Megapixels @ Megahertz

AGIPD Detectors for the European XFEL and beyond

J. Becker[1], A. Delfs[1], R. Dinapoli[2], P. Göttlicher[1], H. Graafsma[1, 5], D. Greiffenberg[2], H. Hirsemann[1], S. Jack[1], A. Klyuev[1], H. Krüger[3], M. Kuhn[1], T. Laurus[1], A. Marras[1], D. Mezza[2], A. Mozzanica[2], D. Pennicard[1], J. Poehlsen[1], I. Sheviakov[1], B. Schmitt[2], J. Schwandt[4], X. Shi[2], S. Smoljanin[1], **U. Trunk[1]**, J. Zhang[2], M. Zimmer[1]

[1]DESY, Photon Science - Detector Group, Hamburg, Germany
[2]Paul-Scherrer-Institut (PSI), SLS Detector Group, Villigen, Switzerland
[3]University of Bonn, Bonn, Germany
[4]University of Hamburg, Hamburg, Germany
[5]Mid Sweden University, Sundsvall, Sweden

Outline

The AGIPD System
European XFEL
Single molecule imaging
Requirements

AGIPD 1.1 Readout ASIC
Architecture
Dynamic gain switching
Performance

AGIPD Detector systems gen. 1: SPB & MID endstations
Overview
First user experiments
Results

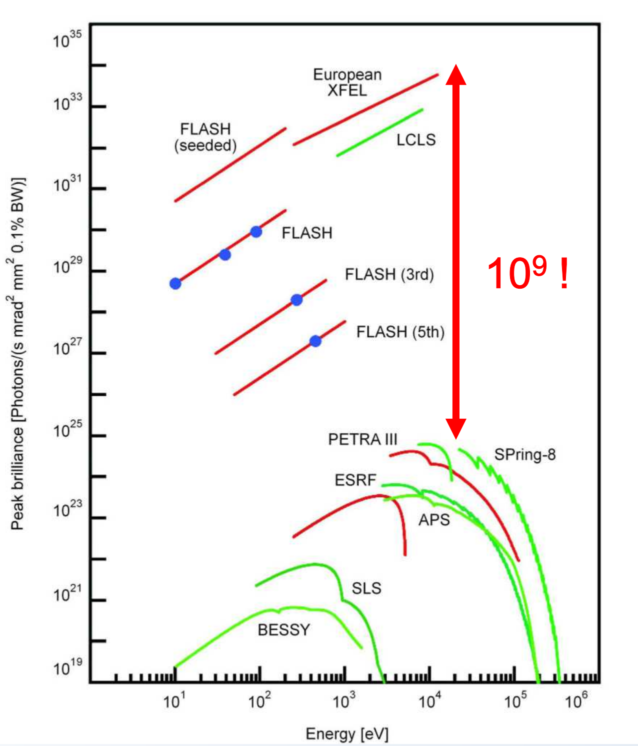
AGIPD Detector Systems gen. 2: SFX & HiBEF endstations
Readout boards
Optical communications
Cooling and mechanics

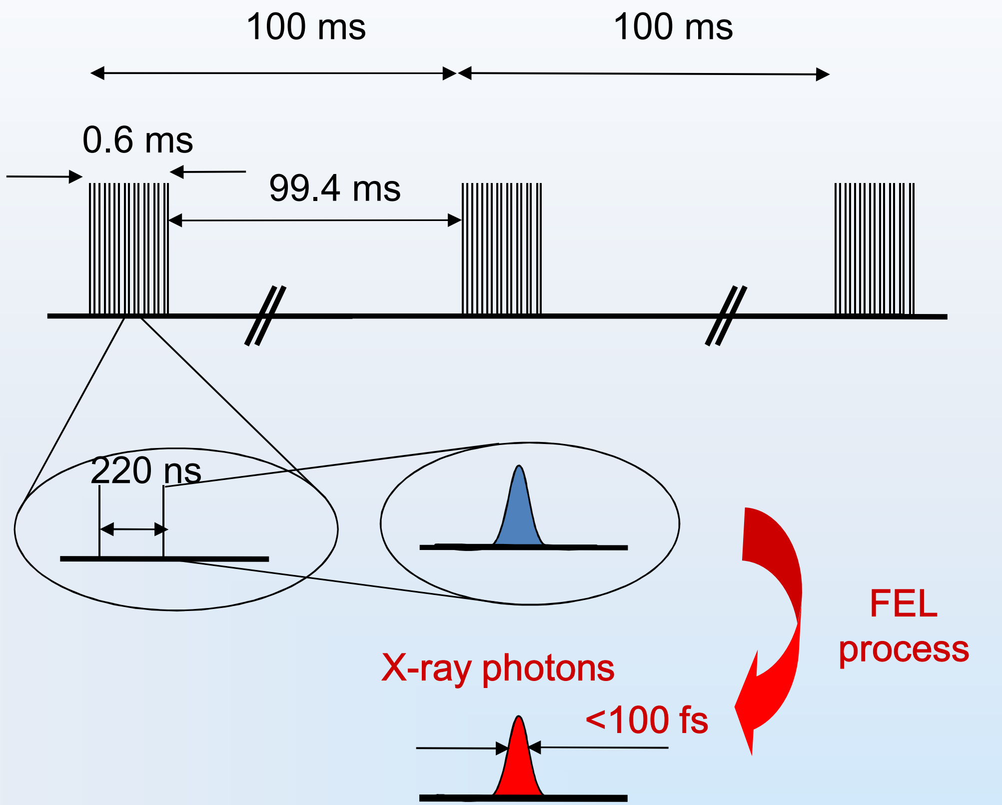
New ASICS: AGIPD 1.2 and ecAGIPD
AGIPD 1.2
Electron-collecting AGIPD
AGIPD06 demonstrator

Beyond AGIPD

Conclusion
Summary
Outlook

European XFEL properties





Eγ=250eV…12keV

av. Rate:

- 27kHz XFEL
- 120Hz LCLS
- 60Hz SCSS

Detectors:

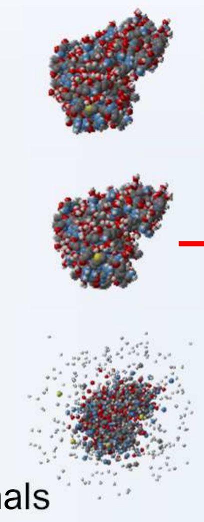
- LPD (500µm x 500µm) - 1Mpix installed
- AGIPD (200µm x 200µm) – 2 × 1Mpix installed, 4Mpix & 1Mpix under construction
- DSSC (230µm x 200µm hexagonal) - 1Mpix under construction

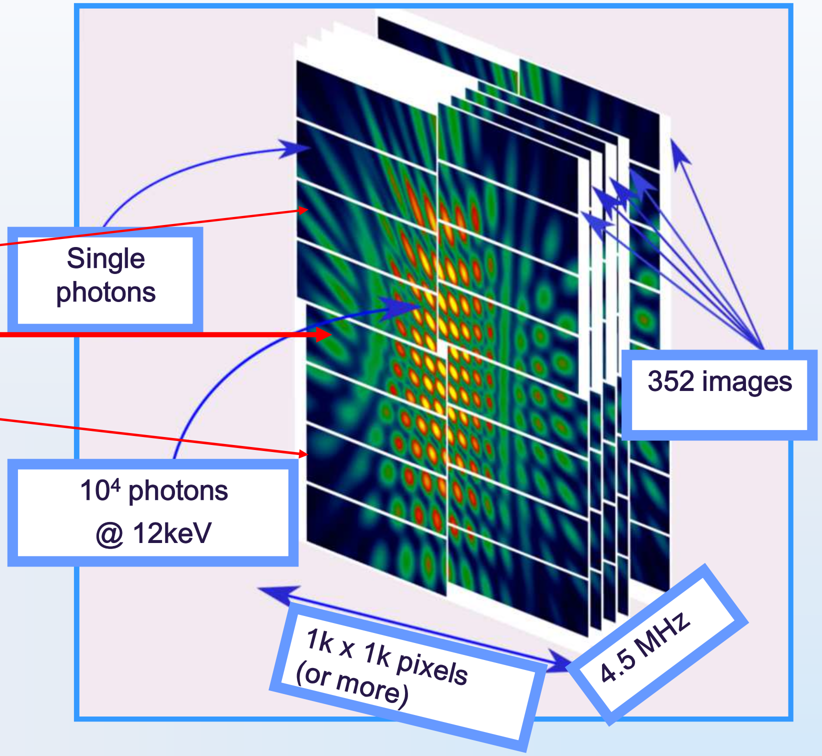
AGIPD Scientific Case:
Single Molecule Imaging & SFX

