PAUL SCHERRER INSTITUT

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The GOTTHARD charge integrating readout detector: design and characterization

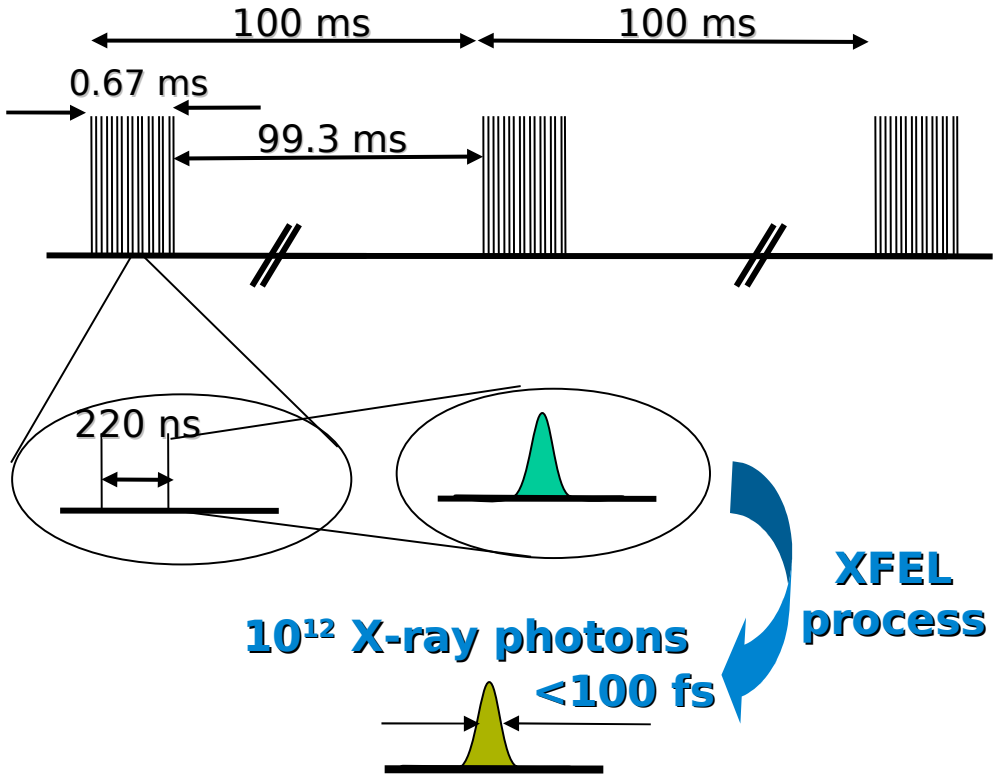
Outline

- Requirements for a strip detector for the XFEL
- Basic principles: preamplifier with automatic gain switching logic
- Read out chip development:
  - Prototype history
  - Design features of the Gotthard 1.0 ROC
- ASIC characterization:
  - Noise at low rates
  - Noise at the lower gains
  - Non linearity
  - Response to fast (X-FEL like) pulses
  - Readout speed and cross talk
- The DAQ system: design and prototyping
- Conclusions

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%)
- Strip pitch 50μm or smaller
- Fast front-end: integration-store-reset cycle in <220 ns
- 1 MHz frame rate:
  - Ability to record as many frames per bunch train as possible
  - fast feedback is a plus: control systems, veto
- Radiation tolerant design: ~GRad dose on the sensor (<< on the ASIC)

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

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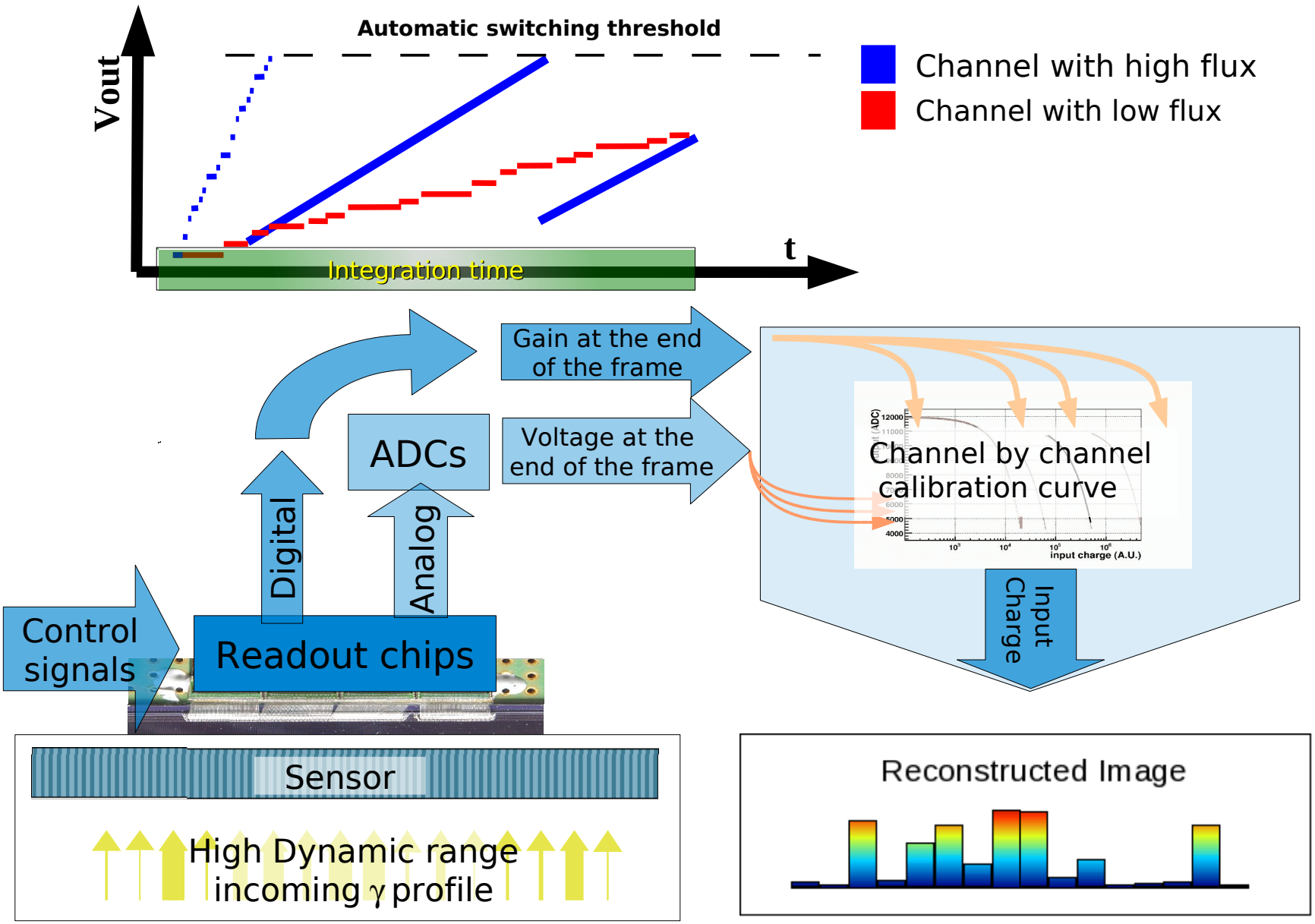
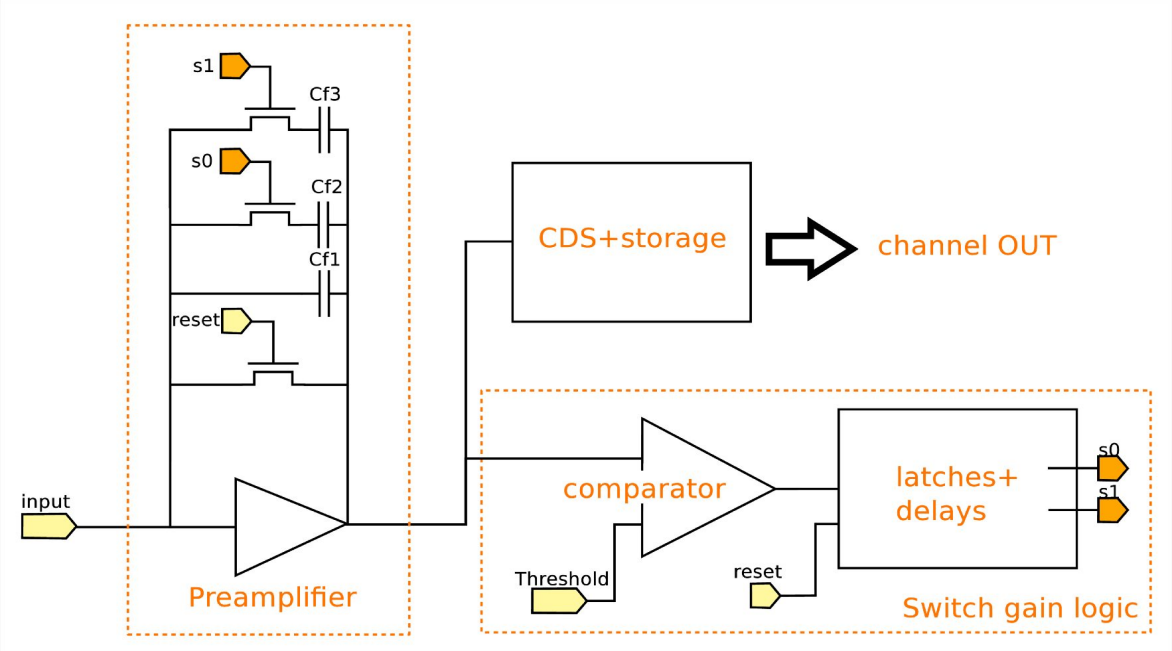
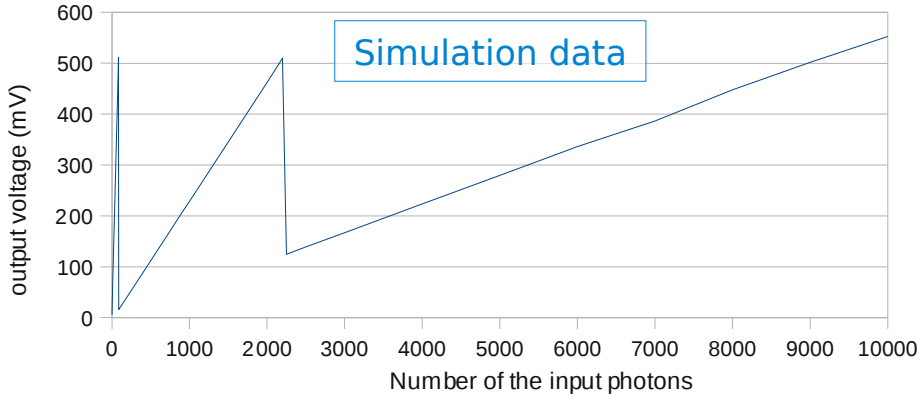
Automatic switching gain:principle



