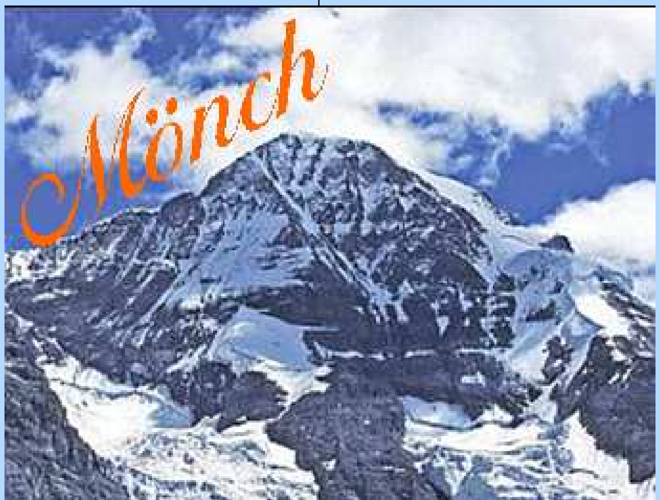
PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen



Paul Scherrer Institut

Roberto Dinapoli roberto.dinapoli@psi.ch

Charge integration detectors for X-ray applications

Single photon counting detectors for X-ray applications

Yesterday

- Introduction of Paul Scherrer Institut
- Chip design at PSI
- Basics of X-ray synchrotron radiation emission
- Detectors developed by the SLS Detector group for X-ray detection
  - Single photon counting detectors

1. PILATUS (2D)
2. MYTHEN (1D)
3. EIGER (2D)

OUTLOOK

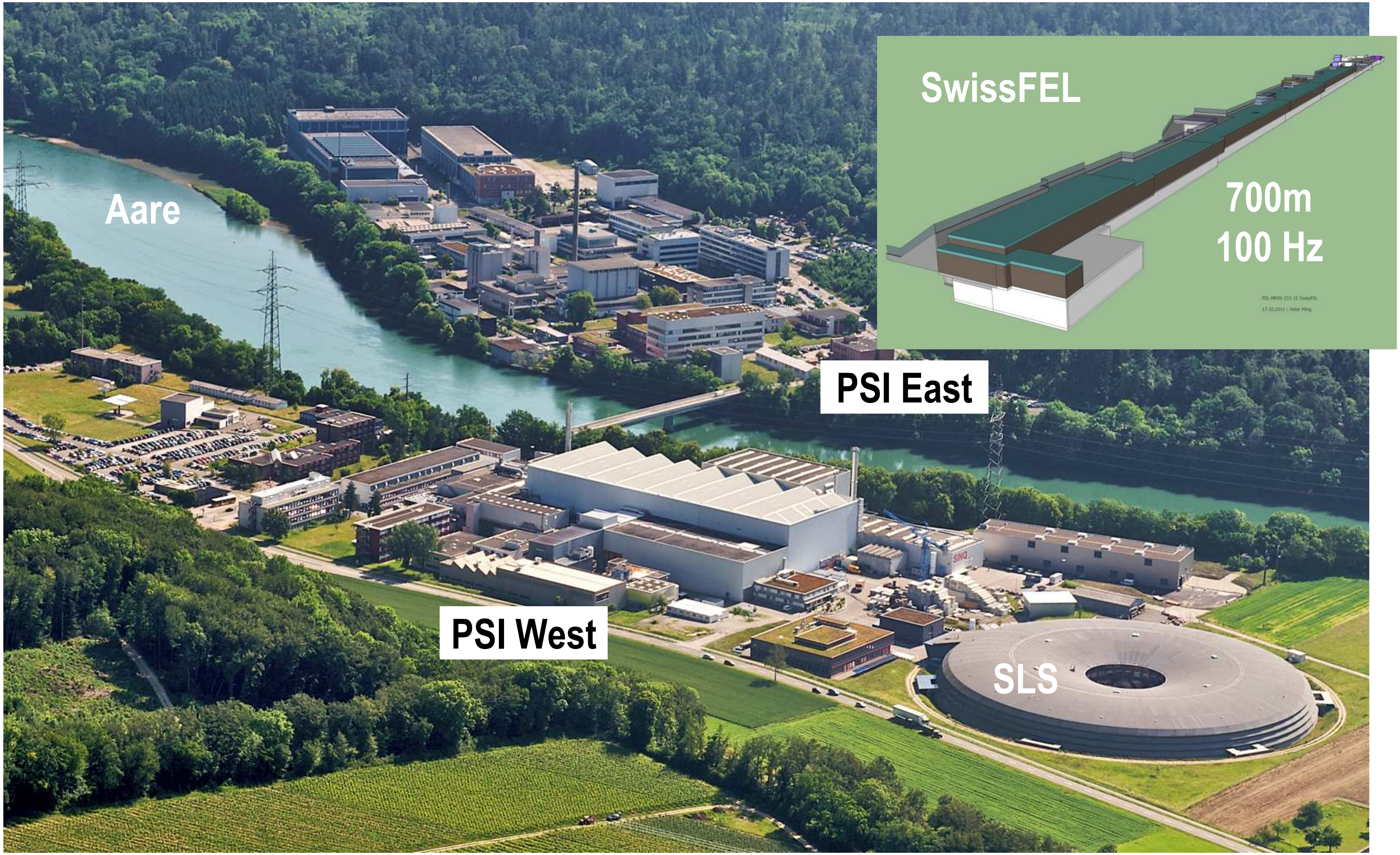
Single photon counting detectors for X-ray applications

- Summary of the single photon counting detector talk
- Basic of charge integration with analog readout
  - Charge integration detectors

1. AGIPD (2D, XFEL)
2. GOTTHARD (1D, XFEL & Synchrotron)
3. JUNGFRAU (2D, XFEL & Synchrotron)
4. MÖNCH (2D, XFEL & Synchrotron)

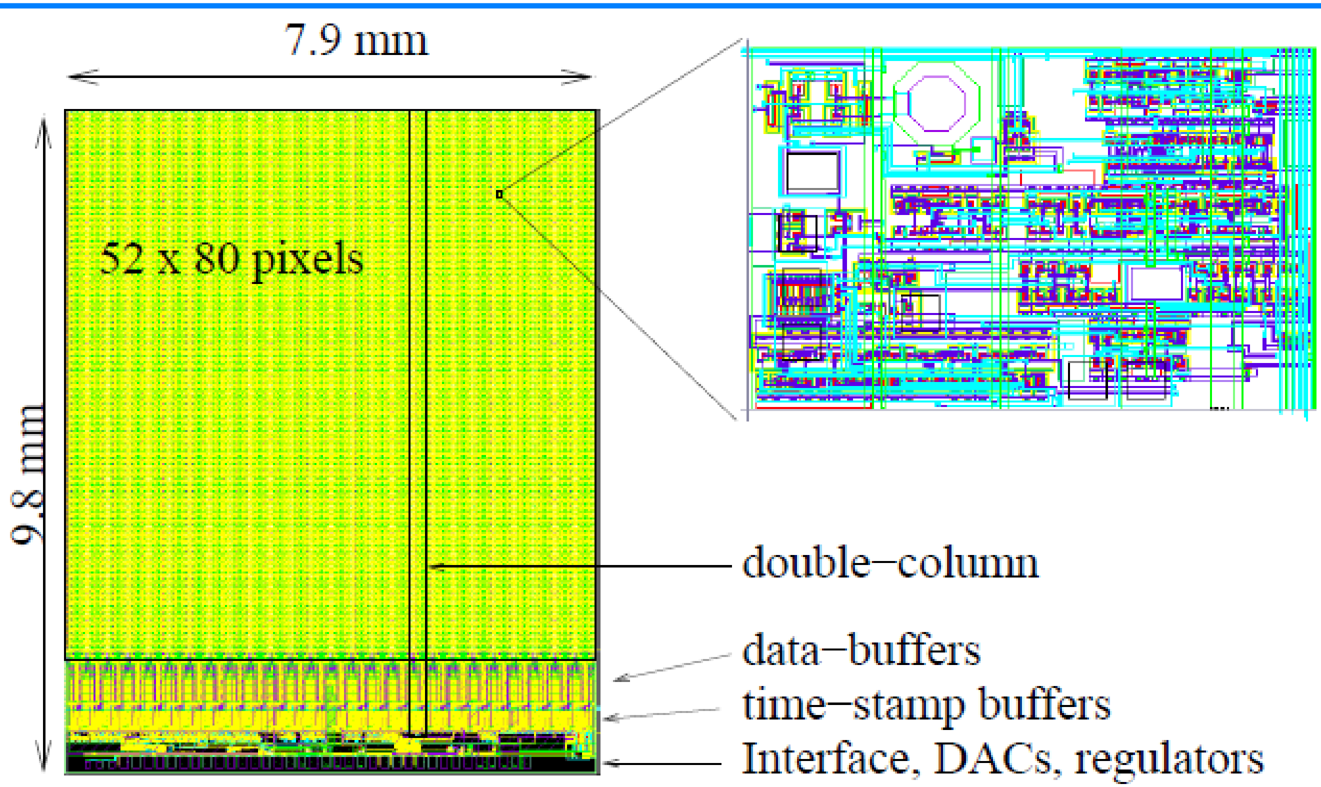
- MÖNCH

PAUL SCHERRER INSTITUT (2011)



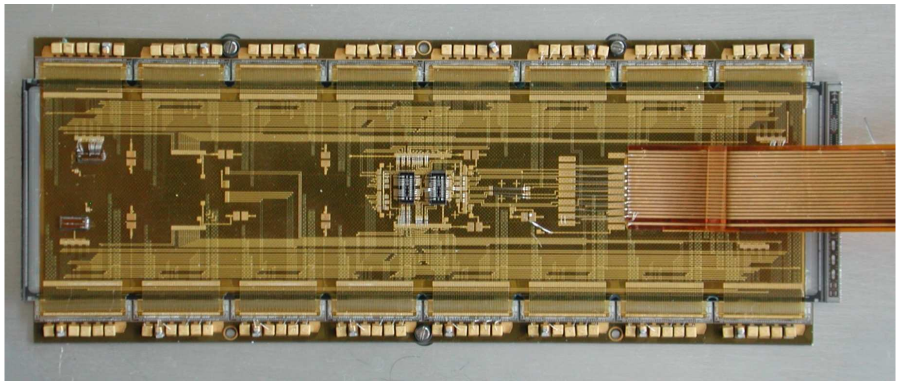
~1700 Staff employees; 30Km from Zurich

The CMS Pixel Chip (Roland Horisberger)

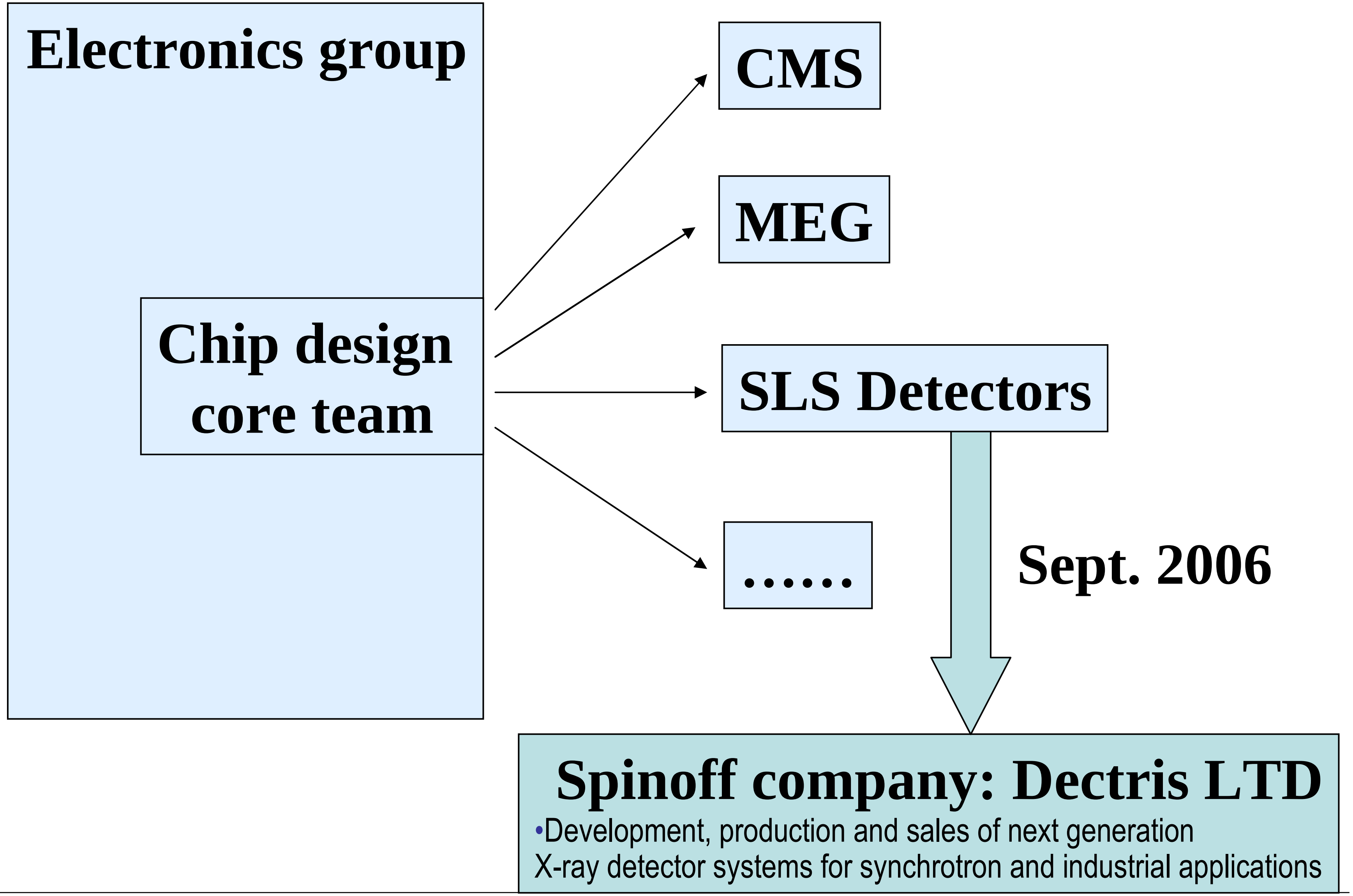


- Technology: 0.25 um IBM
- Pixel size 150x100 um^2
- Tested up to 100MHz/cm^2 ~ 20 kHz/pixel
- Time resolution: 25 ns
- Deadtime/ pixel: 100ns
- Module: 416 x 160 pixels (62.4 x 16 mm^2)

CMS module based on PSI46 Chip



Chip design at PSI



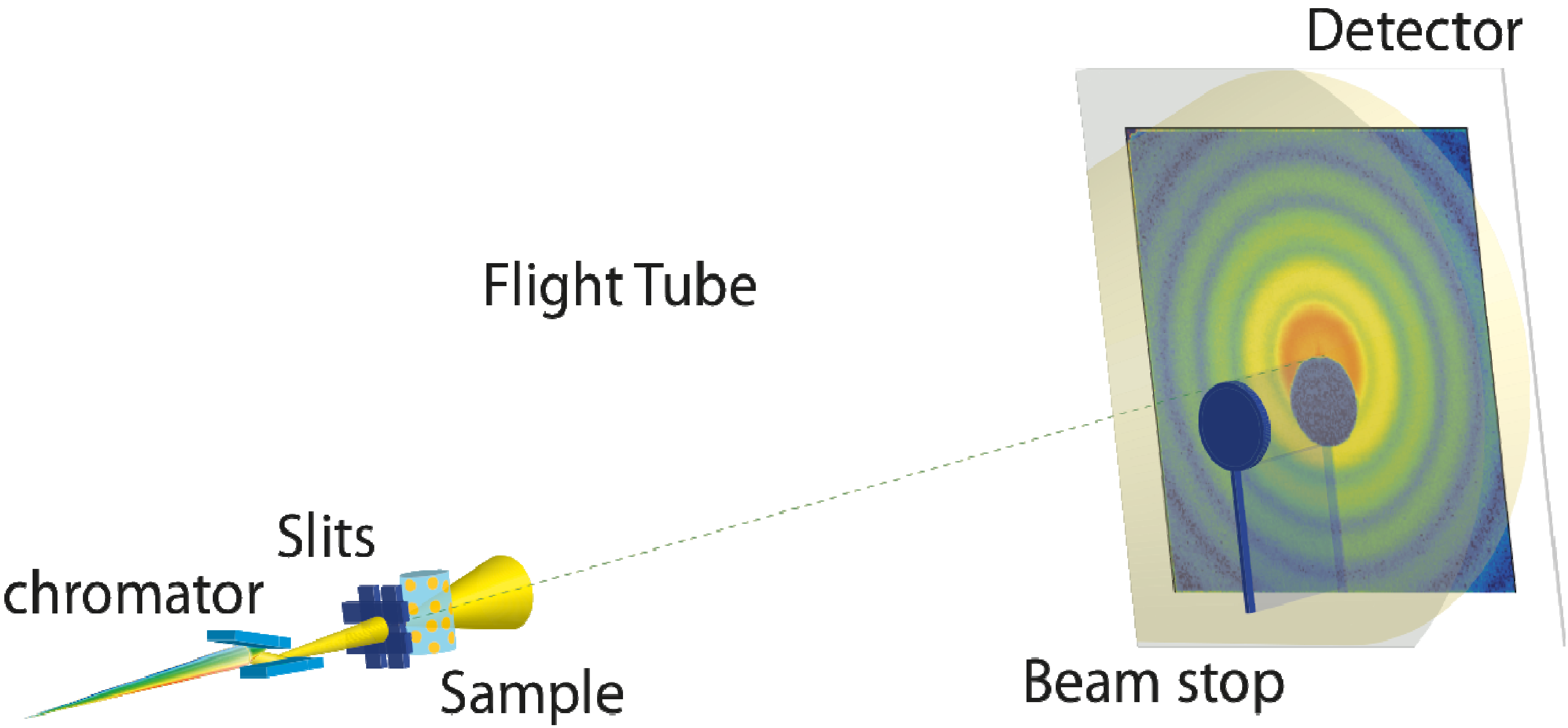
Chip design at PSI

Particle physics	CMS	Pixel chip for the inner tracker New version for LHC luminosity upgrade
	MEG	Domino sampling chips (DRS4) New version for MEEE (DRS5)

X-ray detection	Synchrotron light (Mythen,Pilatus,Eiger) XFEL light (Agipd, Gotthard, Jungfrau, Mönch)

Astronomy	Sensor design
Research	HiZ – Neutrons – Low energy X-ray – Electrons Detectors

Basics of X-ray detection

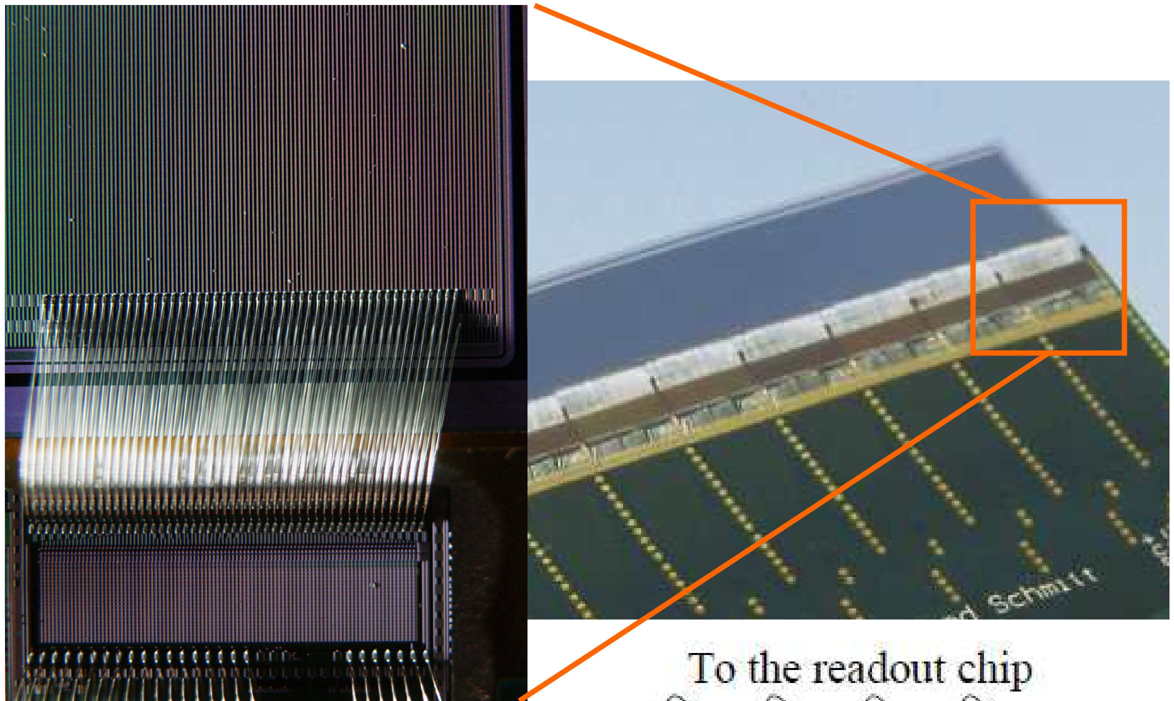


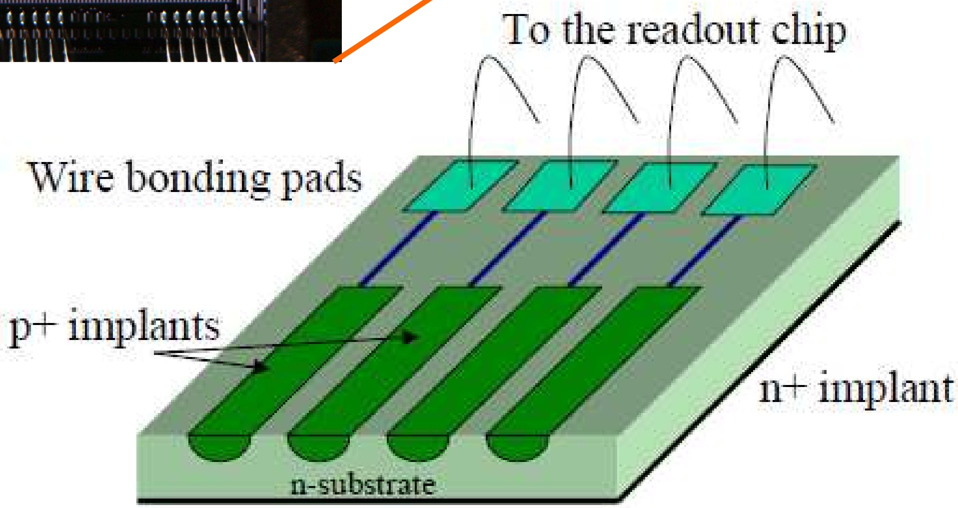
Tasks that we perform at PSI

- Specs definition
- Chip design CAD mantainance (HW and SW)
- ASIC design
- Sensor design
- Bump-bonding masks design
- Bump bonding
- Wirebonding
- Design of the ASIC test system (HW,firmware,SW)
- ASIC tests

- Full readout system (HW,firmware,SW)
- Mechanics and cooling design (and partly production)
- Data transfer to long term storage
- Design of the wafer testing system
- Detector assembly
- Detector tests
- Detector commissioning
- Detector „mass“ production
- Detector support

1D hybrid detectors (strips)