Just before XFEL pulse

During the pulse

After pulse

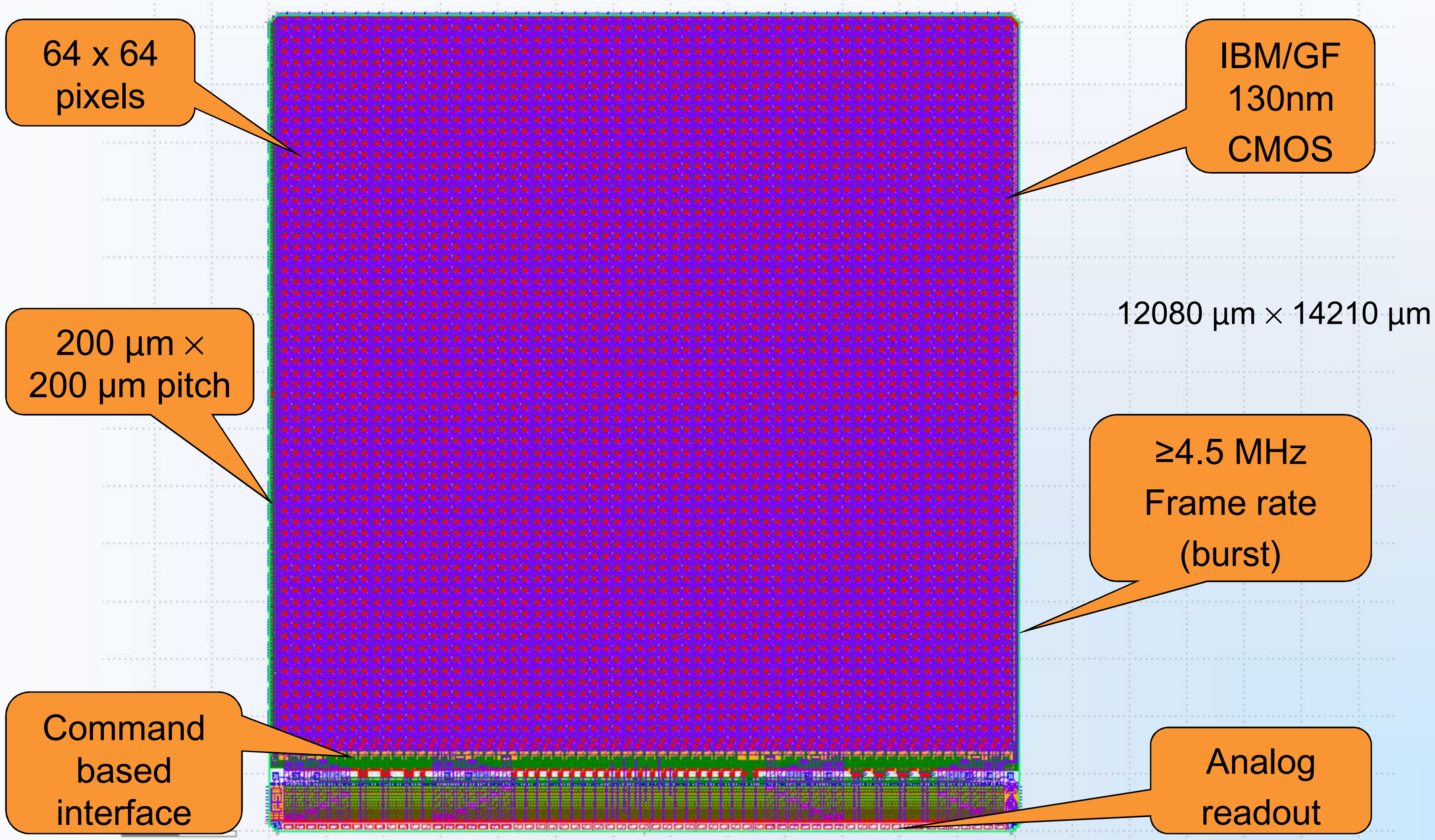




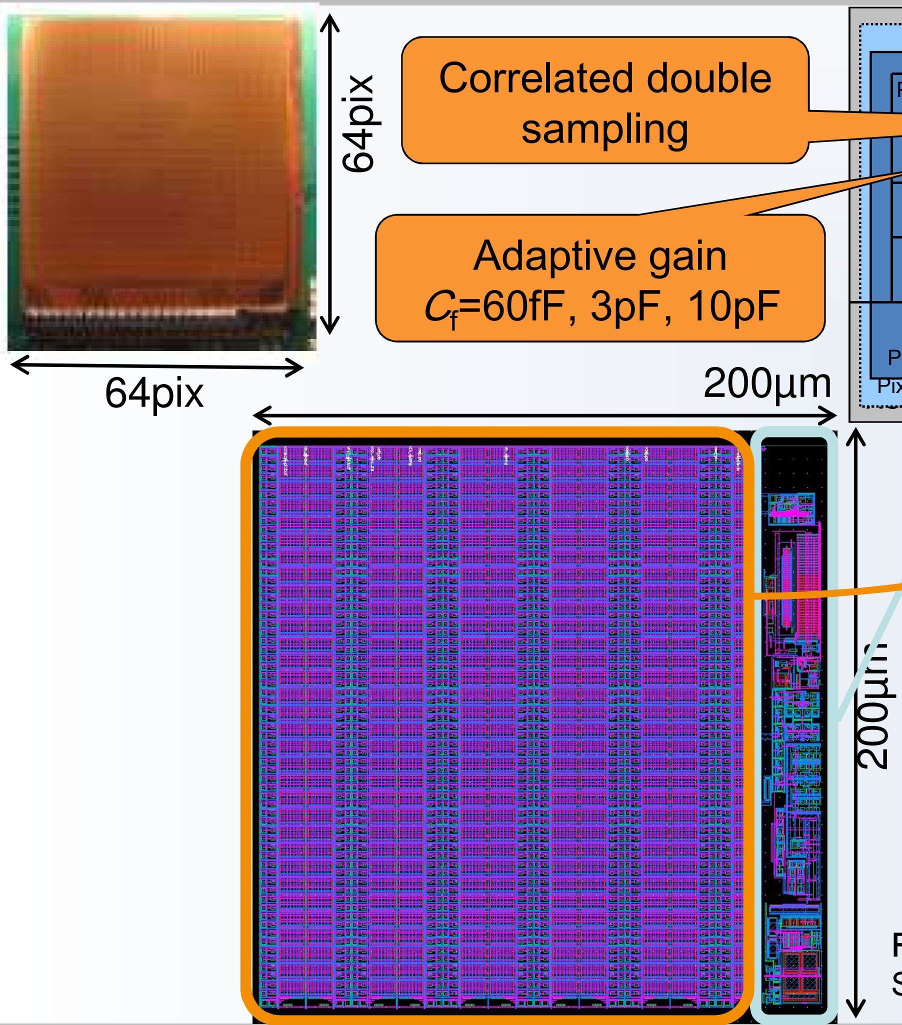
- Time structure of the photon signals
  - Pipelined architecture
  - Random access mode
    - External veto capability
- High radiation dose at small angles: 10^4 photons/(pixel shot)
- over 3 years: 1 GGy @sensor
  - Radiation damage of silicon sensor
  - Radiation damage of underlying electronics (≫10 MGy)
    - Radiation hard design

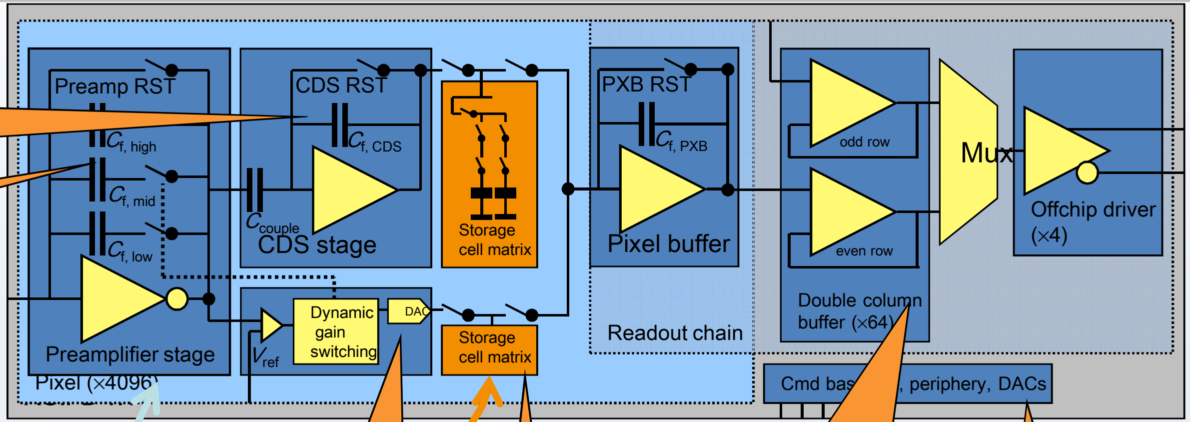
- 500 µm silicon sensor
- 200 µm square pixels
- Vacuum compatibility
- Detector with central hole