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}



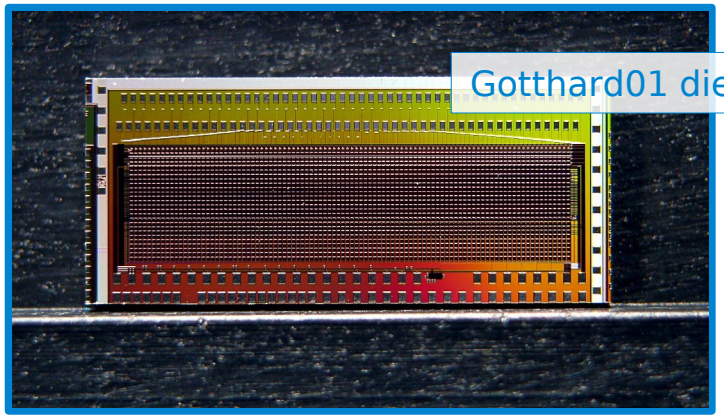


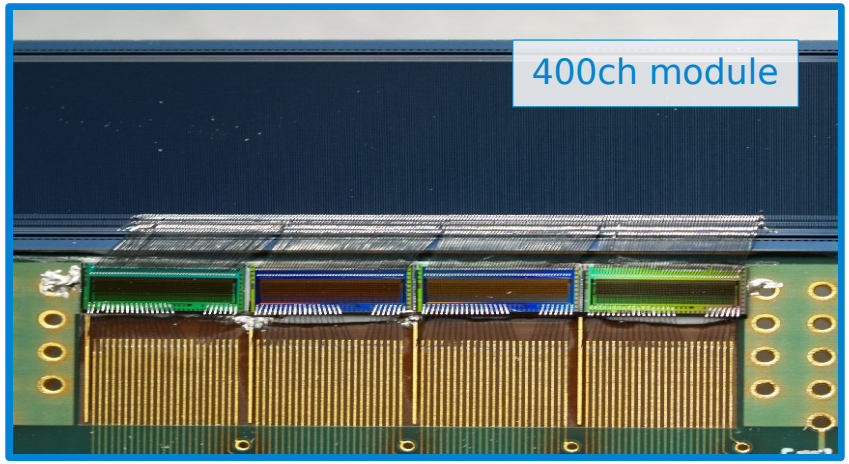
- Logic after comparator to:
  - Switch a 2nd time if 1st switch not enough
  - Avoid a 2nd switch on spikes due to the 1st one
- Switching has to be FAST (<10ns)

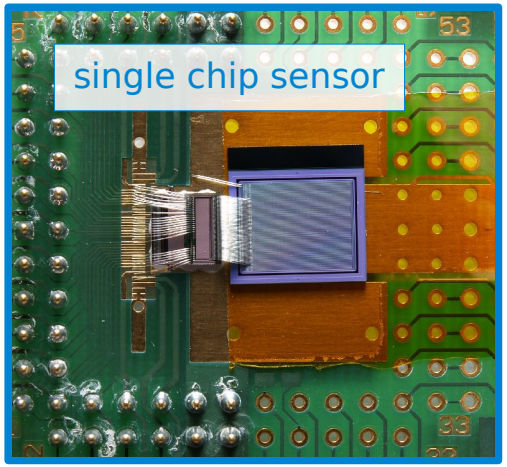
GOTTHARD 0.1 – the starting point

GOTTHARD:
Gain Optimizing microsTrip sysTem witH Analog ReaDout

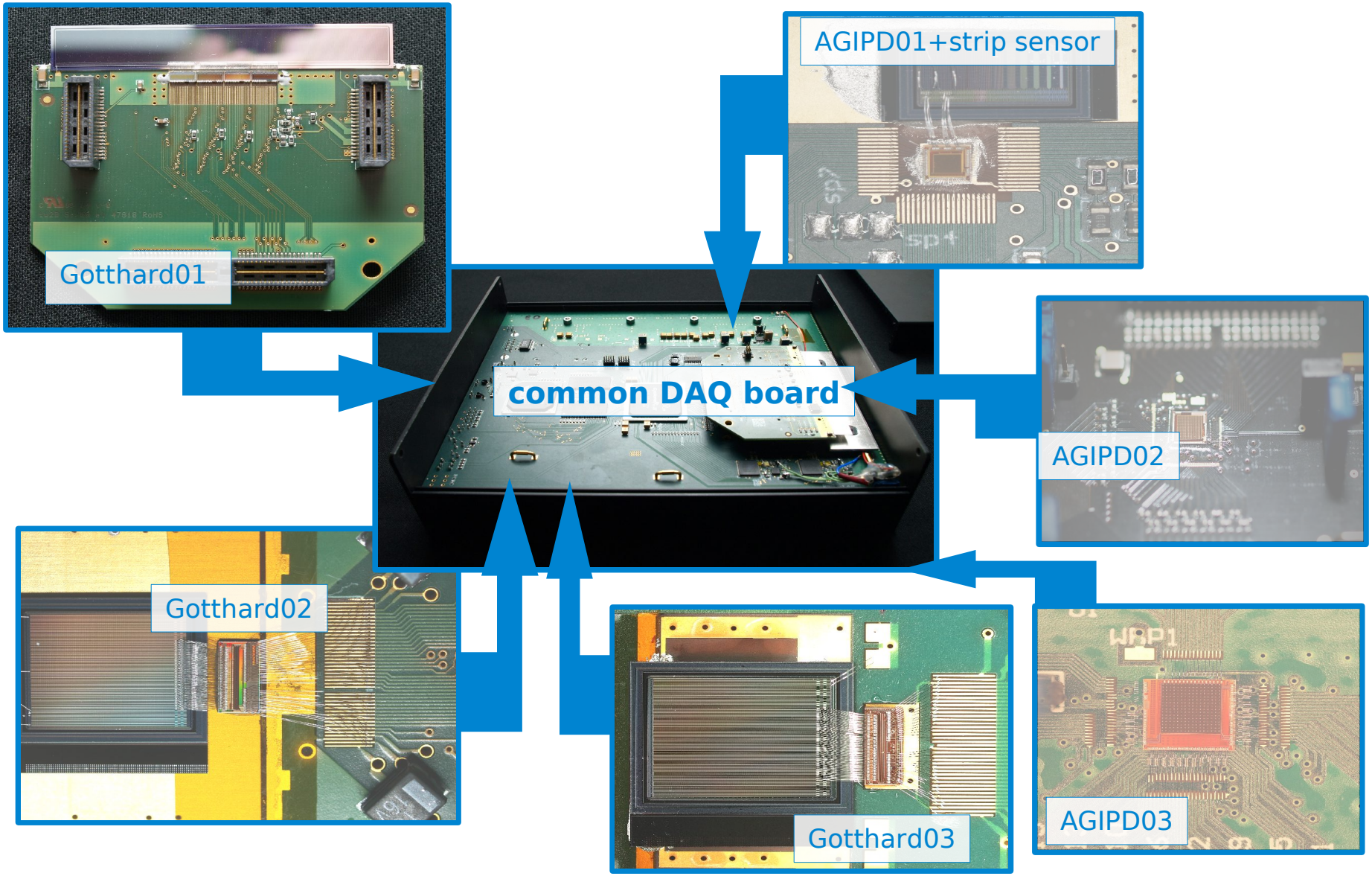
- designed in 2004 in UMC0.25μm technology
- 100 channels
- 4 gain stages with automatic gain switching
- double sample and hold circuit to perform offline CDS
- source follower based output bus
- single ended output





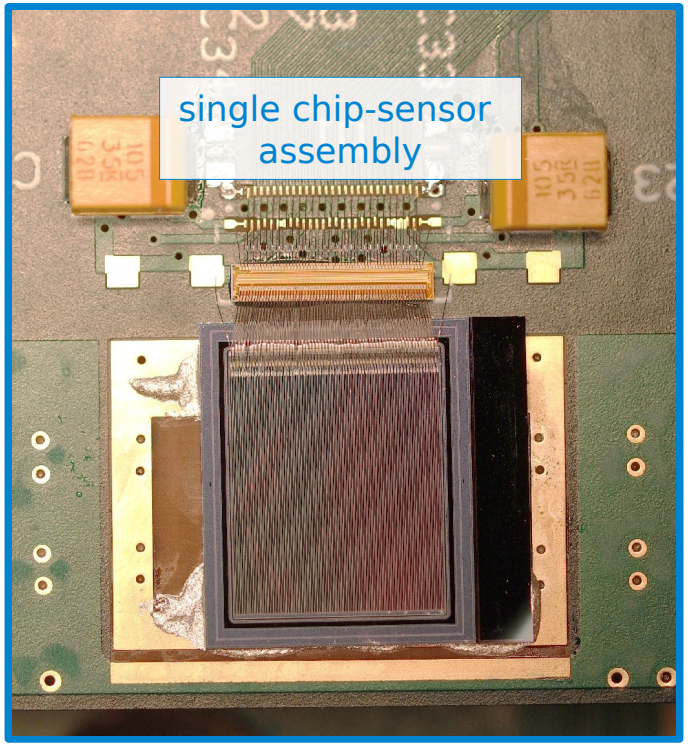


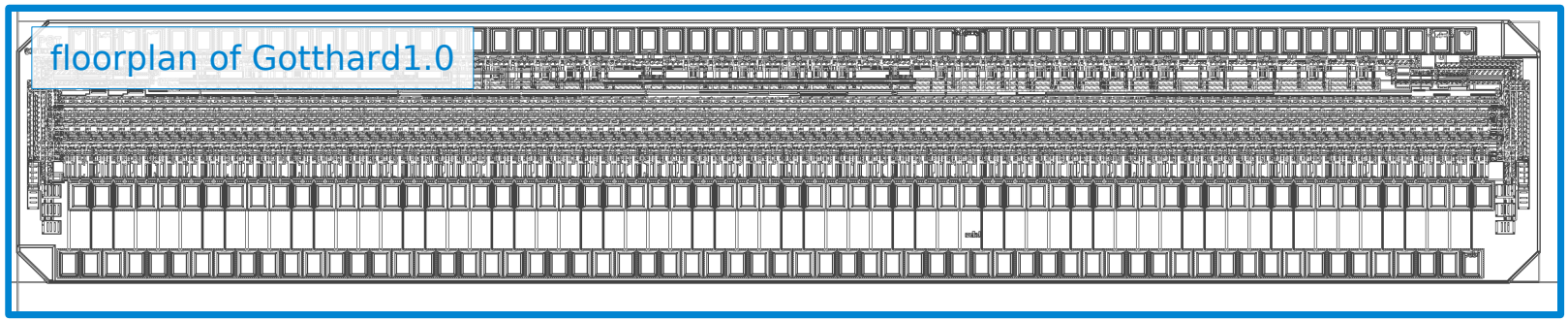
Prototypes (2008-2010)



GOTTHARD 1.0

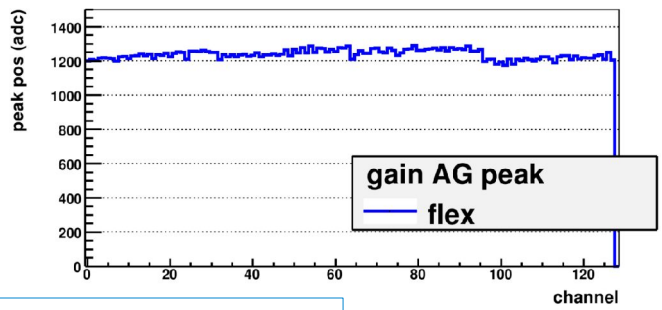
- 6.3x1.4mm^2 - 128 channels - 50μm pitch
- 3 automatic gain stages + 1 High Gain mode
- fast off pixel buffers, to sustain 32MHz readout with no cross-talk
- 4 diff. analog outputs, 8 digital (gain) outputs
- ~ 1mW/ch.
- back from fab. 10th Jun.
- Preliminary tests completed