Strip detectors

- High segmentation
- Small data throughput
- Lower cost per area

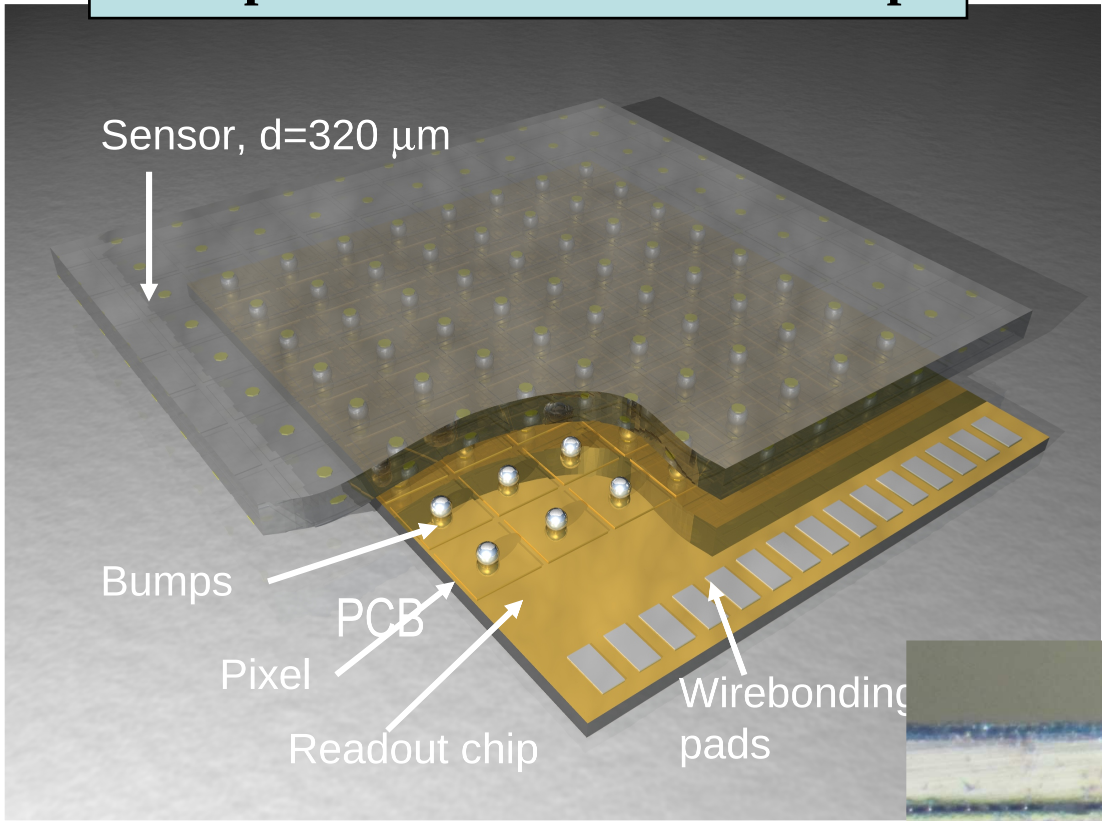
Powder diffraction

Fluorescence emission spectrometers

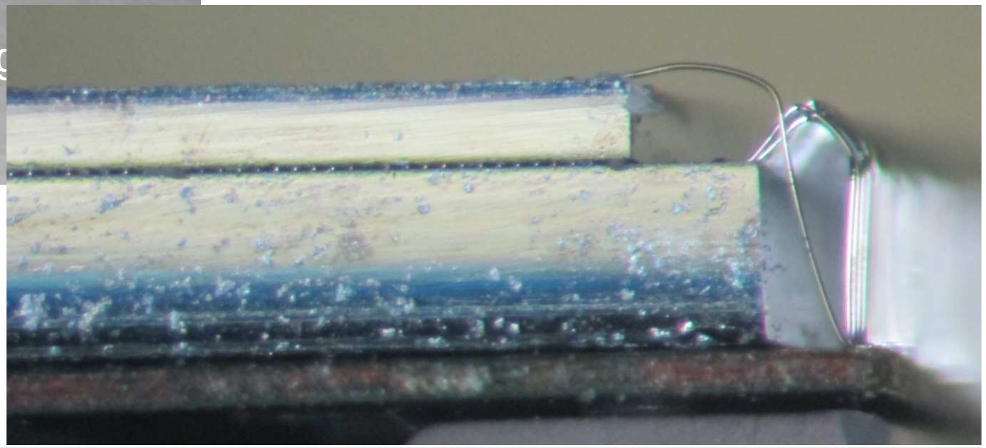
Beam position monitors

2D hybrid detectors (pixels)

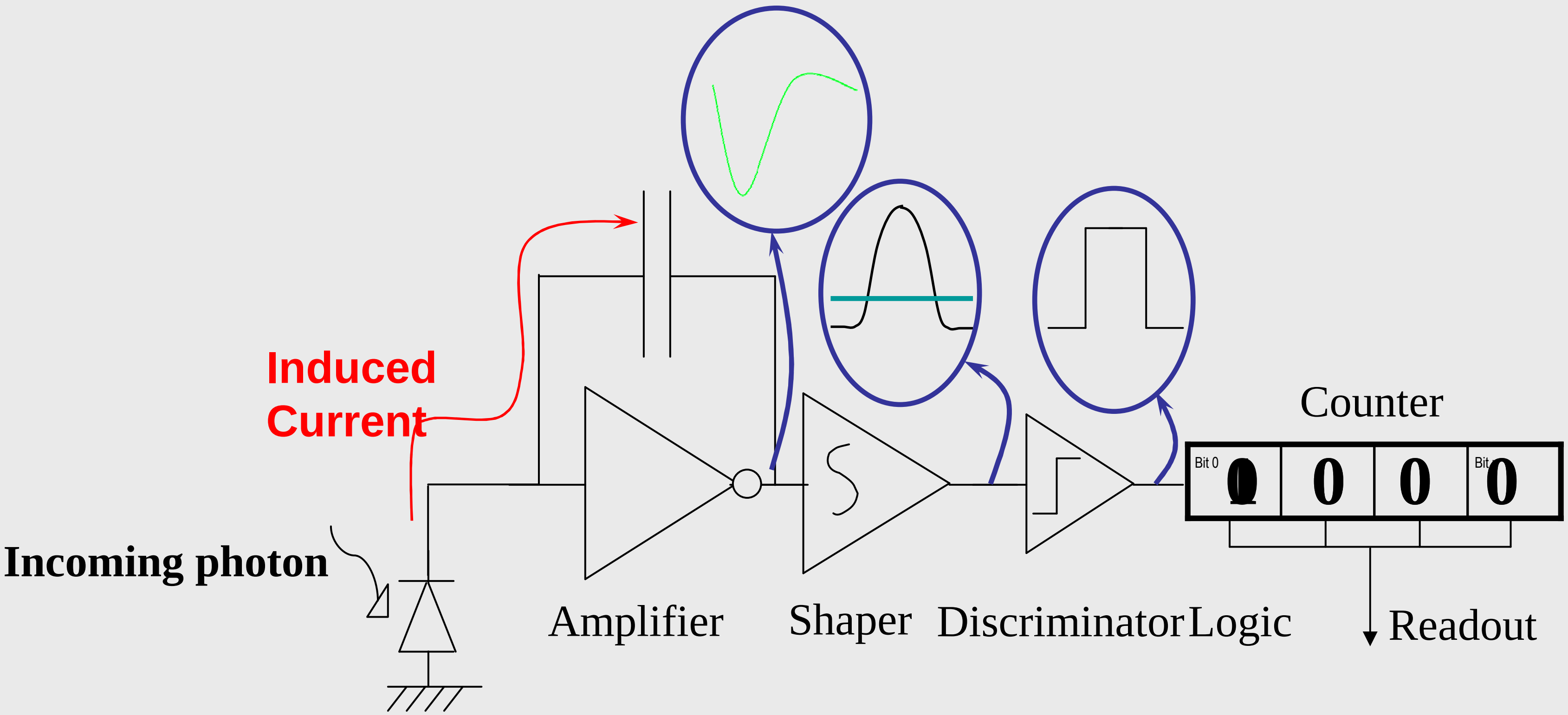
A silicon detector bump-bonded with a readout chip



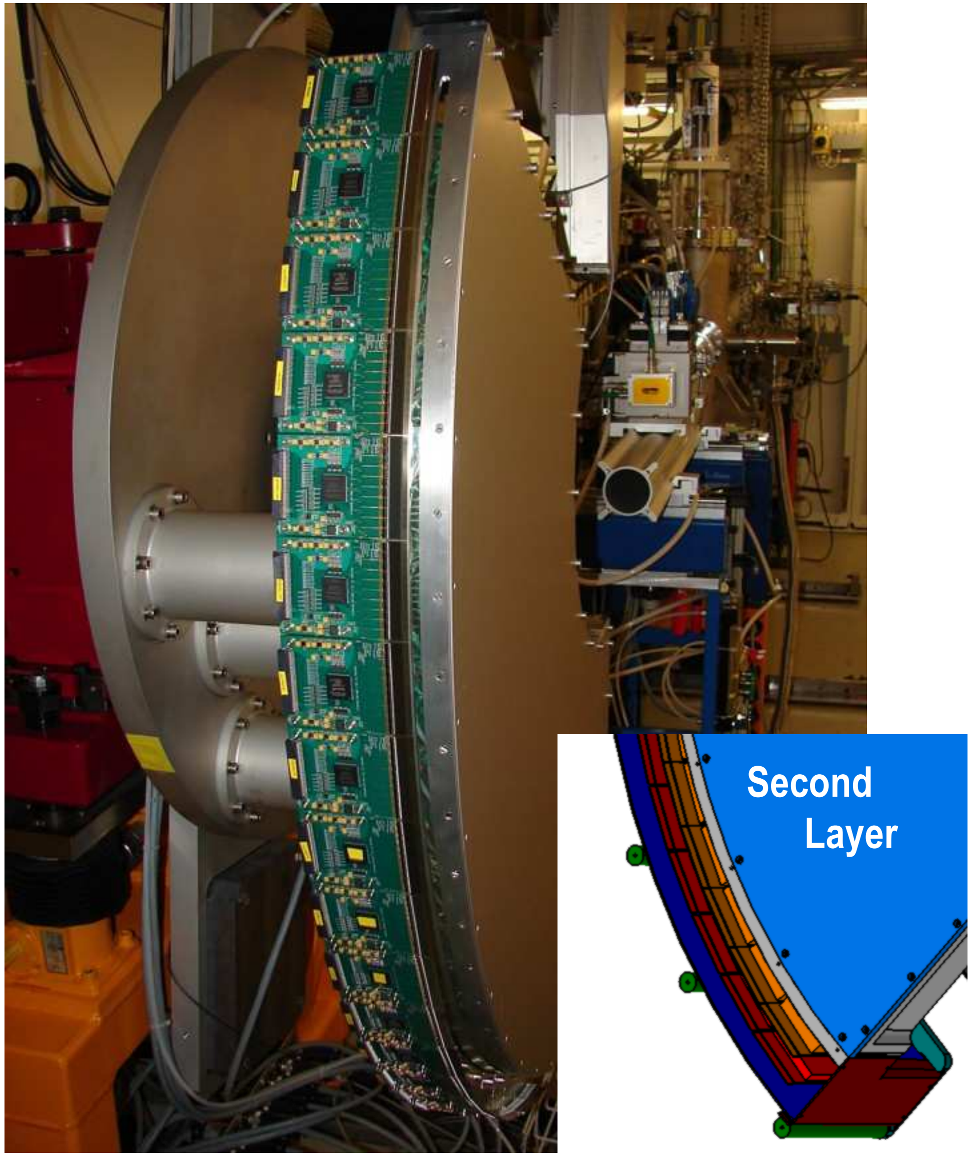
2D information!

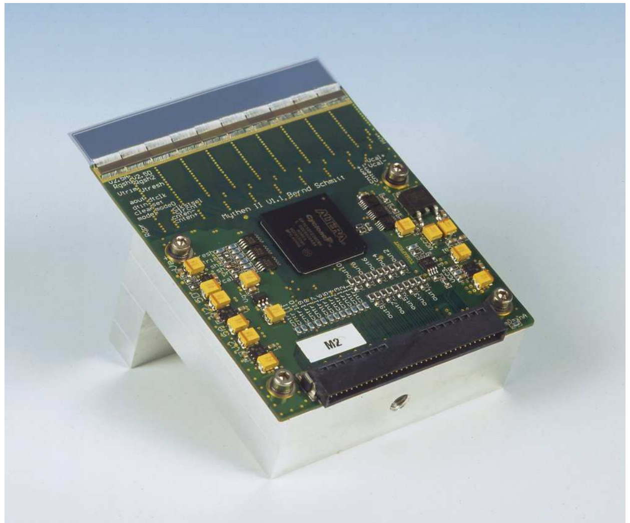


Simplified working scheme of a channel



Mythen II full detector





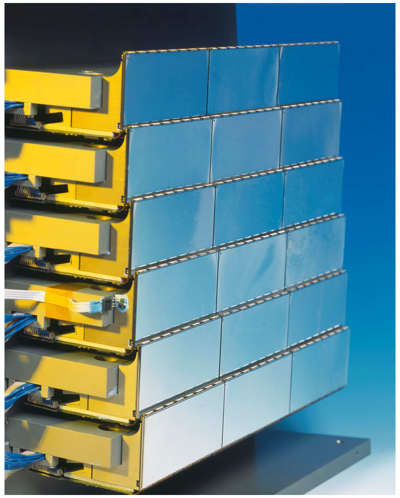
- full 120^{o} spectrum taken in less than a second
- makes measurements 5000-15000 times faster
- solves problem of radiation damage in organics

- unique tool for time resolved 1D experiments (powder diffraction)

120^{o} Mythen system at the Powder diffraction end station, MS beamline

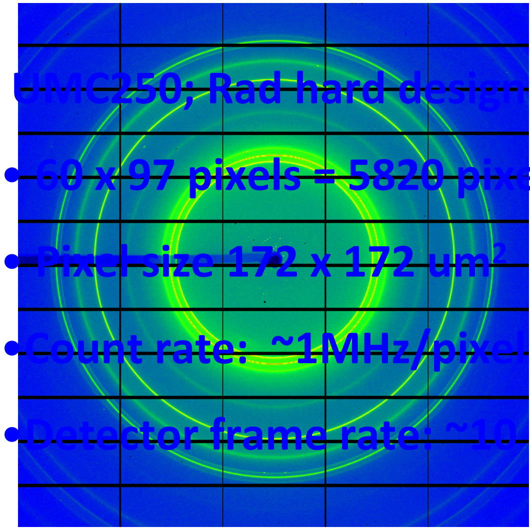
Single photon counting pixel detectors

PILATUS I



- DMILL rad-hard technology
- Pixel size: 217x217 μm²
- Chip pixel array: 44 x 78
- Count rates <10kHz/pixel
- Det. Frame rate: 2 Hz

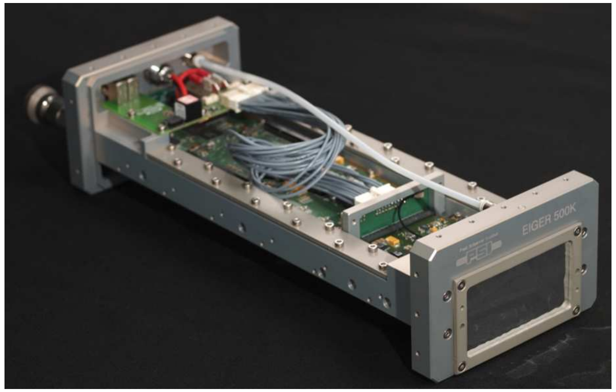
PILATUS II



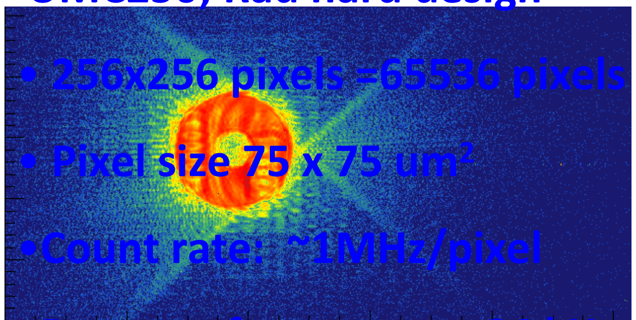
UMC250; Rad hard design

- 60 x 97 pixels = 5820 pixels
- Pixel size 172 x 172 um²
- Count rate: ~1MHz/pixel
- Detector frame rate: ~10 Hz

EIGER

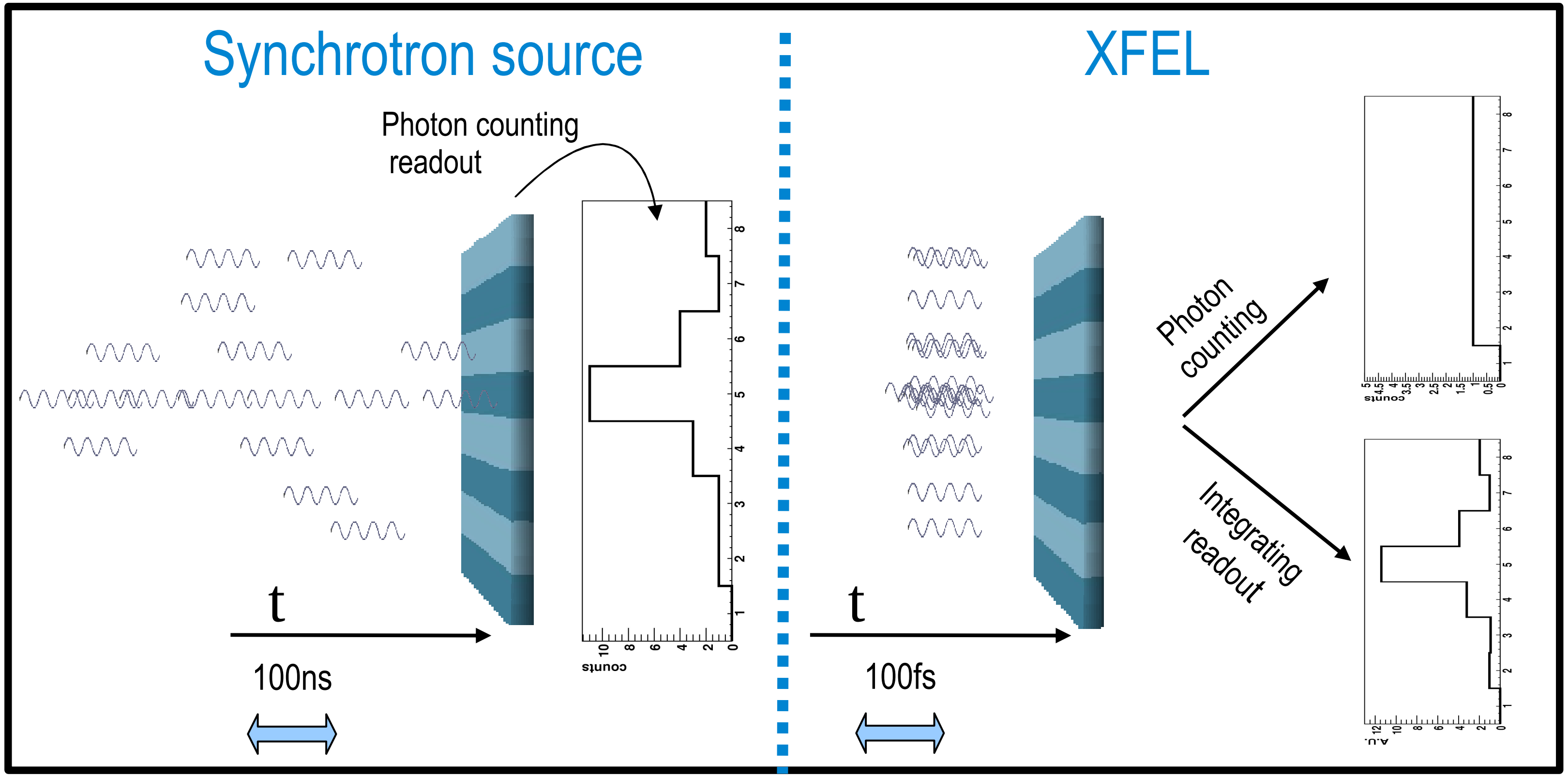


UMC250; Rad hard design



- 256x256 pixels =65536 pixels
- Pixel size 75 x 75 um²
- Count rate: ~1MHz/pixel
- Detector frame rate: ~24 kHz

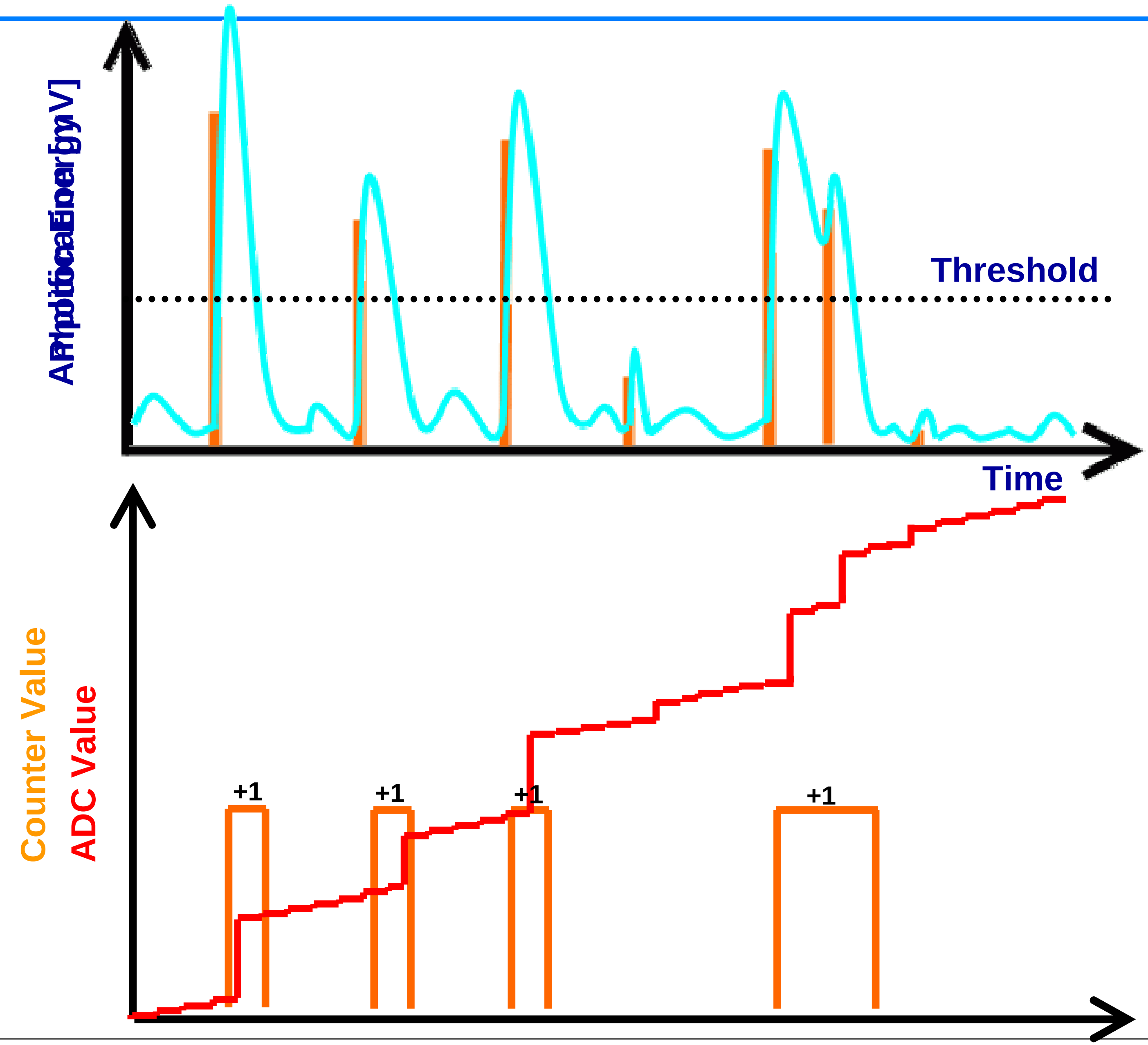
XFELs and synchrotrons



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

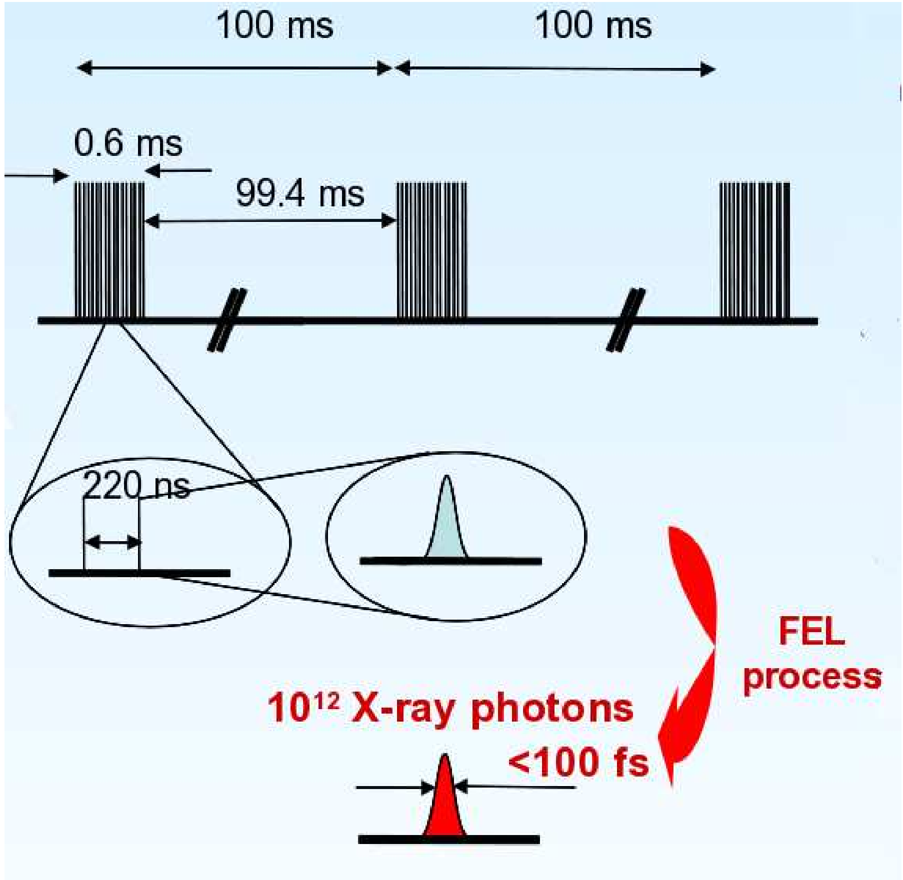
XFEL:
- Fewer intense bunches
- All photons coming at once
- High number of particles/channel per bunch
- EUXFEL: 1GGy