AGIPD 1.1 ASIC



AGIPD 1.1 ASIC





Correlated double sampling

Adaptive gain
C_f=60fF, 3pF, 10pF

Analogue encoding of gain

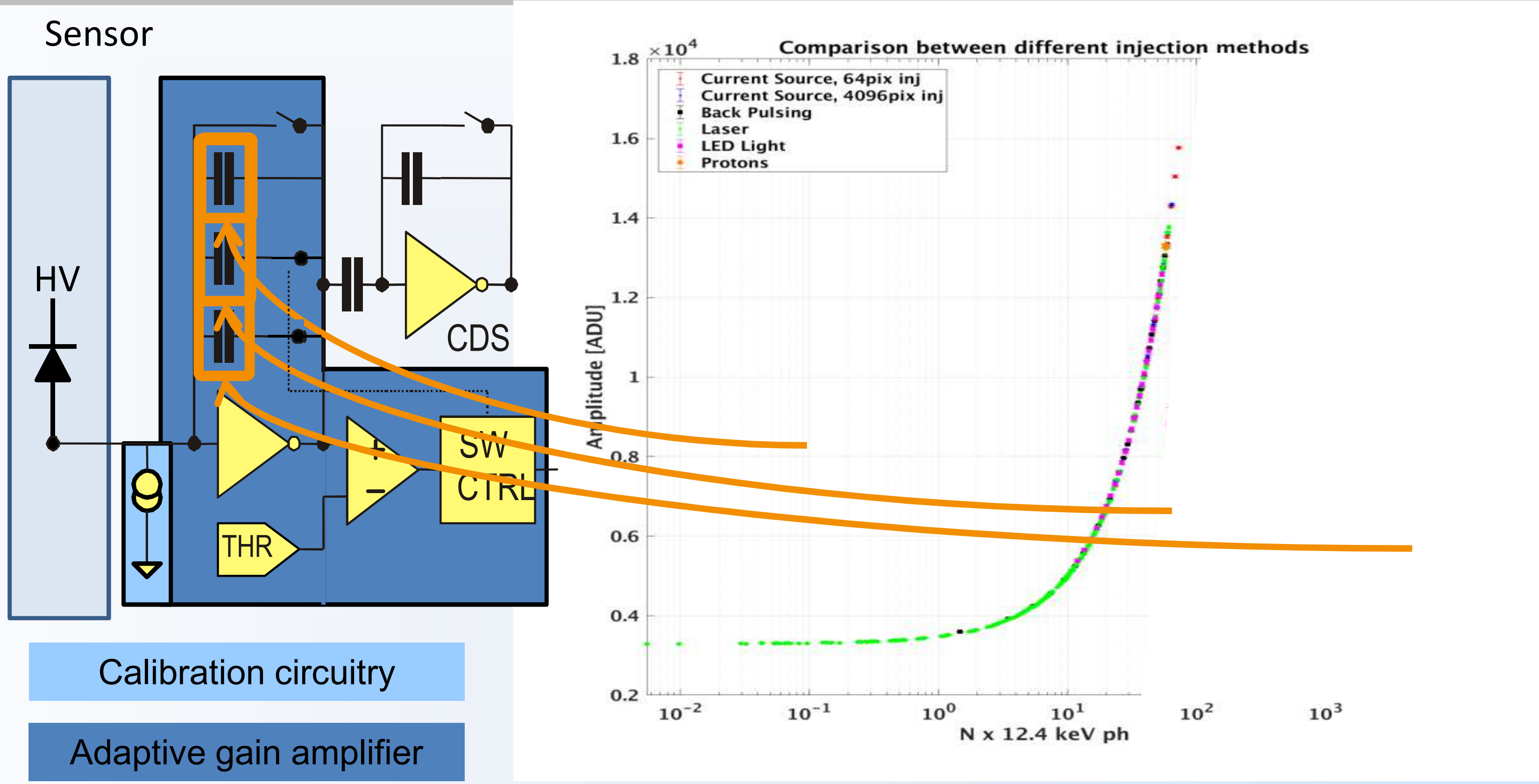
Analogue RAM for 352 images

Interleaved row Double column readout

Command based control via serial IF

Remaining Issue:
Separation between med/low gain signals disappearing with burst length → AGIPD 1.2

Adaptive gain switching



Calibration circuitry

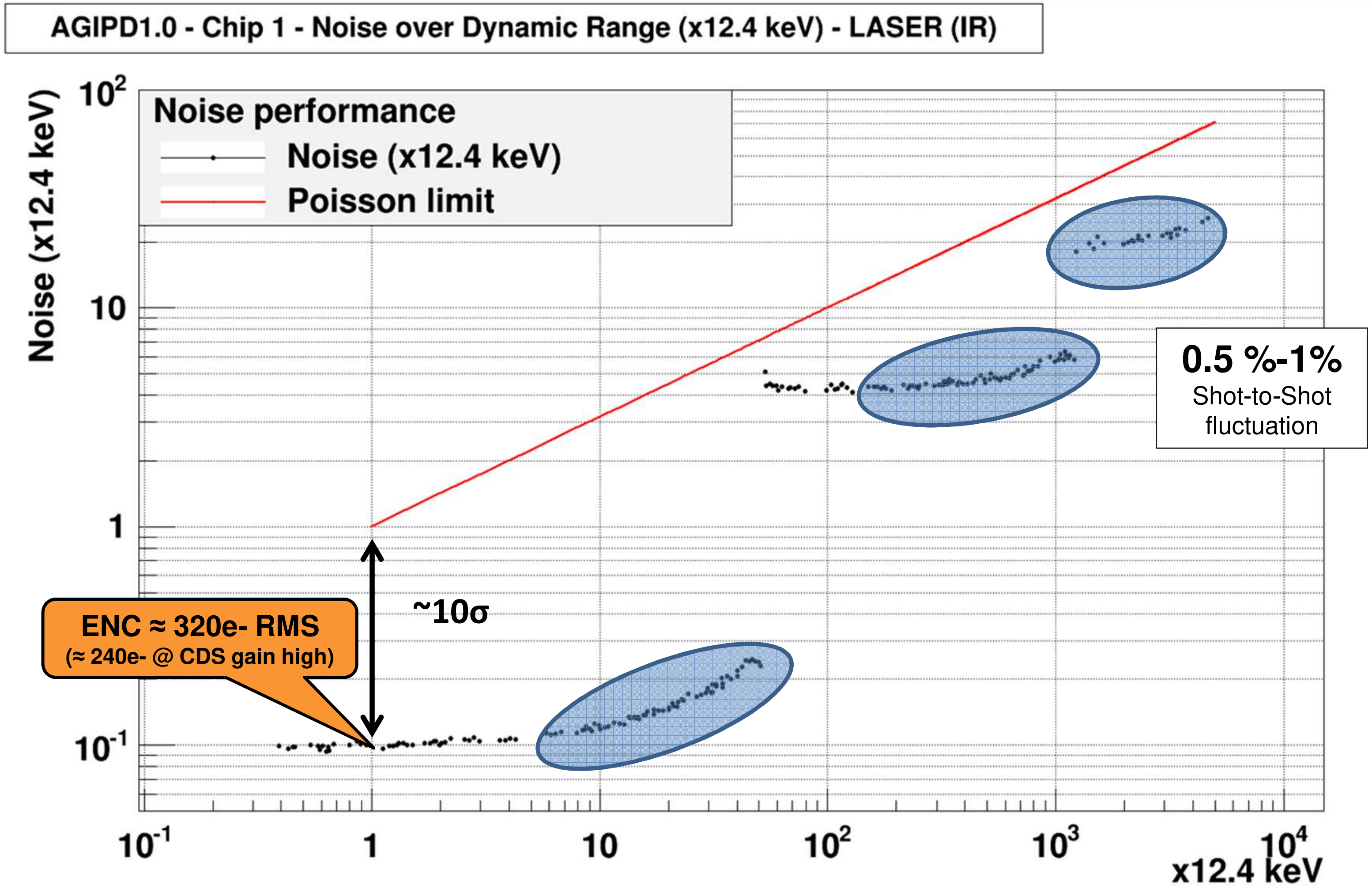
Adaptive gain amplifier

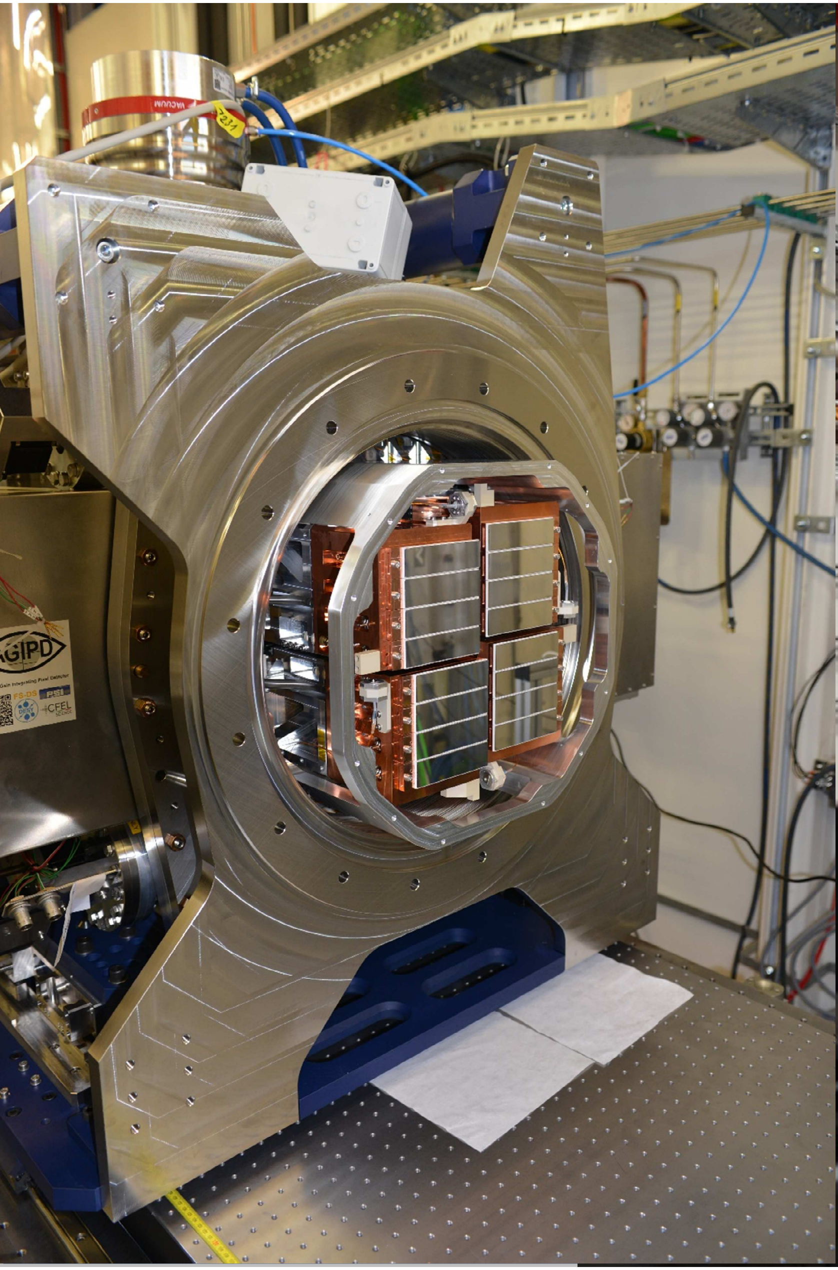
Line spectra covering all 3 gains with (1MeV) Protons@LABEC

