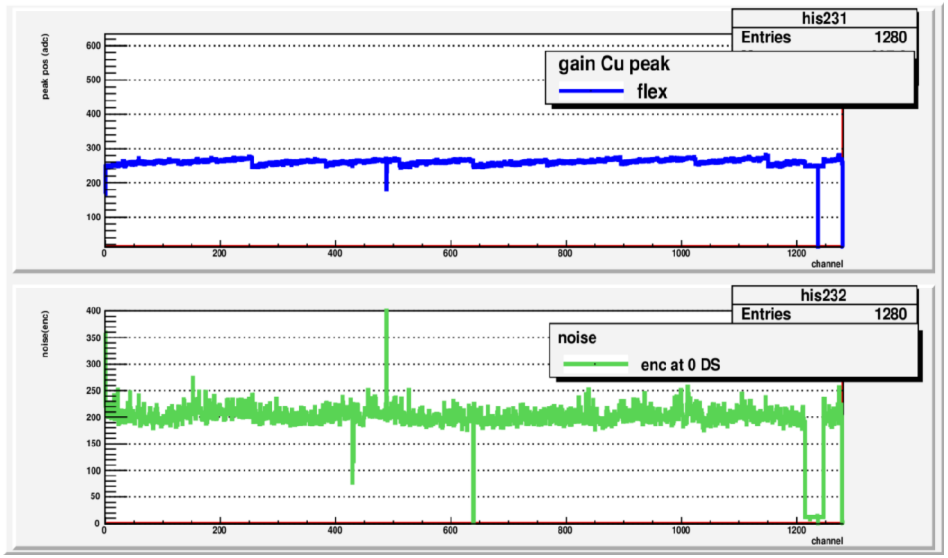
GOTTHARD module: overview



- 67mm x 130mm
- 50 μm pitch, 1280ch/module (same as MYTHEN)
- 10 chips, 4 analog outputs per chip
- 40 ADC channels @50Mhz,14bits
- Gbit Ethernet data transfer for readout
- Fast readout (>1MHz to FPGA)
- up to 250 images can be stored in the FPGA

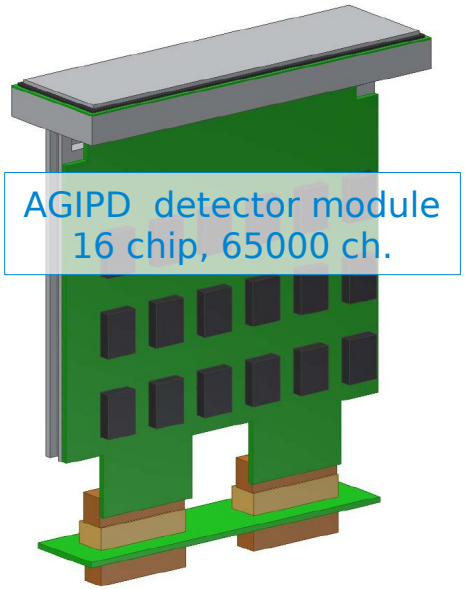
GOTTHARD specification summary

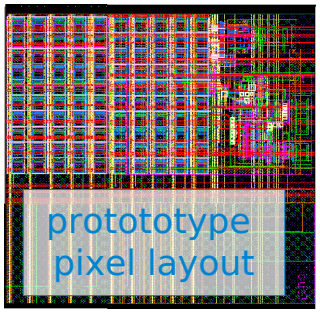




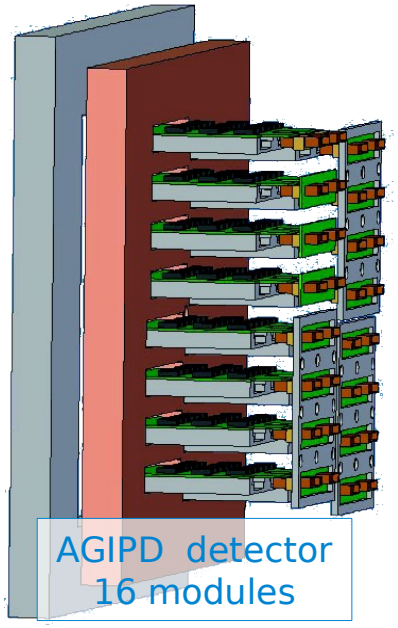
	Specifications
module size	6.7x13 cm
sensitive area	64x10mm
sensor thickness	320-500 µm
pitch	50 µm
dynamic range	10^4 12keV photons
min Energy	<3.5 keV
linearity	better than 0.5%
point spread function	O(pitch)
min int. time	80ns
dead time	<50ns
cooling	air (fan)
readout time = 1 / frame rate	>50kHz continuos 1MHz burst
XFEL ready	YES

2D detector for E-XFEL





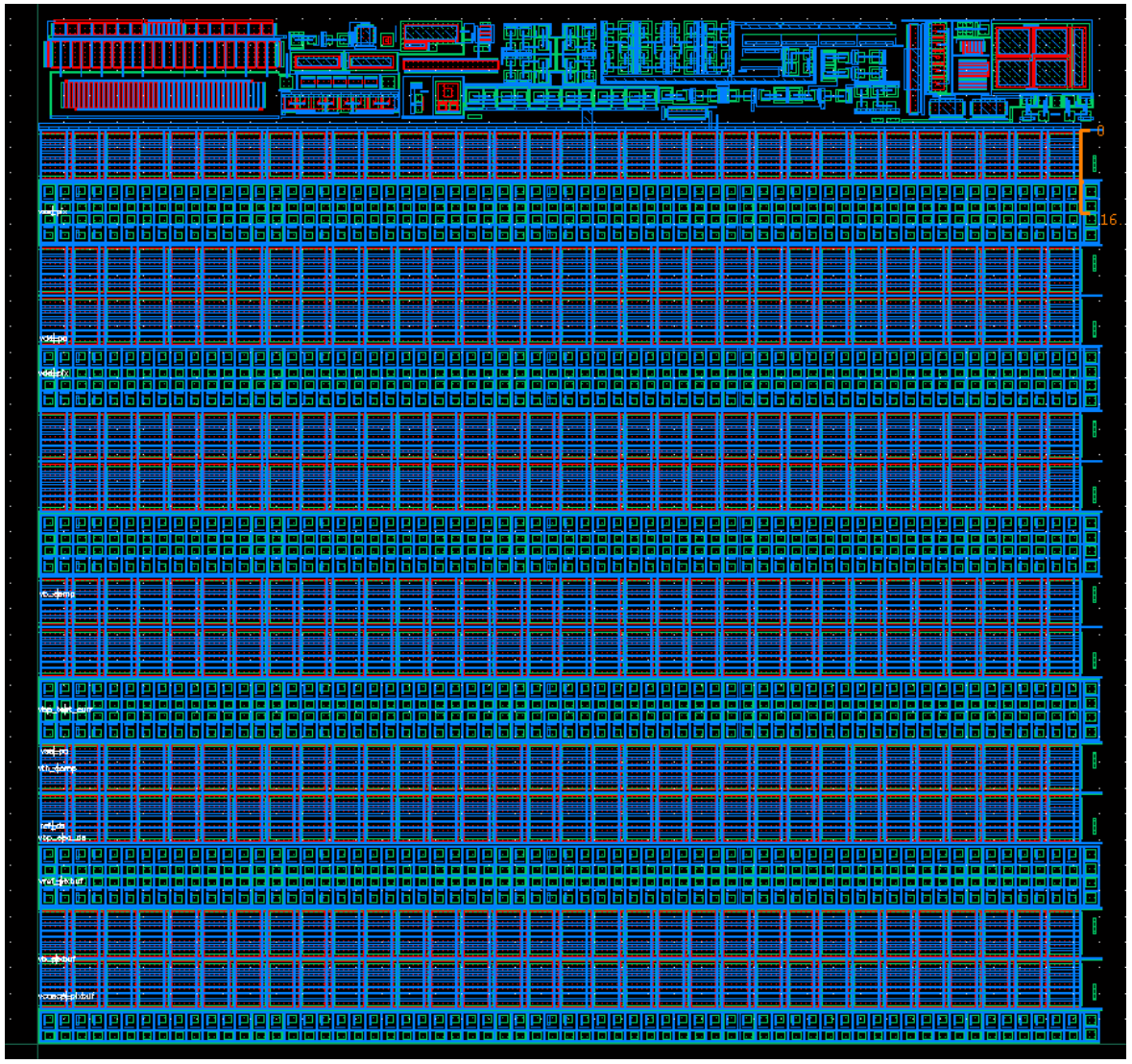
AGIPD:
Adaptive Gain Integrating Pixel Detector



- 200x200μm^2 pixel size
- 64x64 pixels per chip
- 8 chip/module,
- 1024x1024 total pixel count

- ~350 on-pixel storage cells
- driven by the E-XFEL bunched time structure
- limiting the pixel size and spatial resolution.