Counting vs. Integrating



Common chip testboard

XFEL detector development



Beam Characteristics:

- Bunch train repetition rate 10 Hz
- Bunch train duration 600 µs
- Number of bunches/train 2700
- Separation of bunches 220ns
- (SASE) Each bunch consists of ~10^{12} ph arriving in <100 fs
- Wavelength: 0.1-6 nm (12.4-0.2 keV)

Challenges:

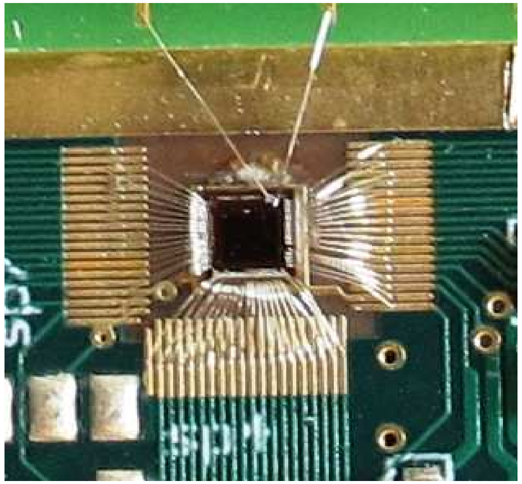
- „Instantaneous“ energy deposition
- Large number of bunches per train
- Very short separation between bunches
- Large dynamic range:
  0 to 10^4 ph/pixel (=3.3 10^6 e^-/pix)
- Single photon resolution (low rate regions)
- Limited by statistic (high rate regions)
- High radiation tolerance: expected to survive a ~GRad dose (on the sensor)

AGIPD

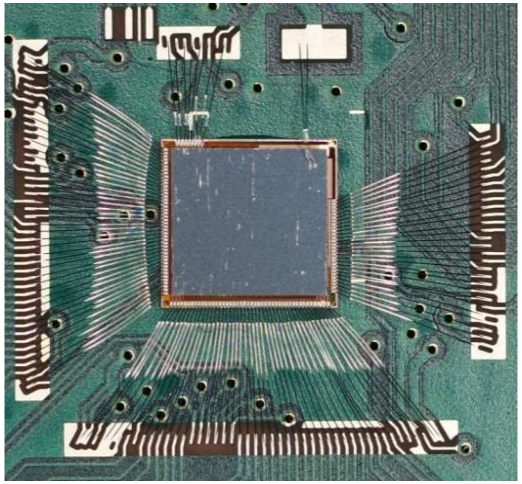
AGIPD 1

Active area:13x13 mm^2
- **64x64 pixels**
- **200x200 μm^2 pixel**
- **Single photon resolution**
- **Dynamic range 10^4 x12keV ph.**

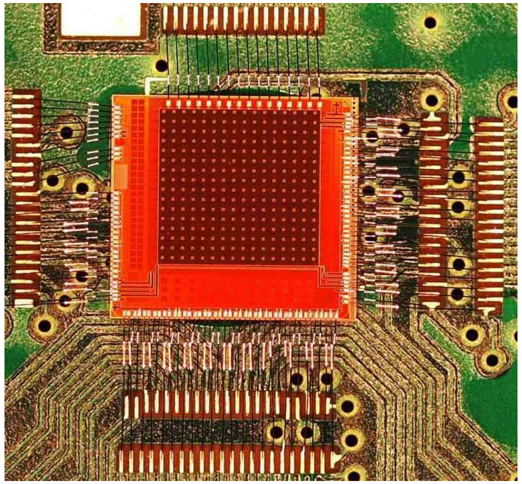
AGIPD 0.1



AGIPD 0.2

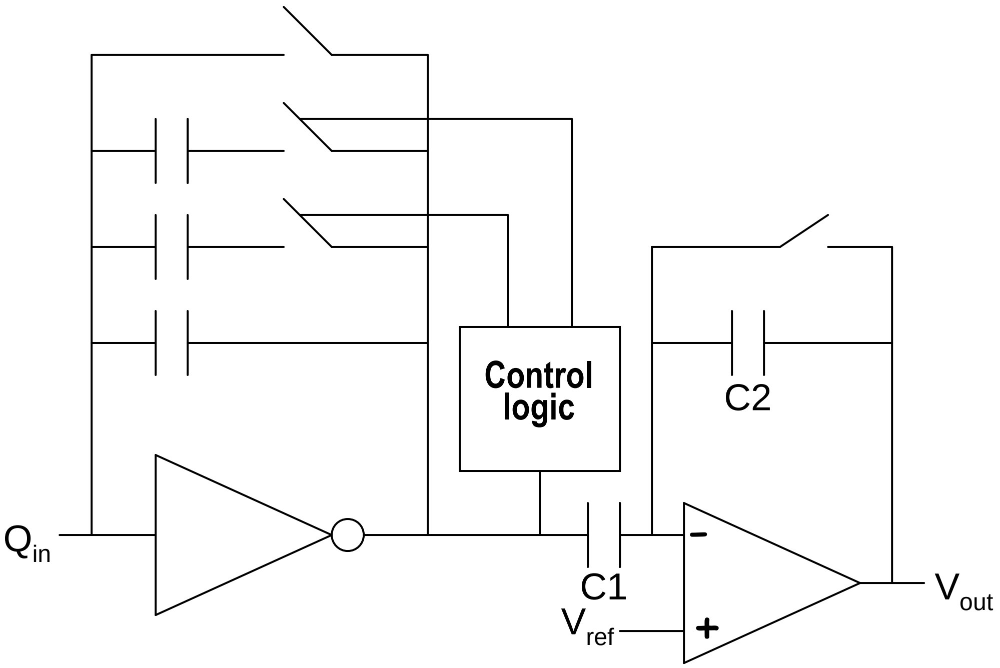


AGIPD 0.3



(DESY, Bonn, Hamburg, PSI)

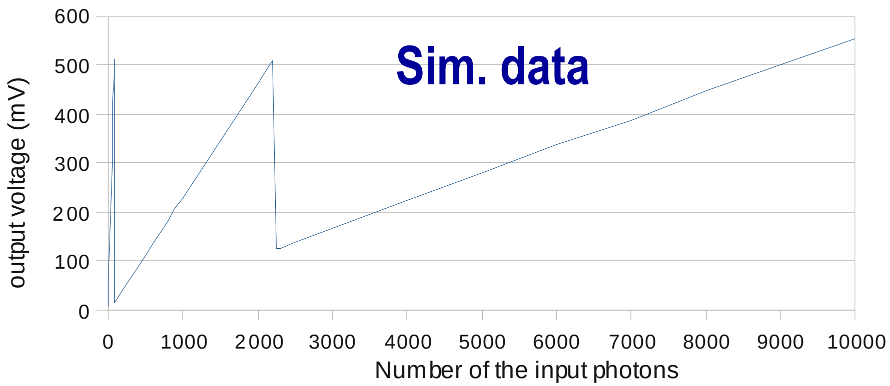
Preamplifier with automatic gain switching



Charge Integrating

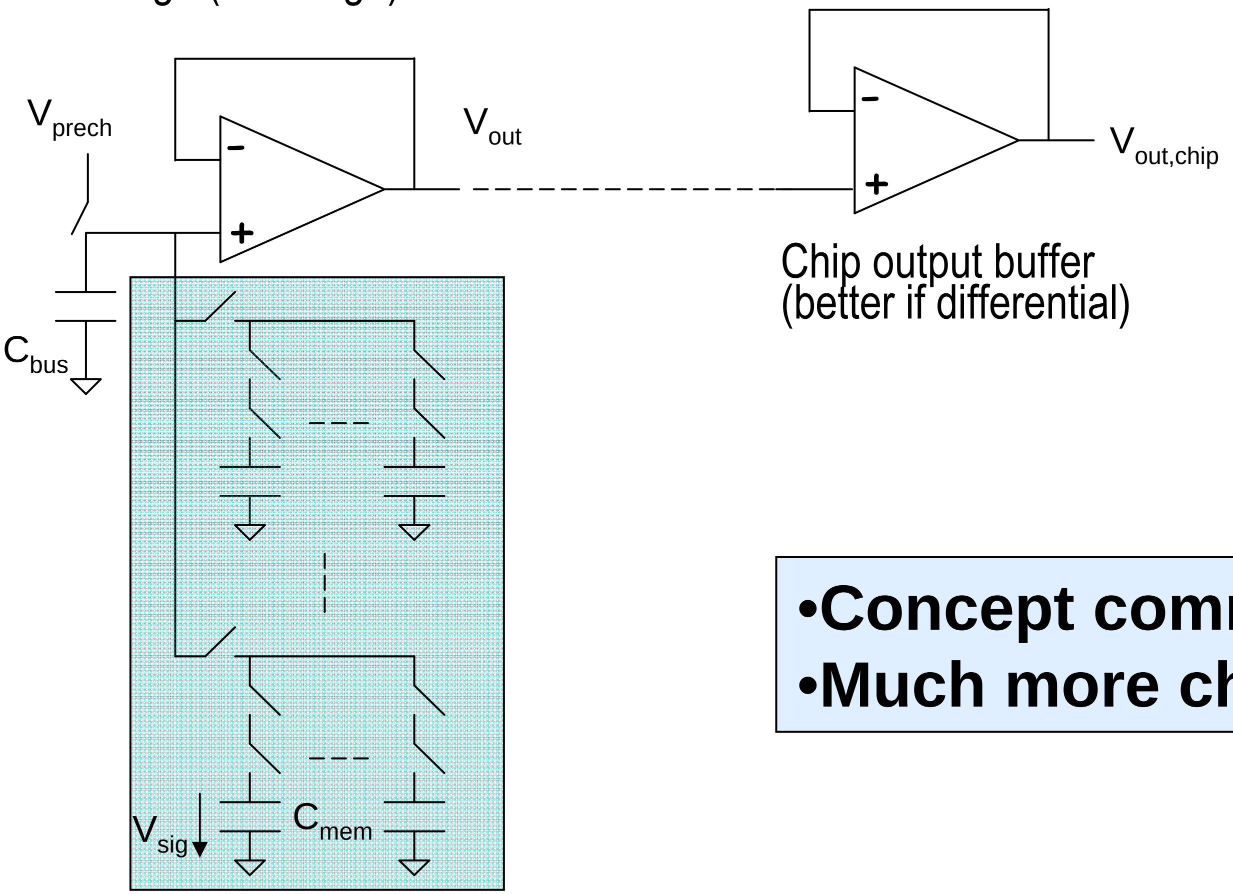
Correlated double sampling

- Common for 1D and 2D
- The gain is automatically adapted to the input photons.
- Single photon resolution + high dynamic range.
- Correlated double sampling buffer reduces reset noise and 1/f noise.



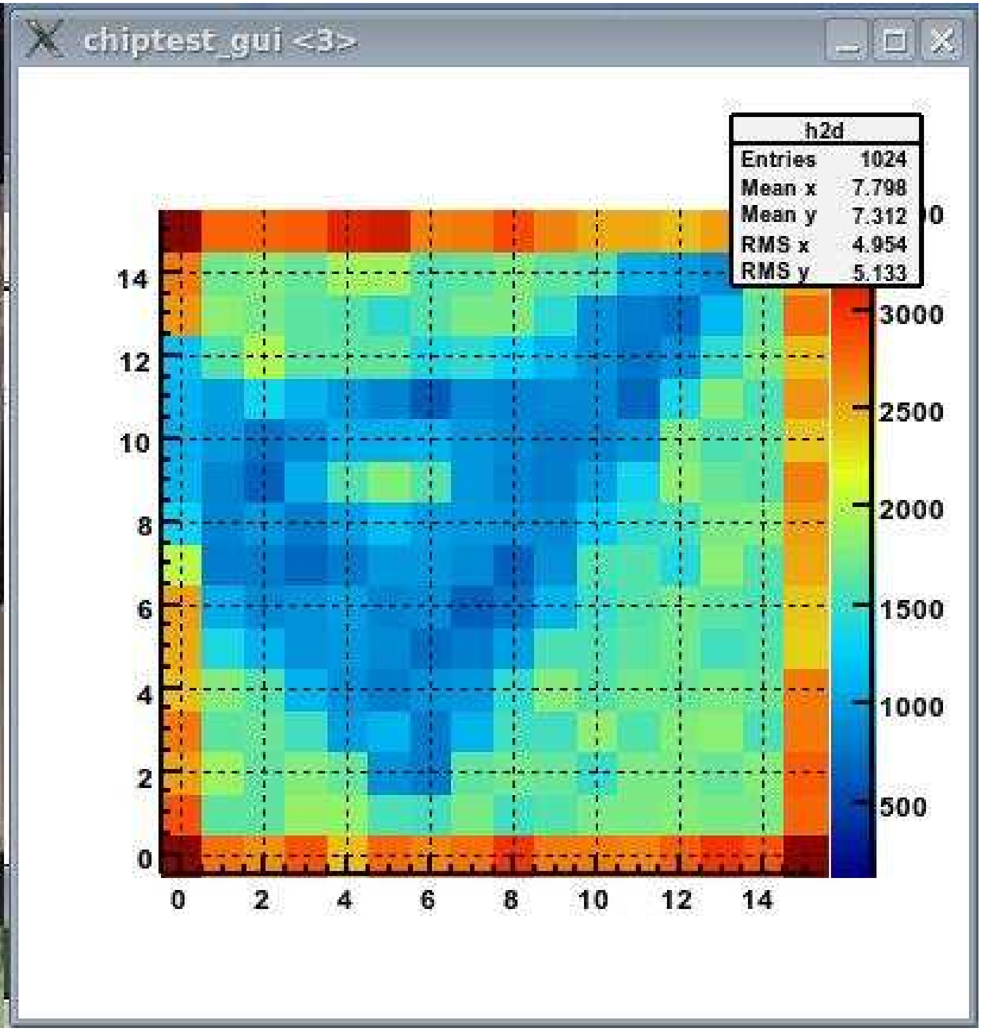
Storage and readout

Voltage (or charge) local readout buffer

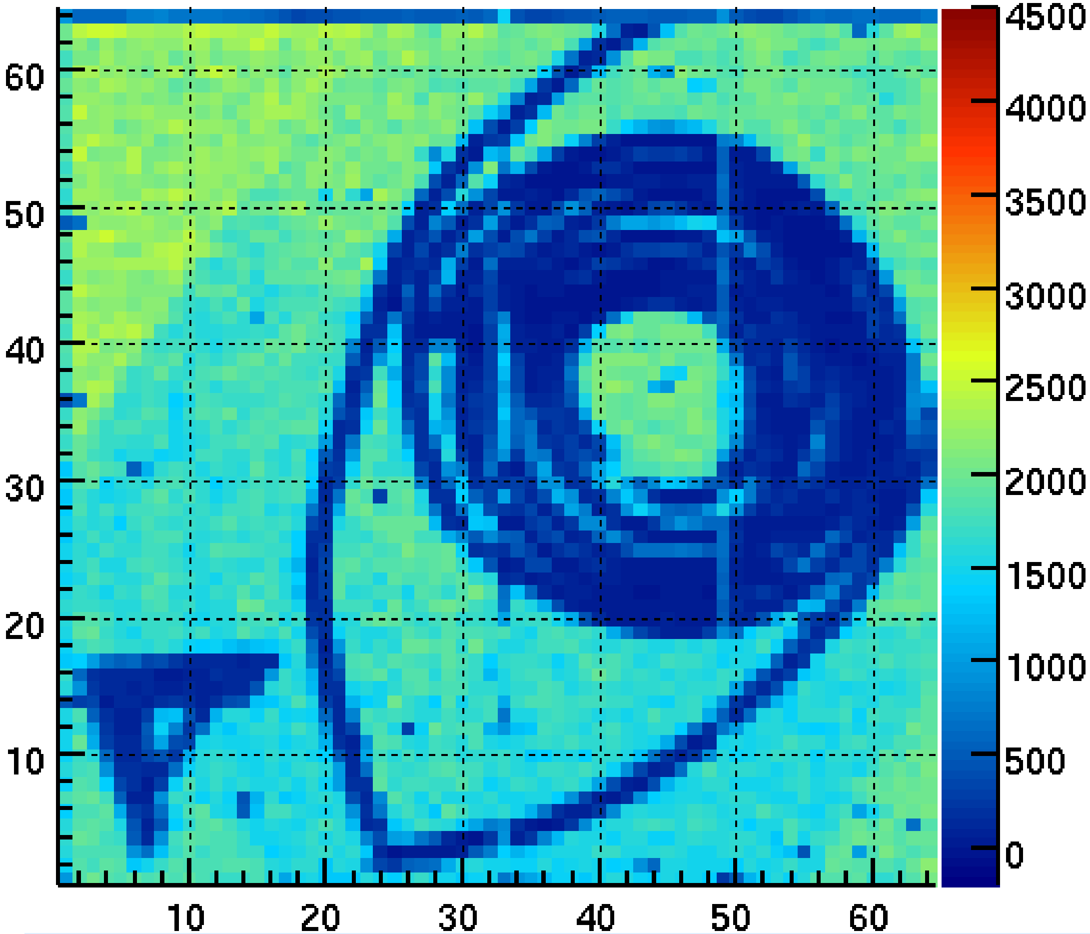


- Concept common for 1D and 2D
- Much more challenging for 2D

AGIPD02 – First Image



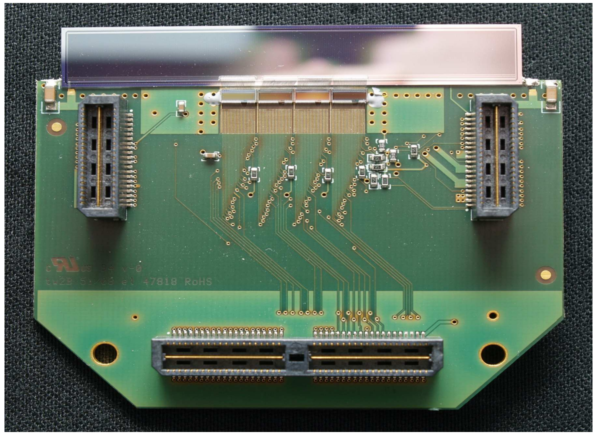
AGIPD



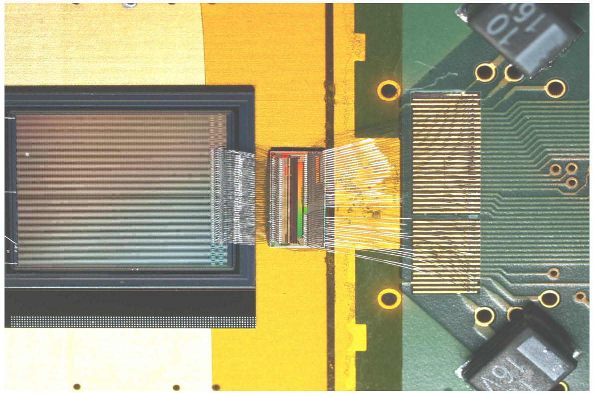
- •Noise ~300e-
- •Dynamic range ~10^4 photons @12keV
- •Frame rate not yet there, ok for full detector prototyping

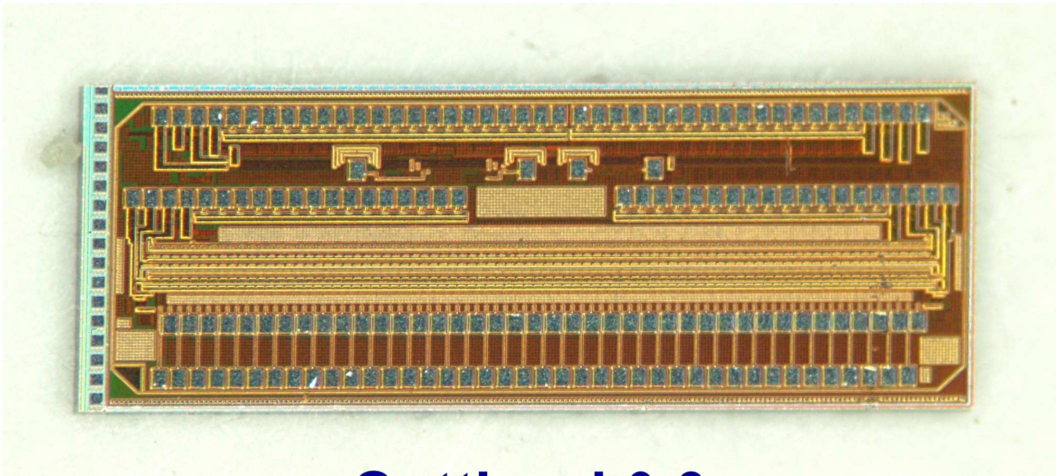
GOTTHARD (Aldo Mozzanica)