High gain: 50-80 Photons with single photon sensitivity.

Low gain: 5000 photons with linear gain +5000 photons with 1% nonlinearity.

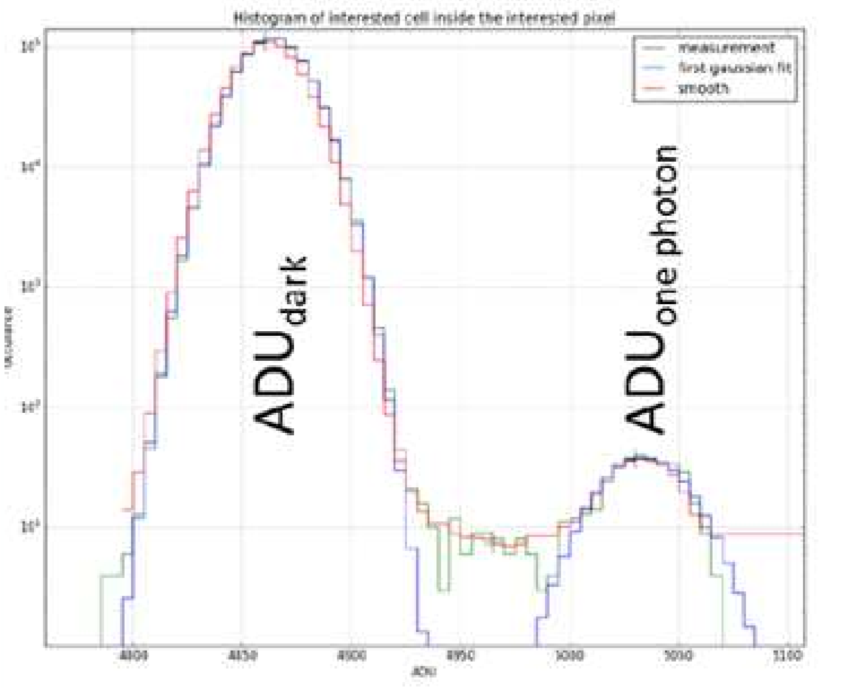
AGIPD Detector noise

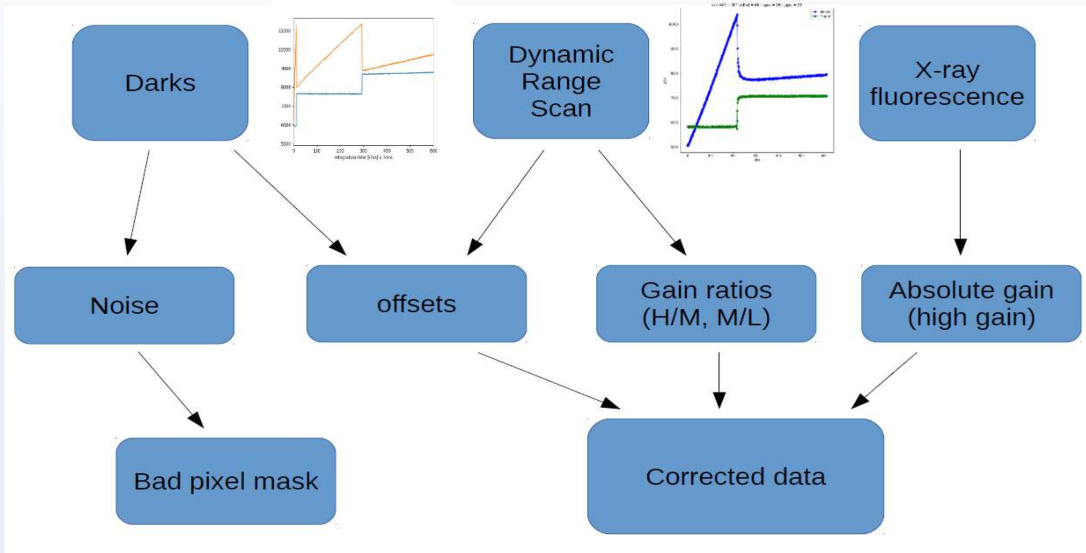



AGIPD

AGIPD 1Mpix Systems:
Calibration

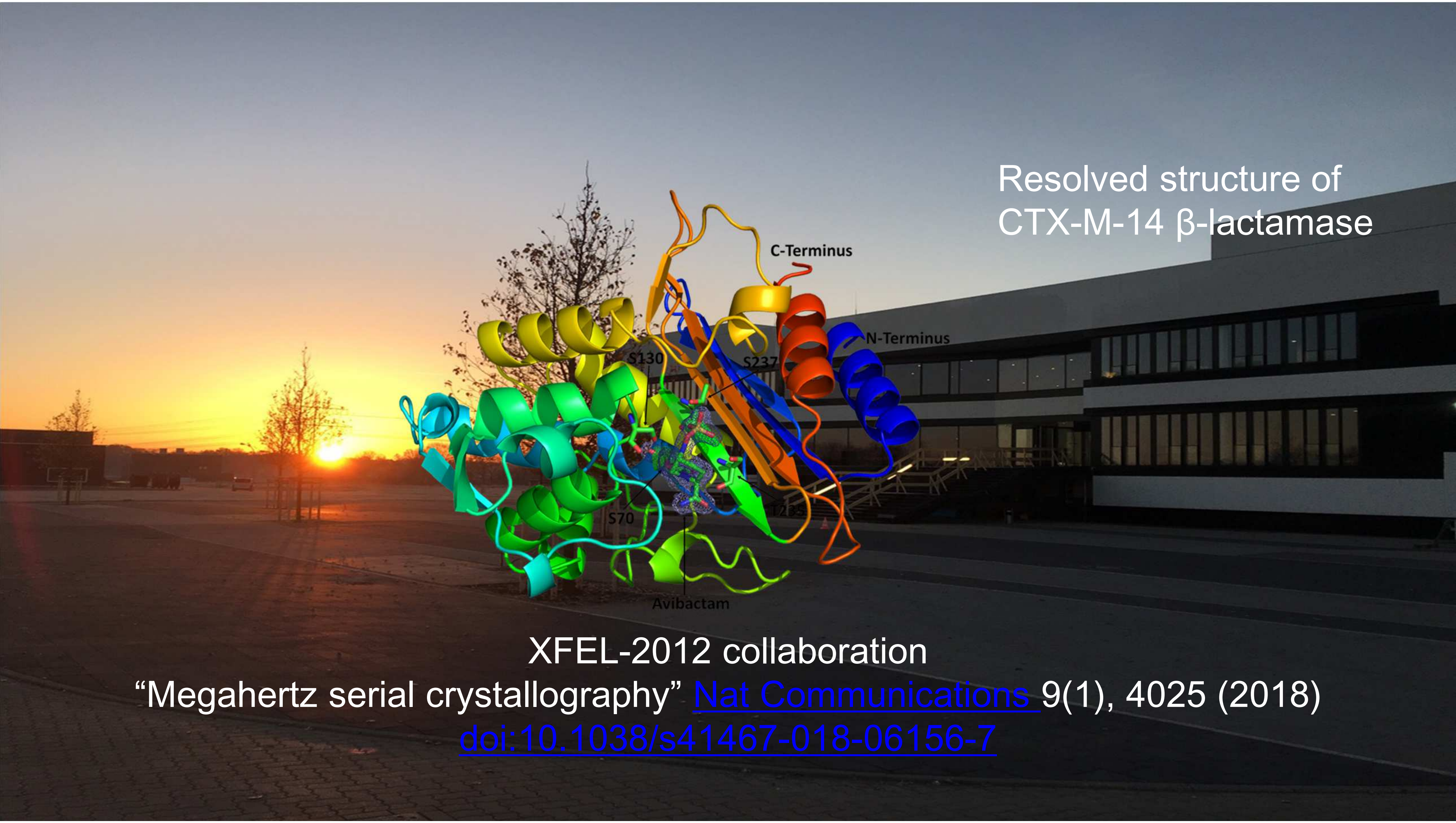
Feed calibration frame work with
- Pulsed capacitor dynamic range scans for all memory cells used
- Cu-K_α data at XFEL
- Dark data for High and Medium gain level