AGIPD status



200 µm

4 prototypes submitted

AGIPD04 16x16 pixel matrix currently under test

Fine tuning of the parameters for noise optimization is ongoing

Verification of storage cell radiation hardness to be completed

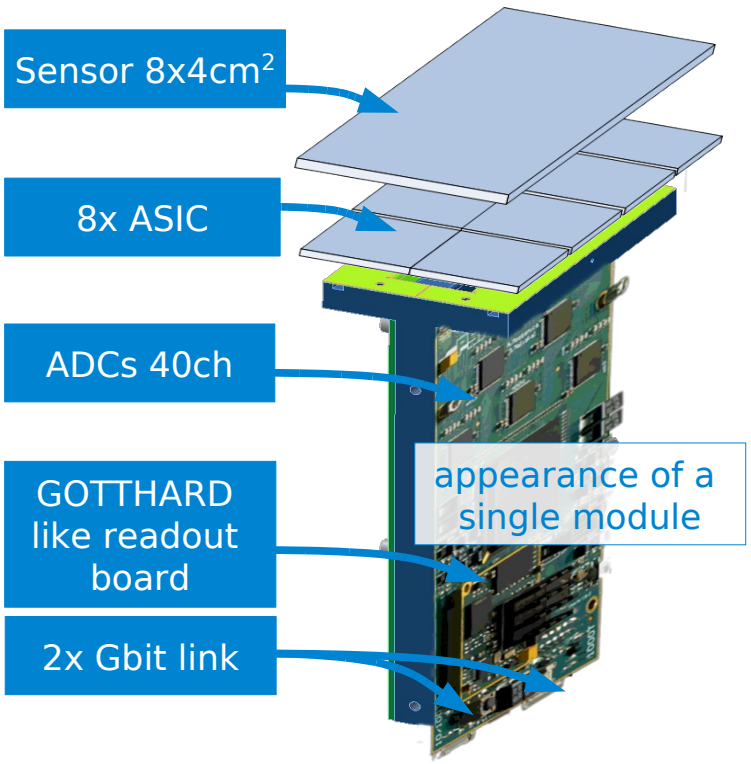
Full chip submission end 2012

First module production planned in 2013

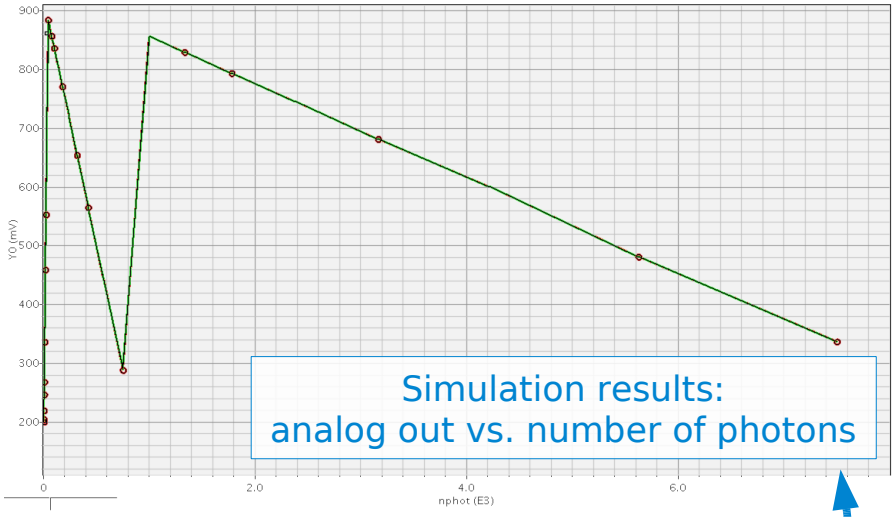
Pixel layout with 352 memory cells

=> if no storage cells the pixel size can greatly be shrunk

2D detector: baseline design



ASIC technology	UMC110nm
mudule pixel count	525k
mudule size	80x40 mm²
sensor thickness	320-500 µm
pixel size	75x75 mm²
dynamic range	up to 10^4 12keV photons
noise r.m.s.	<150 e.n.c.
min Energy	<3 keV
linearity	better than 1%
point spread function	1 pixel
dead time	<50ns
cooling	liquid
readout time = 1 / frame rate	400Hz



>8000 photons

- ASIC and readout system based on GOTTHARD
- Dimensions, sensor and mechanics from EIGER
- Timeline: ASIC->Q1/2013; module->Q4/2013; 4M detector->2014

2D detectors: future options 1/2

Higher resolution pixel detector

- 50 μm pixel pitch
- design similar to the 75 μm detector
- only 2 gain stages
- Same noise and linearity performances
- Dynamic range per pixel ~2000 12keV photons
- Range in terms of γ/mm^2 only slightly lower

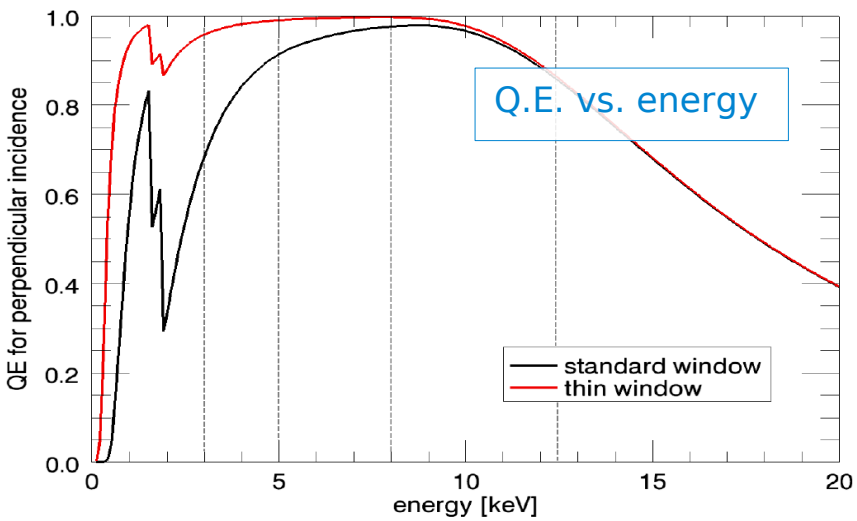
mudule pixel count	1M
mudule size	80x40 mm^2
pixel size	50x50 mm^2
dynamic range	up to 2000 12keV photons
noise r.m.s.	<150 e.n.c.
min Energy	<3 keV
linearity	better than 1%
point spread function	1 pixel
readout time = 1 / frame rate	>200Hz

2D detectors: future options 2/2

Low noise pixel detector

several schemes under study:

- analogue multi-sampling
  - tested with AGIPD where noise 340->125 e.n.c.
- trapezoidal weighting function
- increased preamplifier gain (in combination with one of the others)
- Sensors with new entrance window have to be used (Q.E. >0.8 @500eV)
- Pixel size may be driven by charge sharing consideration



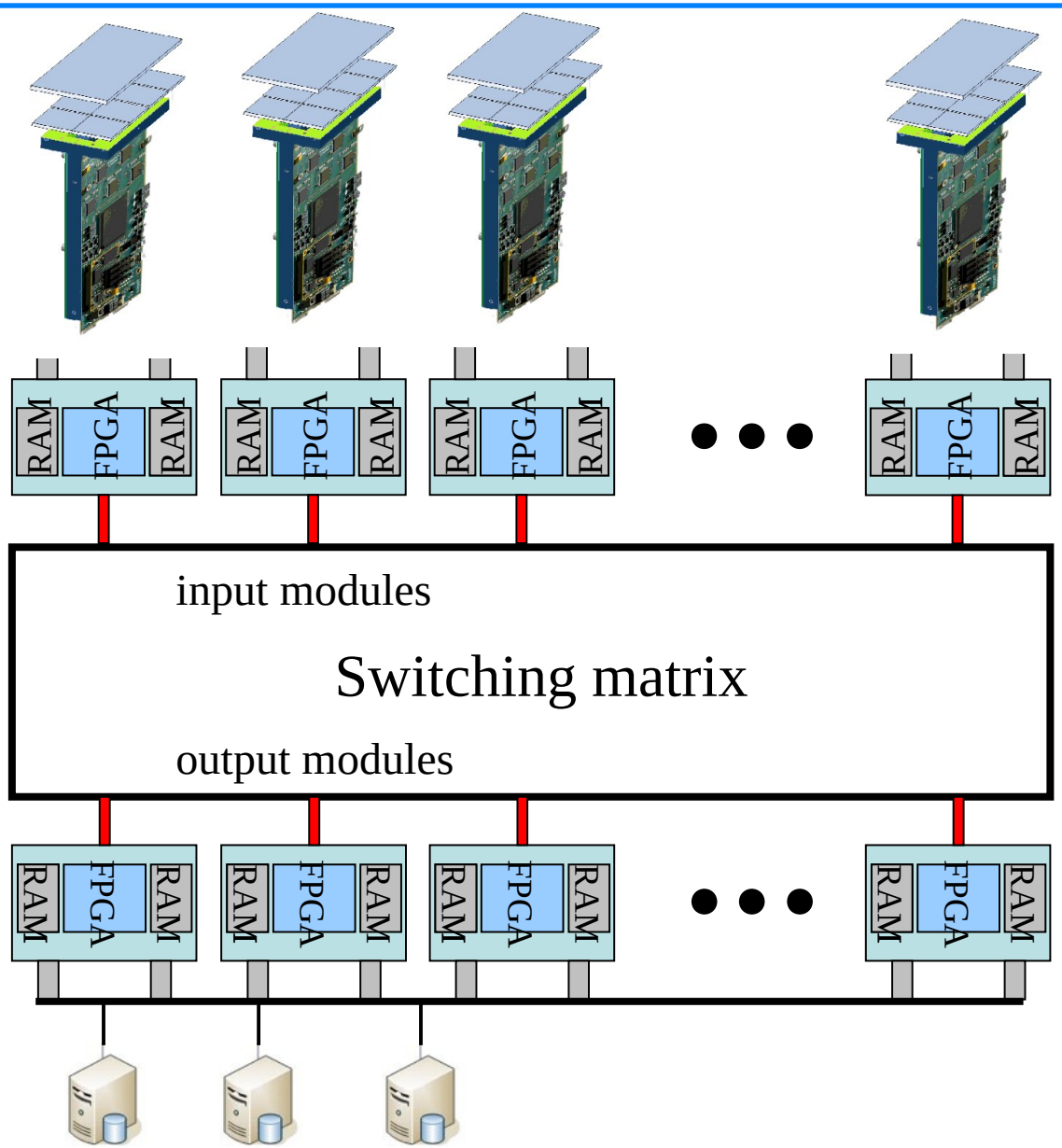
mudule pixel count	500k-1M
mudule size	80x40 mm^2
pixel size	$(50\text{-}75\ mm)^2$
dynamic range	down to 100 12keV photons
noise r.m.s.	50~80 e.n.c.
min Energy	1~1.5 keV at 5 sigma
linearity	better than 1%
point spread function	1 pixel
readout time = 1 / frame rate	>200Hz

Low energy photon detection threshold for charge integrating system is a complex matter, see the following paper:
The single photon sensitivity of the Adaptive Gain Integrating Pixel Detector, J. Becker, AGIPD collaboration, in press

The image builder 1/2

- Large area 2D system will have a high number of 1G or 10G network connections and high (even if not as high as in EIGER case) bandwidth requirements
- e.g. a 9M pixel has 36 network connections and generates 1.8GBytes/s
- Reconstruct the images from the various packets is a CPU intensive task
- Some sparsification algorithms could be done in firmware but require full image information
- A custom build FPGA based image builder would greatly reduce the hardware requirement and ease the detector operation
- It would allow the deployment of even bigger system e.g. 49M

The image builder 2/2



- Number of input is equal to the number of modules
- Number of output is equal to the max. bandwidth/10Gbit
- e.g. a 9M pixel will have 18 input boards and 2 outputs
- Modular: same motherboard, different number of daughter boards

Conclusions

- Charge integrating strip detector for the SWISSfer are being developed in house
- The GOTTHARD 1D detectror has been designed, with the following performances:
  - single photon resolution for energies down to few keV
  - low noise and high linearity on the full dynamic range
  - readout at 1MHz frame
- The complete GOTTHARD detector system is being commissioned
- A 2D readout ASIC with 75μm pitch based on the GOTTHARD and EIGER detectors is being designed
- 2D pixel detector with smaller pixel and/or lower noise are being considered
- The development of a image builder will reduce the IT requirement and will simplify the use of the detectors.