Gotthard 0.1



Gotthard 0.2

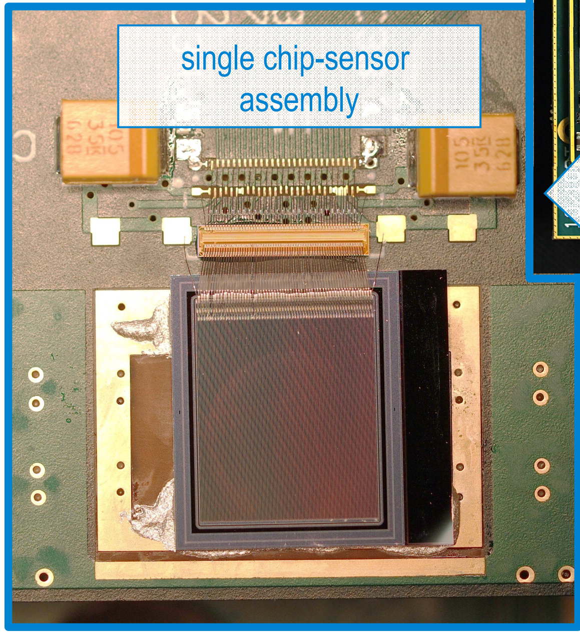


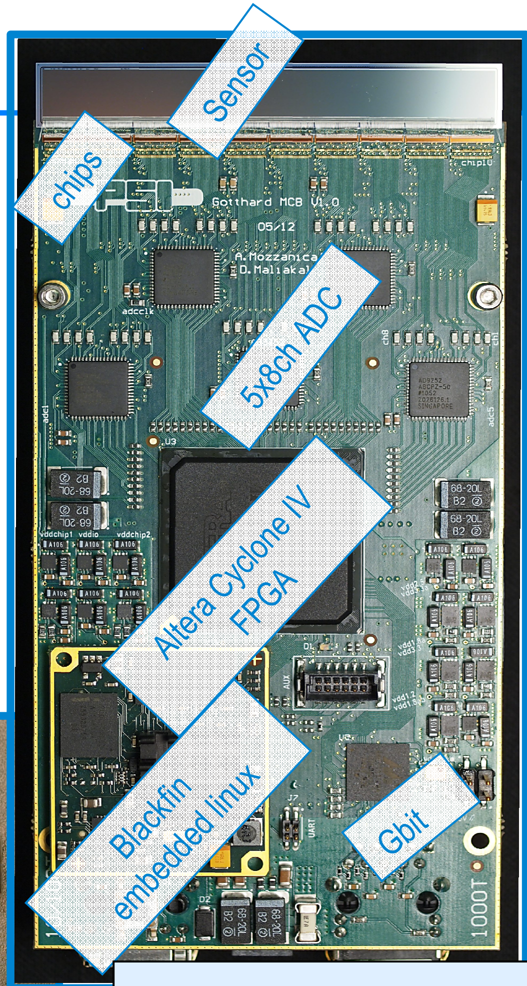


Gotthard 0.3

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 (130nm IBM), shared engineering run foreseen



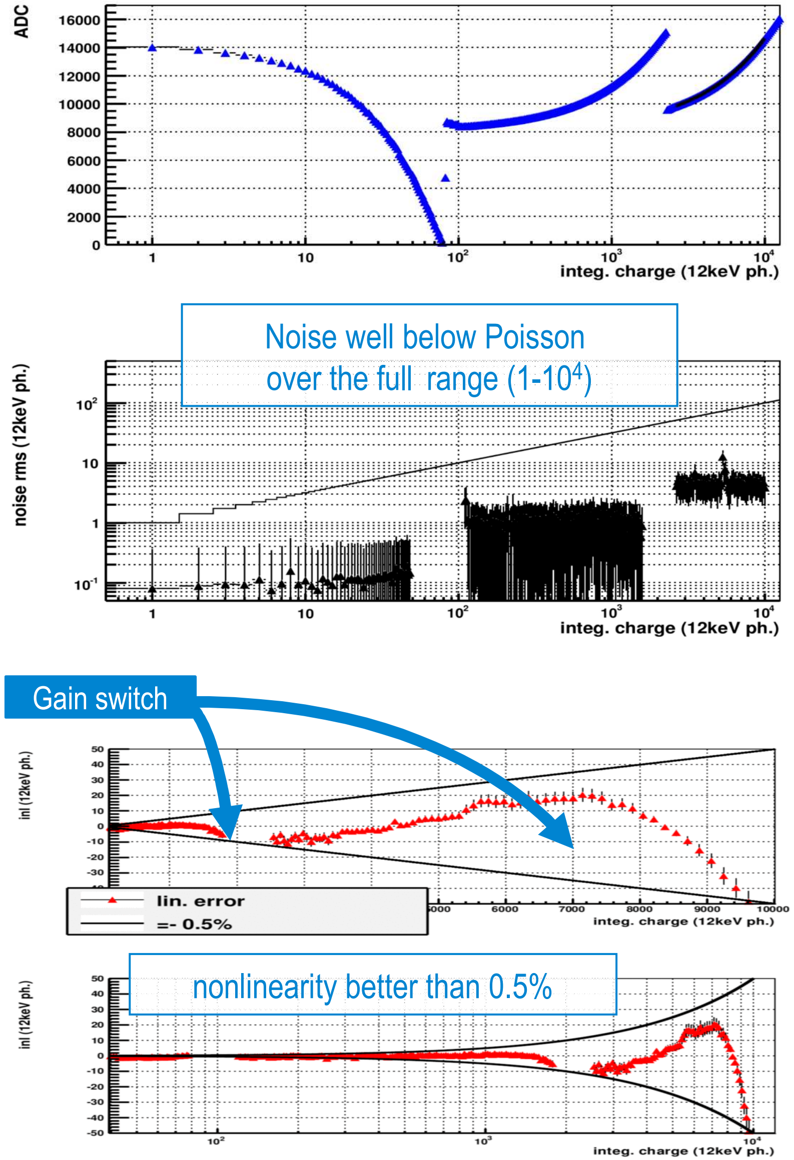


FULLY EQUIPPED MODULE

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

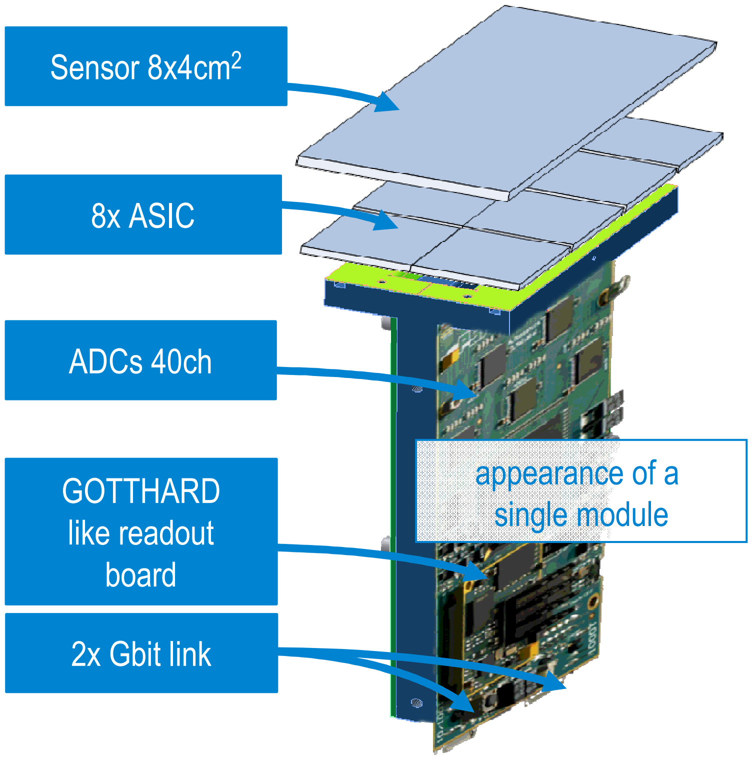
Noise (ENC), gain1: 260e$^-$ rms

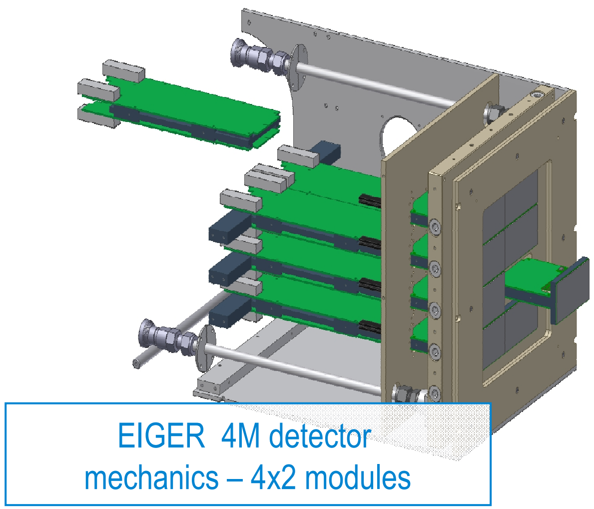


JUNGFRAU

• **SwissFel** will have a much simpler bunch structure: 1 single bunch with a repetition rate of 100Hz, the detector can be read out in the interbunch time (no on-chip storage needed)

ASIC technology	UMC110nm
mudule pixel count	525k
mudule size	80x40 mm^2
sensor thickness	320-500 μm
pixel size	75x75 mm^2
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

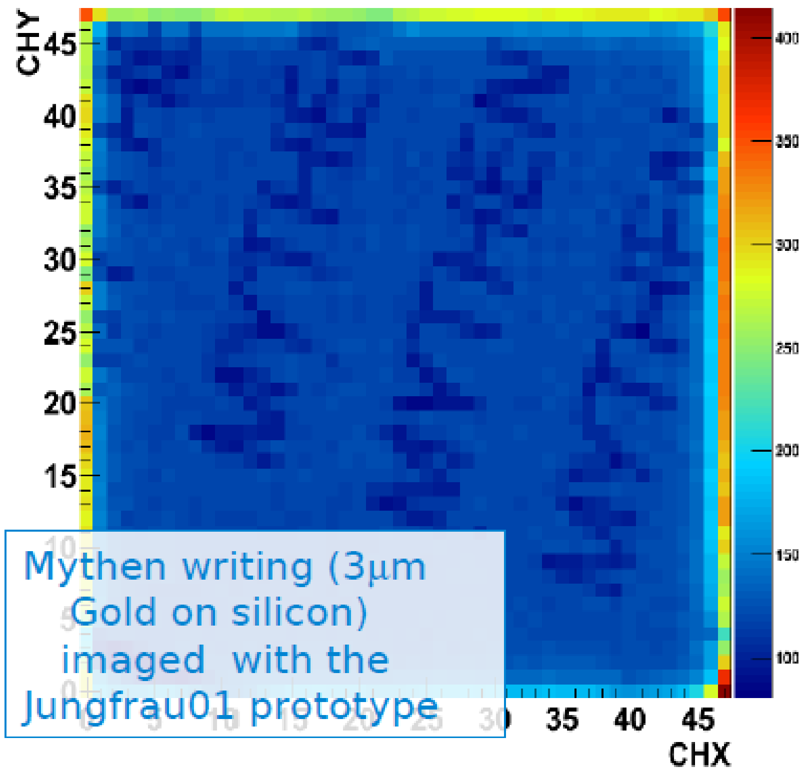




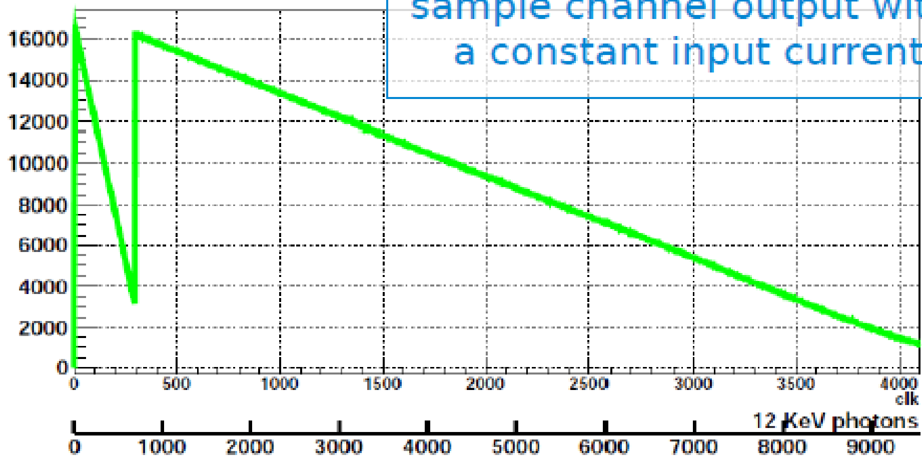
• ASIC and readout system based on GOTTHARD

•Dimensions, sensor and mechanics from EIGER

Jungfrau0.1

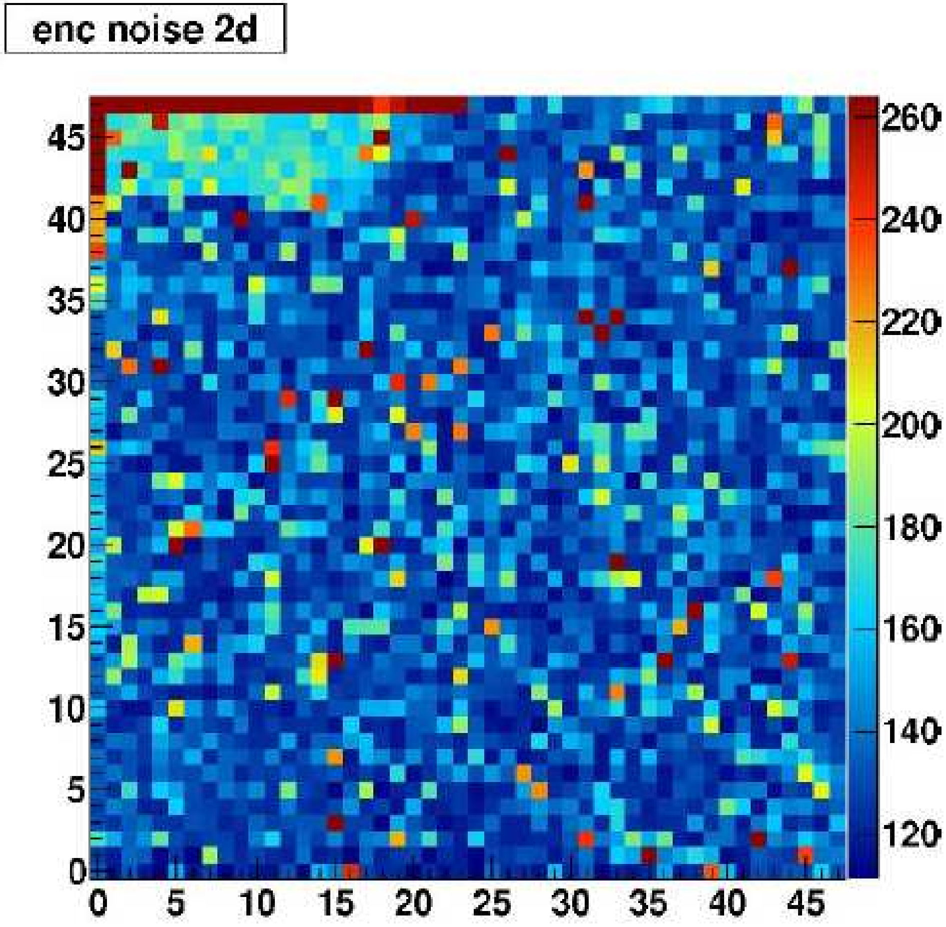


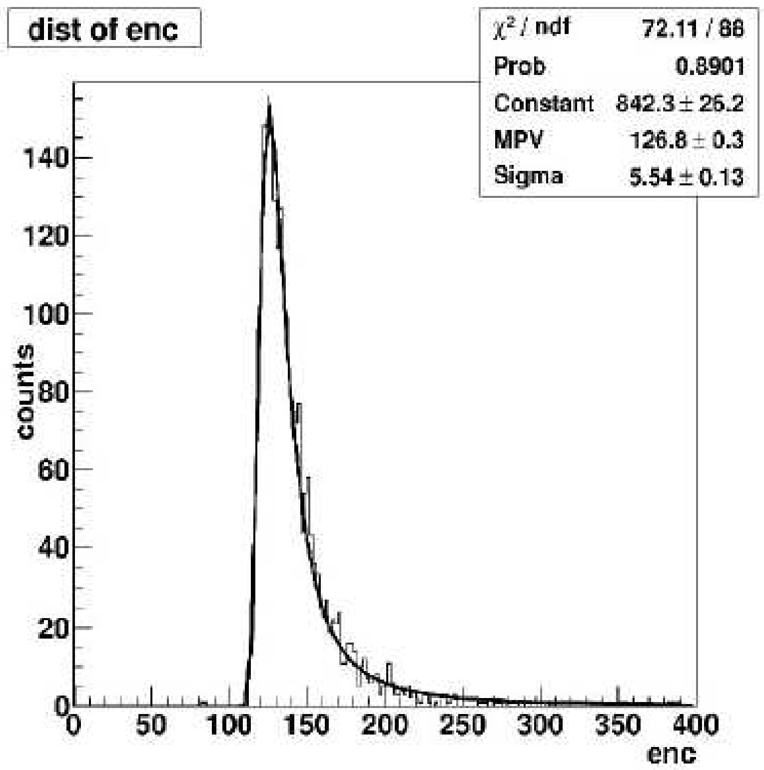
Mythen writing (3μm Gold on silicon) imaged with the Jungfrau01 prototype



sample channel output with a constant input current

Jungfrau0.1





Preliminary results with JUNGFRAU02: Better but not yet solved.

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MÖNCH

AGIPD
GOTTHARD
JUNGFRAU

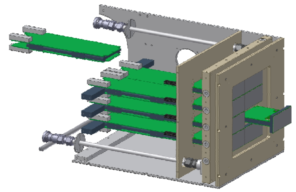
Experience in charge integration

Many design blocks ready

- **Still in a very early stage**
- **Much smaller pixels (25-35µm)**
- **Main challenges:**
  - **Very small pixel area**
  - **Long integration time (leakage currents)**

MÖNCH
charge integration
2D detector
for synchrotron
Radiation (&FEL?)

MÖNCH motivation



LOOKS WRONG… ☹

MÖNCH motivation

3970 m **4107 m** **4158 m**

MUCH BETTER NOW ☺

Why charge integration at fine pixel pitch?

Pros:

- Both XFELS and synchrotrons
- Higher photon flux
- Can still work with high charge sharing
    + Charge sharing can improve resolution (“***low flux”*** only)

-> very small pixels are feasible!

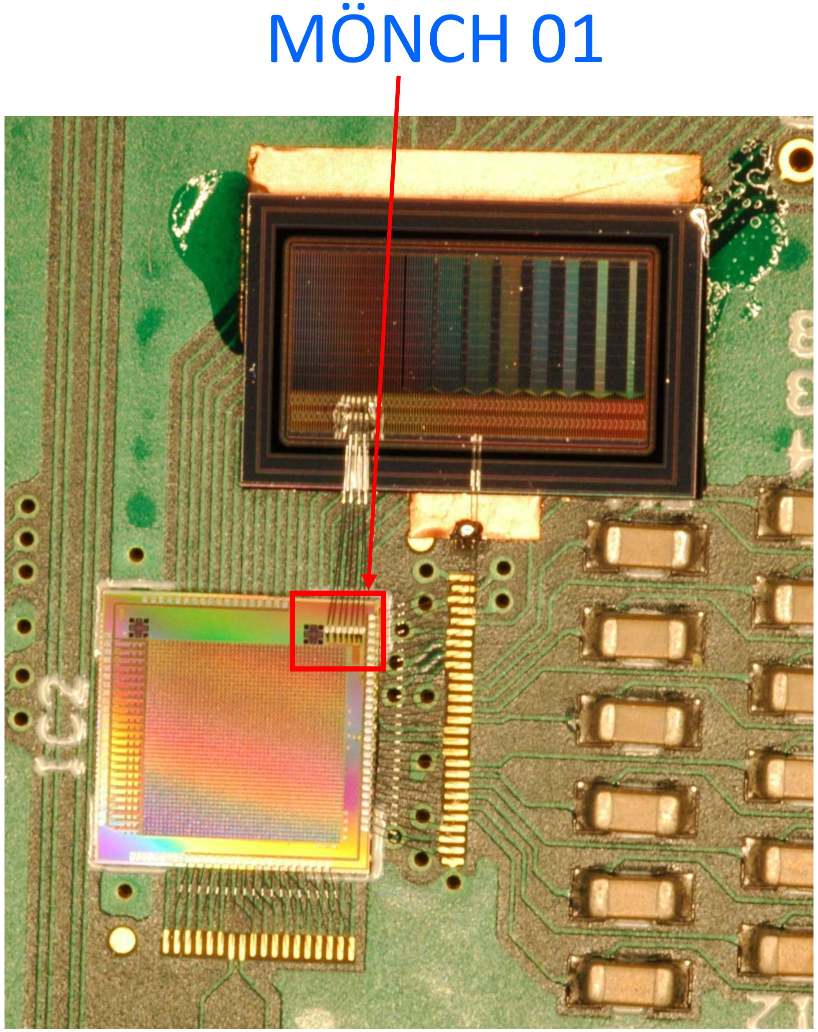
- Energy information (“***low flux”*** only)
- Lower energies (~keV) accessible

Cons:

- In “***low flux***”: 1 photon/image per cluster of 4-9 pixels
- Leakage current challenge
- Bump-bonding swamp
- Calibration nightmare
- Data throughput/storage/analysis hell

MÖNCH prototypes

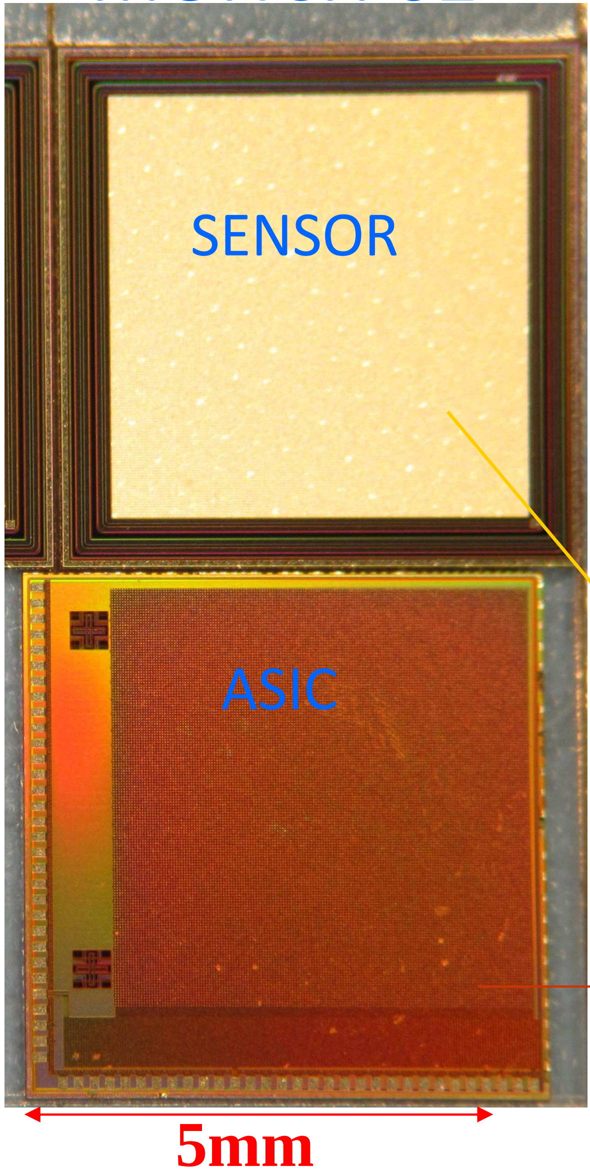
- UMC 110nm AE (Al only)



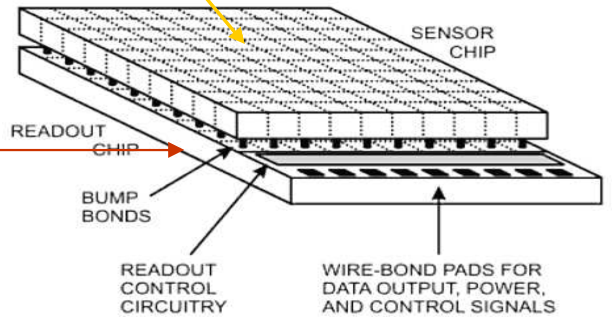
- "Guest" of Jungfrau01 MPW
- Seven single pixel channels
- No layout optimization
- No dynamic gain switching
- Wirebonded to a strip detector for calibration