Calibration framework follows a modular concept and allows removing, adding and exchanging building blocks
- Huge number of fits!
- 65,536 pixels
- 352 memory cells
- 3 Gains + 3 Offsets
- ≈138,000,000 fits / module
- 16 Modules → 2.2×10^9 constants
- computation time, fit quality, non-constant fit ranges

Time & Resources:
- DAQ: ≤ 2h
  - @ European XFEL
- Calibration: ≤ 4h
  - on DESY Maxwell cluster



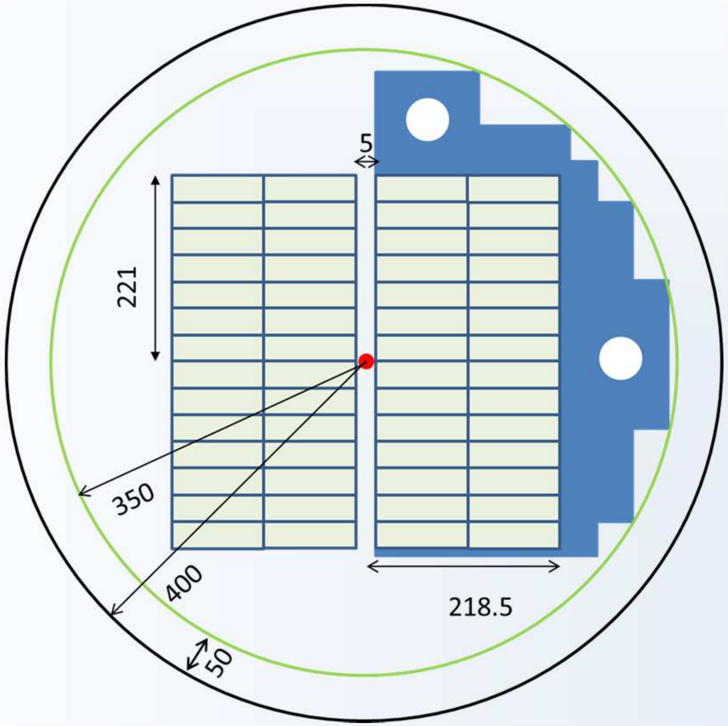
Resolved structure of CTX-M-14 β-lactamase

XFEL-2012 collaboration

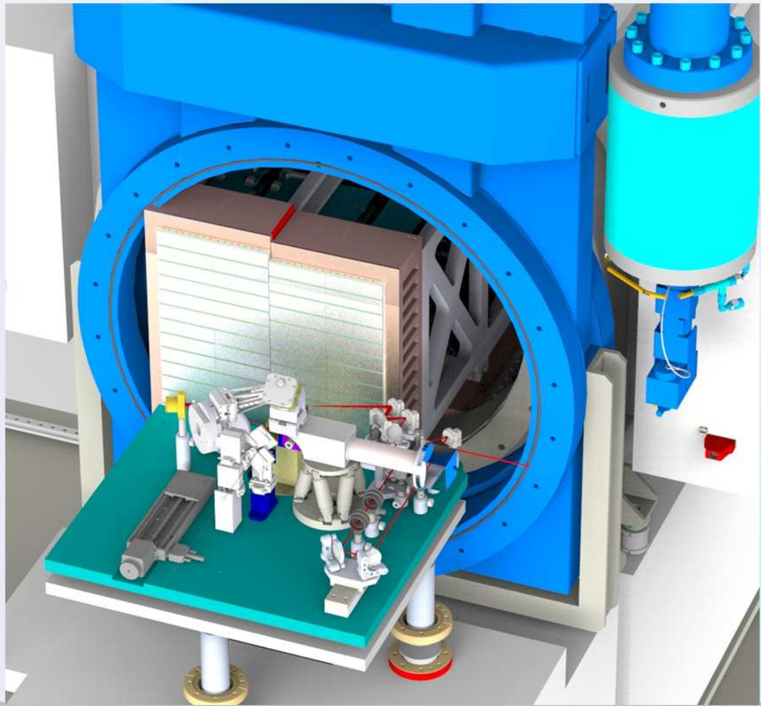
"Megahertz serial crystallography" Nat Communications 9(1), 4025 (2018)

doi:10.1038/s41467-018-06156-7

AGIPD 4M Detector for SFX

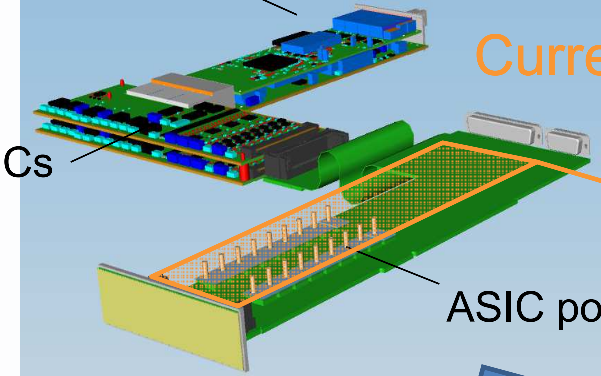


- 4 x 14 Front-End-Modules, arranged in
  - 2 x 14 Double-Modules
- Two halves
  - 2 x 14 FEMs each
  - Independent in-vacuum x-motion

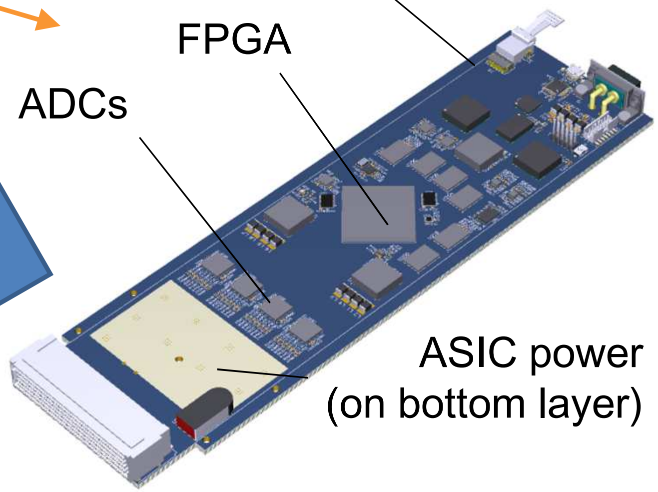


- In-vacuum z-motion
  - through gate valve
    - inner diameter 800mm
  - into sample chamber
  - travel range of 400 mm

AGIPD 4M Detector for SFX

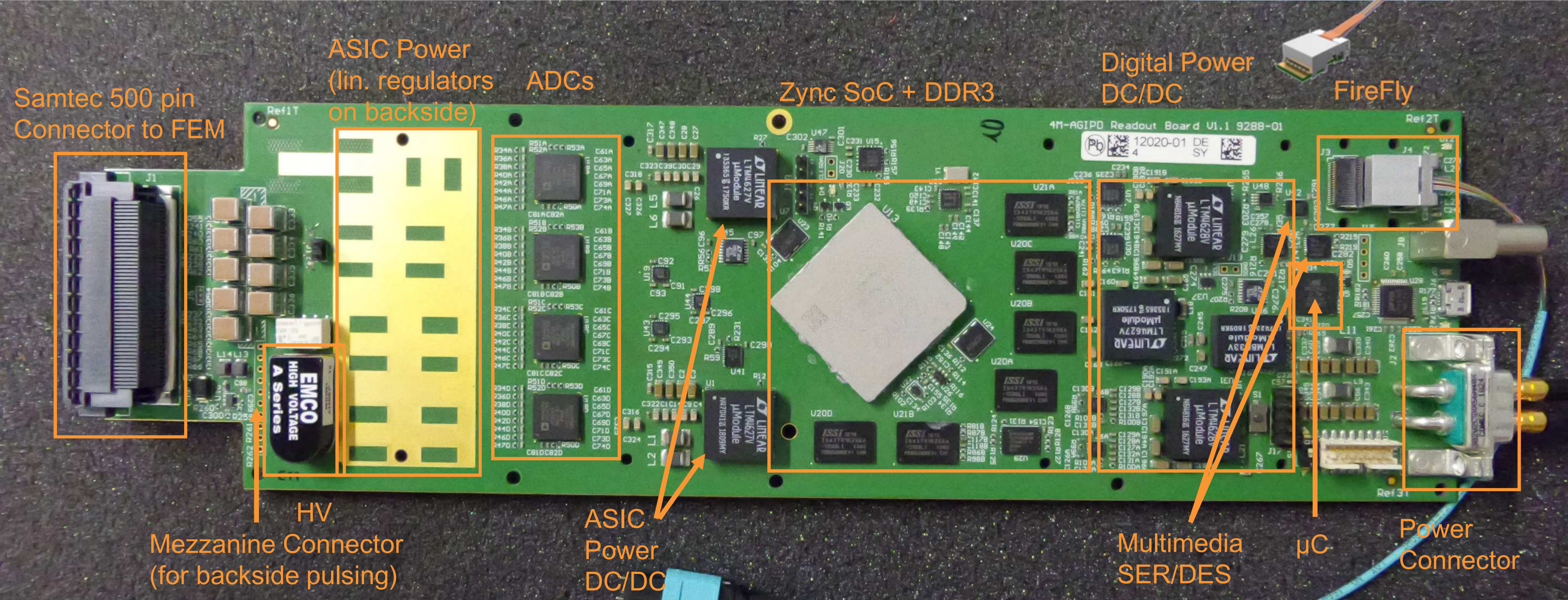


Advantages
- Short analogue signal path
- Local DC/DC -> less power cables
- Control and DAQ completely based on optical data transmission