Acknowledgments

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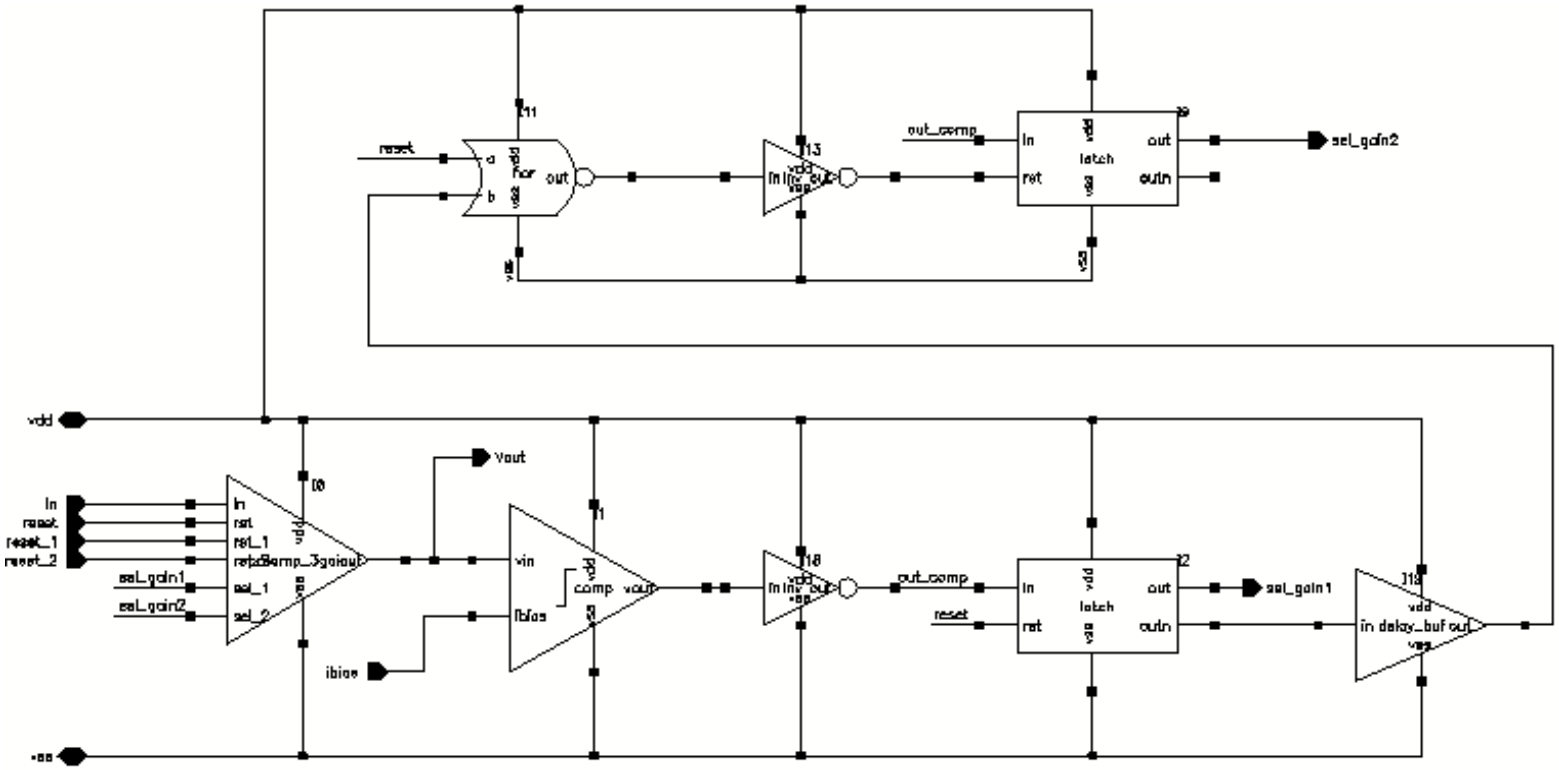
I. Johnson, D. Maliakal, C. Ruder, V. Radicci, B. Schmitt and X. Shi

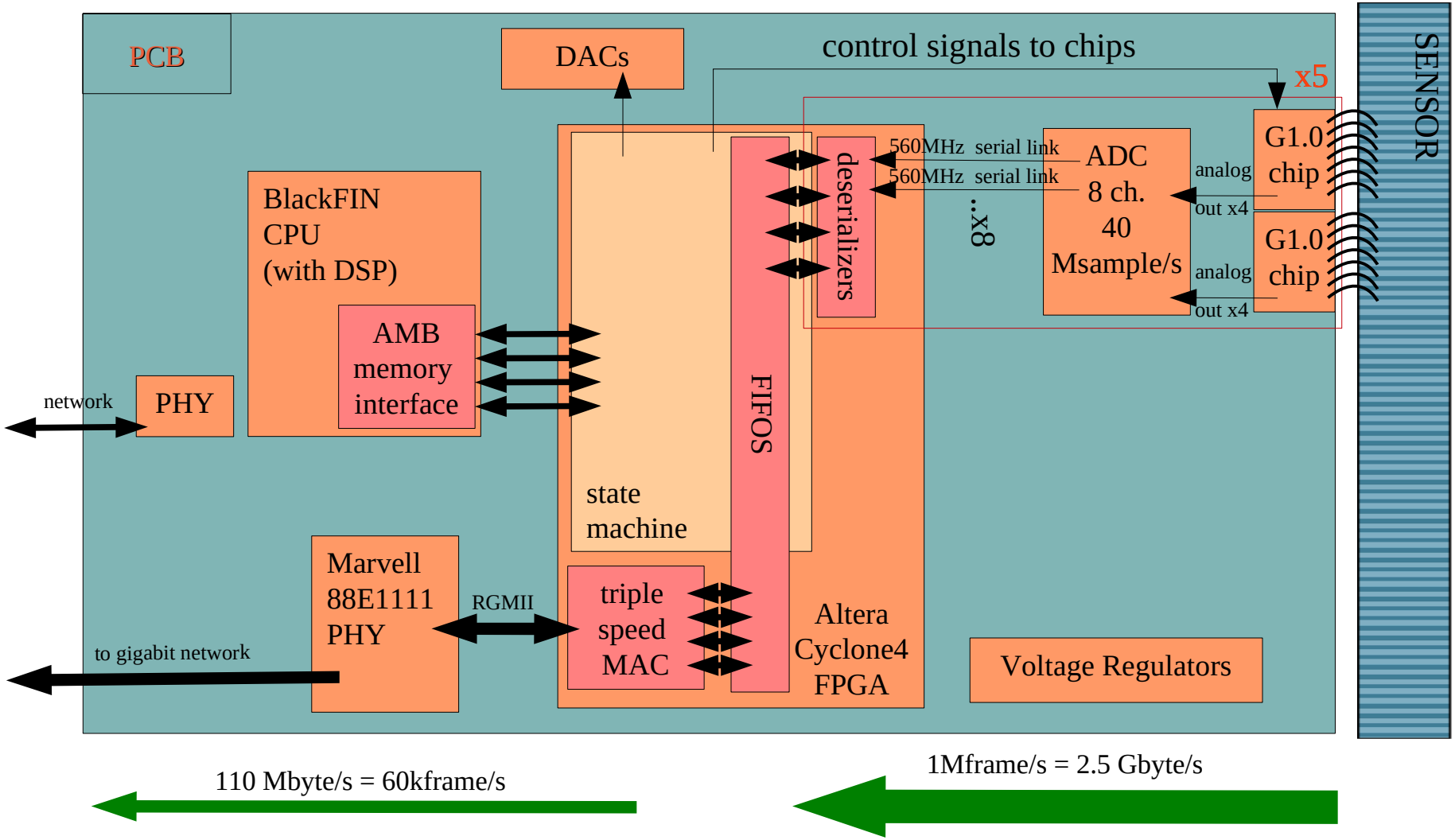
Paul Scherrer Institut, 5232 Villigen, CH

Backup slides

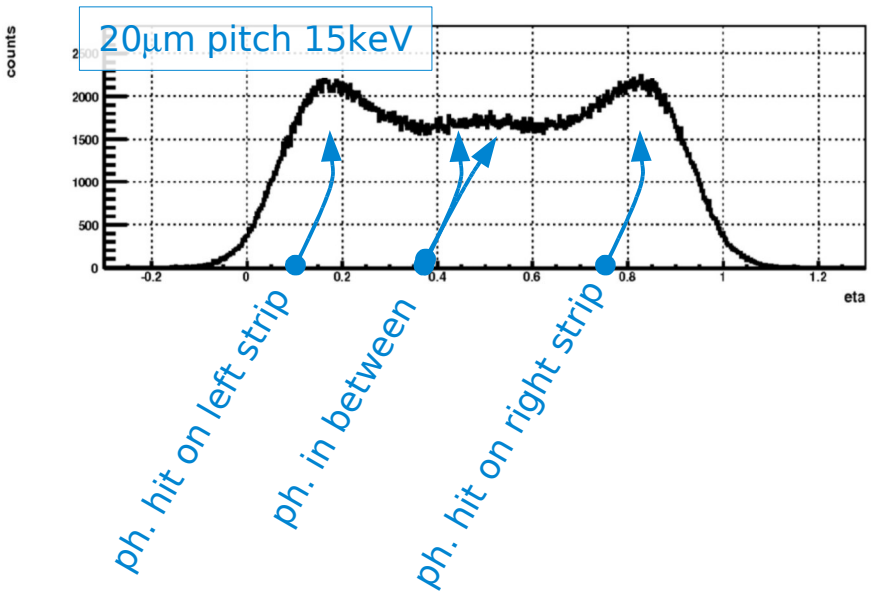
gain switching logic



GOTTHARD module: block diagram



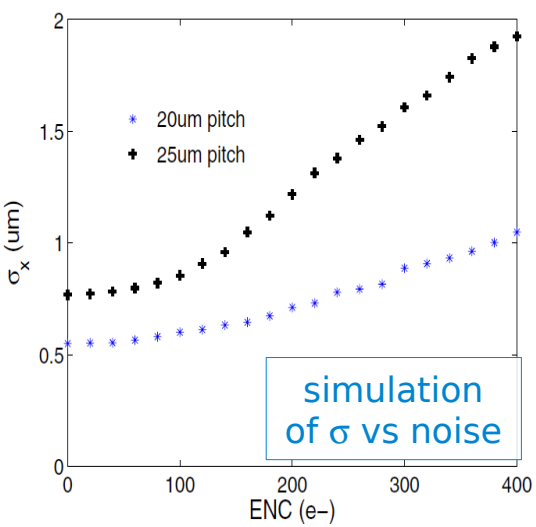
G01-charge interpolation

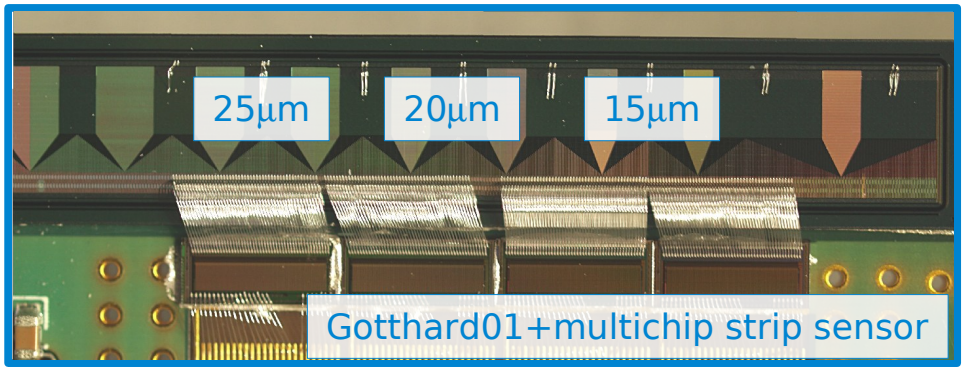


Eta algorithm for position reconstruction:

- $\eta = Q_R/(Q_L+Q_R)$
- eta distribution $N(\eta)$ are collected for a uniform photon field
- the hit position is then:

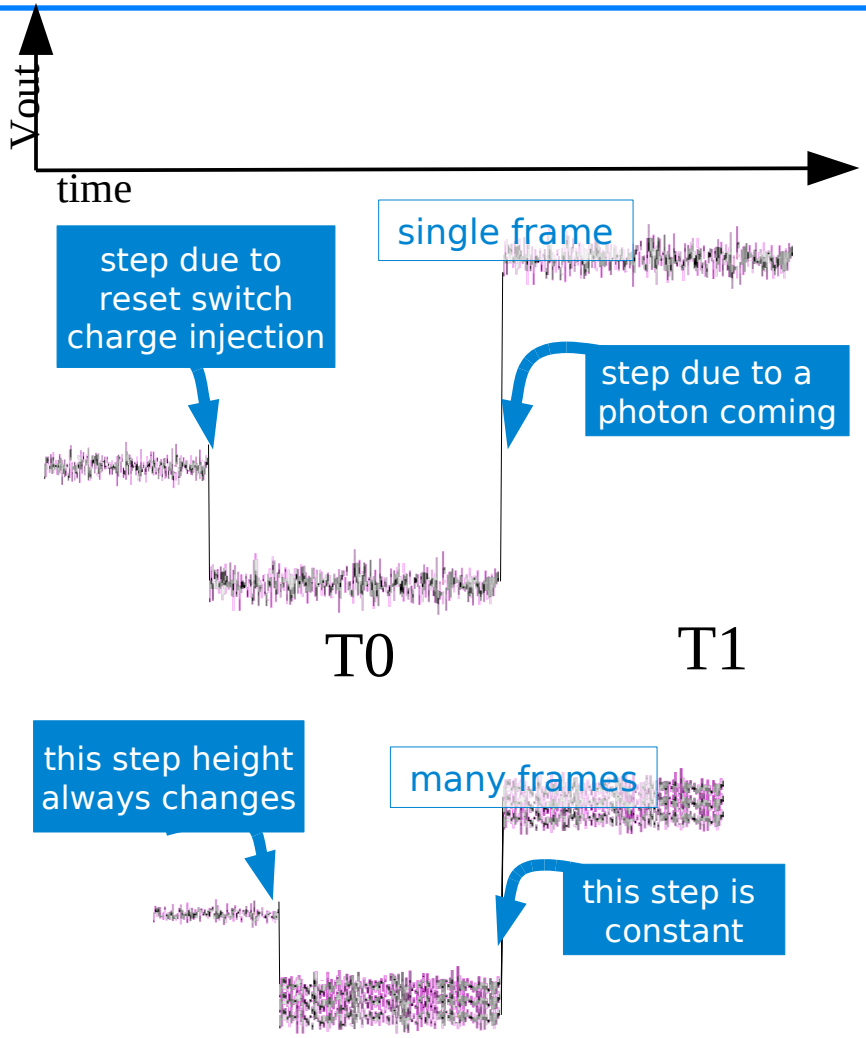
$$x_\eta = p\frac{\int_0^{\eta_0}\frac{dN}{d\eta}d\eta}{\int_0^1\frac{dN}{d\eta}d\eta}$$

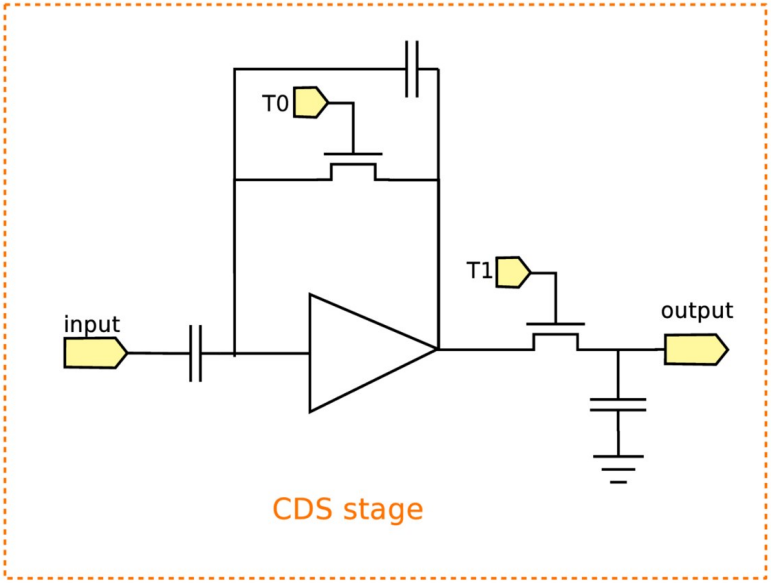




Correlated Double Sampling

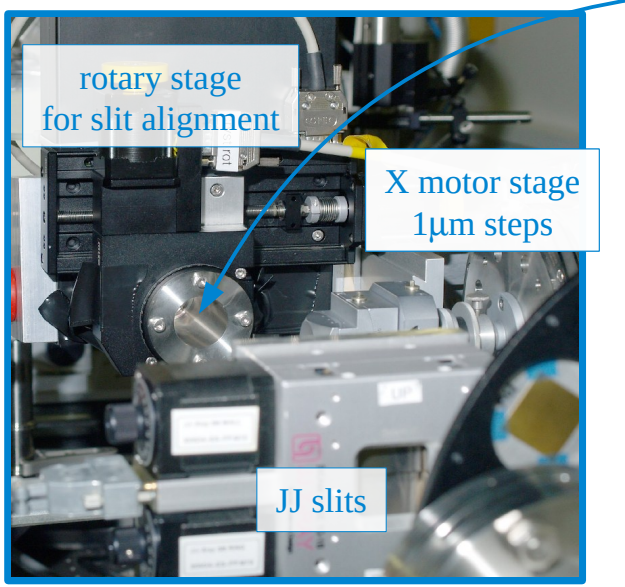
- The main contribution to the noise in the highest gain is the reset noise
- if we only sample the signal at T1 we see the reset noise
- if we measure at T1 and T0 and make the difference, reset noise contribution is eliminated

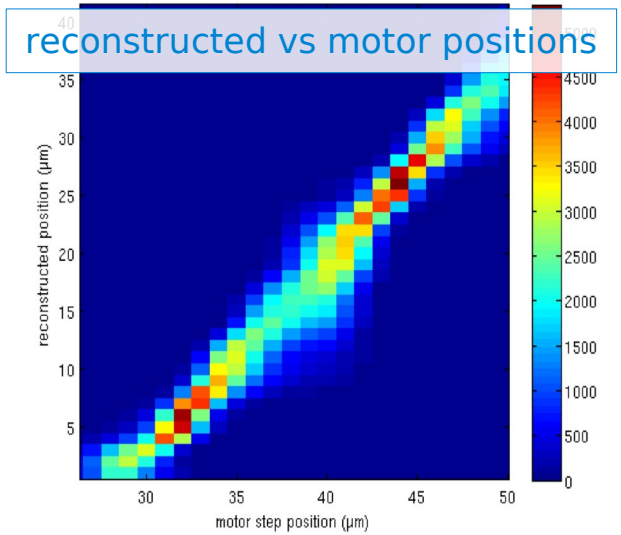


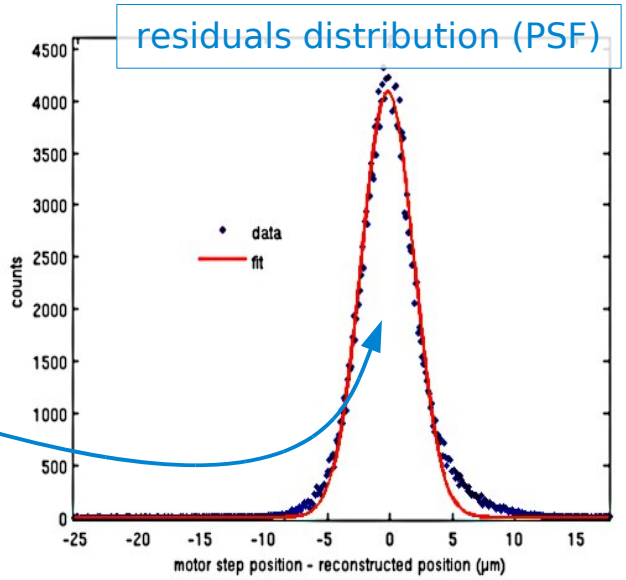


G01-charge interpolation/2

- To measure the spatial resolution a 2μm W slit has been scanned in 1μm steps in front of the strips
- slit parallel to strips
- Vertical beam size ~100μm
- Strip pitch 20μm, 15keV beam