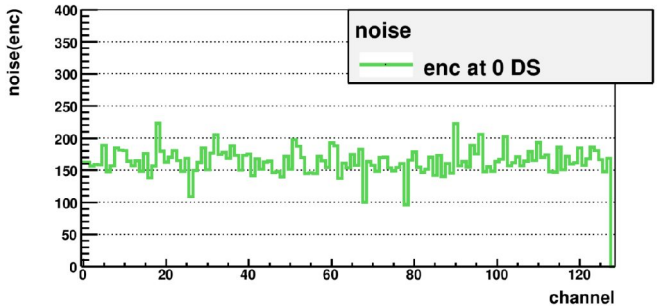


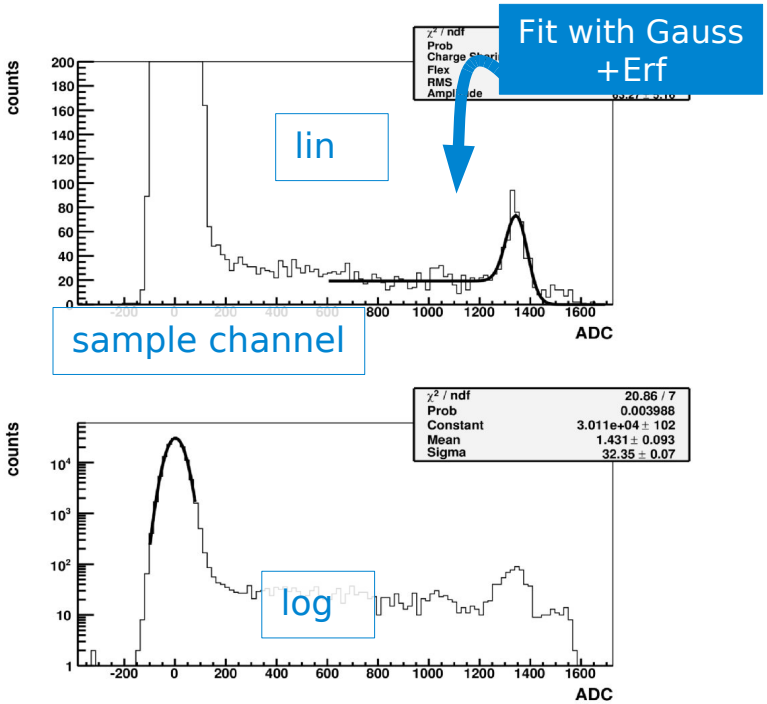
Noise – high gain mode

- measured with X-ray tube and Ag fluorescence light (22 keV)
- 120 V detector bias
- ~ 1 us integration time



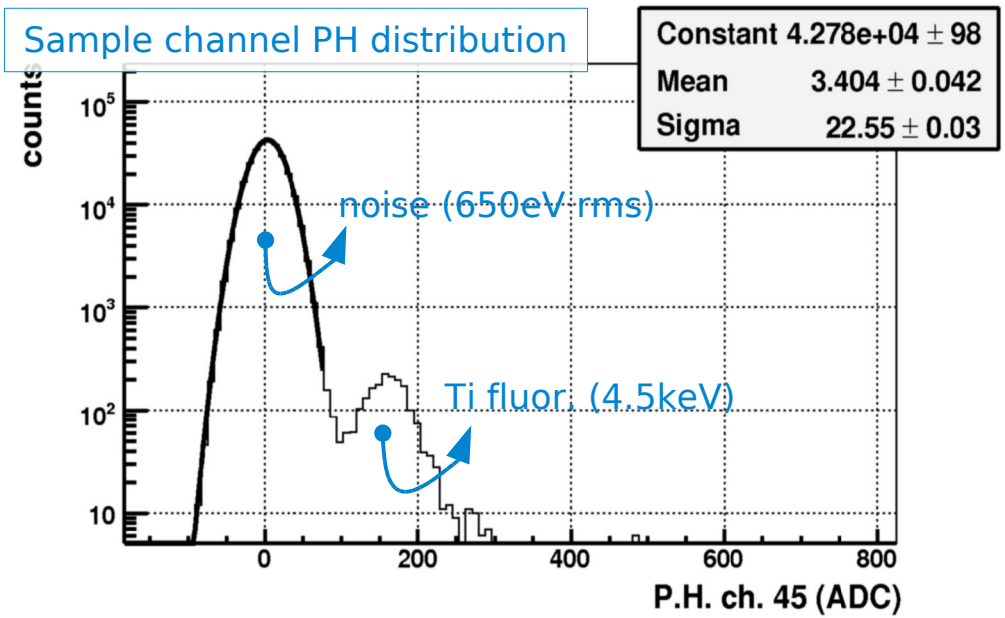
ch. to ch. variations





- P.H. of each channel is fit: peak pos. gives the gain, sigma of the gaussian at 0 the noise
- Noise ~ 160 e.n.c.

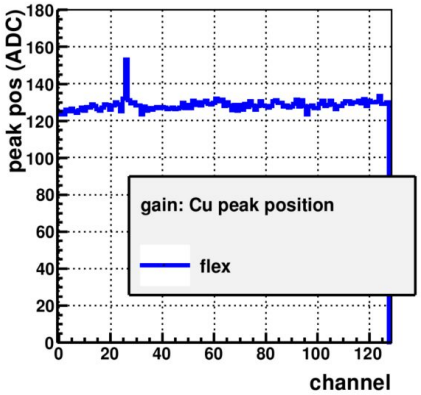
Low energy sensitivity

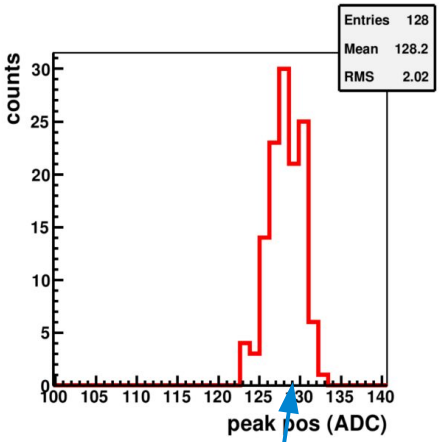


- Measured on Gotthard0.3
- single photon resolution can be retained down to ~3.5 keV photon energy
- At lower energy 2 or more γs can still be separated from the noise floor
- Sensors with thin “entrance window” have to be developed
- Silicon drift sensors will be tried soon
- Lower noise version of the chip is planned

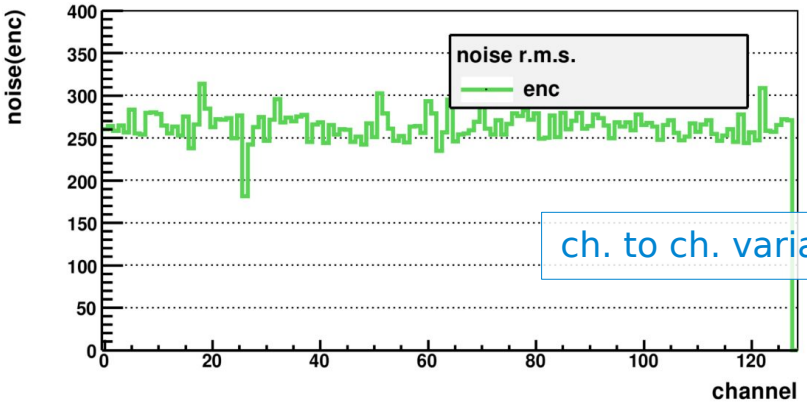
Noise – Gain 1

- 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

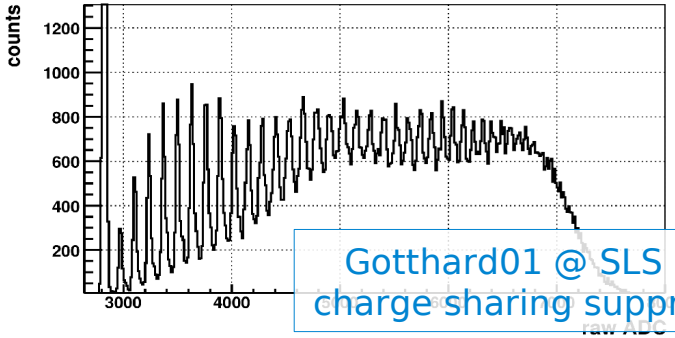




gain dispersion 1.5%

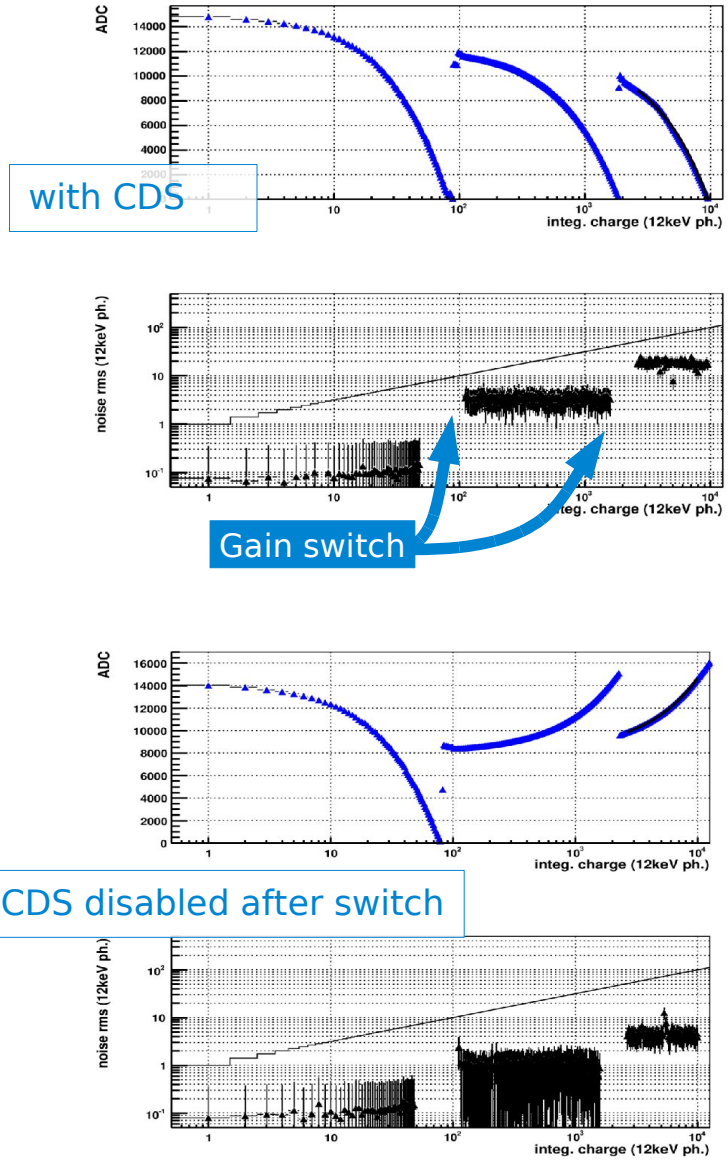


ch. to ch. variations



Gotthard01 @ SLS
charge sharing suppr.