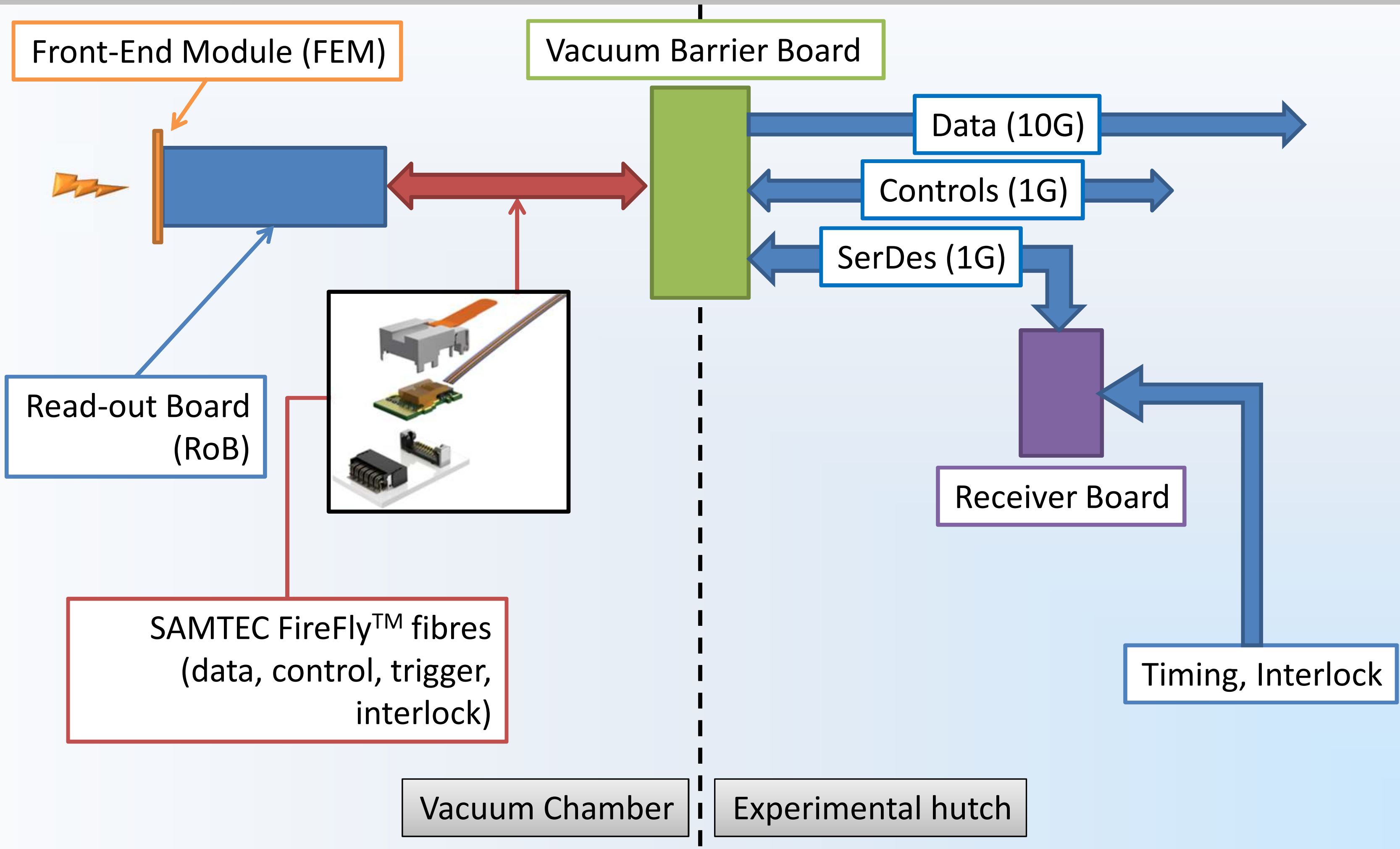
Challenges
- Complete redesign of two boards
  - Readout board in vacuum
  - Receiver board outside vacuum
- Cooling of PCB in vacuum

AGIPD 4M Detector for SFX

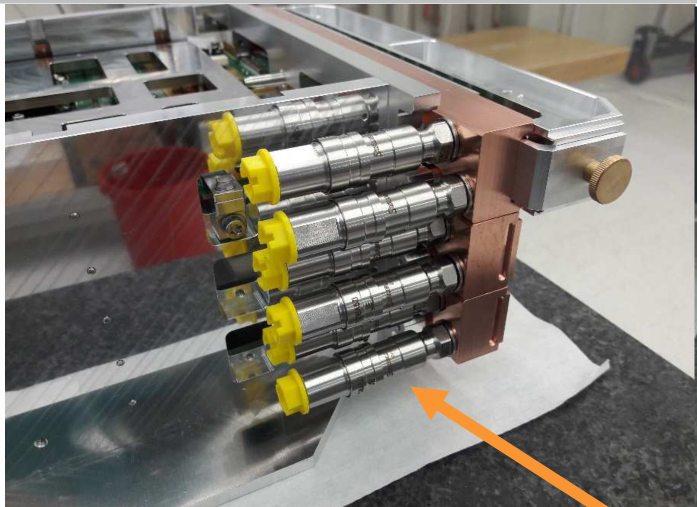


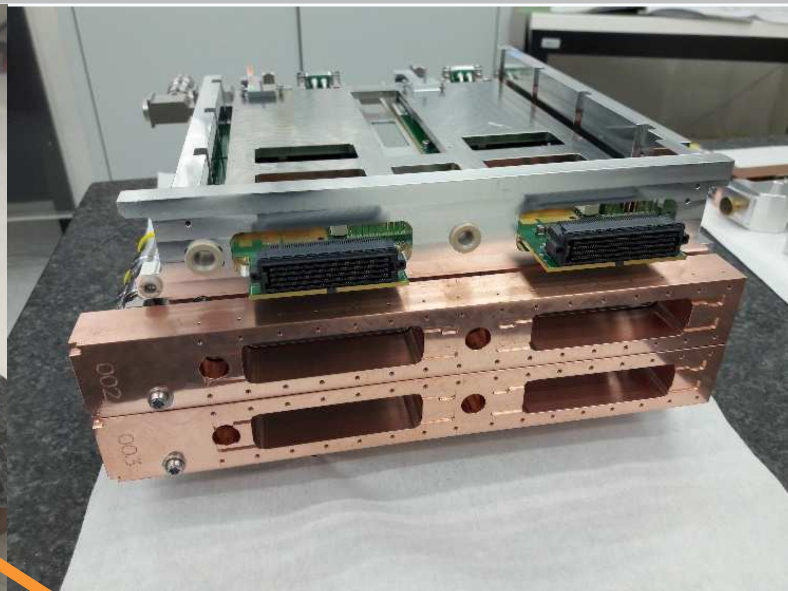
- Series production started
- Successful commissioning without major issues
- SW/FW development in in progress