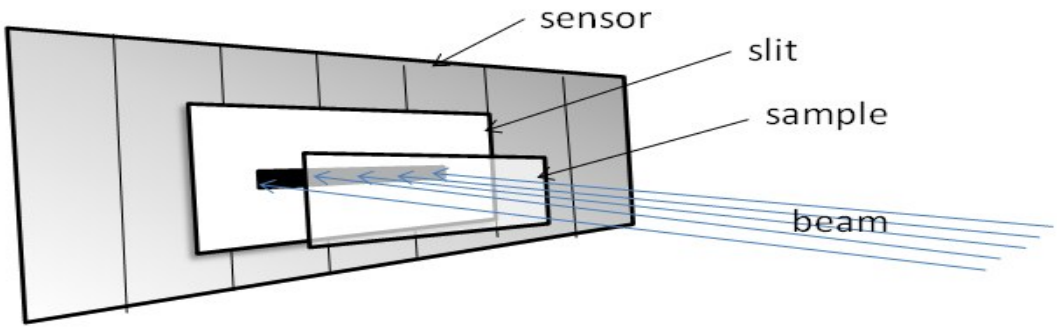


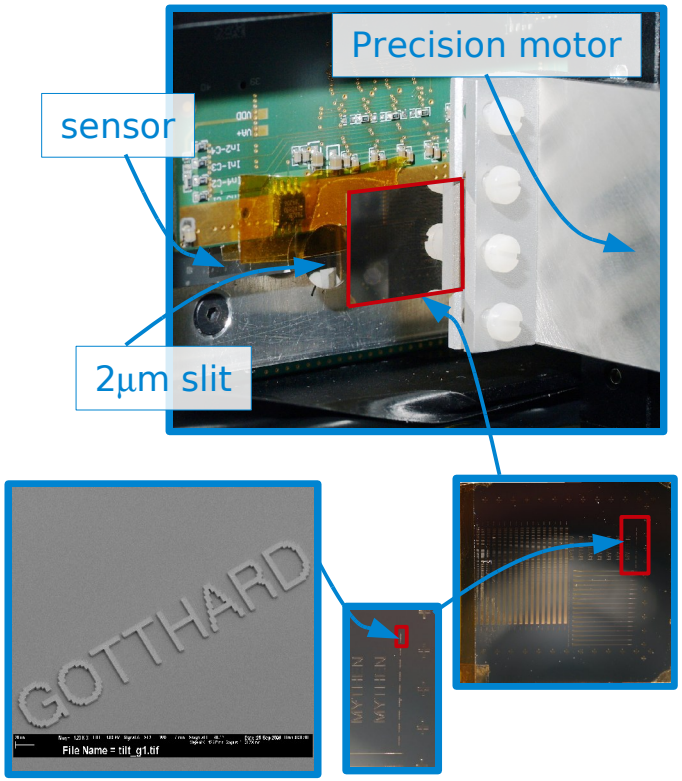


FWHM=4.2μm

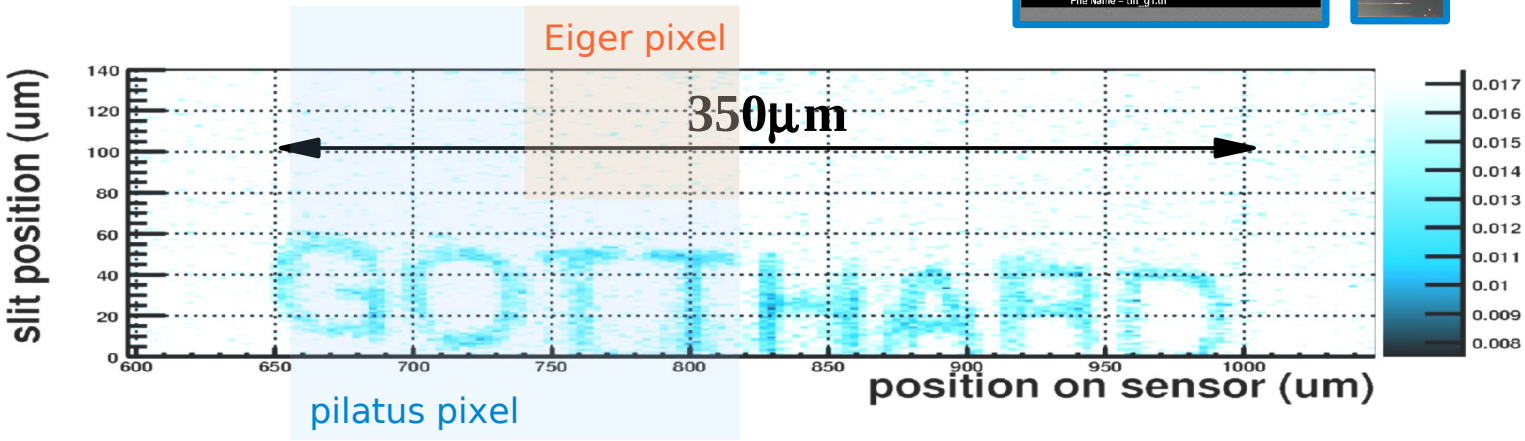
σ=1.78μm

G01-charge interpolation/3

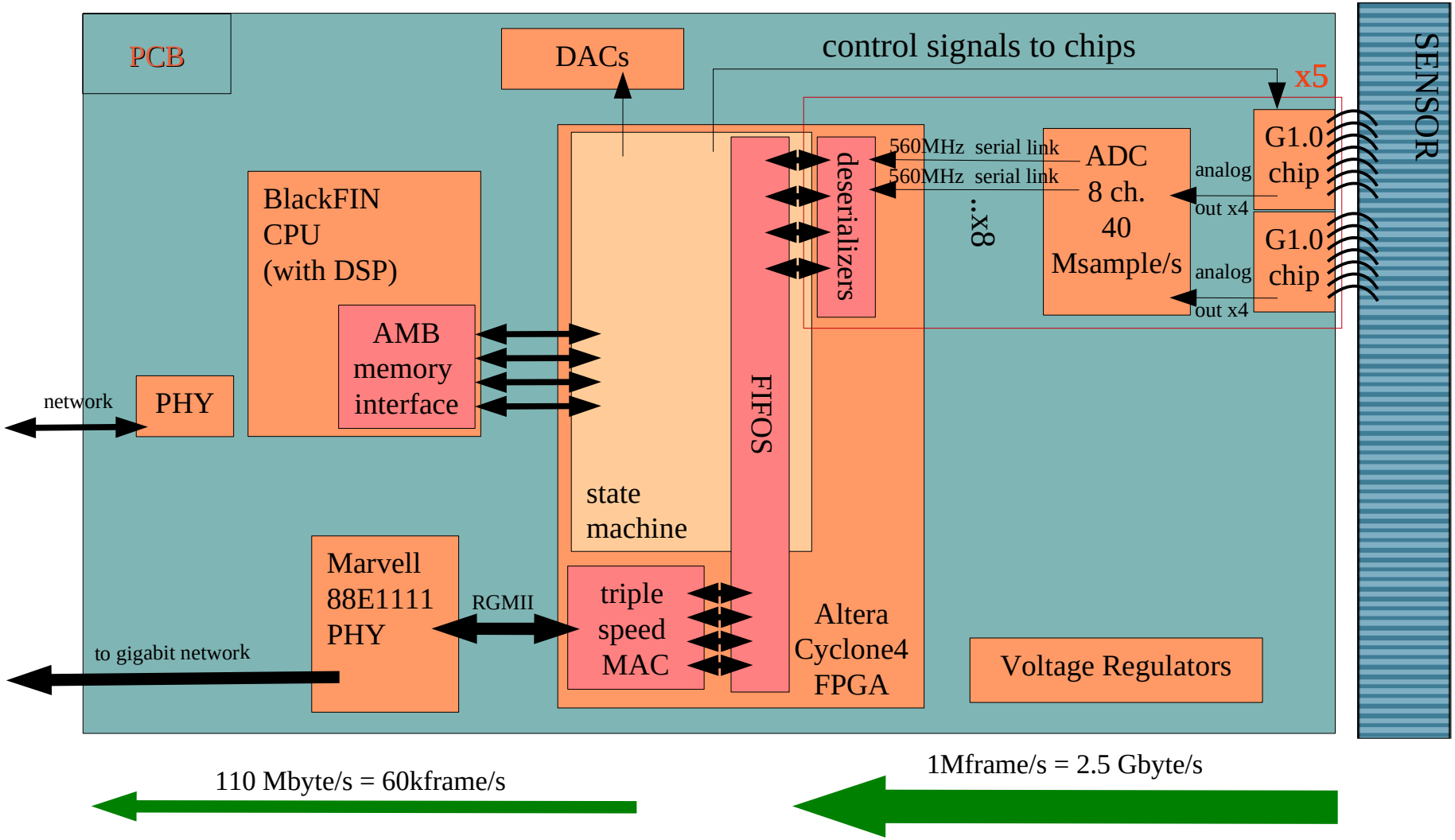




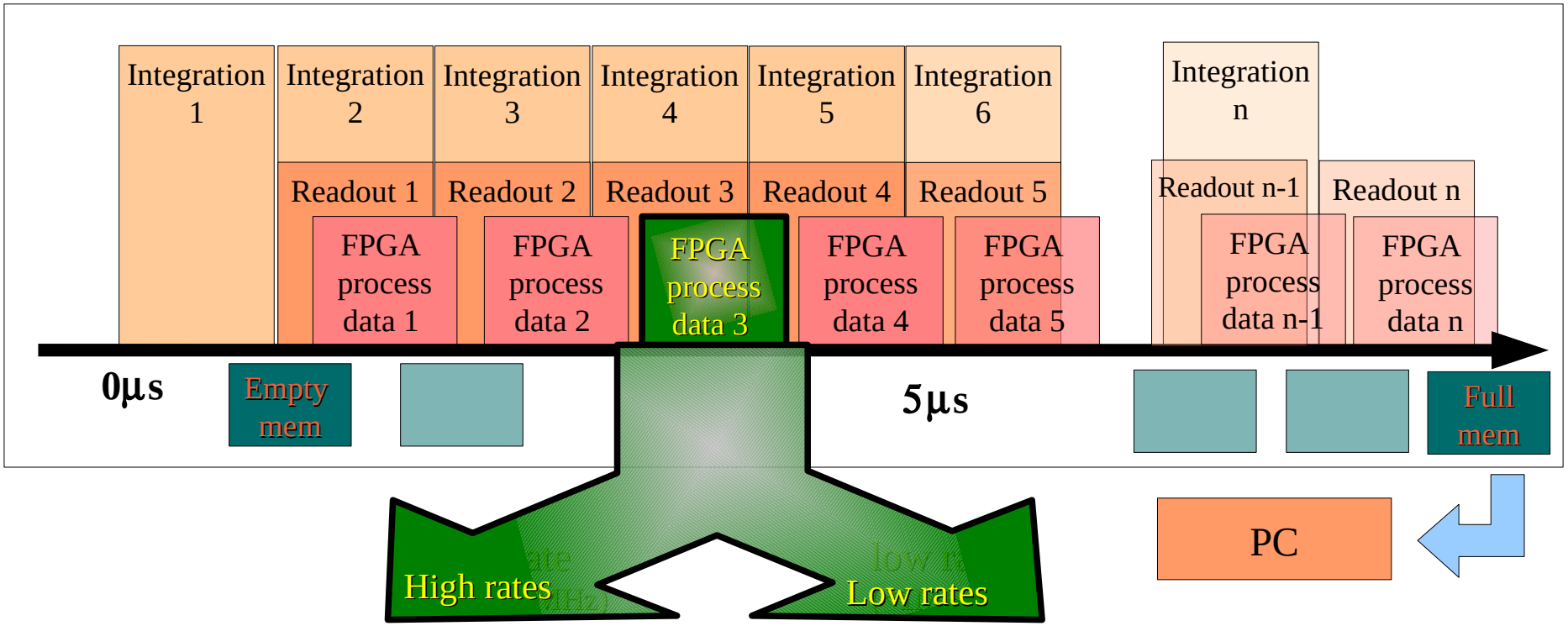
- 3µm thick gold writing on 300µm silicon substrate
- 15 keV beam, vertically defined by a 2µm W slit
- sample is vertically moved in 1µm steps
- 20000 “single photon” images per step



GOTTHARD module: block diagram

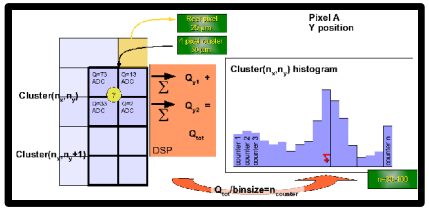


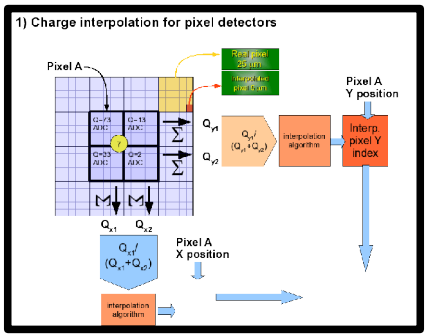
“counting mode”



Loop on channels, for each one:

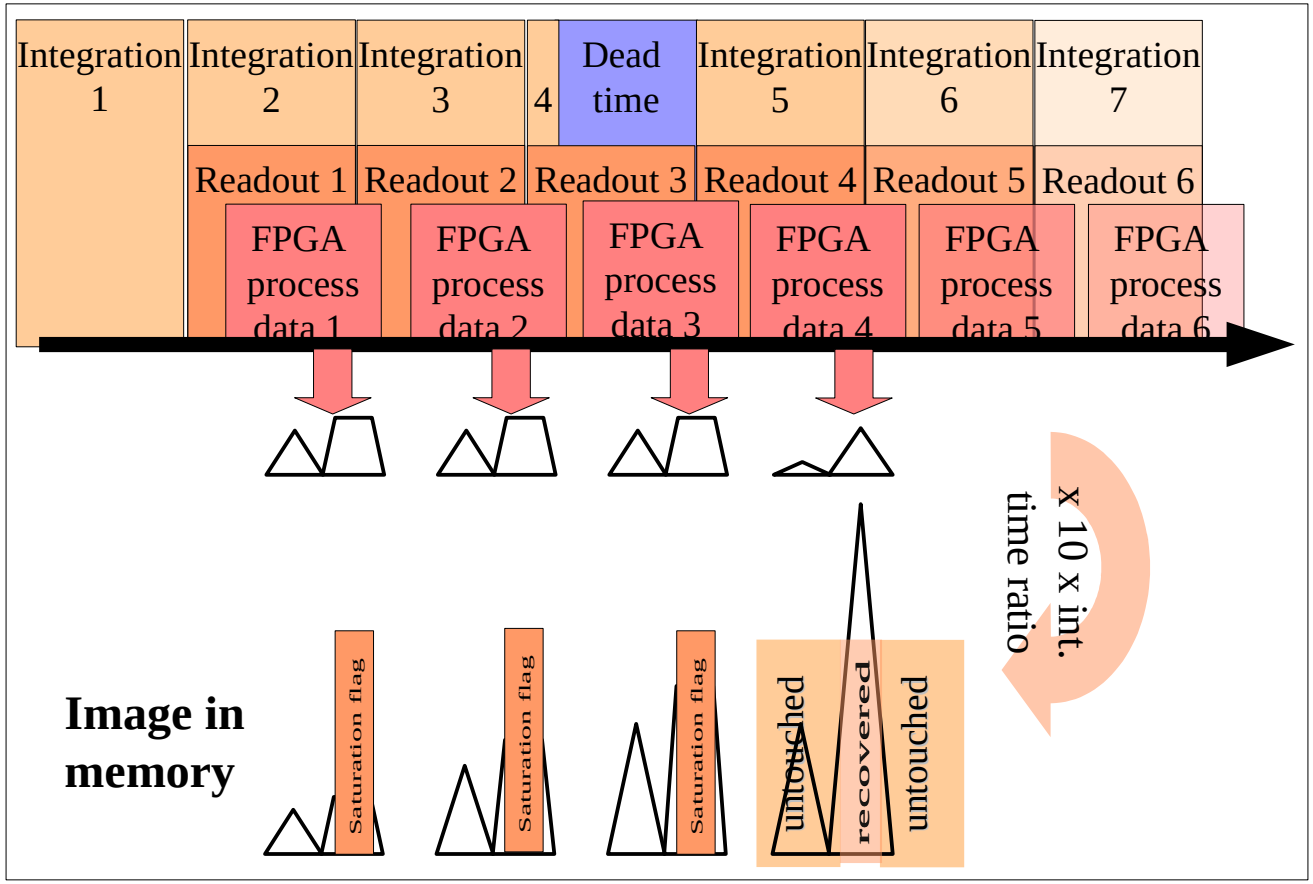
- Subtract dark frame
- Divide ACD out by single photon peak =>number of photons in the integration time
- Add this number of photons to the channel counter





Rate Capabilities (W/O gain switch)

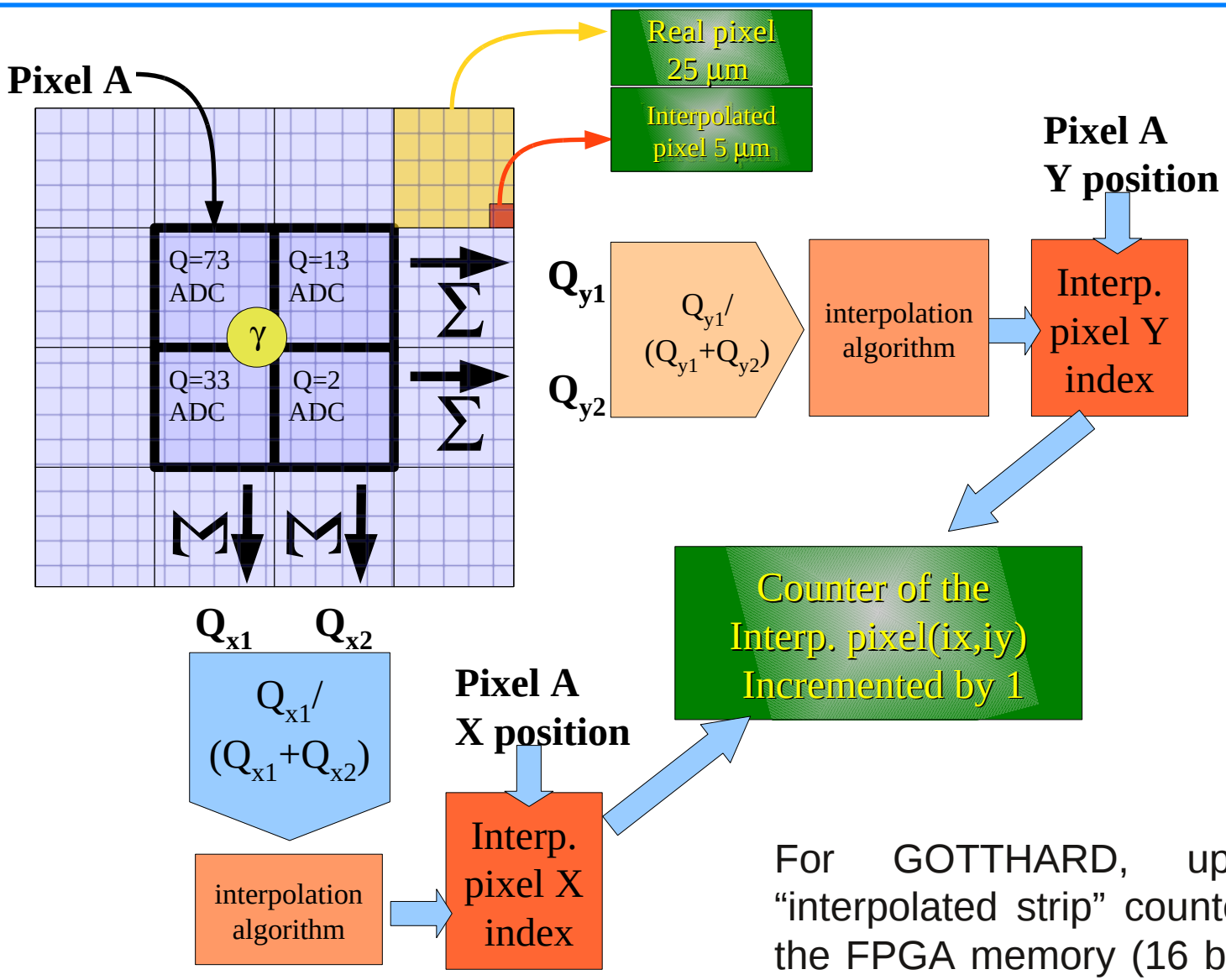
The rate capabilities of a integrating system are equal to the integration time multiplied by the dynamic range of the pixel. A range of 60 photon and 1MHz frame rate gives 60MHz max rate with no dead time. For bigger rates a high dynamic range mode is possible:



E.g. 1 over 10 integrations with a shorter int. time: Dead time still less than 10%

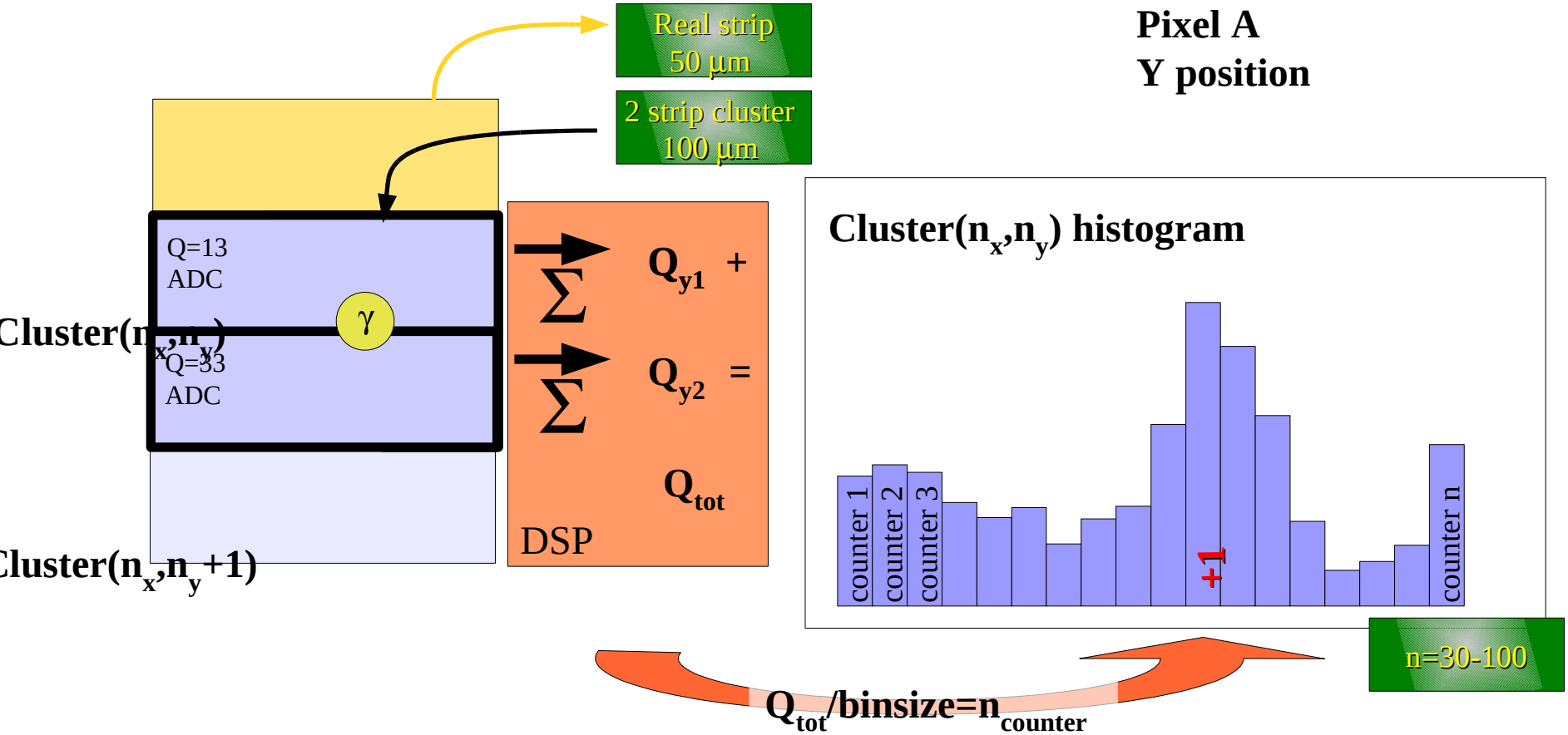
In principle extremely high fluxes are possible (recovered part has not full statistics)

Interpolation in FPGA (25um pitch)