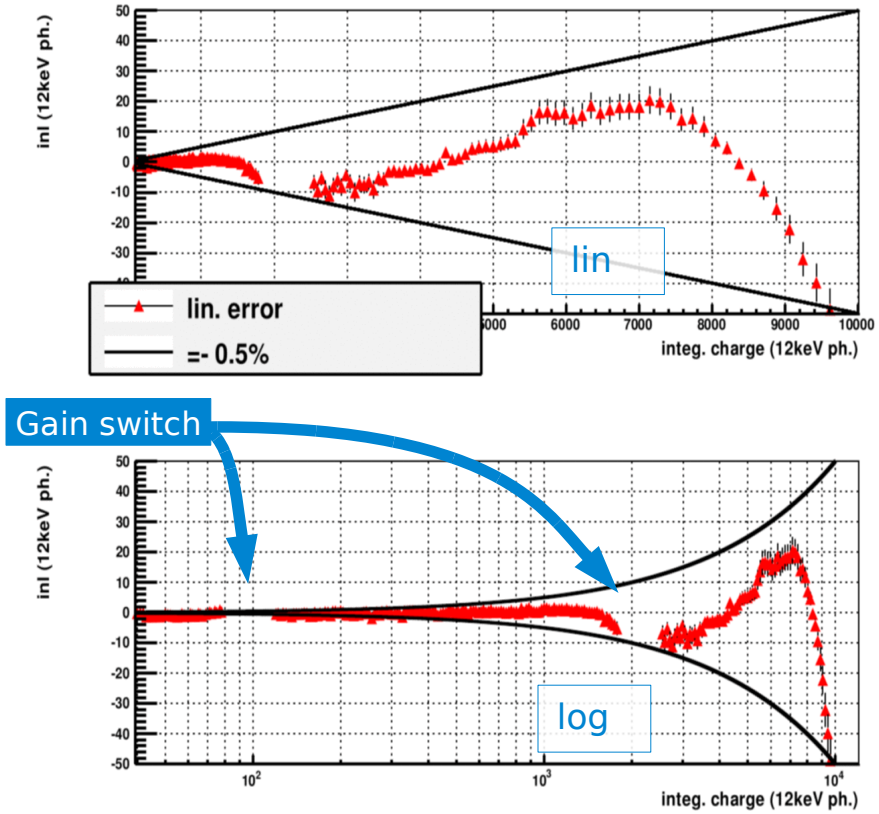
Noise – many photons



- 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

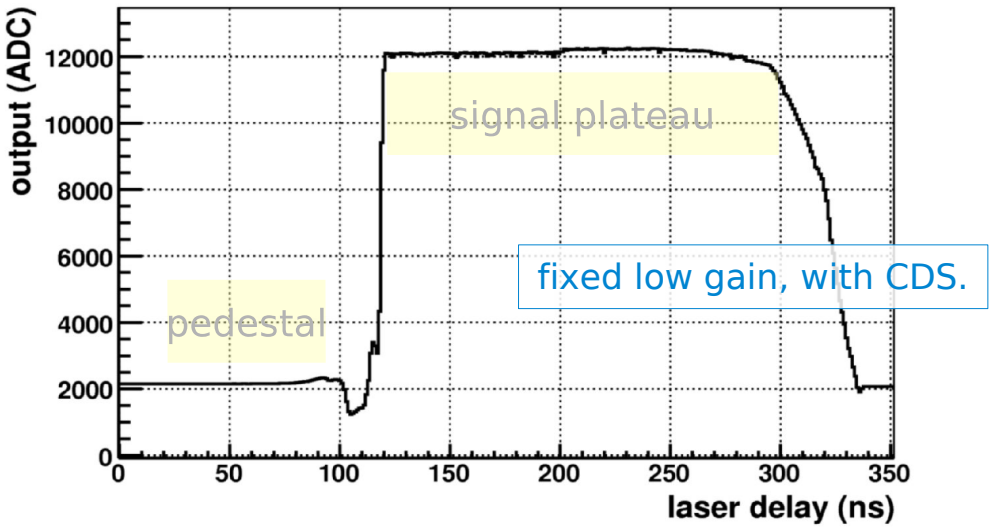
CDS disabled after switch

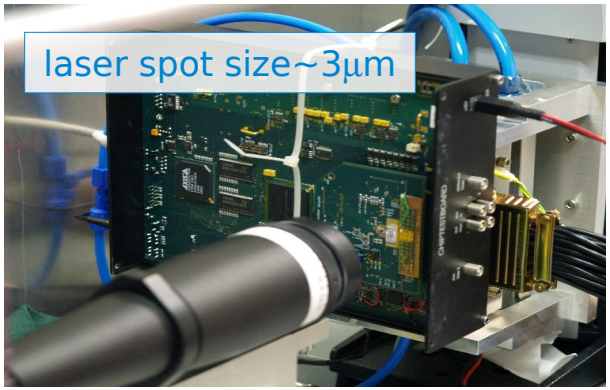


- for each stage a linear fit is performed
- for each intensity the difference between the line and the measured ADC value is plotted
- linearity errors within +- 0.5% (source effects included) in the design input range (0-10^4 ph.)
- On smaller ranges better linearity can be achieved

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

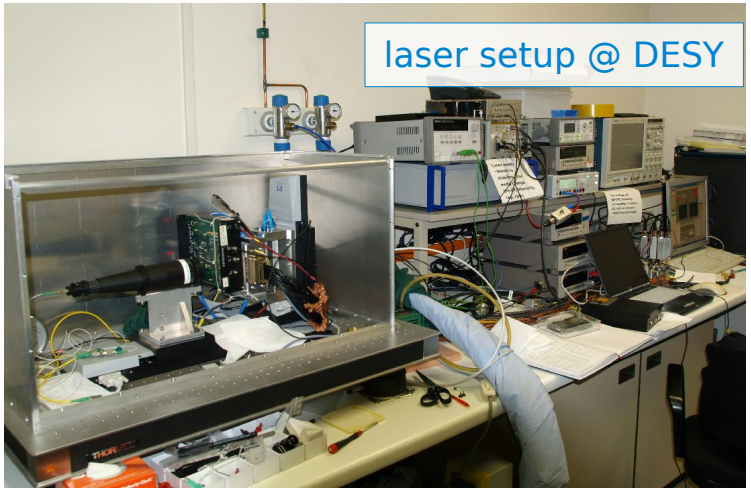


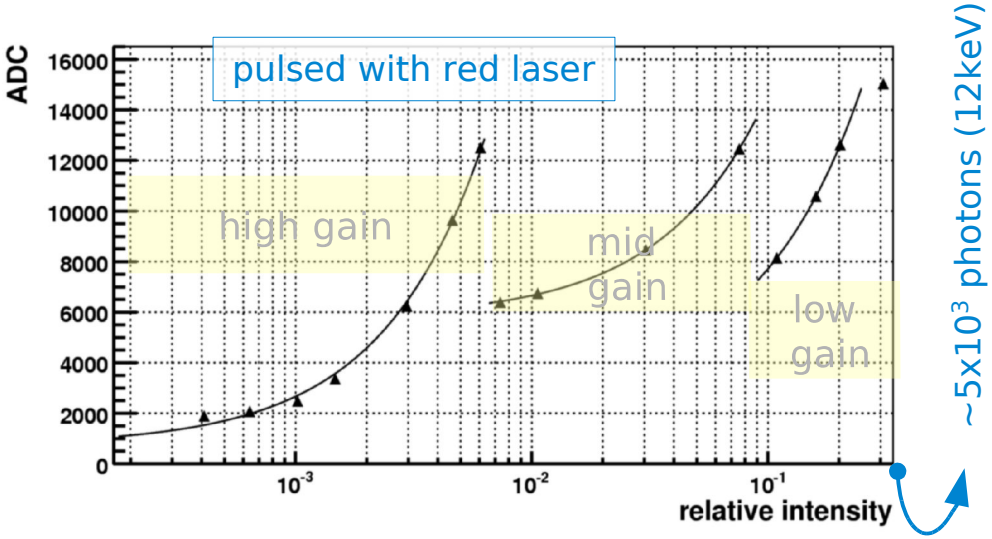


- similar result (in terms of speed) with or without automatic gain switching
- the preamplifier+switching circuitry can work at E-XFEL rates (4.5MHz)

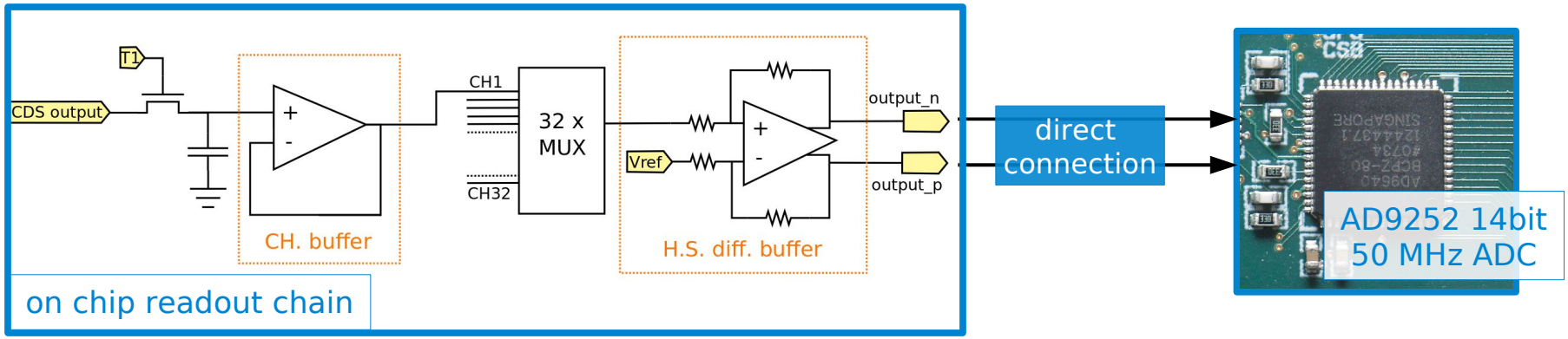
Switching gain at speed

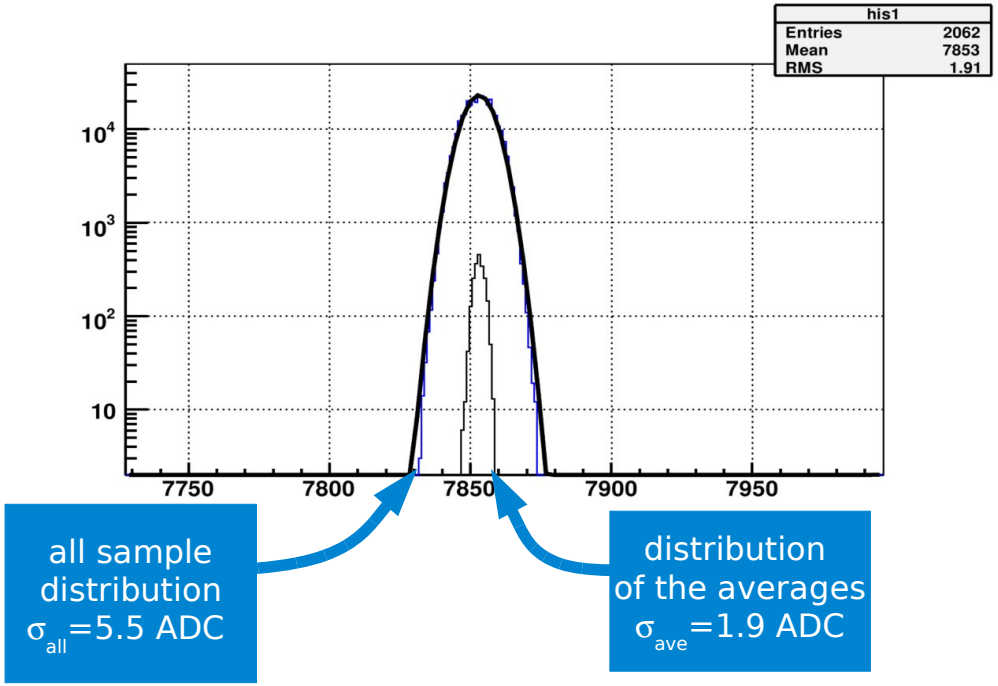
- Measured with Gotthard0.3 prototype
- Integration time 200ns, pulse in the middle of it
- Point dispersion mainly due to the uncertainty on the laser attenuation filters
- Switching works at the required speed