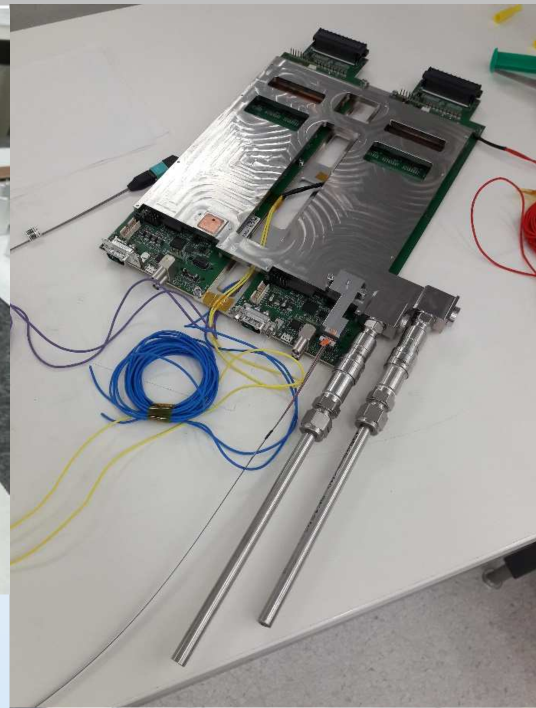
AGIPD 4M Detector for SFX

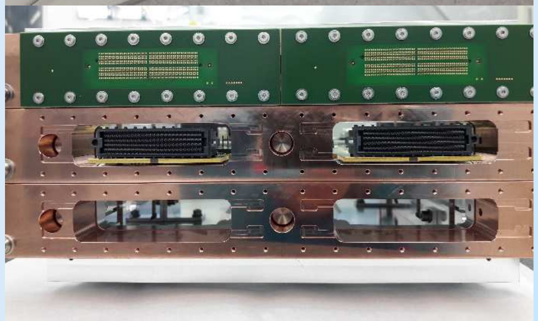


AGIPD 4M Detector for SFX
In-Vacuum Cooling



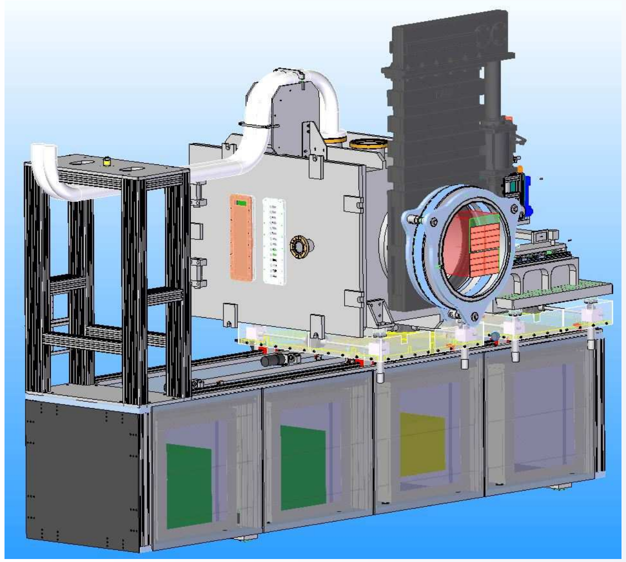


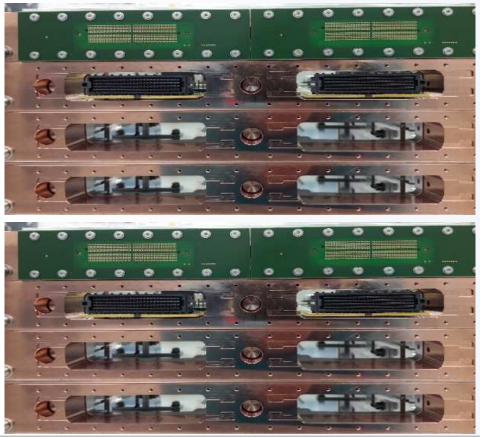




Liquid Cooling of
- Modules
  - Cooling channels in Copper frame
  - Coolant: Silicone oil
- Readout boards
  - Coolant: Water
- In-Vacuum connectors

AGIPD 1M Detector for HiBEF
@HED Endstation of European XFEL





The HiBEF (Helmholtz International Beamline for Extreme Fields) experiment @ EuXFEL needs a 1Mpix detector for E_{ph}≥25keV

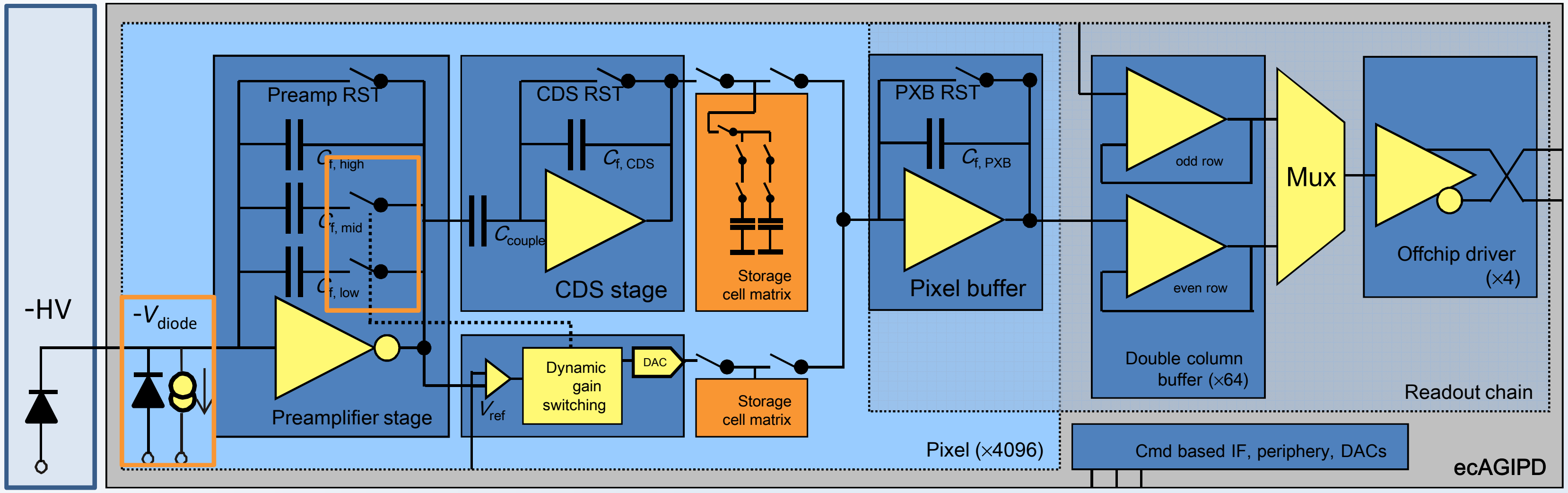
- The existing AGIPD detector collects positive charges (holes)
  - Easier to realise radiation hard sensors
  - Slower – less demanding to handle large charges (circuit wise)

- AGIPD is not suitable for experiments with photons above ~15keV
  - The Silicon sensor gets inefficient ~15keV

- High-Z Semiconductors, esp. GaAs promise efficient sensors for E_{ph}≥25keV
- Composite (III/V) Semiconductors feature relatively short charge carrier lifetimes
- Collection of Electrons (i.e. the fast component) is required

New ASICs: AGIPD 1.2 and ecAGIPD

AGIPD 1.2:
- Improve Med<->Low gain detection
- Modified storage cells
- Taped out Aug. 2018
- Back mid April 2019
- Shows ≈ 30% better 'gain separation' from wafer testing (no burst readout)
- Module production at IZM and ADVACAM under way

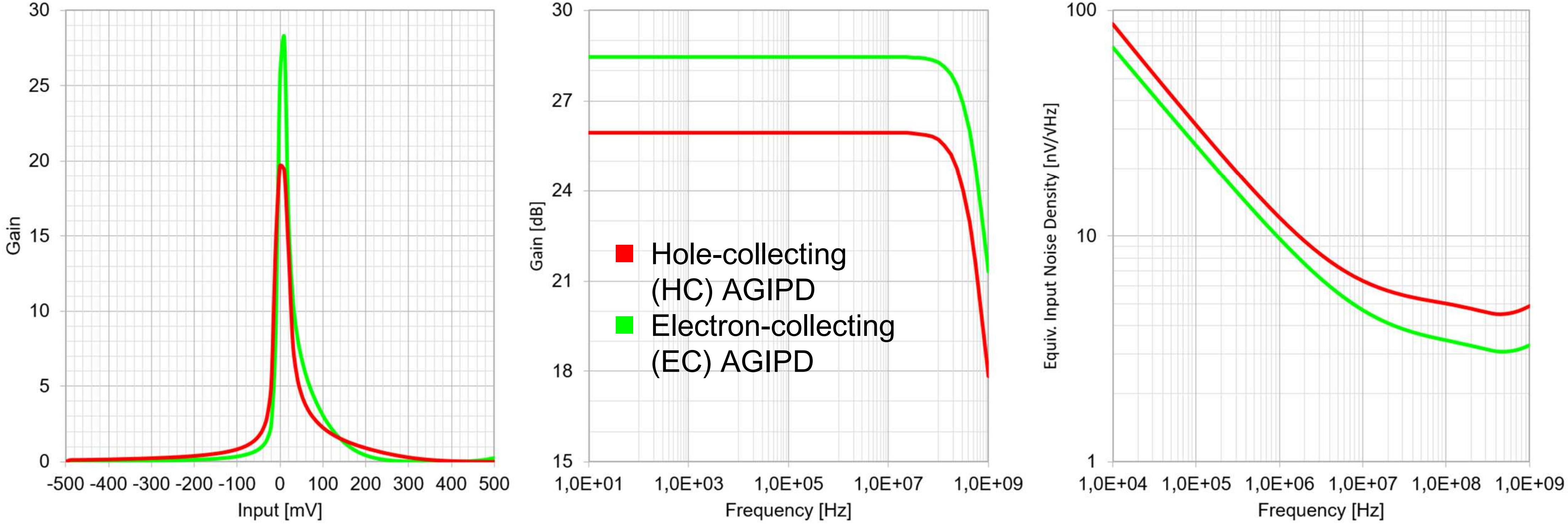


- Triple-well structure at negative (V_{diode}~-1V) voltage containing
  - Input protection diode
  - Current source for test stimulus = current mirror driven by existing source
  - Feedback switches
- Modified Preamp
  - New baseline at ~400mV
- Discriminator of opposite polarity
- Changed gain encoding
  - Hi <-> Lo
- Swapped output pads