For GOTTHARD, up to 25000 “interpolated strip” counters could fit in the FPGA memory (16 bits) giving 1um pitch

Spectral imaging



100 energy bin per strip doublet @ 16 bit (65k counts) per channel can be fit in the FPGA memory

Channel noise 150e- (E.N.C.) =>
Cluster noise <200e- =>
Photon energy resolution <700eV

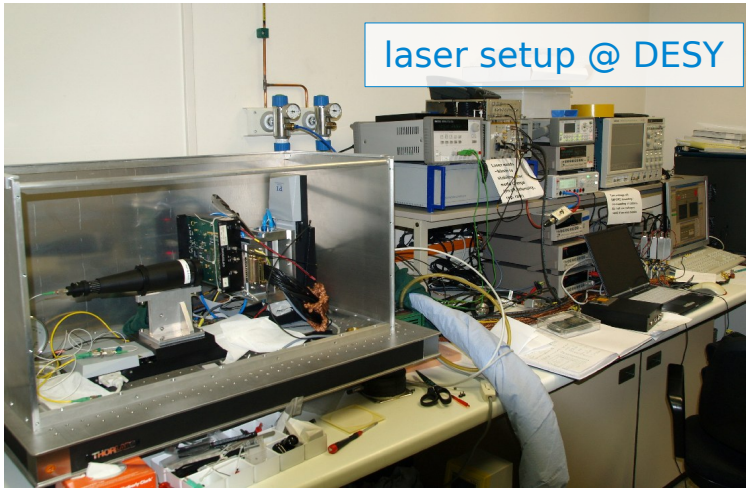
Comparison Table

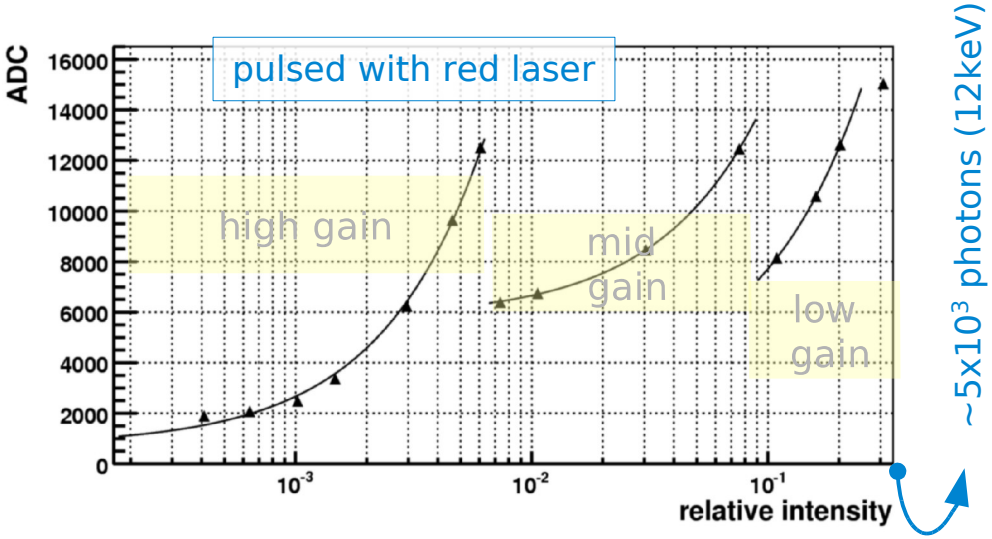
	Photon Counting	Standard charge integrating	Charge integrating, "counting" mode
dynamic range	up to 2^{24} (=1.7×10^9)*	10^{4-5} with gain switching*	up to 2^{nbit} (FPGA memory)
At low rate	noise free	Noise increase with int. time	noise free^{++}
max acq. time	inf.	limited by dark current	inf.$^{++}$
max count rate	~1MHz at 90% eff. *	Practically inf.	Practically inf. (increasing dead time)***
min Energy	~3keV *	only sensor dependent	only sensor dependent****
min pitch	limited by charge sharing	small pitches possible	small pitches possible
Photon energy background subtraction	Possible	Possible at very low rates	Possible at low rate $^{+}$
linearity	OK, except for high count rates	Depends on electronics, within Poisson noise	OK
point spread function	O(pitch)	O(pitch)	O(pitch/SNR) with charge interpolation^{+}
dead time	down to ~0*	down to ~0 **	down to 0
readout time = 1 / frame rate	limited by the digital data transfer, 24kHz*	limited by the ADC, (~1MHz strips,~1kHz for pixels**)	n.d.
XFEL use	NO	YES	NO
Notes	* best values for current system **** incompatible with + and ++	** planned detectors	*** incompatible with +

PRO
CONS
Implementation dependent

Switching gain at speed

- Measured with Gotthard0.3 prototype
- The switching has been tested with a sub-nanosecond laser pulse hitting the strip sensor
- Integration time 200ns, pulse in the middle of it
- Point dispersion mainly due to the uncertainty on the laser attenuation filters
- Switching works at the required speed

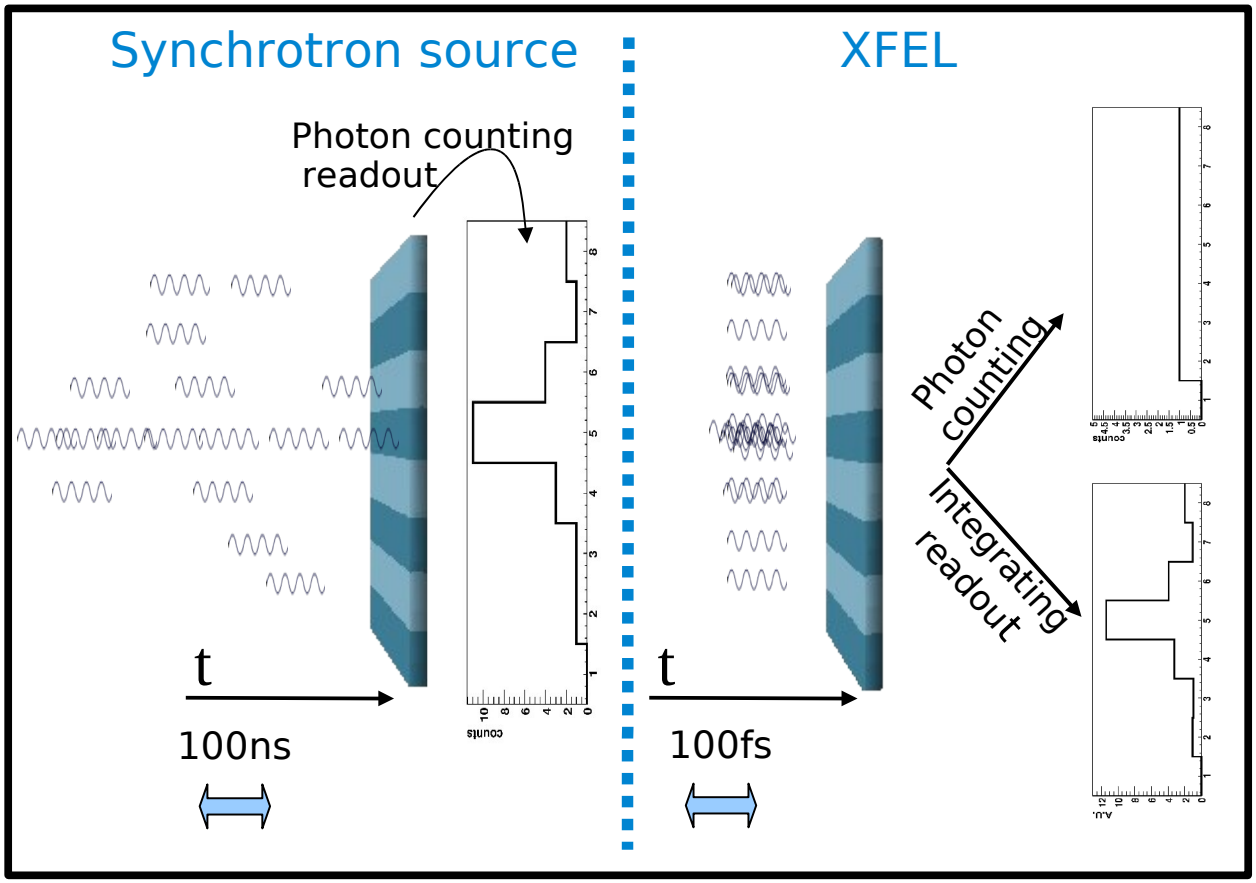




XFELs => charge integration

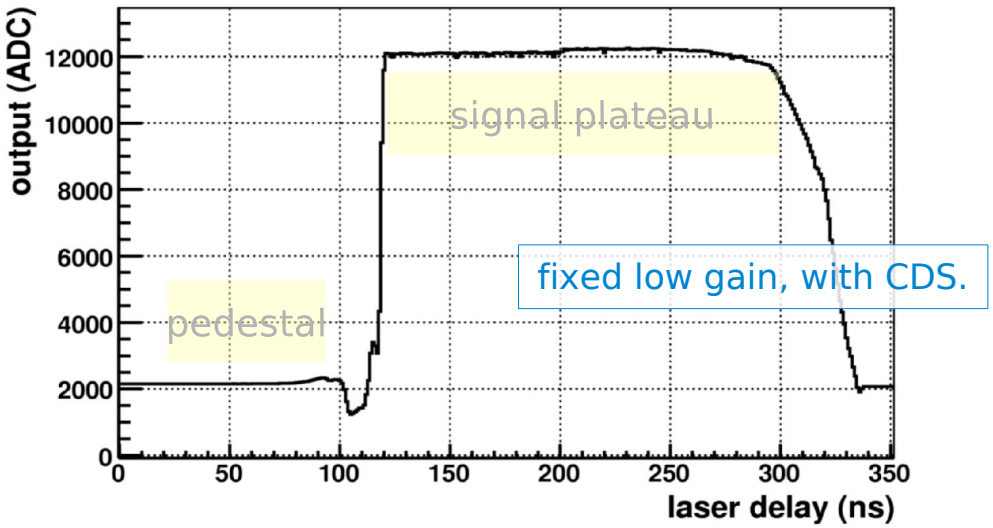
Synchrotron source:
- Huge number of “weak” photon bunches
- Photons impinge on the detector with a random time distribution

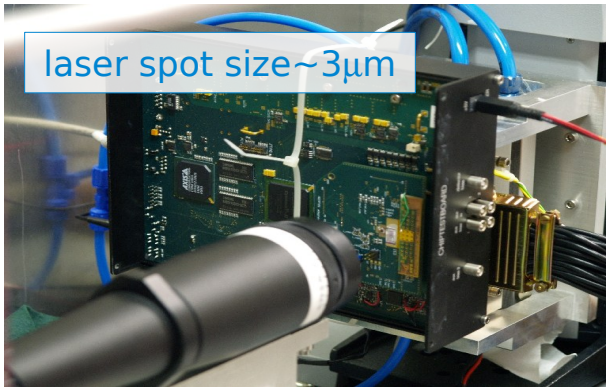
XFEL:
- Fewer intense bunches
- All photons inside the bunch coming at once
- Up to 10^4 photons per ch. per bunch