MÖNCH prototypes

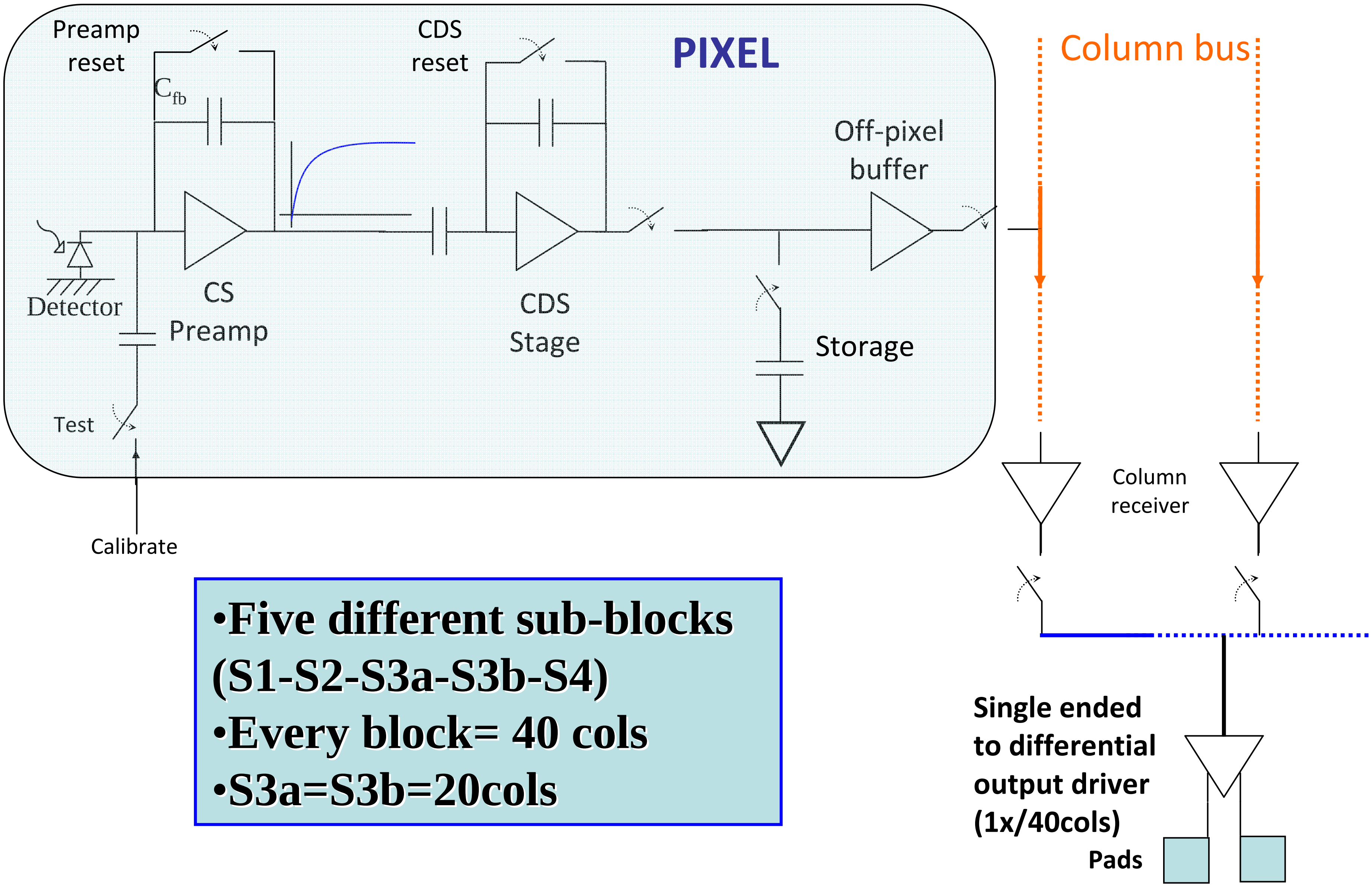
MÖNCH 02



- Complete hybrid pixel detector
- Active area:4x4 mm^2
- 160x160 pixels
- 25x25 μm^2 pixel
- Big layout optimization effort
- High testability

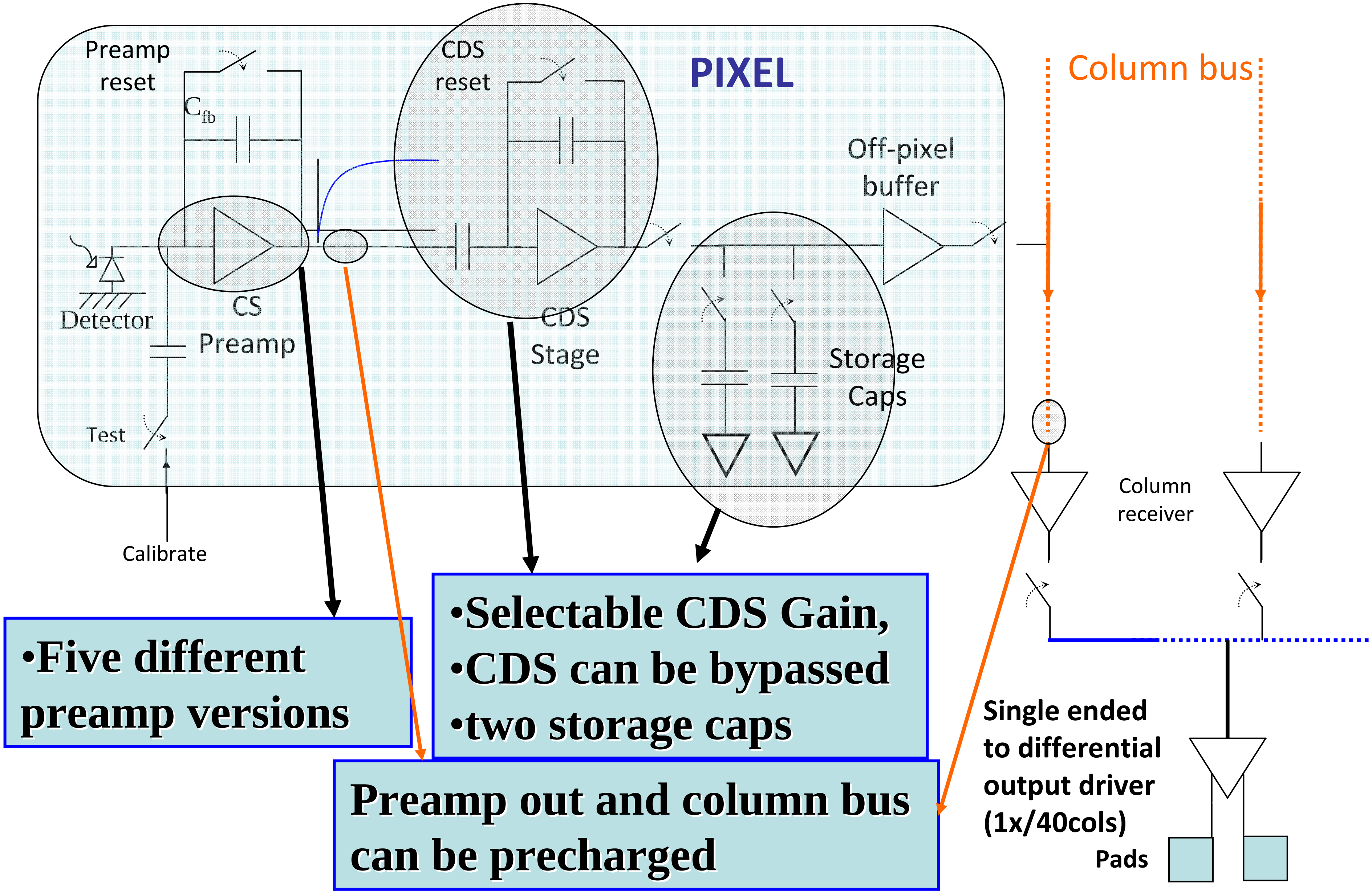


Basic working principle



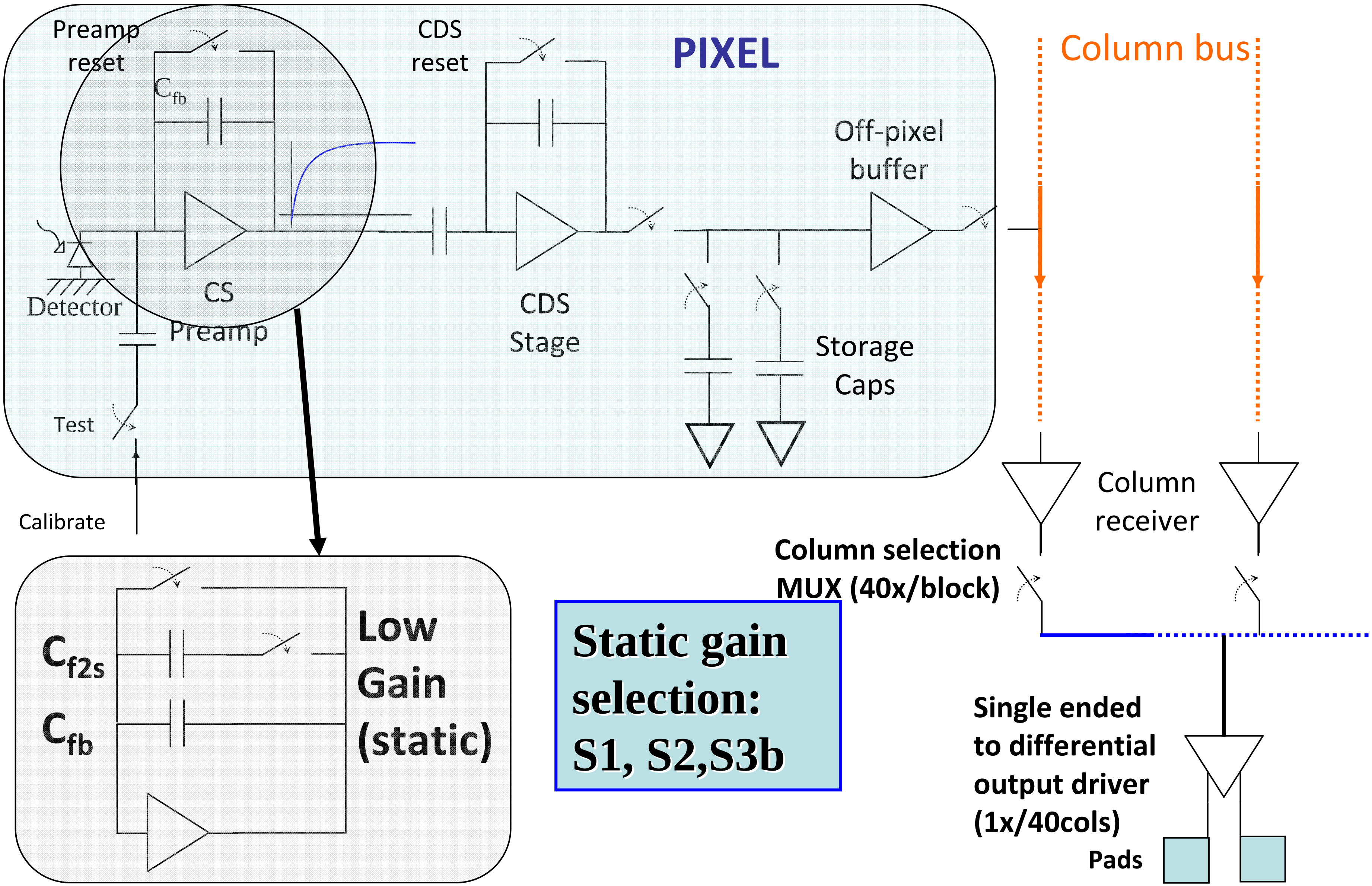
- **Five different sub-blocks (S1-S2-S3a-S3b-S4)**
- **Every block= 40 cols**
- **S3a=S3b=20cols**

Variations



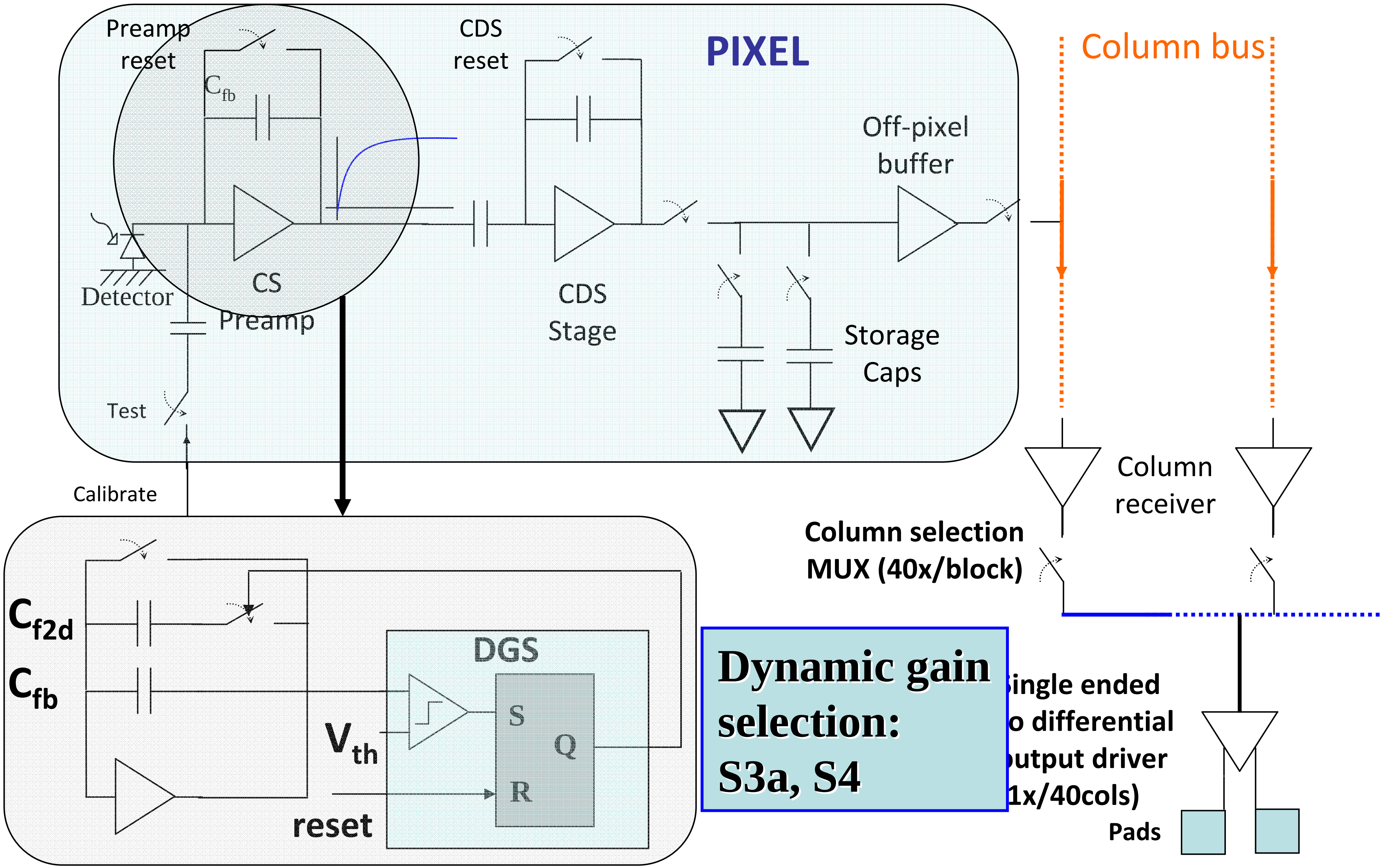
Preamp reset
C_{fb}
CDS reset
PIXEL
Column bus
Off-pixel buffer
Detector
CS Preamp
CDS Stage
Storage Caps
Test
Calibrate
Column receiver
•Five different preamp versions
•Selectable CDS Gain,
•CDS can be bypassed
•two storage caps
Preamp out and column bus can be precharged
Single ended to differential output driver (1x/40cols)
Pads

Variations



Static gain selection: S1, S2,S3b

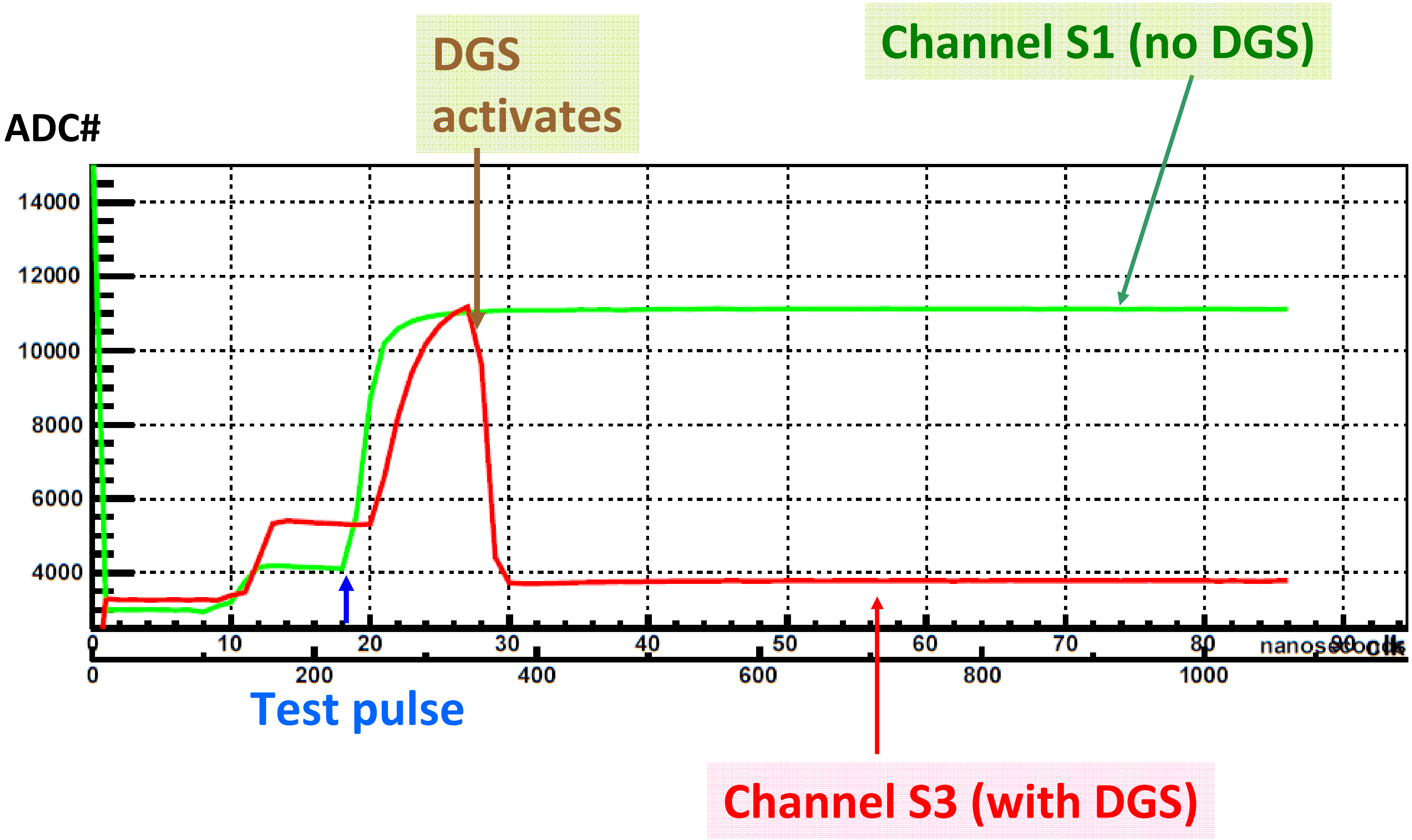
Variations


Preamp
reset
C_{fb}
CDS
reset
PIXEL
Column bus
Off-pixel
buffer
Detector
CS
Preamp
CDS
Stage
Storage
Caps
Test
Calibrate
Column
receiver
Column selection
MUX (40x/block)
C_{f2d}
C_{fb}
DGS
S
Q
R
V_{th}
reset
Dynamic gain
selection:
S3a, S4
ingle ended
o differential
utput driver
1x/40cols)
Pads

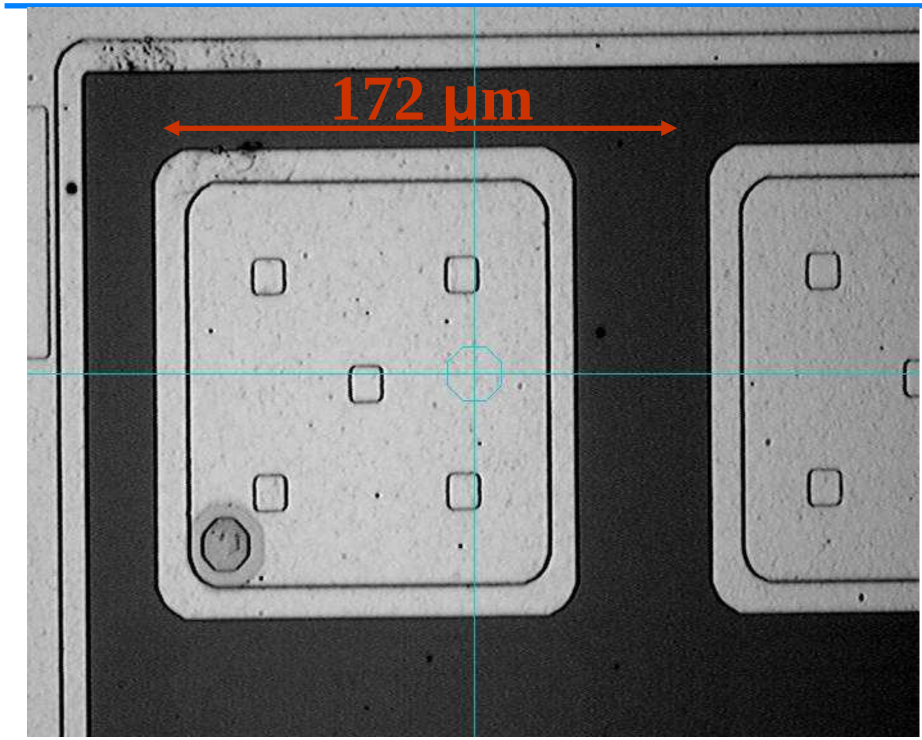
Main test results

Main test results:
PRELIMINARY!