Readout Noise



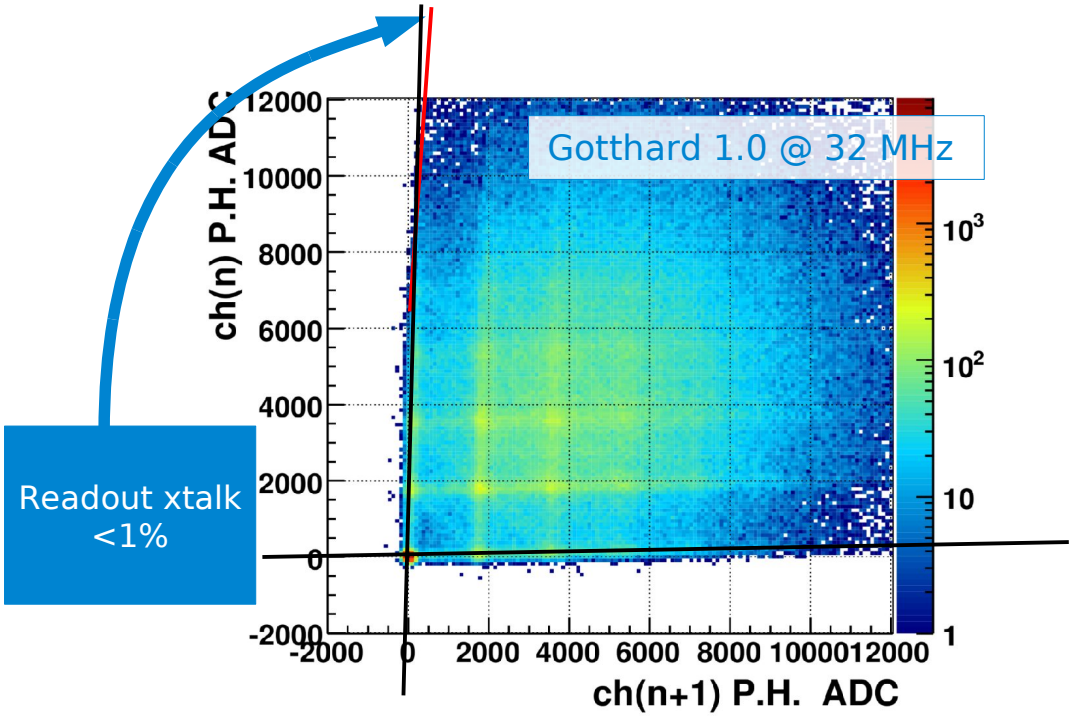


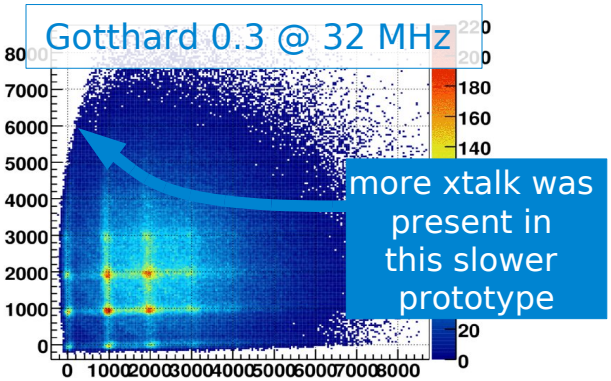
- Reading many times the value stored on one channel capacitor --> preamp. and CDS disconnected
- repeated for many frame, frame average computed
- Readout noise σ_{read} is

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

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

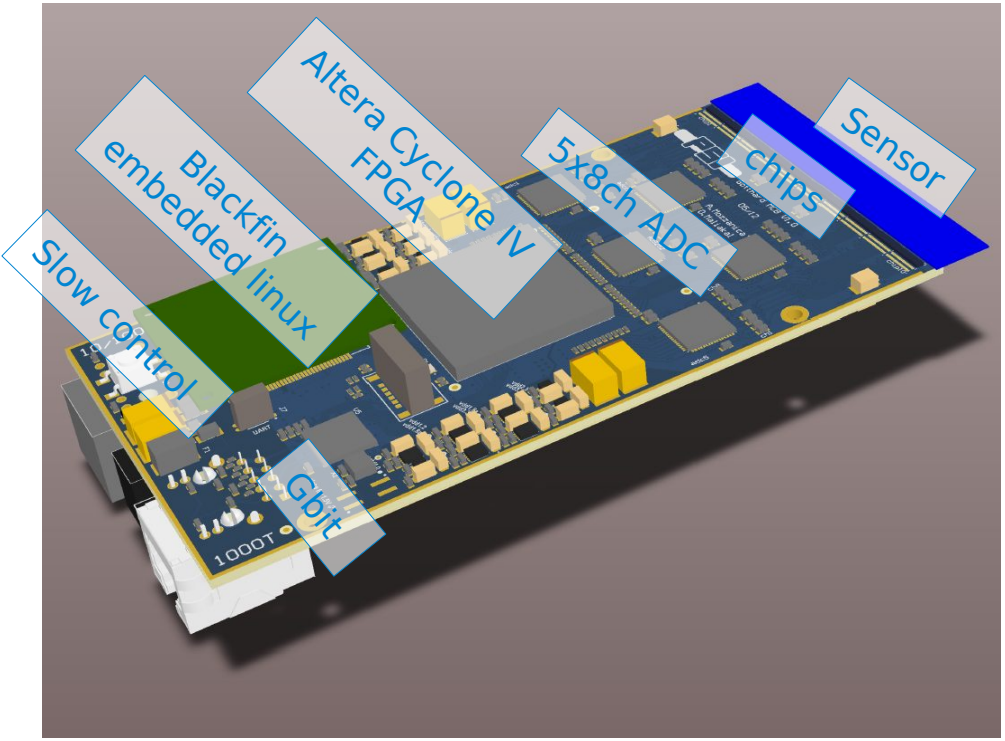
Readout speed





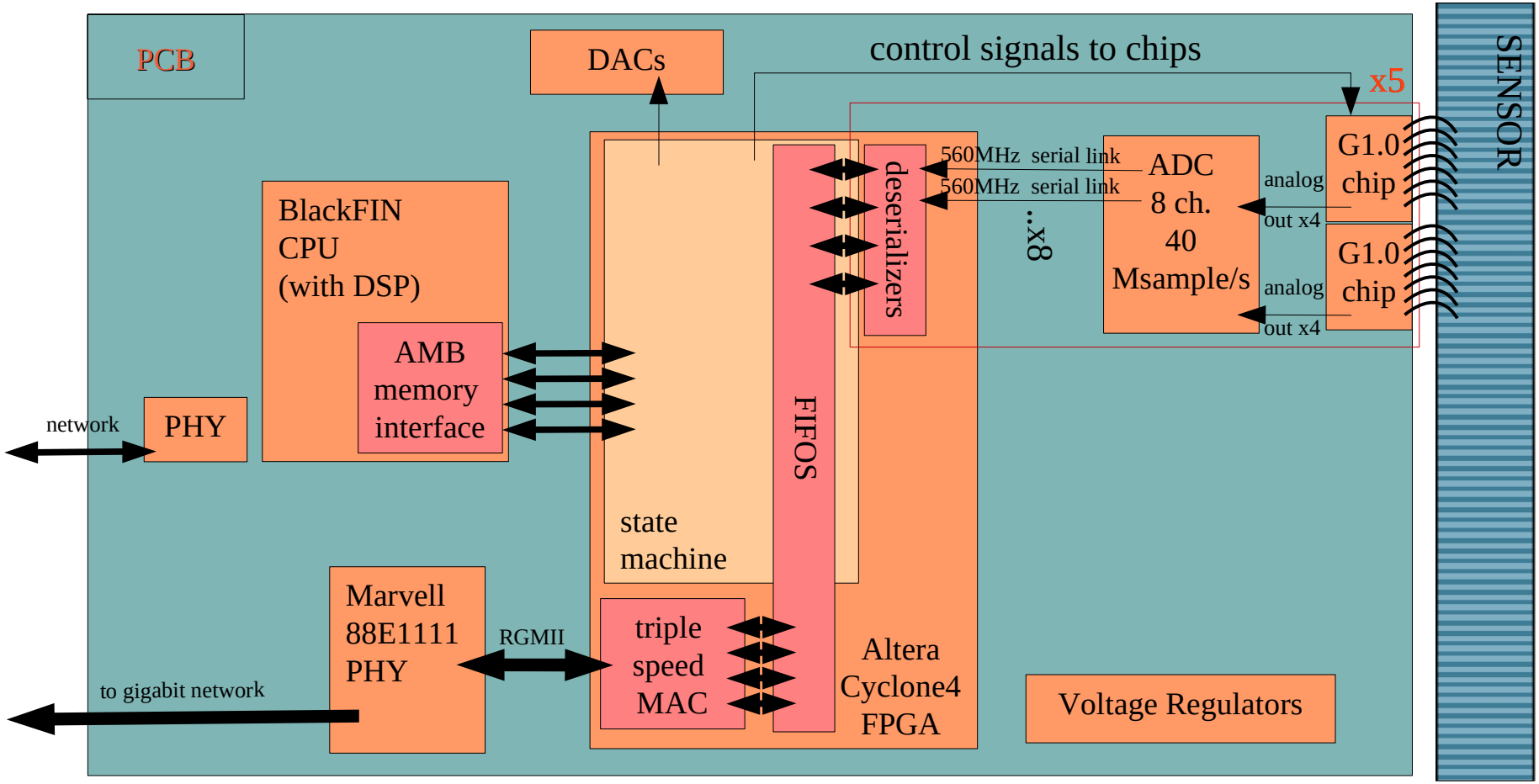
- Measured at high gain, with a large integration time
- from 0 to 7-8 ph. per frame per ch.
- events with 0 on ch. and few on the nearby one allow to estimate the cross talk
- 1.5% (Va dependent) xtalk due to charge coupling between strips
- < 1% xtalk due to readout
- room for improvement (timing,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

GOTTHARD module: overview

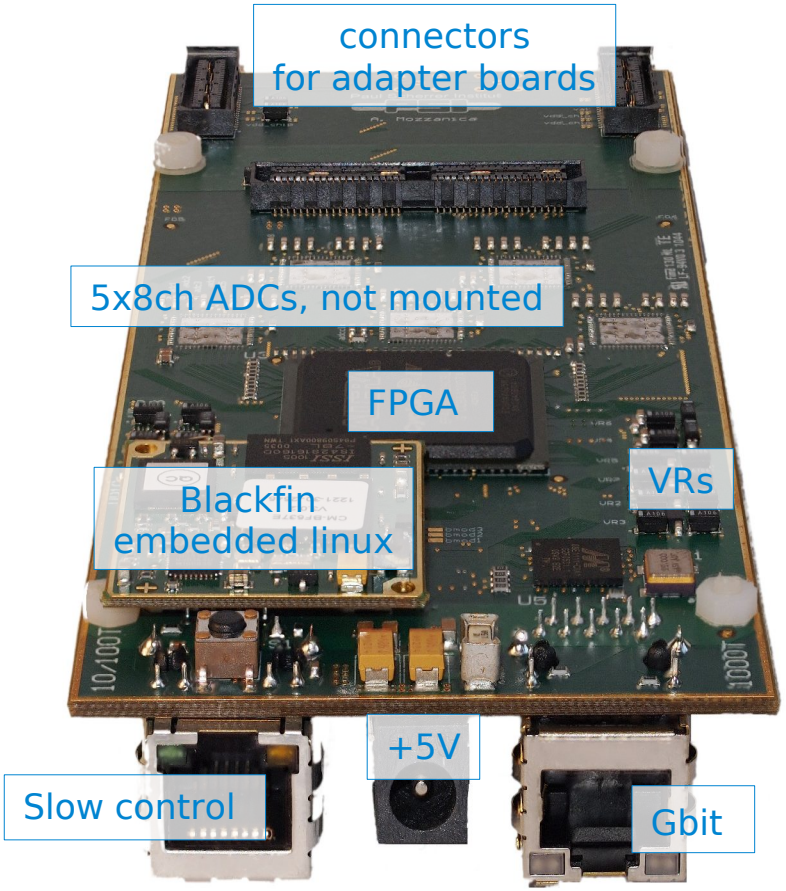


- 67mm x 130mm
- 50 μm pitch, 1280ch/module (same as MYTHEN)
- 10 chips, 4 analog outputs per chip
- 40 ADC channels @50Mhz,14bits
- Fast readout (1MHz)
- Gbit Ethernet data transfer allows 100kHz cont. rate; 1MHz chip readout possible:
  - in bursts (E-XFEL)
  - with FPGA data spars.
- 100T Ethernet for control/setup
- Back from manufacturer in late July 2011