Frontend speed tests

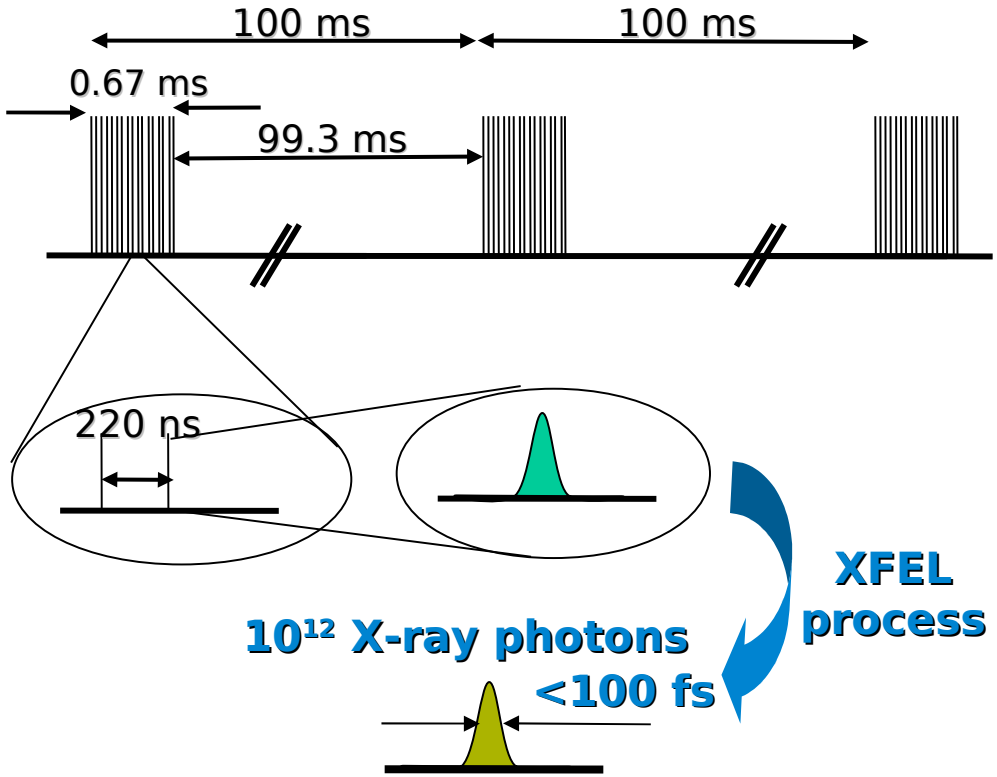
- On Gotthard0.3 prototype
- delay scan with a high intensity laser pulse (~500 12keV photons)
- with a 200ns integration time
- CDS output settles in <30ns
- integration times as small as 80-50ns can be used





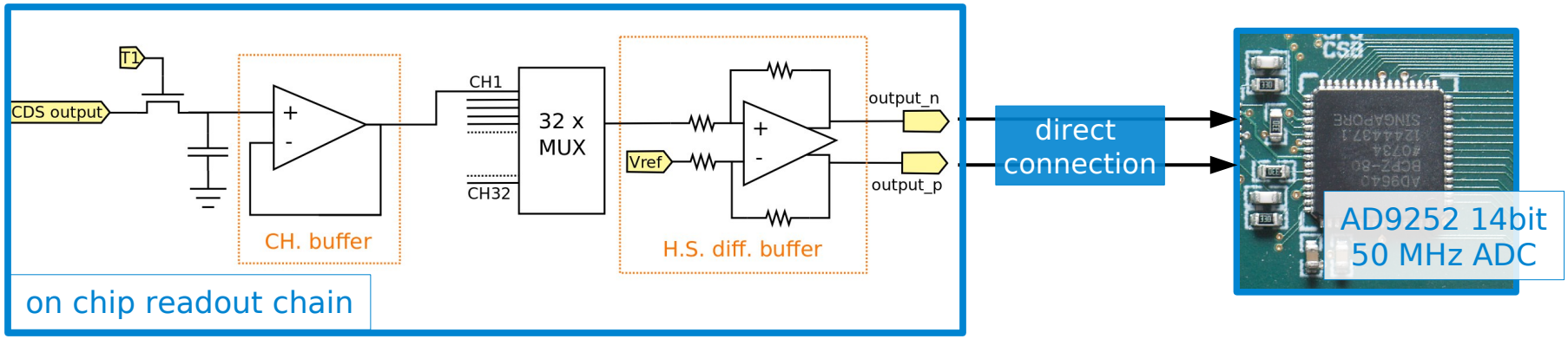
- similar result (in terms of speed) with or without automatic gain switching
- the preamplifier+switching circuitry can work at E-XFEL rates (4.5MHz)

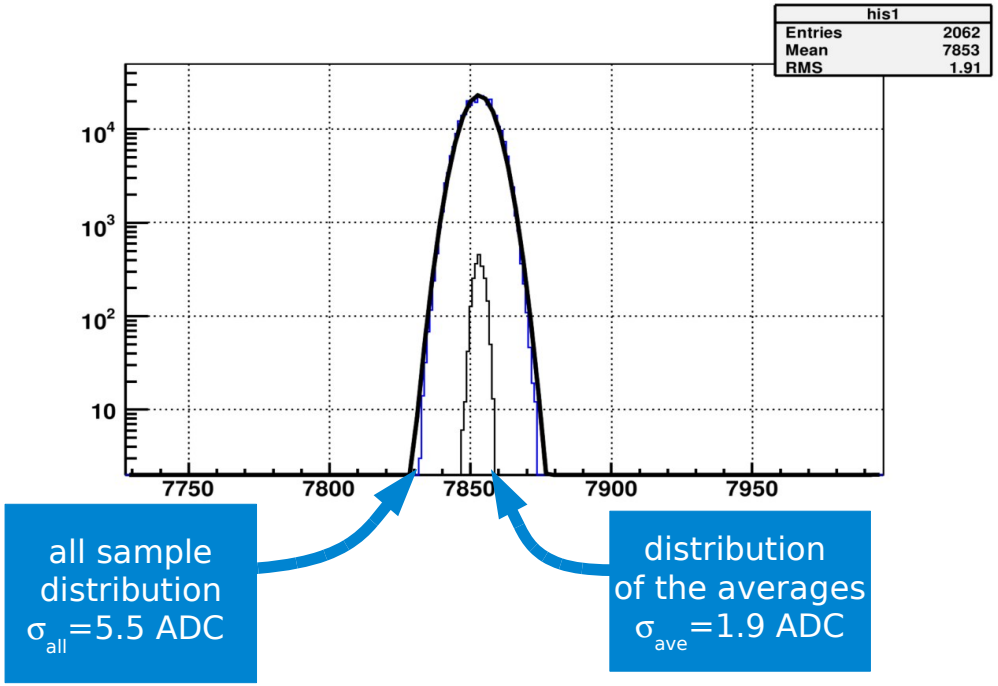
European XFEL bunch structure



- 100 fs long X-ray pulses
- ~3000 pulses per bunch train, 10 trains per second
- Frame rate in the bunch train:4.5 MHz
- Imaging (100% occupancy)
- No easy solution, only a fraction of the frames will be recorded

Readout Noise



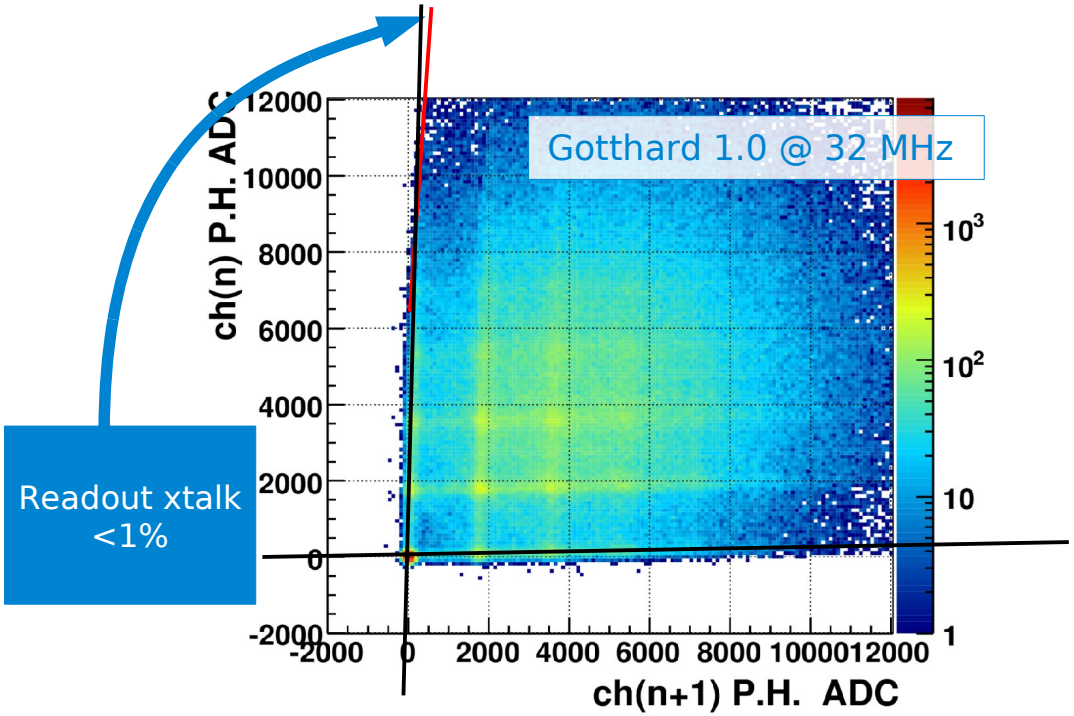


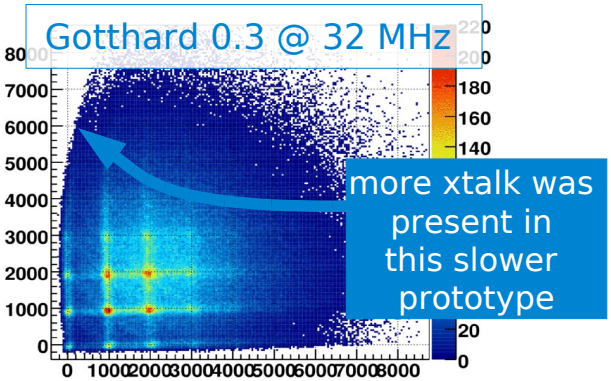
- Reading many times the value stored on one channel capacitor --> preamp. and CDS disconnected
- repeated for many frame, frame average computed
- Readout noise σ_{read} is

$$\sigma_{read}=\mathrm{sqrt}(\sigma_{all}^2-\sigma_{ave}^2)=5.2\mathrm{ADC}$$

- ~90 (25) e.n.c. in gain1 (HG)

Readout speed





- Measured at high gain, with a large integration time
- from 0 to 7-8 ph. per frame per ch.
- events with 0 on ch. and few on the nearby one allow to estimate the cross talk
- 1.5% (Va dependent) xtalk due to charge coupling between strips
- < 1% xtalk due to readout
- room for improvement (timing, biasing..)

Automatic switching gain:principle