Dynamic Gain Switching functionality

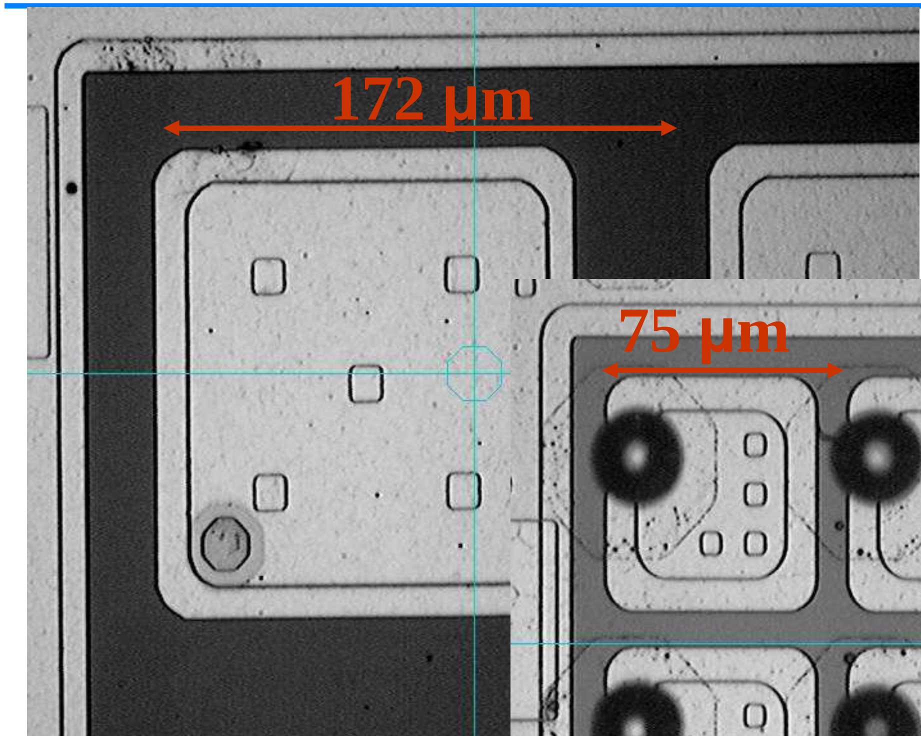


Fine pitch bump-bonding

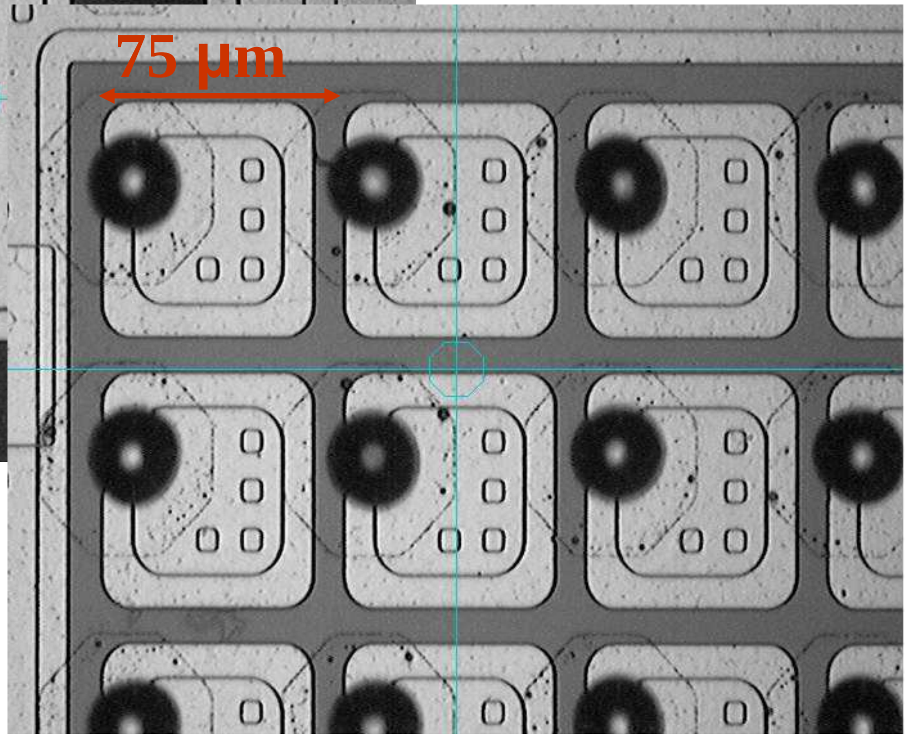


PILATUS

Fine pitch bump-bonding

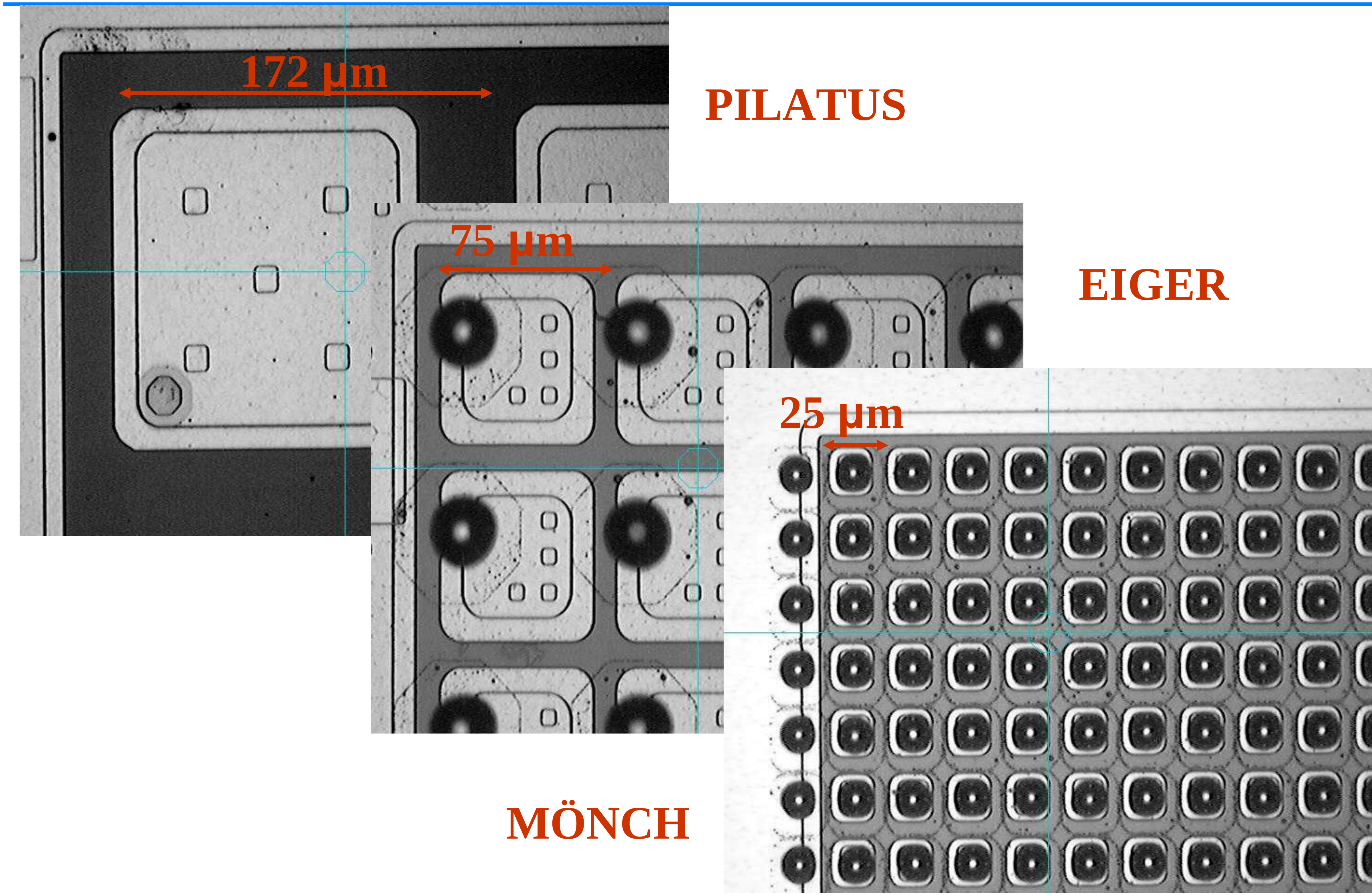


PILATUS



EIGER

Fine pitch bump-bonding

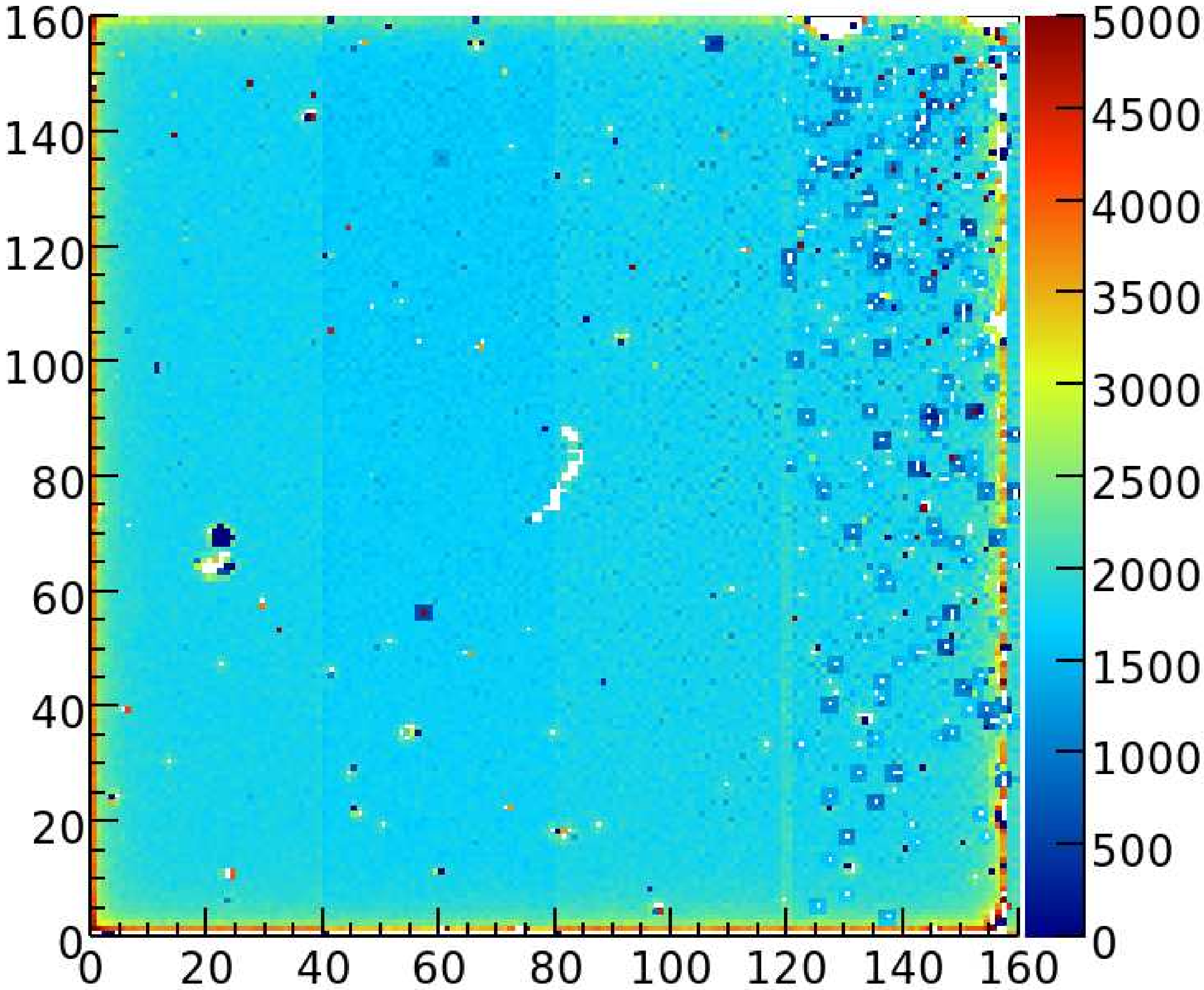


PILATUS

EIGER

MÖNCH

Bad pixels map



- **Yield: ~97%**
- **Very first prototypes**
- **Single chip processing**
- **Low tolerance with UBM masks**
- **Alignment precision**

**** Big improvement possible ****
(… and new bump-bonder coming soon..)

First images

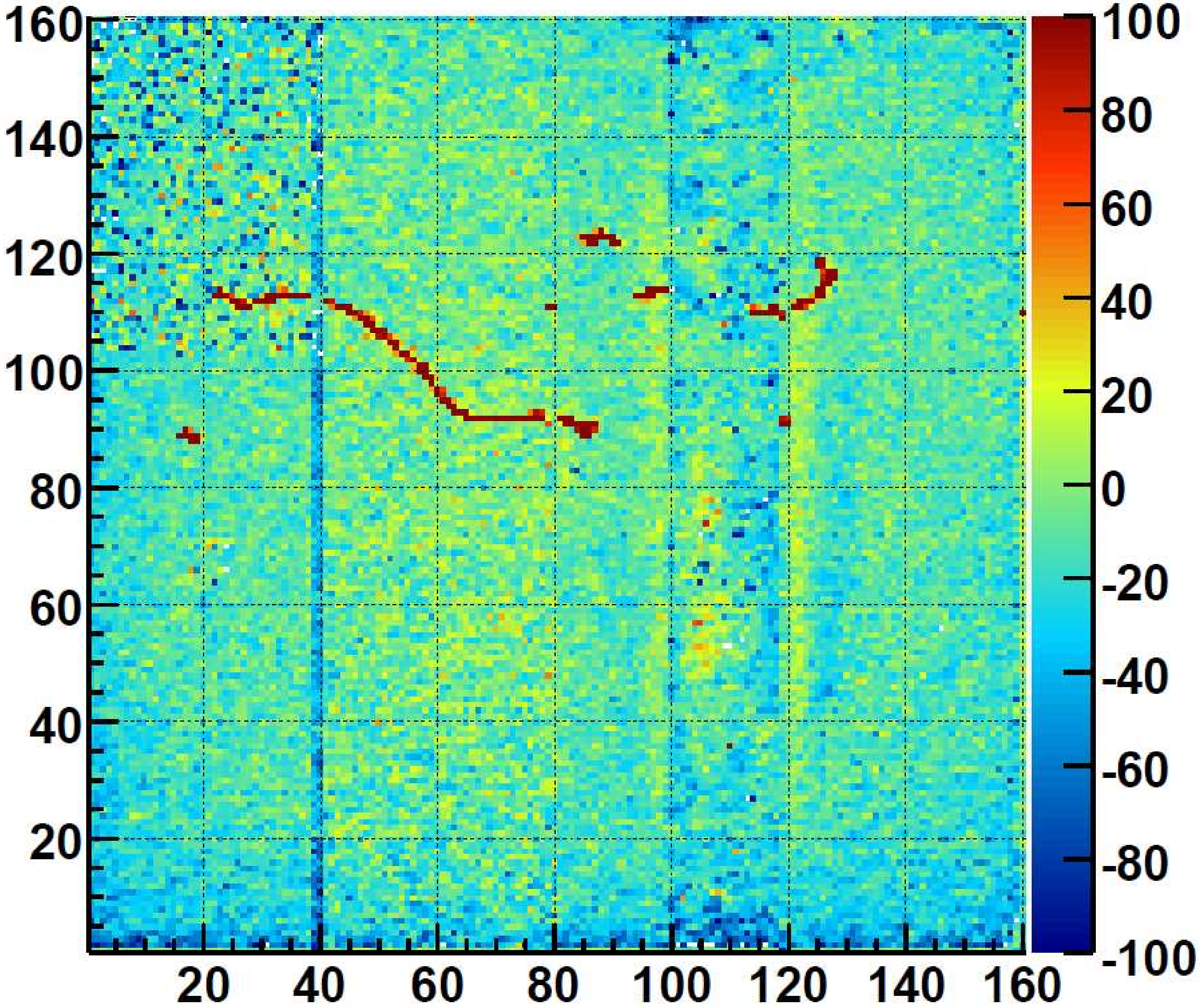
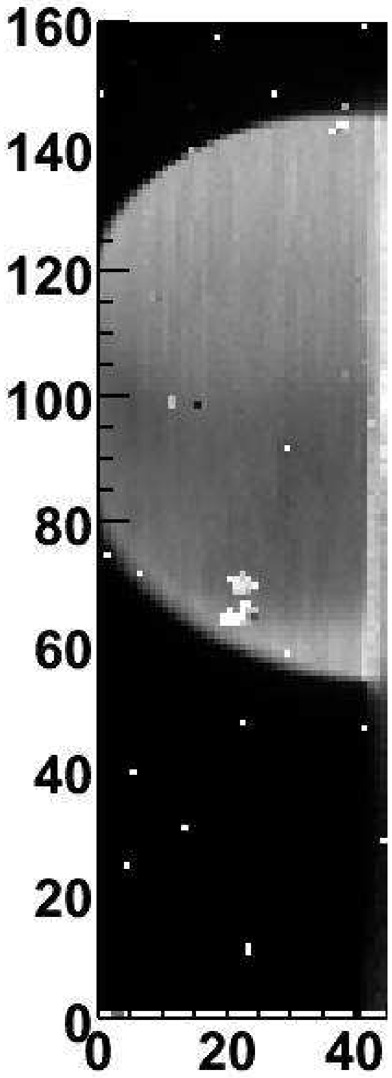


Image taken with a ^{90}Sr radioactive source.
=>All blocks are functional.

Imaging tests (S1 only)

METAL RING

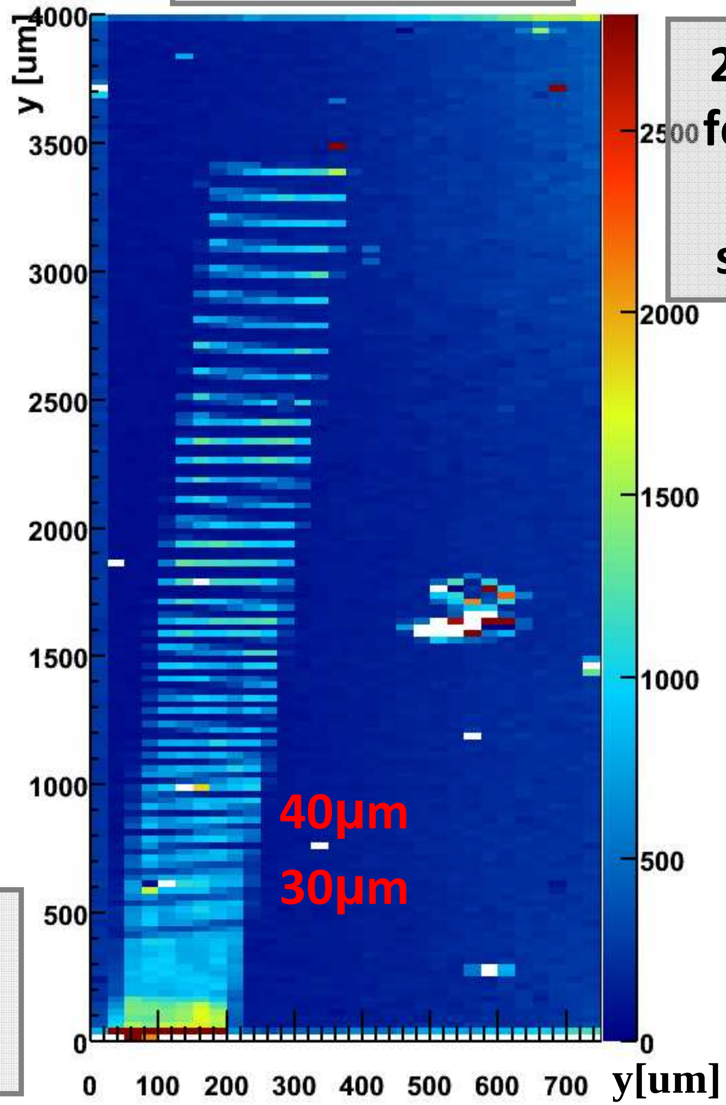


Fish egg(??)

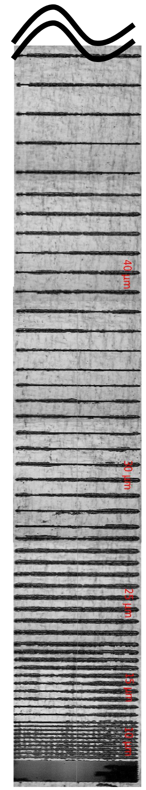
Metal ring

Frame rate: 400Hz

W SLITS



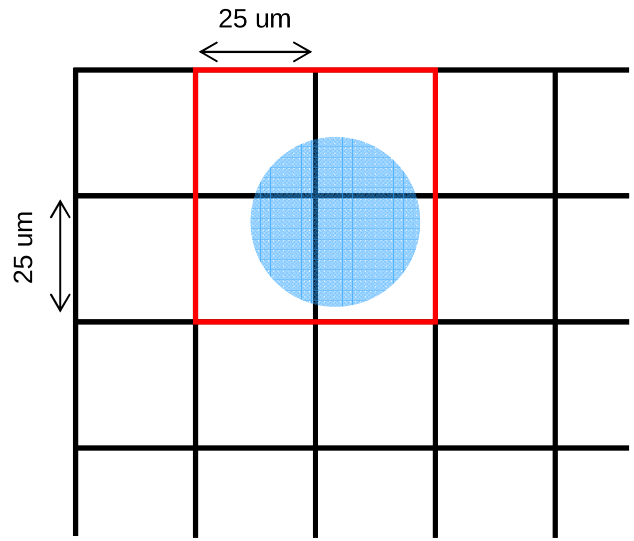
25 um thick W foil and groups of 2µm wide slits at 12 keV



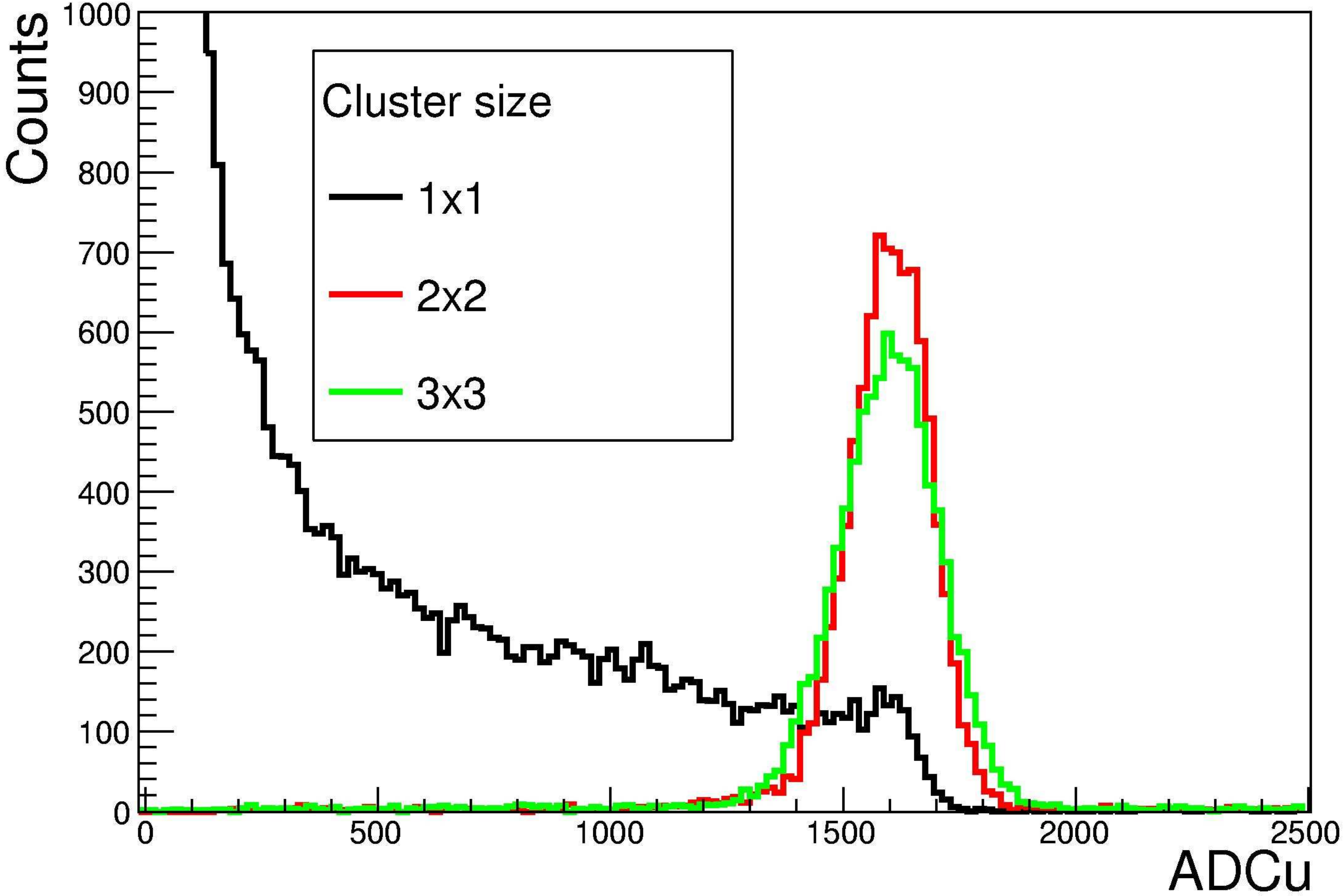
Finding hits

Charge spread over multiple pixels
due to diffusion (charge sharing)