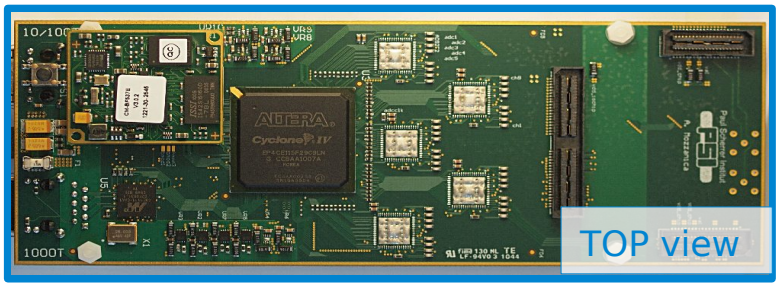
GOTTHARD module: block diagram



Prototype PCB



- Similar to the real module but with chip replaced with connectors
- Used to develop/test:
  - CPU and FPGA comm.
  - Gigabit UDP packets tx.
  - ADC to FPGA interface
- Board firmware (Gigabit MAC) developed in collaboration with Fachhochschule Nordwestschweiz (Brugg)



GOTTHARD specs. and timeline

	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
readout time = 1 / frame rate	100kHz continuos 1MHz burst
XFEL ready	YES

- Full characterization of Gotthard 1.0 to be finished soon
- Gotthard module integration (ASIC+sensor+readout) by the end of Summer
- Commissioning and calibration of the modules before the end of the year
- Available for experiments at the SLS in 2012

Conclusions

- A charge integrating strip detector for XFEL beams is being developed at PSI
- The GOTTHARD1.0 ROC has been designed, manufactured and tested
- the measurements showed:
  - single photon resolution at high gain for energies down to ~3.5keV
  - low noise and high linearity on the full dynamic range
  - Gain switching works, for slow and fast (XFEL) signals
  - readout at 1MHz frame rate is possible
- a prototype of the DAQ system has been tested
- The final DAQ board is now in fabrication
- The complete GOTTHARD detector will be commissioned by the end of the year

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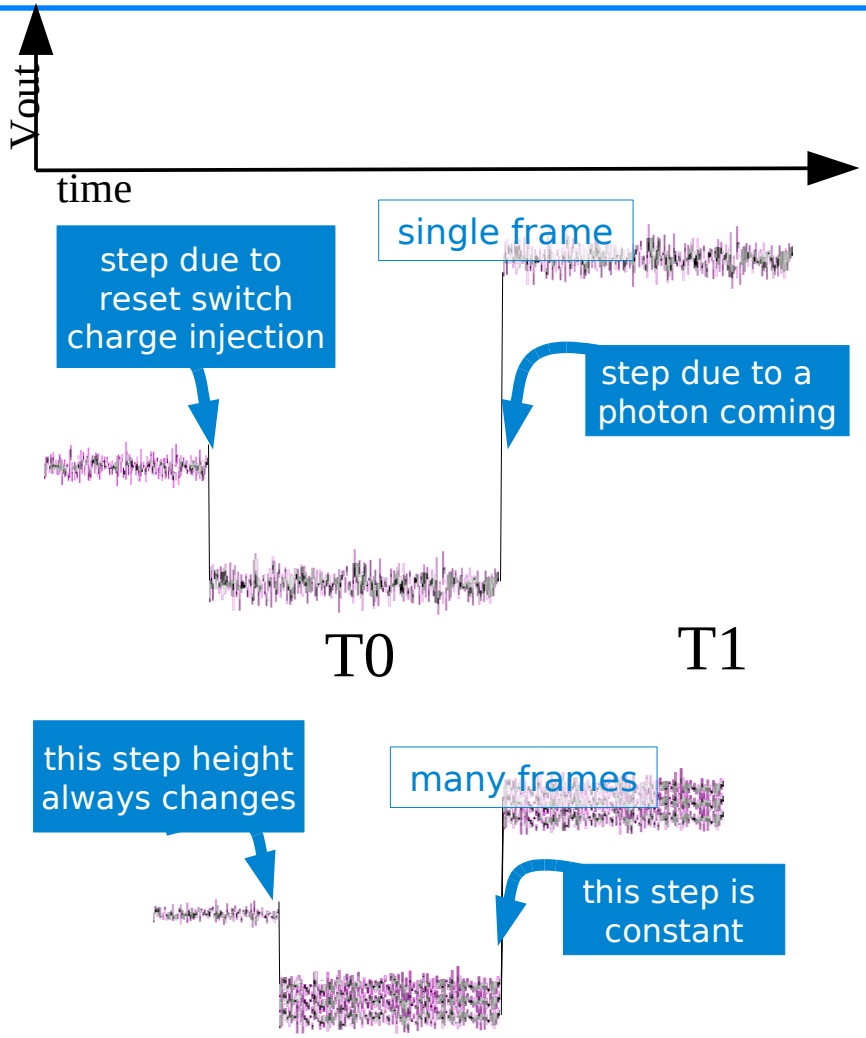
J.BECKER, H. GRAAFSMA, M. LOHMANN

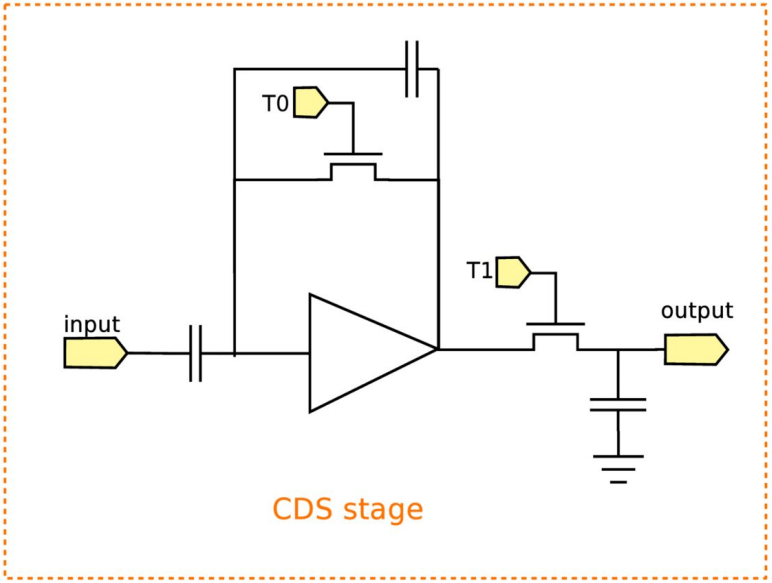
DESY, 22607 Hamburg, DE

Backup slides

Correlated Double Sampling

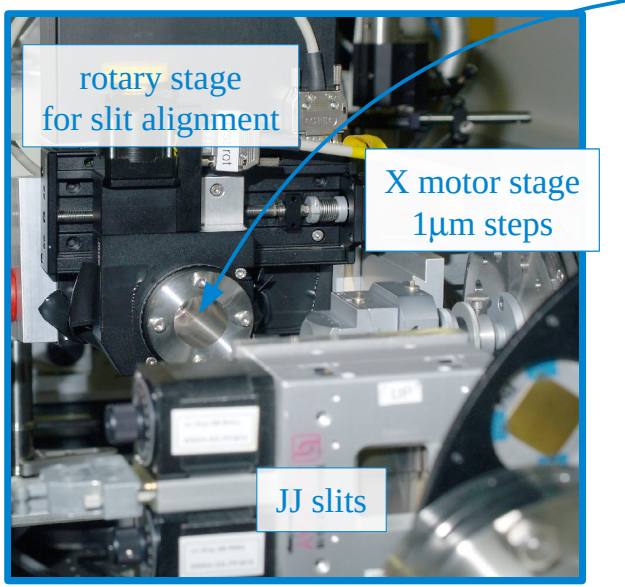
- The main contribution to the noise in the highest gain is the reset noise
- if we only sample the signal at T1 we see the reset noise
- if we measure at T1 and T0 and make the difference, reset noise contribution is eliminated