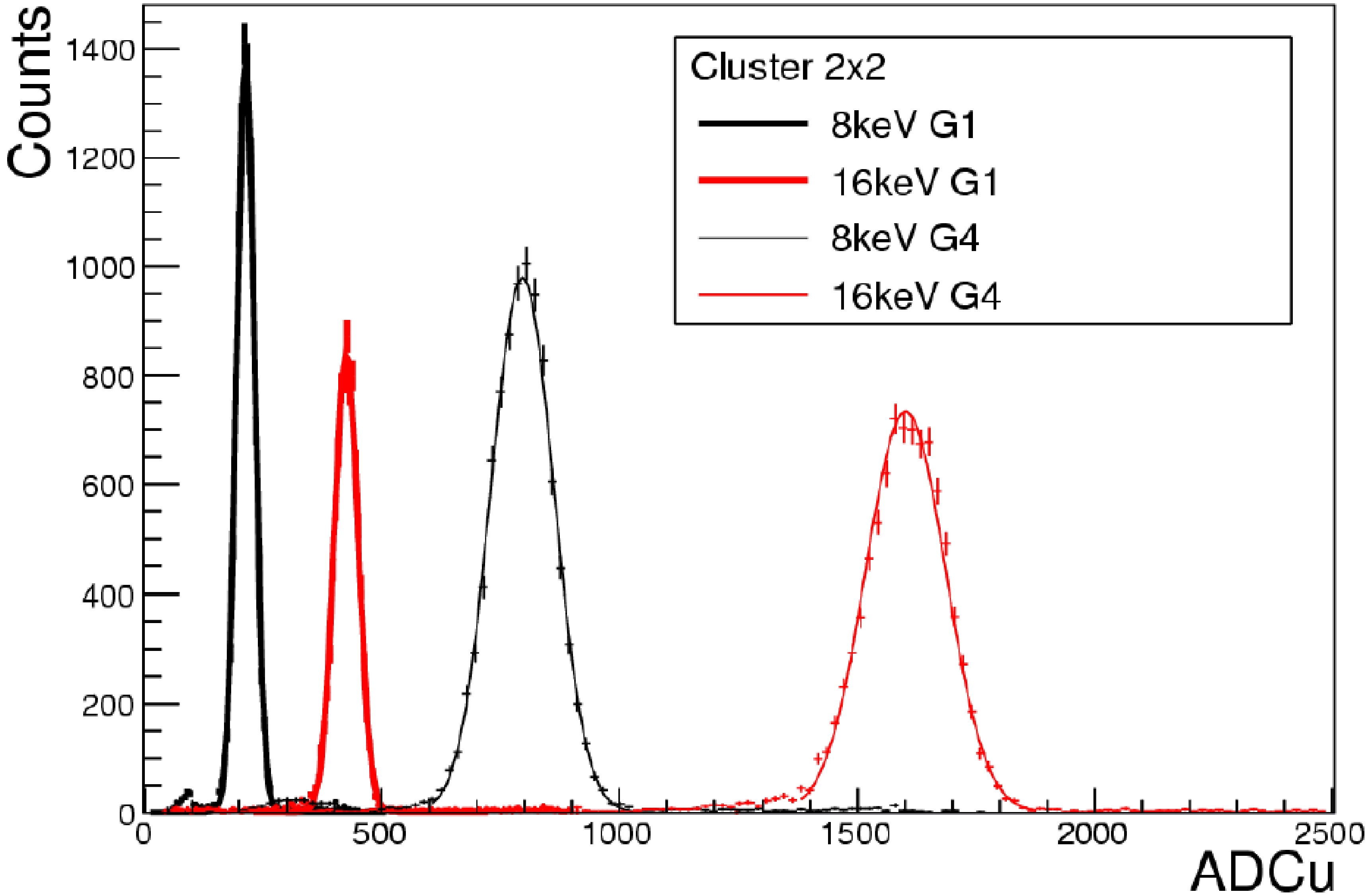
Charge distribution: 2d gauss
If the total signal of a cluster is above
noise floor → hit detected



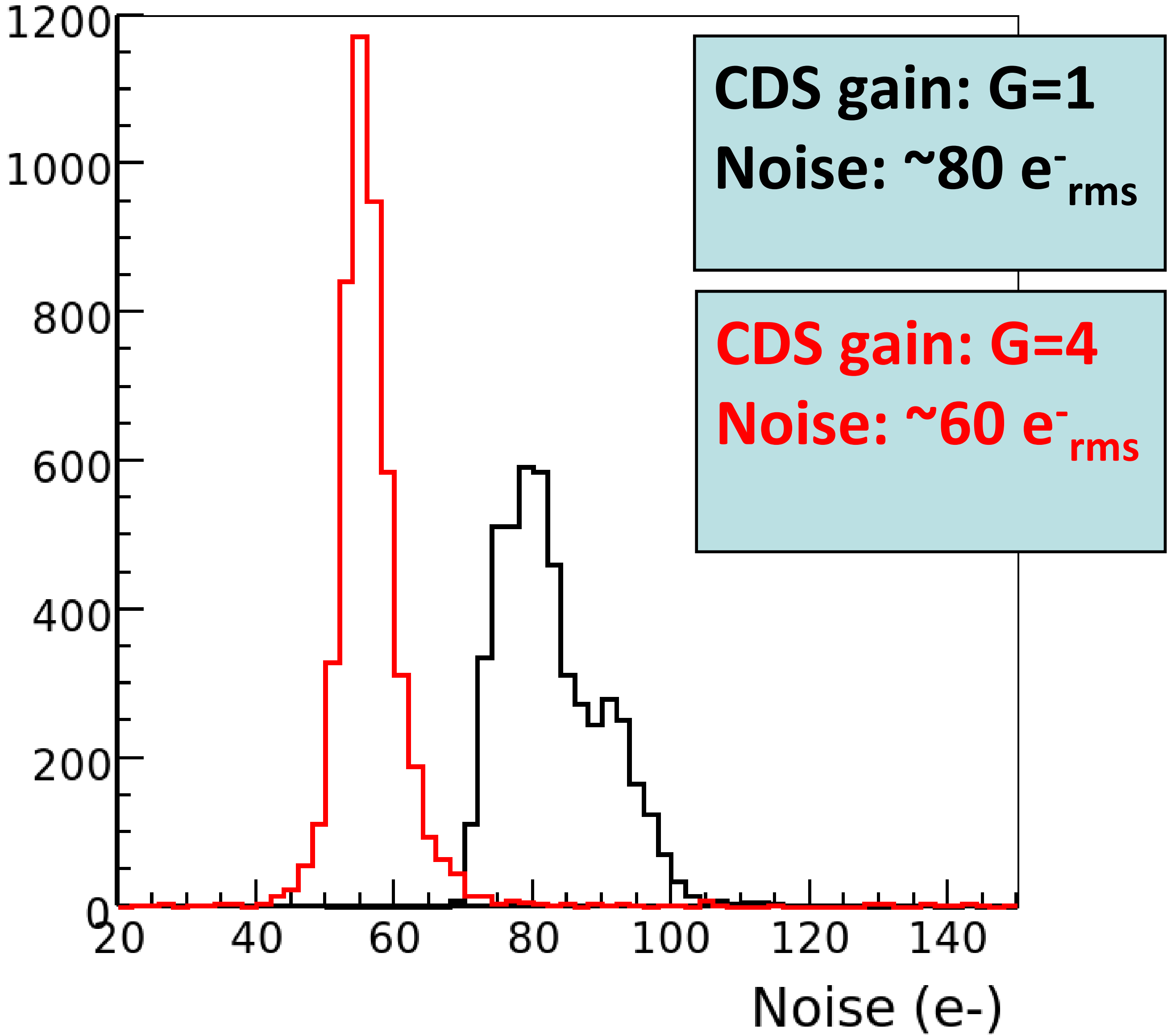
Impact of cluster size



Calibration



Main test results



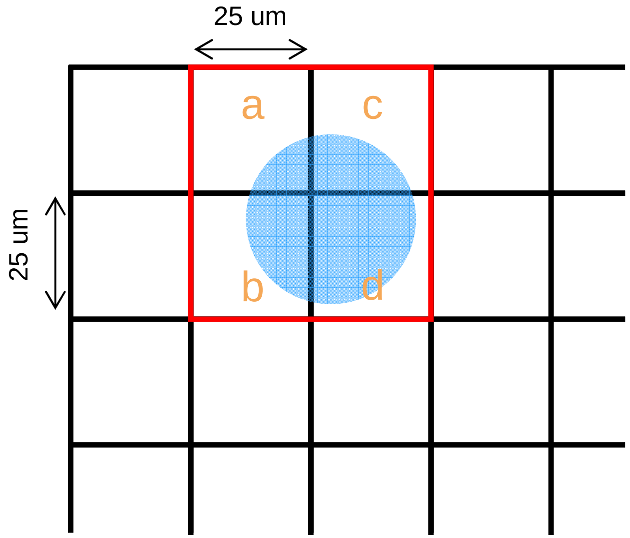
- **Block: S1**
- **Preamp gain:** ***static HIGH***

Interpolation in 2d

Linear position reconstruction

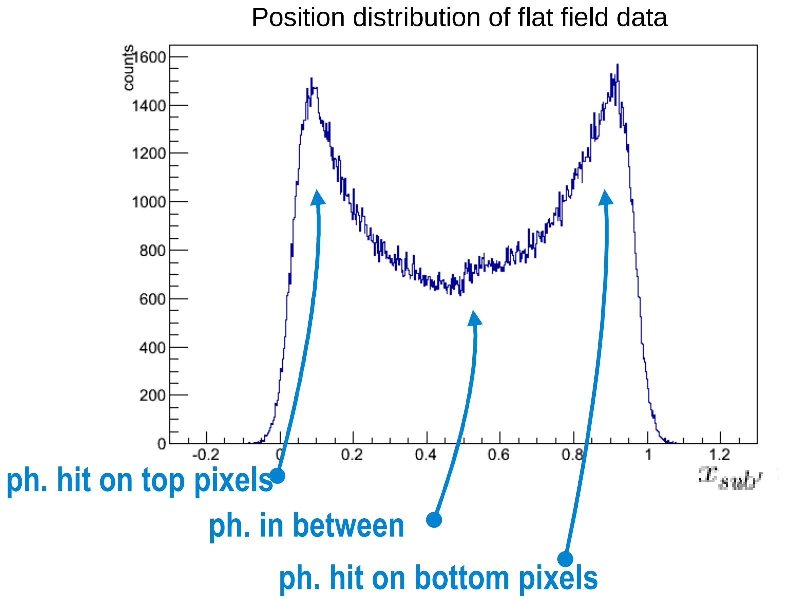
$$x_{sub'} = \frac{a+b}{a+b+c+d}$$

$$y_{sub'} = \frac{a+c}{a+b+c+d}$$

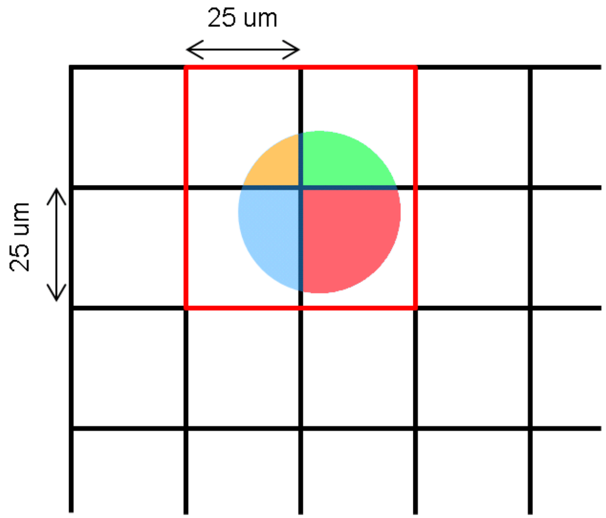


Eta algorithm

$$x_{sub} = \frac{\sum_{n=-\infty}^{x_{sub'}} counts(n)}{tot.counts}$$



Circle area approach

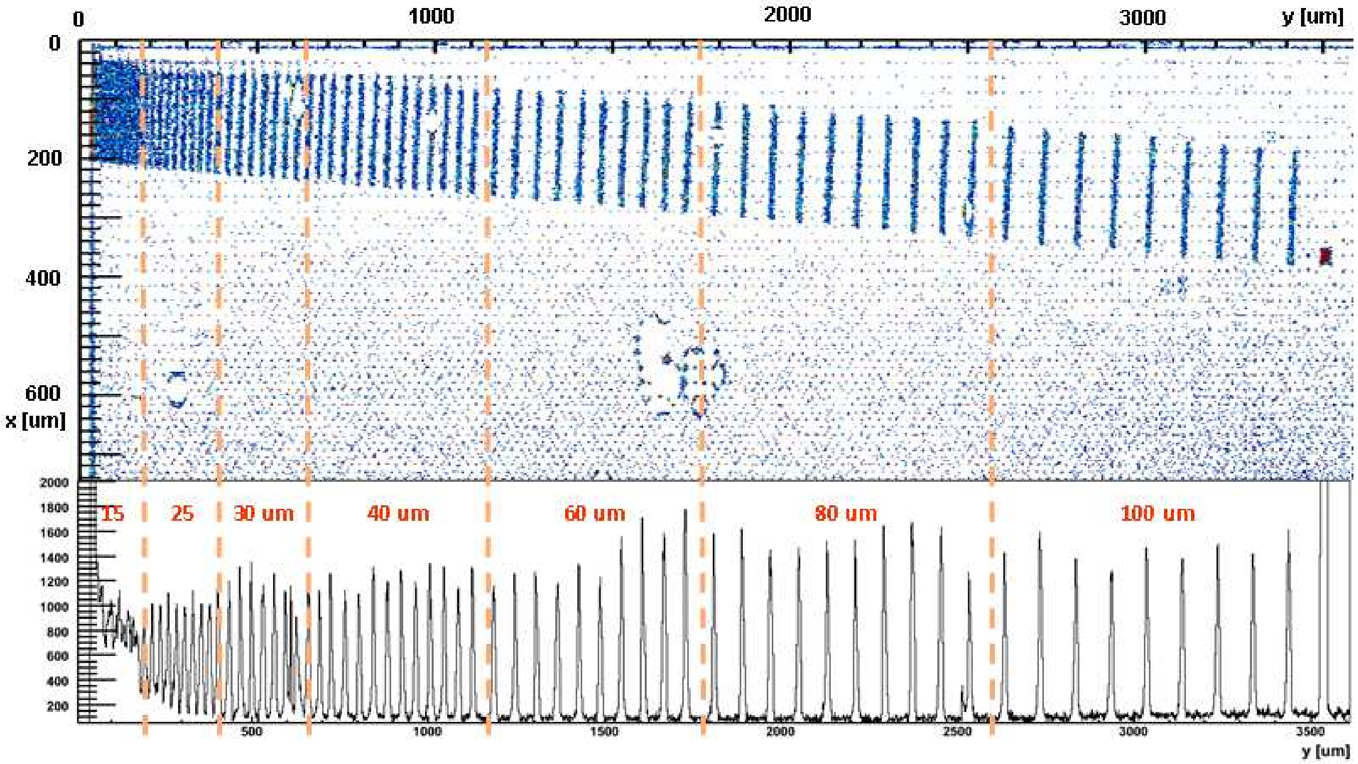


Linear Interpolation in 2d

It works

It gives a high contrast down to 12 um

With interpolation (1 um² bin size):

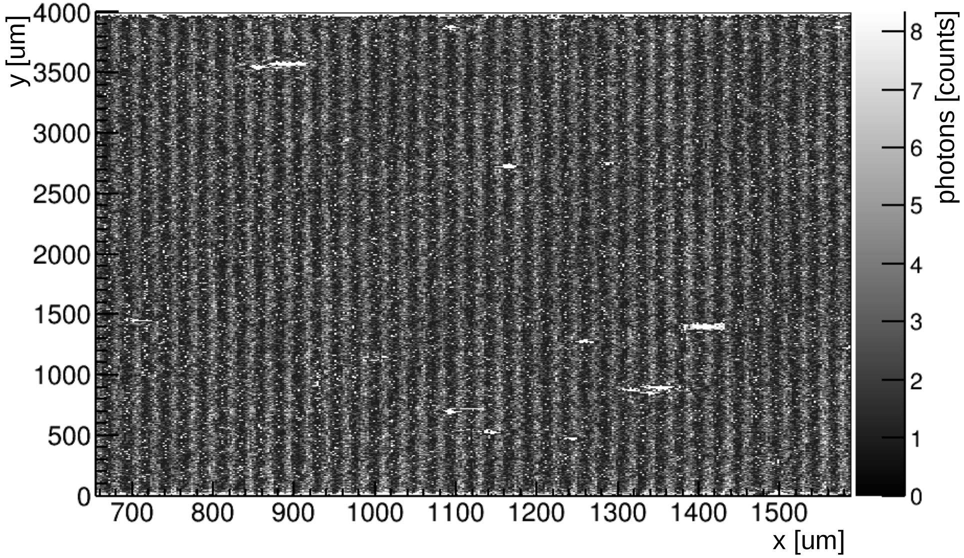


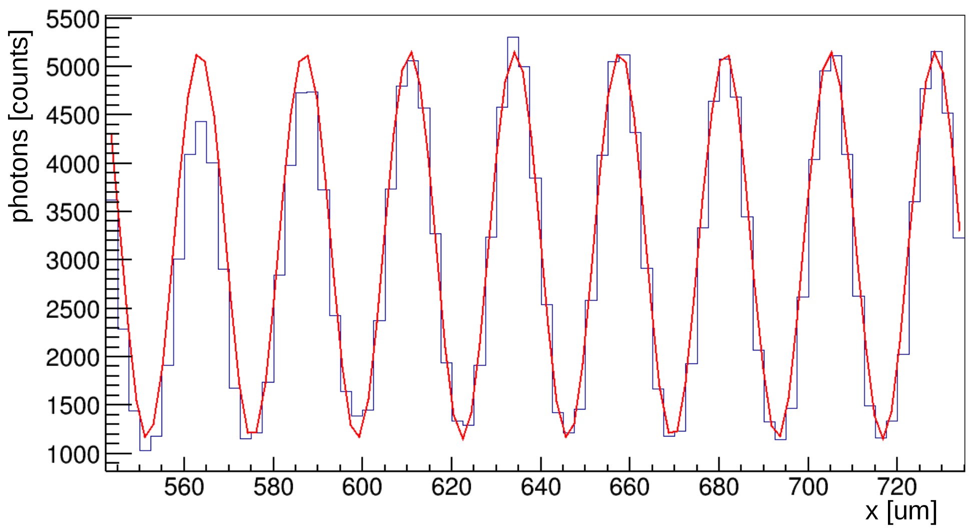
Results: Gold Grating

Period: 24.266 um (23.571 um measured)

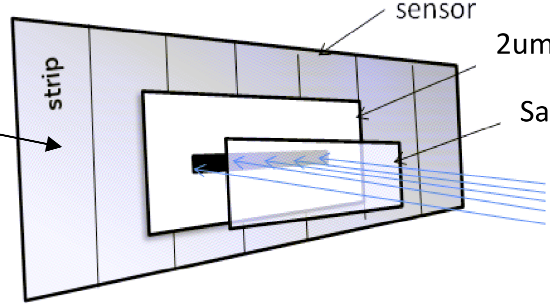
Gold: 50 um thick (Absorption at 15keV ~100 %)

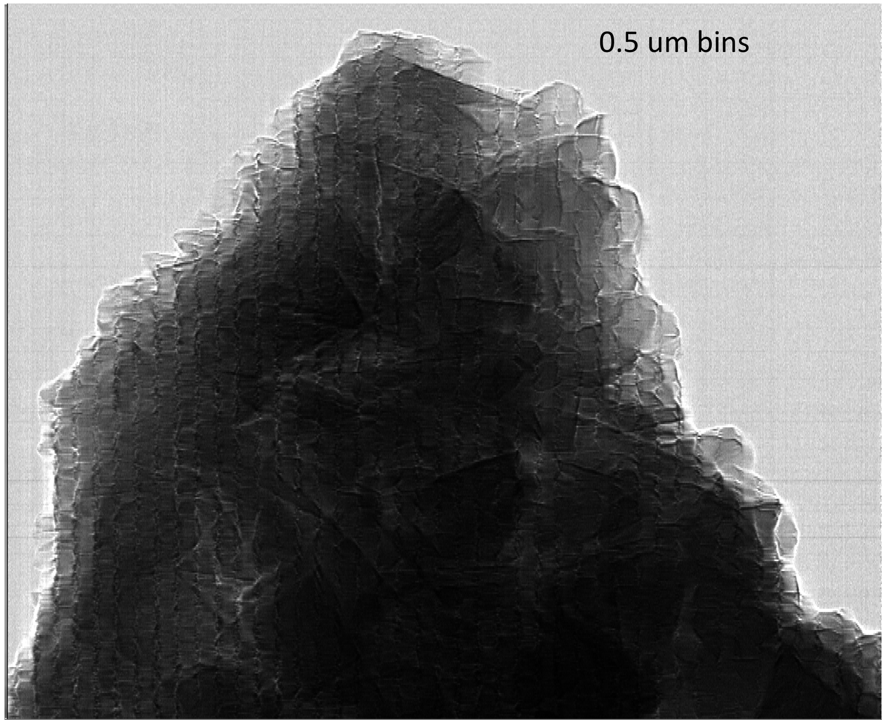
Contrast difference: 78 %





Results: Kidney Stone

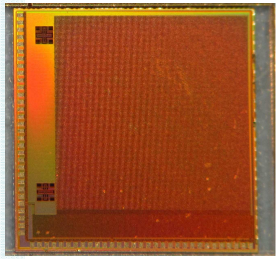




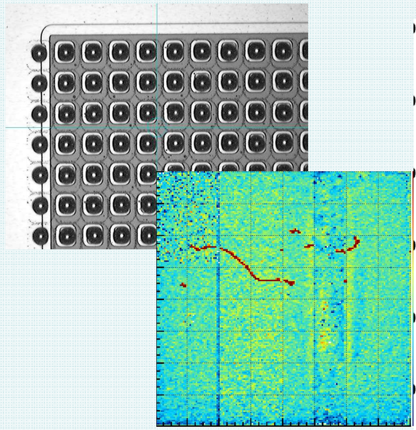
20um pitch, 15keV beam

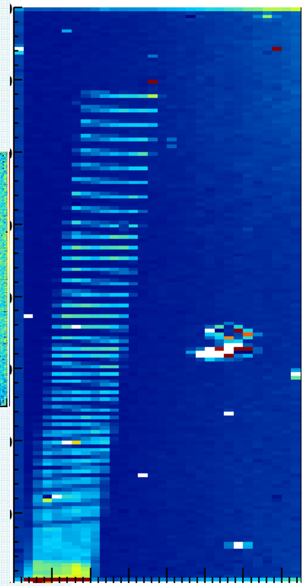
Conclusions

- At PSI we are developing several new detectors based on charge integration and analog readout: GOTTHARD (1D); AGIPD,JUNGFRAU,MÖNCH (2D)



- MÖNCH is intended to investigate the limits of hybrid pixel detectors for X-ray detection.
- MONCH02 is a full chip containing an array of 160x160 pixels with pitch of 25µm. It contains several sub-blocks featuring different pixel archit.