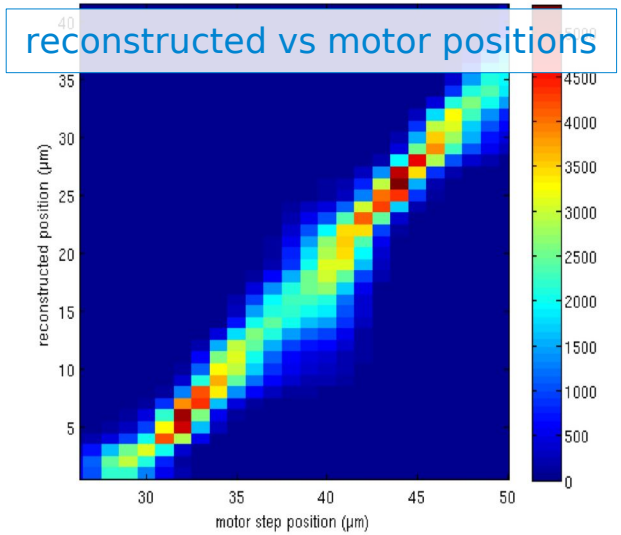


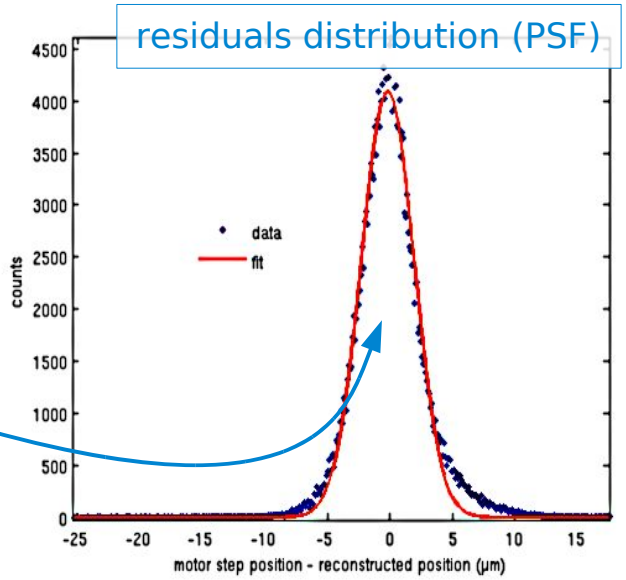


G01-charge interpolation/2

- 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



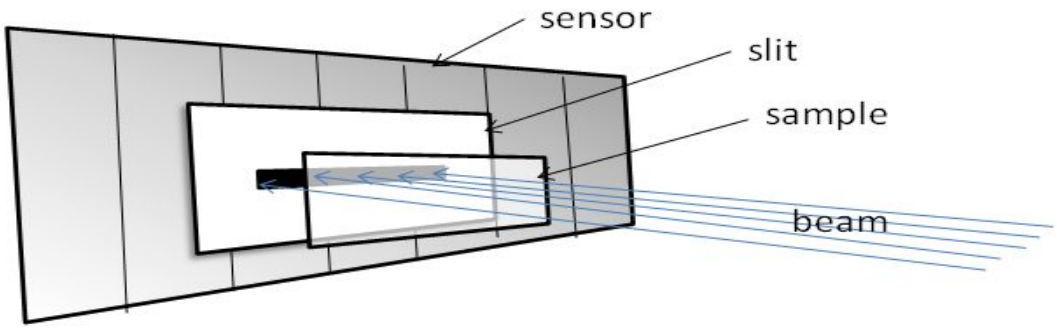


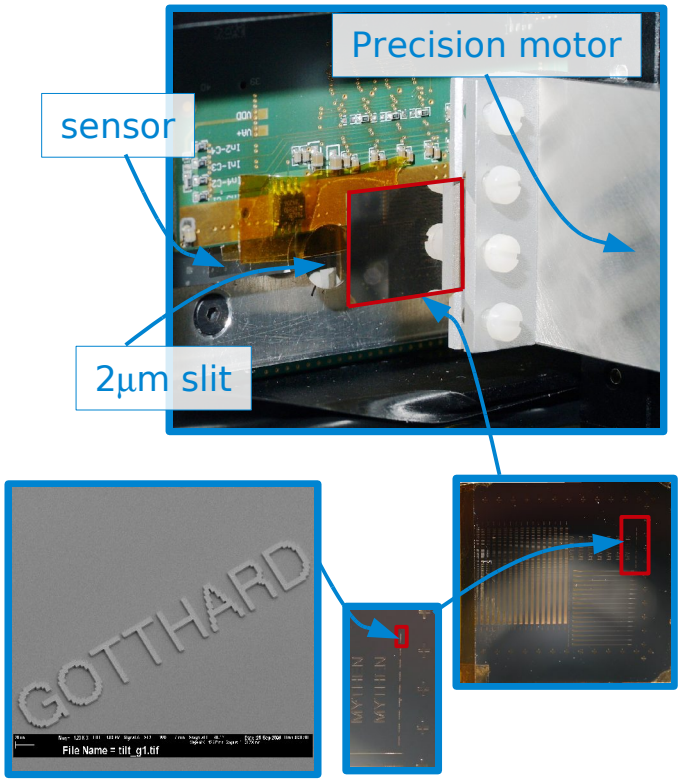


FWHM=4.2μm

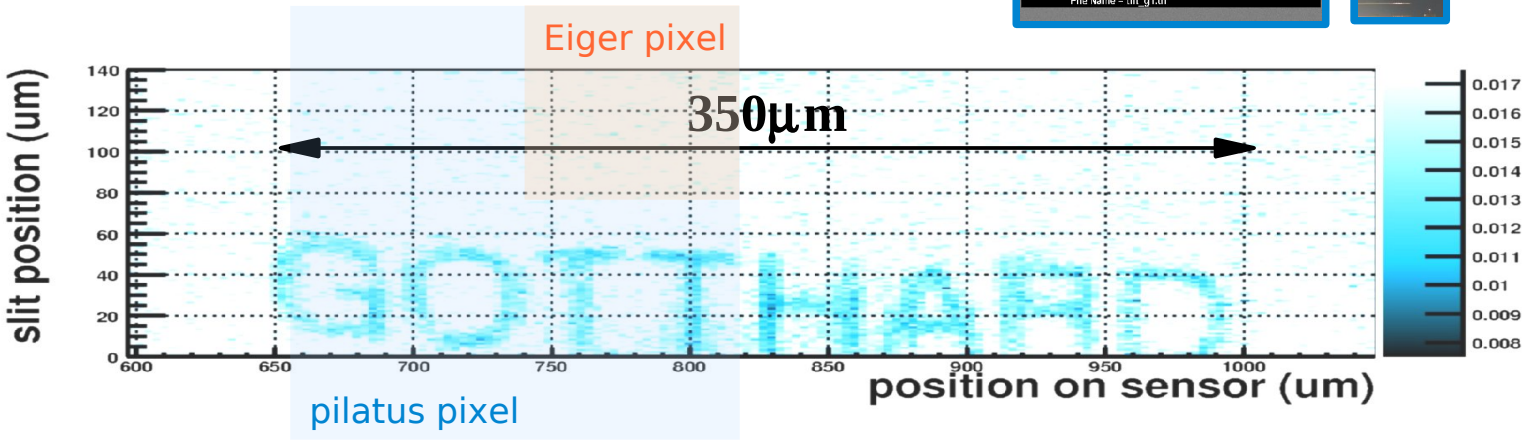
σ=1.78μm

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



Prototypes

- Gotthard01 (UMC0.25) - 100ch
  - 400ch modules, different sensors
  - Extensively tested
- Gotthard02 (IBM 130nm) - 80ch
  - Preamp. noise
- Gotthard03 (IBM 130nm) – 80ch
  - gain switching, fast readout
  - tests successful so far
- AGIPD01 (IBM 130nm) - 12 ch.
  - Preamp. noise
  - switching gain validation
- AGIPD02 (IBM 130nm) - 16x16ch.
  - 10x10 analog memory
  - storage cell variations
  - bump-bondable
- AGIPD03 (IBM 130nm) – 16x16ch.
  - storage cell charge readout
  - serial control interface

Common DAQ system based on embedded CPU + low cost FPGA

- 4 fast ADC channel (14bit,80MHZ)
- 16 slow ADCs, 16 DAC channels
- up to 48 digital I/O
- integrated High voltage P.S.
- 100Mbit/s Ethernet link

Comparison Table

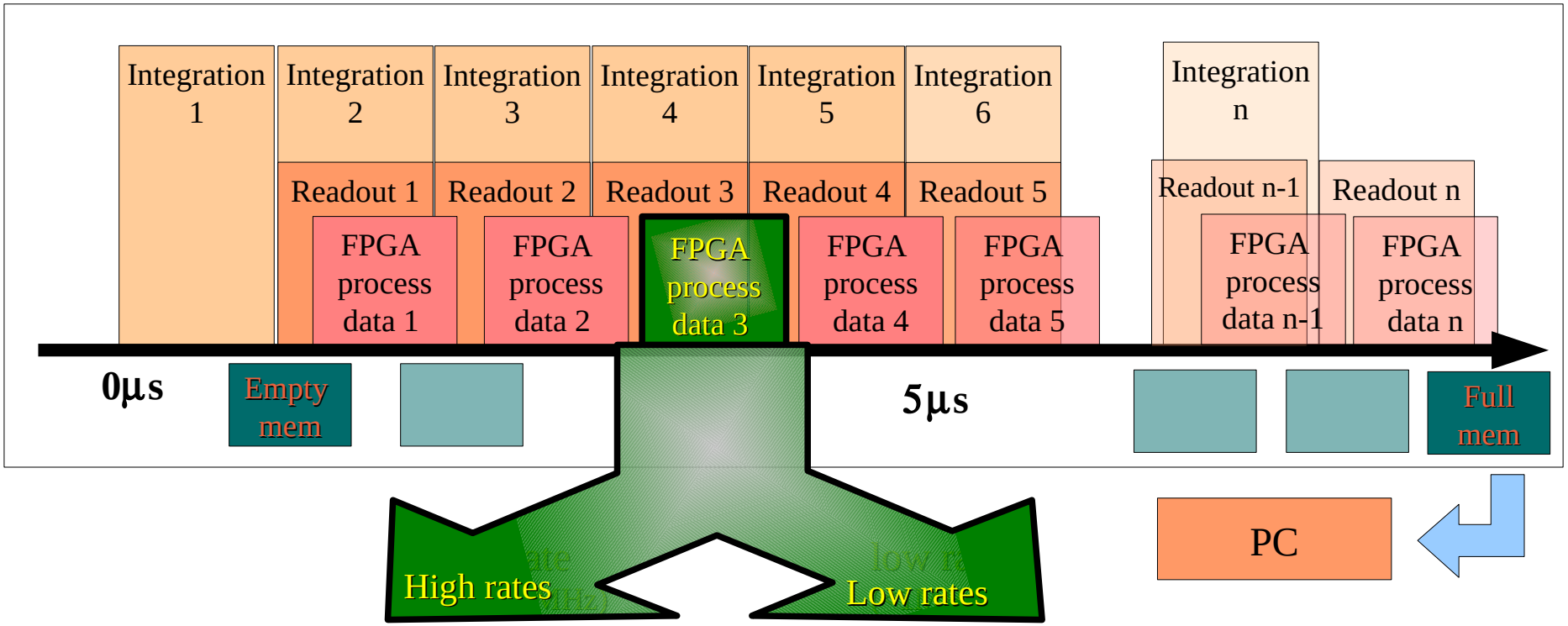
	Photon Counting	Standard charge integrating	Charge integrating, "counting" mode
dynamic range	up to 2^{24} (=1.7×10^9)*	10^{4-5} with gain switching*	up to 2^{nbit} (FPGA memory)
At low rate	noise free	Noise increase with int. time	noise free++
max acq. time	inf.	limited by dark current	inf.++
max count 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, 12.5kHz*	limited by the ADC, (~1MHz strips,~1kHz for pixels**)	n.d.
XFEL ready	NO	YES	NO
Notes	* best values for current system **** incompatible with + and ++	** planned detectors	*** incompatible with +
	PRO		

2d Detector design for SwissFel

	Specifications TBD
mudule pixel count	525k
mudule size	80x40 mm^2
sensor thickness	320-500 µm
pixel size	75x75 mm^2
dynamic range	10^4 12keV photons
noise	<150e-
min Energy	<3 keV
linearity	better than 1%
point spread function	1 pixel
min int. time	80ns
dead time	<50ns
cooling	liquid
readout time = 1 / frame rate	100-250Hz

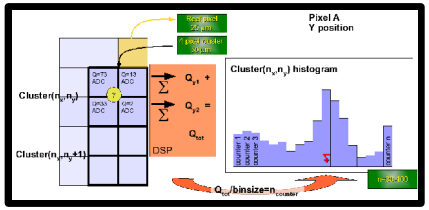
- Storage cells are no longer needed, so the AGIPD electronic can be fit into a 75x75µm^2 pixel
- 256x256 pixels per chip
- 8 chip/module
- mechanics/part of electronics in common with the EIGER and Gotthard projects: shorter development time
- noise (and min. photon energy) will be smaller than GOTTHARD, but has to be measured

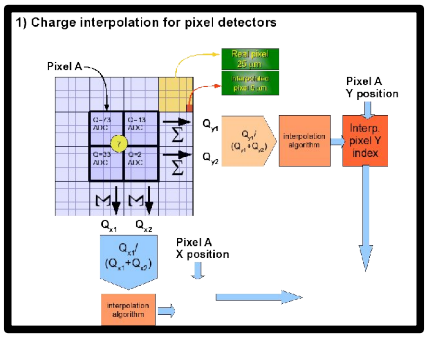
“counting mode”



Loop on channels, for each one:

- Divide ACD out by single photon peak
- Obtain the number of photons in the integration time
- Add this number of photons to the channel counter

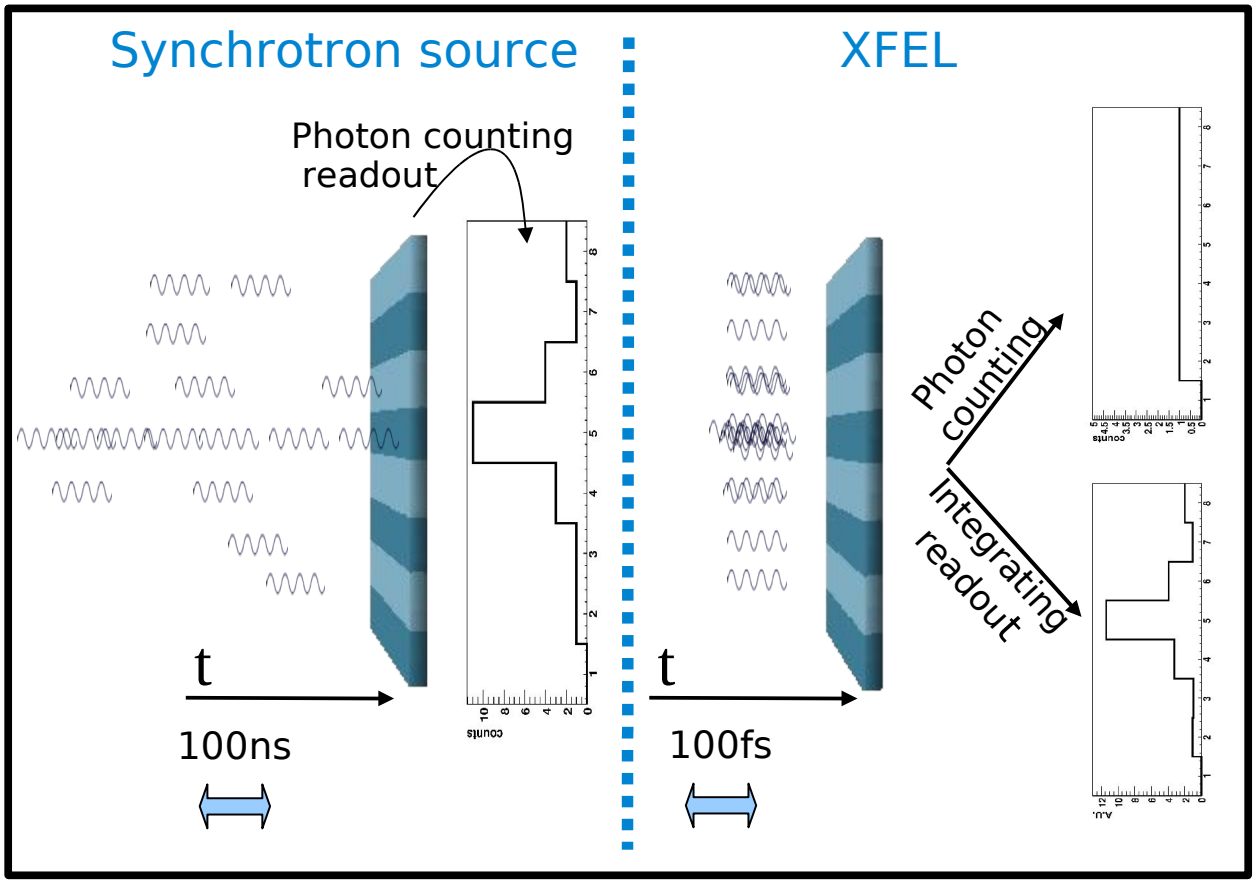




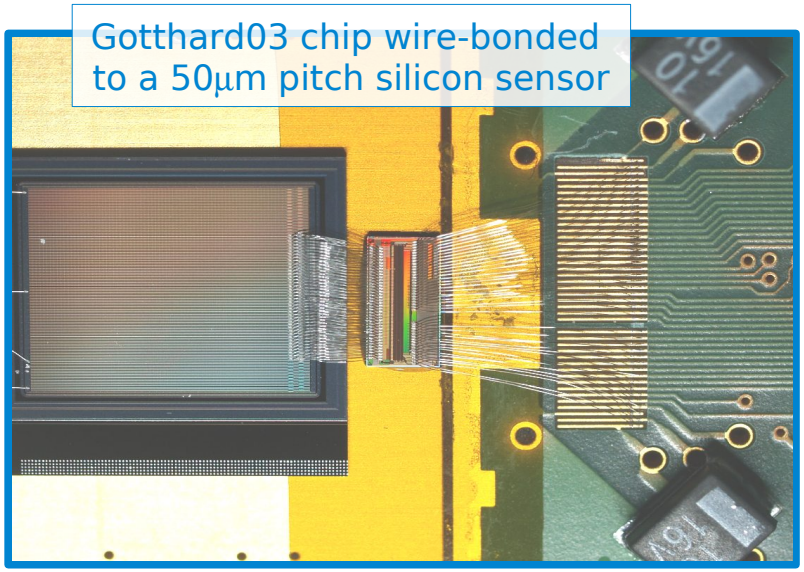
XFELs => charge integration

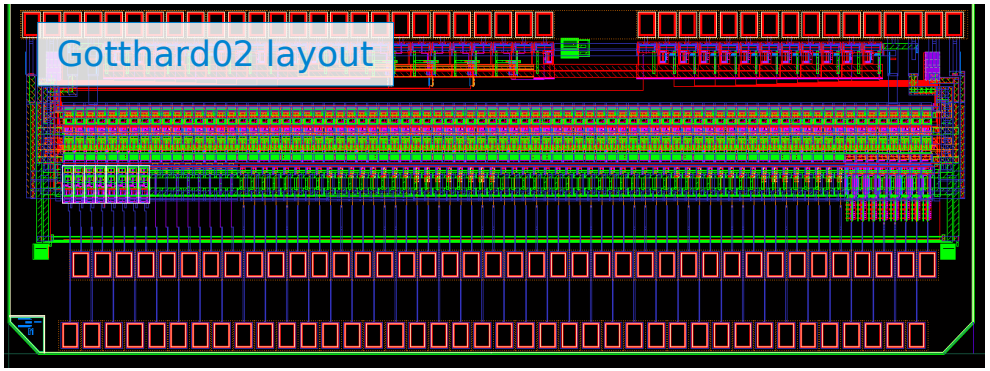
Synchrotron source:
- Huge number of “weak” photon bunches
- Photons impinge on the detector with a random time distribution

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



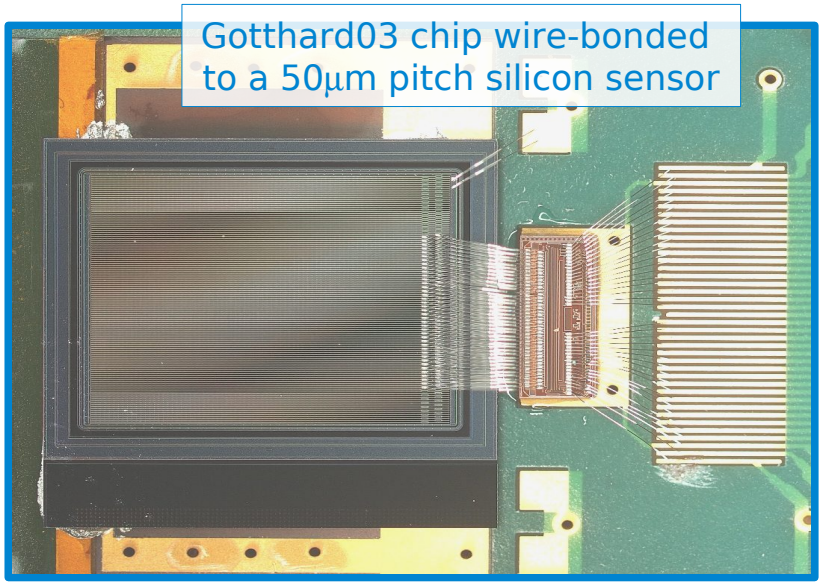
GOTTHARD02

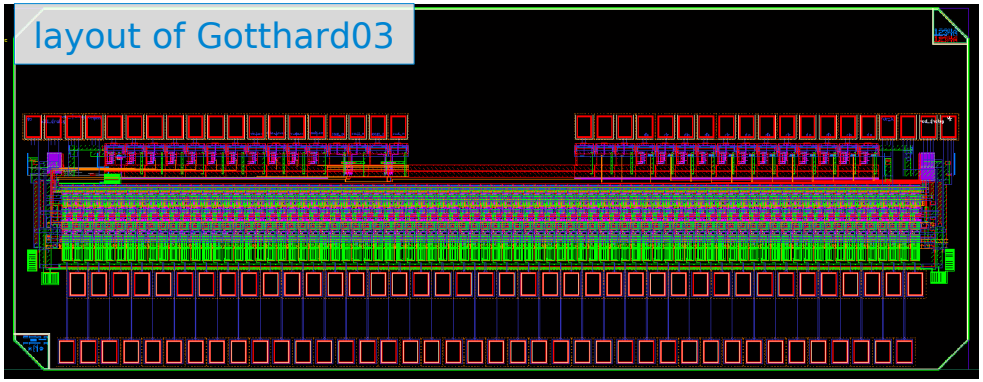




- Designed Oct 2009 in IBM130nm technology
- 80 channels, 8 preamplifier variations (strength and DC gain)
- Each channel has an analog CDS stage and a double sample and hold circuit
- a variation with a multi-sample logic with tunable delay

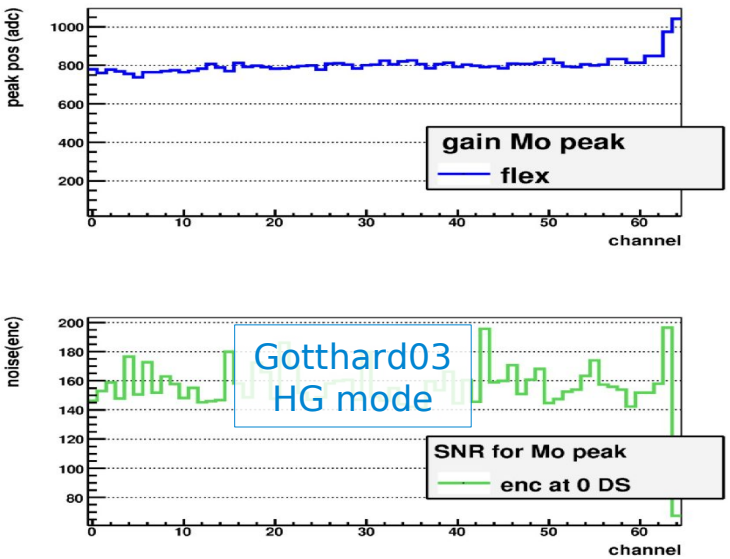
GOTTHARD03

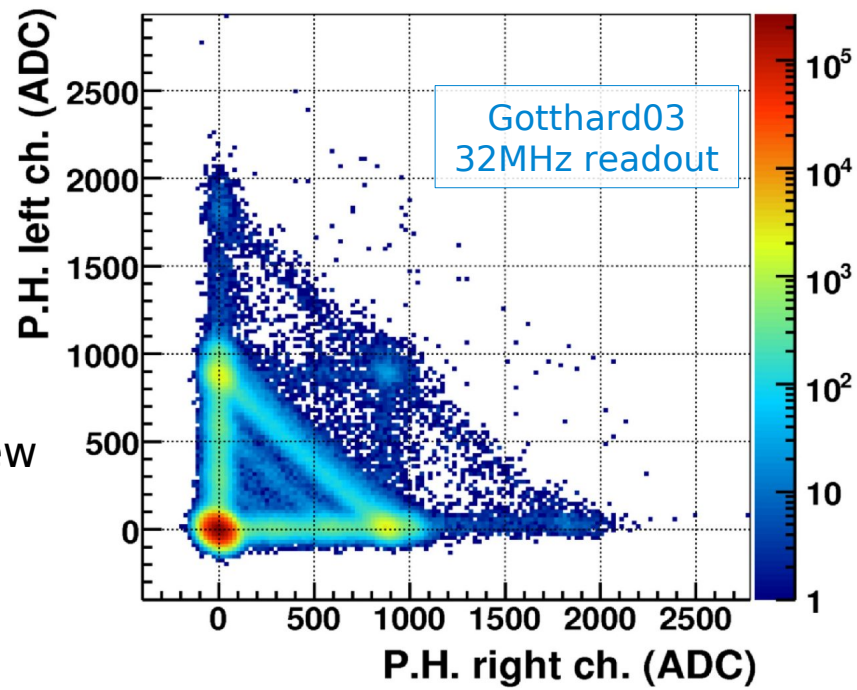




- 80 channels
- Switching logic, 3 gains, with storage and readout of the gain settings
- High gain setting: optional bigger gain in the CDS buffer
- recombination logic to bypass the CDS stage in 2nd & 3rd gain (optional)
- Improved output chain to increase readout speed to 32 ~MHz, without increasing the noise

G03 Noise measurements/2





- Channel by channel gain variation at a few percent level
- Noise between 140 and 180 e-
- Noise variation probably due to different leakage current values
- Noise does not increase at the max. readout clock speed (32MHz)
- Limited cross talk at fast readout speeds