- Preliminary results are encouraging:
    - We can bump-bond at 25 µm pitch
    - All blocks are functional
    - We can resolve small features
    - Noise is ~60 e^{-}_{rms}

A LOT still to be done: we are just at the beginning…

PAUL SCHERRER INSTITUT PSI

ACKNOWLEDGMENTS

SWISS LIGHT SOURCE SLS

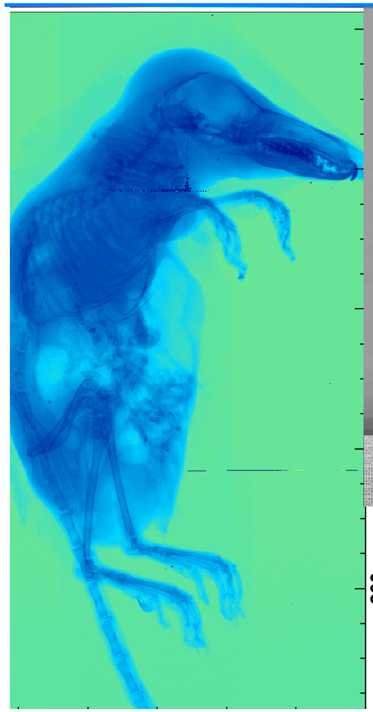
Many thanks to:

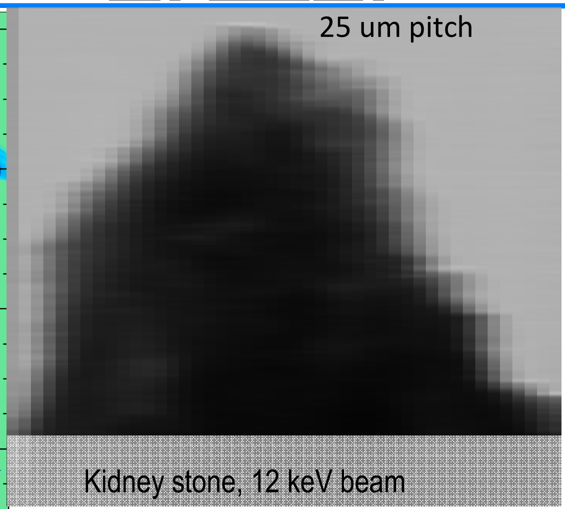
Anna Bergamaschi, Heiner Billich, Beat Henrich, Dominic Greiffenberg, Roland Horisberger, Ian Johnson, Dhanya Maliakal, Beat Meier, Aldo Mozzanica, Peter Oberta, Lukas Schaedler, Nick Schlumpf, Elmar Schmid, Bernd Schmitt, Xintian Shi, Akos Schreiber, Anja Schubert, Silvan Streuli, Dominic Suter, Valeria Radicci, Gerd Theidel.

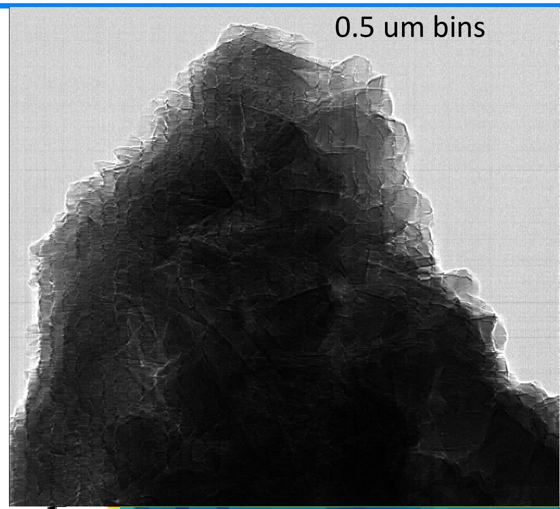
ESRF

Not in the picture:
Julia Jungmann,
Davide Mezza

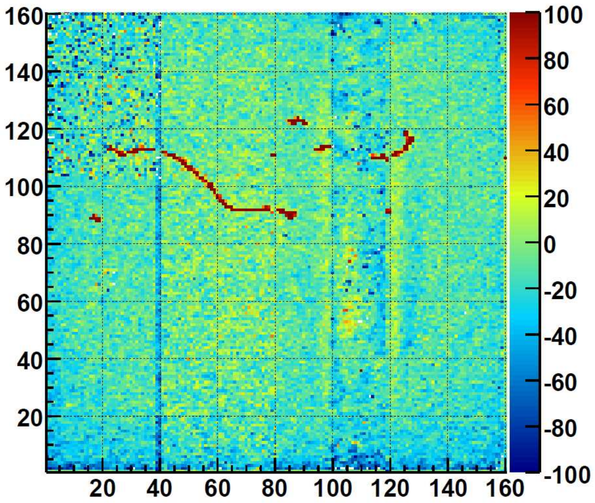
PAUL SCHERRER INSTITUT PSI — SWISS LIGHT SOURCE SLS — *NUM/LTP ETHZ* — ESRF

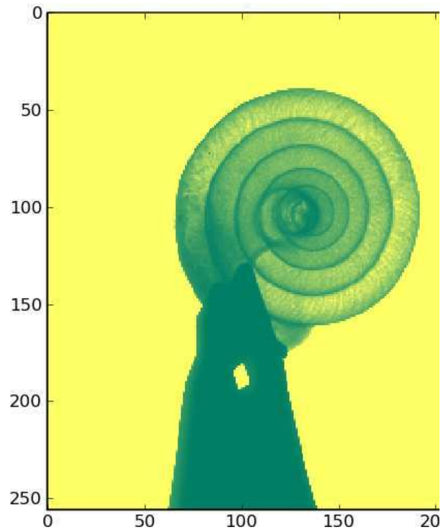


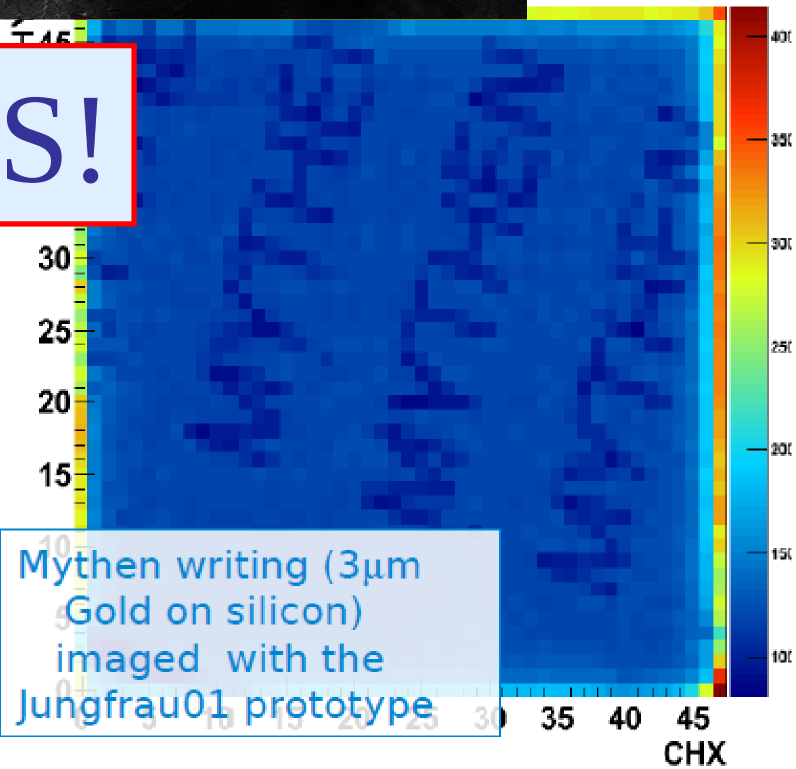




THANKS!

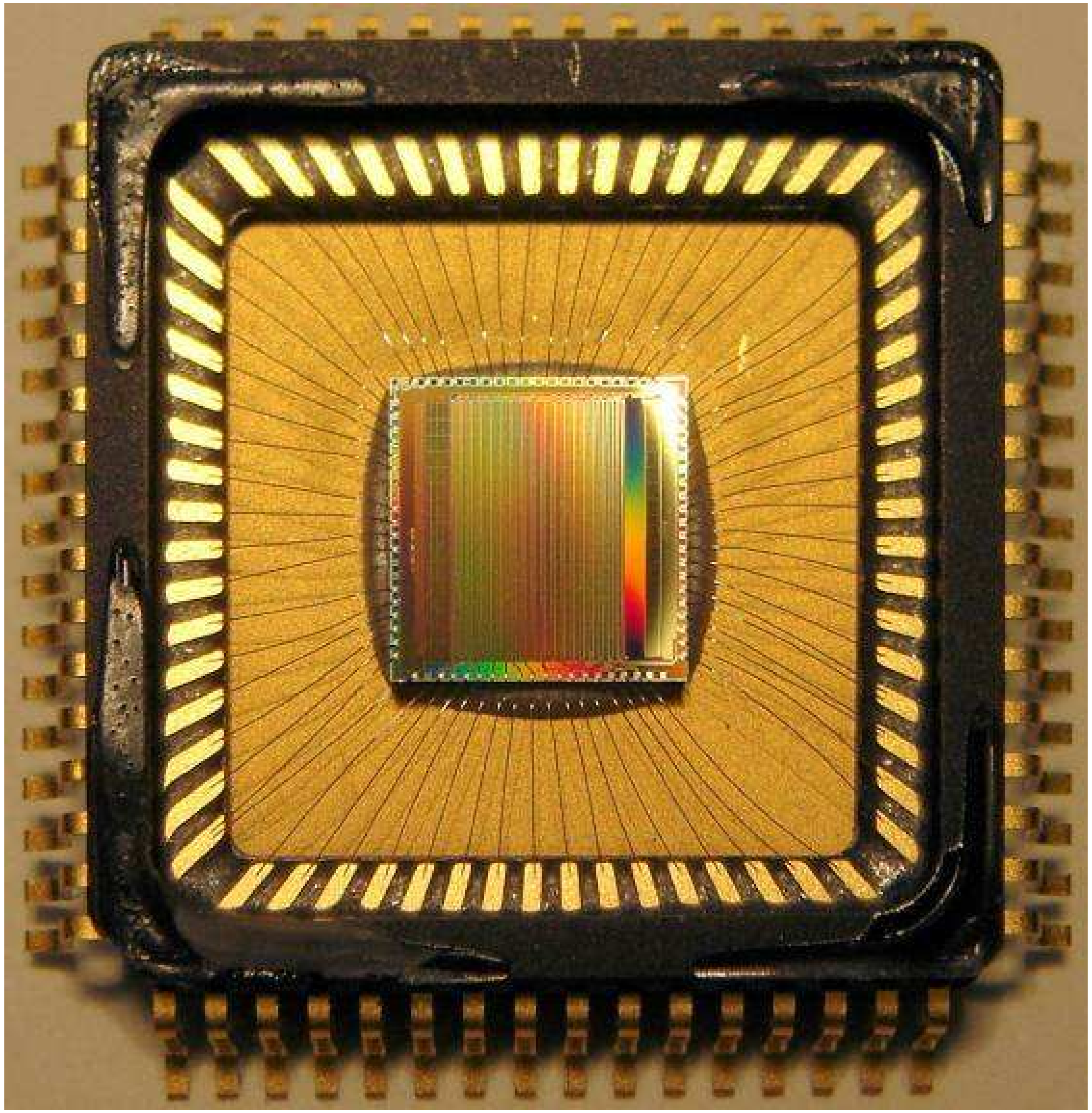




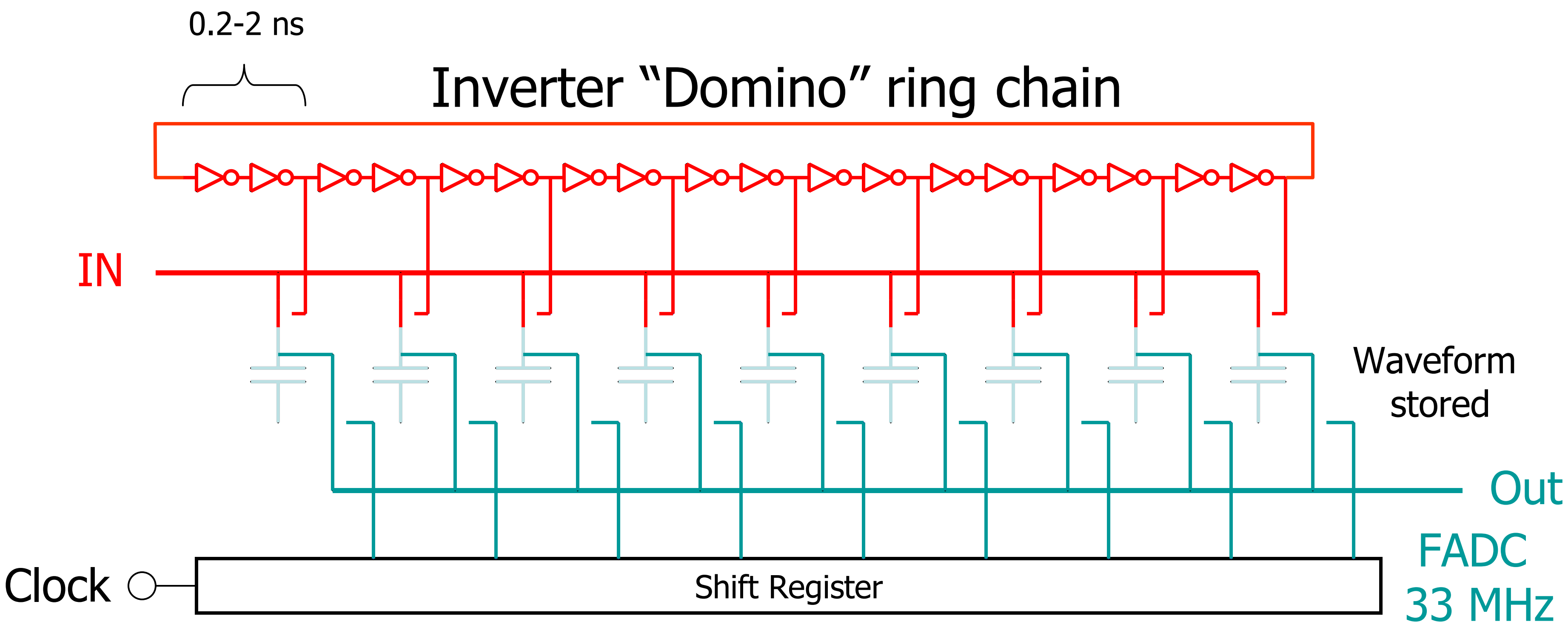


BACKUP SLIDES

5 GS/s Waveform Digitizing Chip DRS4 (S.Ritt, R.Dinapoli)



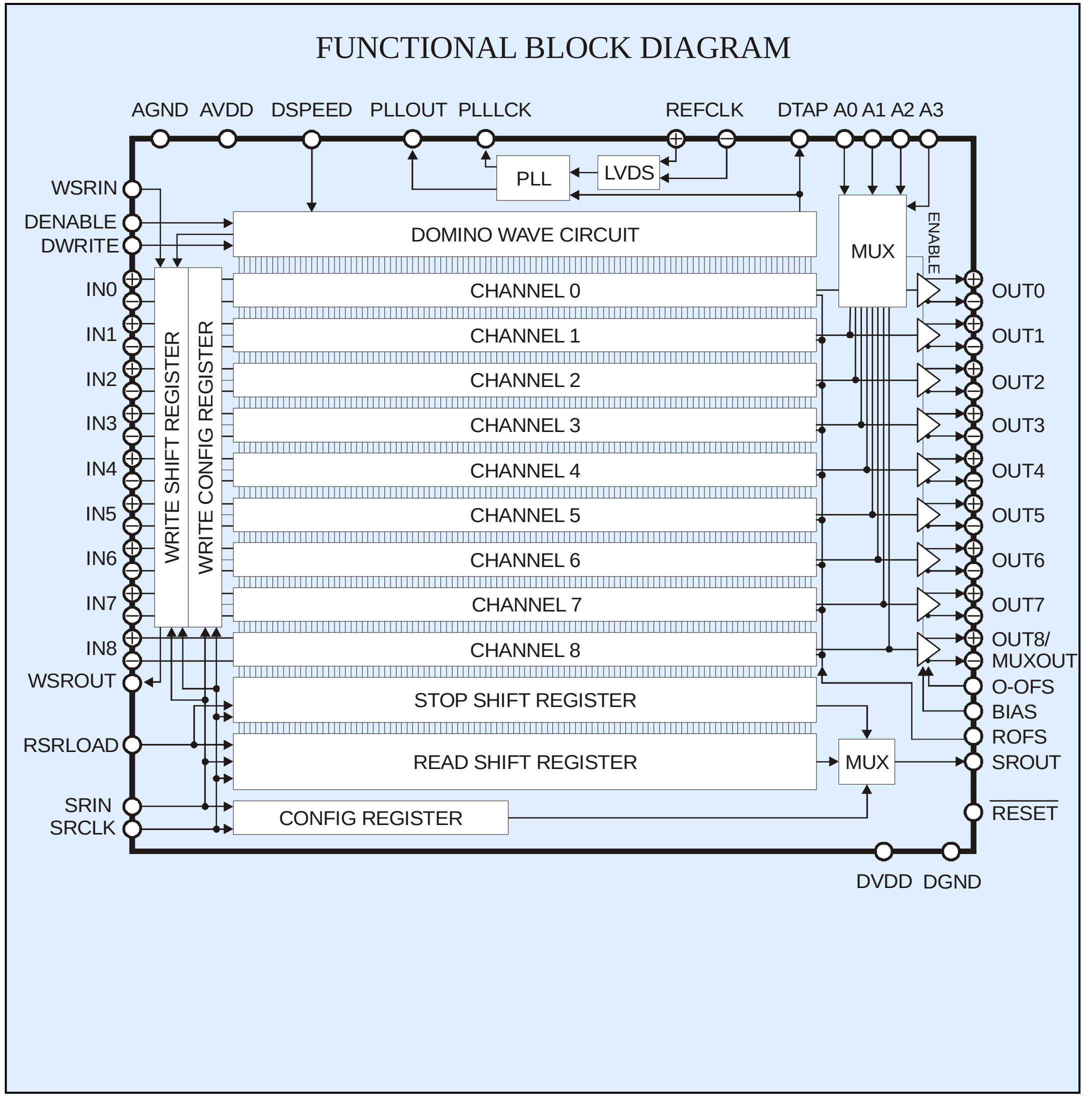
Domino Sampling Chip Principle



"Time stretcher" GHz → MHz

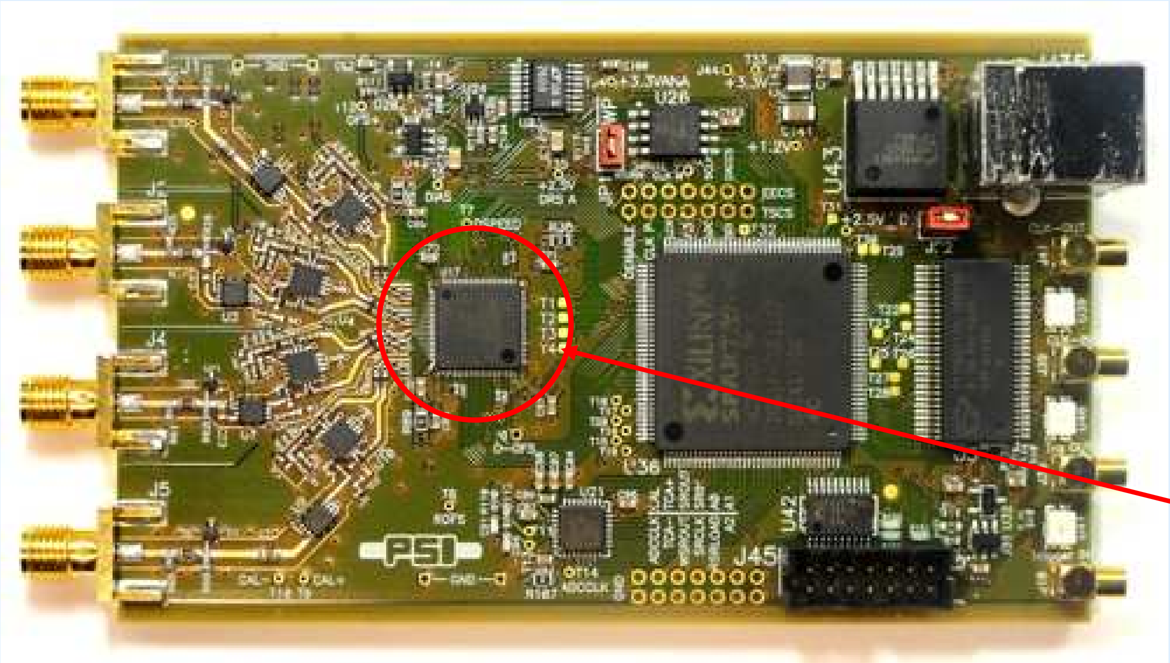
Keep Domino wave running in a circular fashion and stop by trigger → Domino Ring Sampler (DRS)

5 GS/s Waveform Digitizing Chip DRS4



- UMC 0.25 μm rad. hard
- 9 chn. each 1024 bins, cascadable up to 8192
- Sampling speed 0.2 … 5 GS/s
- Bandwidth 950 MHz
- 17.5 mW/chn @ 2.5V
- On-chip PLL stabilization
- Readout speed using ext. ADC: 30 ns * $n_{samples}$
- SNR: 69 dB calibrated
- Aperture jitter: 4 ps at 5 GS/s calibrated

Evaluation Board



- Equivalent to 4-chn. 5 GS/s digital oscilloscope
- Board or packaged chip can be obtained from PSI

Experiments using DRS chip

MEG 3000 channels DRS2

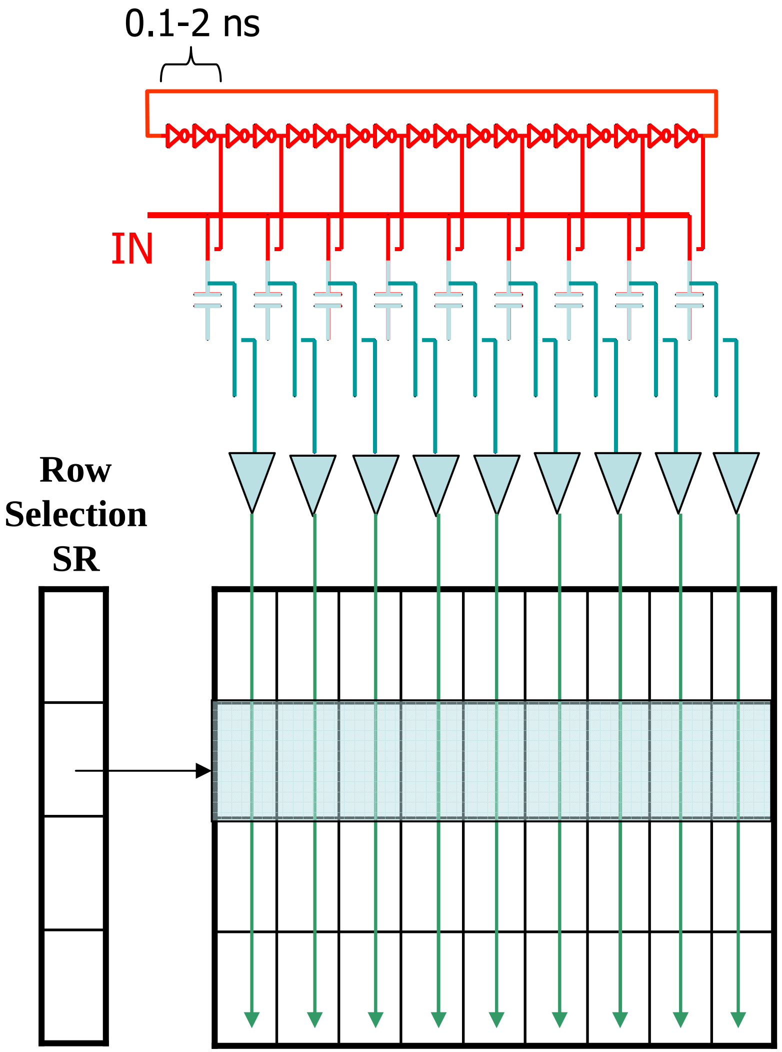
MACE (India) 1200 channels DRS4 (planned)

MAGIC-II 400 channels DRS2

BPM for XFEL@PSI 800 channels DRS4

Several CAEN products (e.g.:V1742 VME Switched Capacitor Digitizer) are based on DRS4

Next step: DRS5



Shorter "Domino" ring chain

Short term storage

Fast buffers

Long term storage

Next step: DRS5