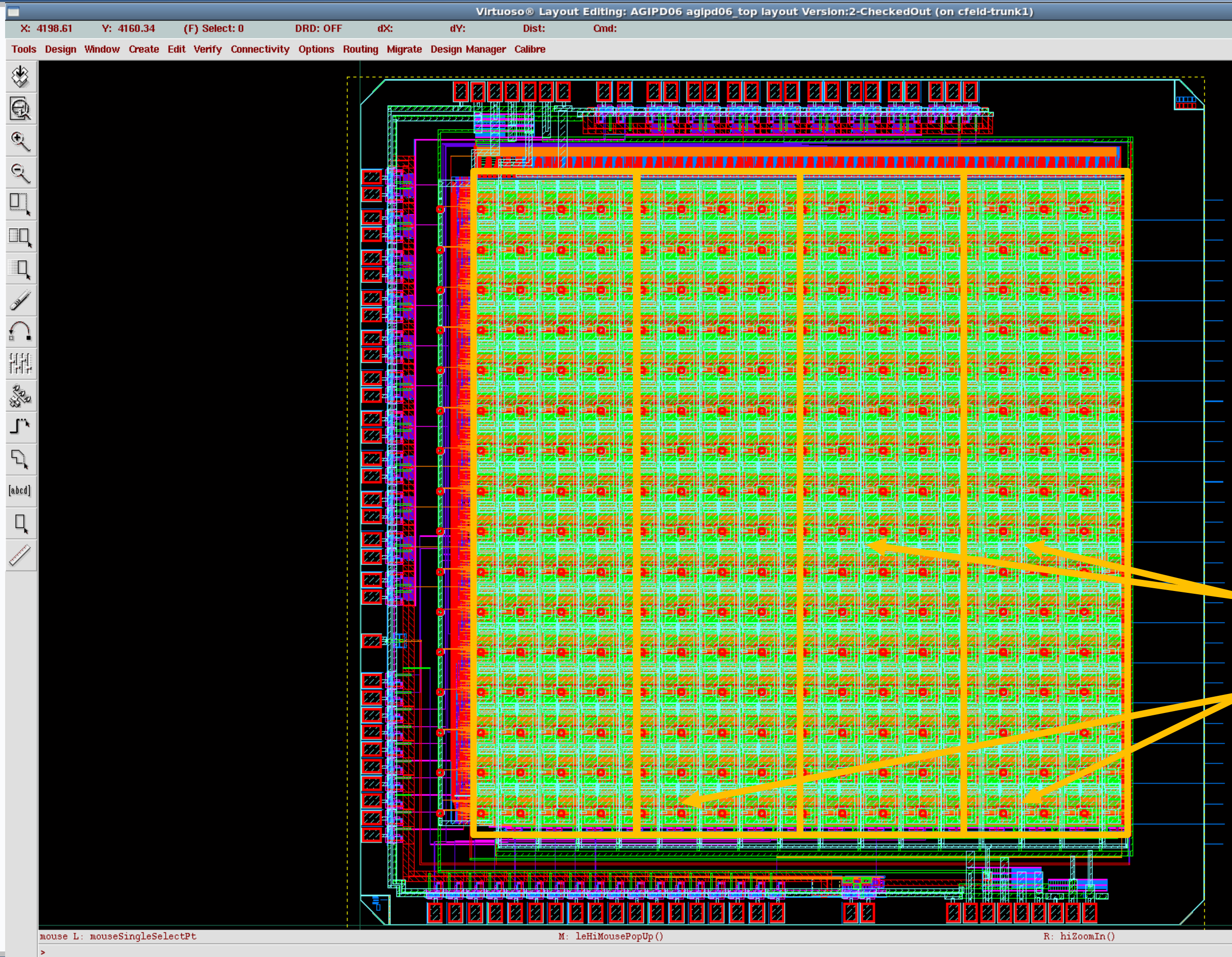
ecAGIPD

ecAGIPD-Preamp

- Higher open-loop gain (29 vs. 19)
- Same bandwidth (-3dB @ ~500MHz)
- Same noise density and power consumption



ecAGIPD: AGIPD06 Prototype



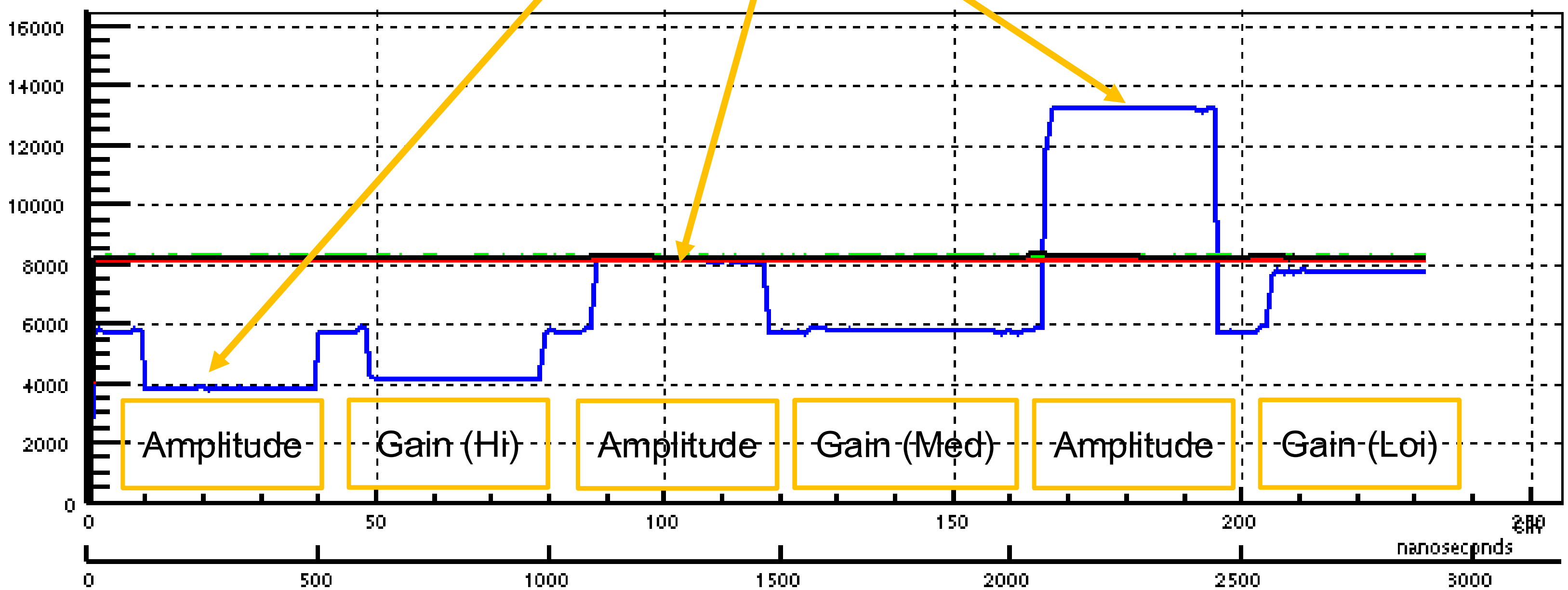
- 16x16 pixels
- SR (i.e. no) periphery
- RX outside guardring to make TW134 happy…

Modifications to investigate 'gain bit' issues:

- Mem cells like in AGIPD 1.2
- Order of mem row & column switches reversed

ecAGIPD: AGIPD06 Prototype

- No Stimulus
  - High gain
- Test Current
  - Switched to medium gain
- Test Current + longer integration time
  - Switched to low gain



Preliminary results:

- EC Preamp works
- Noise $\approx 282\mathrm{e}^-$ $\left(= \sqrt{340^2\mathrm{e}^- - 182^2\mathrm{e}^-}\right)$
- Gain switching works
- Test stimuli work:
  - Pulsed capacitor
  - Current source
- ≈ 20% better 'gain separation' of modifies storage cells

Issues:

- Baseline jump when gain-switching
  - Charge injection?
  - X-talk?
- Excess noise

Beyond AGIPD

European XFEL operation will change in the 2nd half of the 2020s. Currently 2 additional operation modes are foreseen:

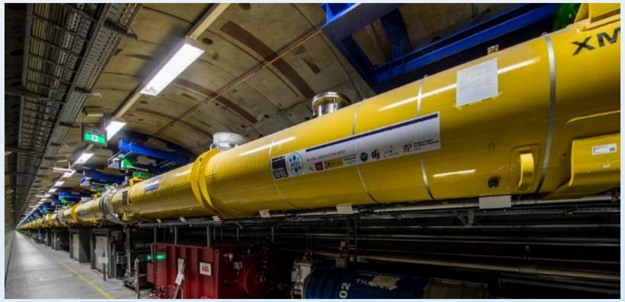
- CW operation at 100kHz
- ‘Long Pulse’ mode with ≤200kHz in 500ms bursts, i.e. 50% duty cycle

On the same time scale the PETRA IV DLLS will become available.

- Intensity will allow to record complete diffraction patterns in ≈10µs

Plans for a possible successor of AGIPD are

- ≥100kHz (CW) imager
- 100 µm × 100 µm Pixels
- Dynamic gain switching
- In-pixel (group) ADC
- (Very) Limited pipeline for burst mode
- High-speed serial link I/O



Going Faster:
With Analogue Readout

Ingredients (1st order):

- Digitisation with *n* bits
- at a rate of f_{ADC}

$$t = \frac{1}{f_{ADC}}$$

$$\tau = \frac{1}{2\pi \cdot Bw}$$

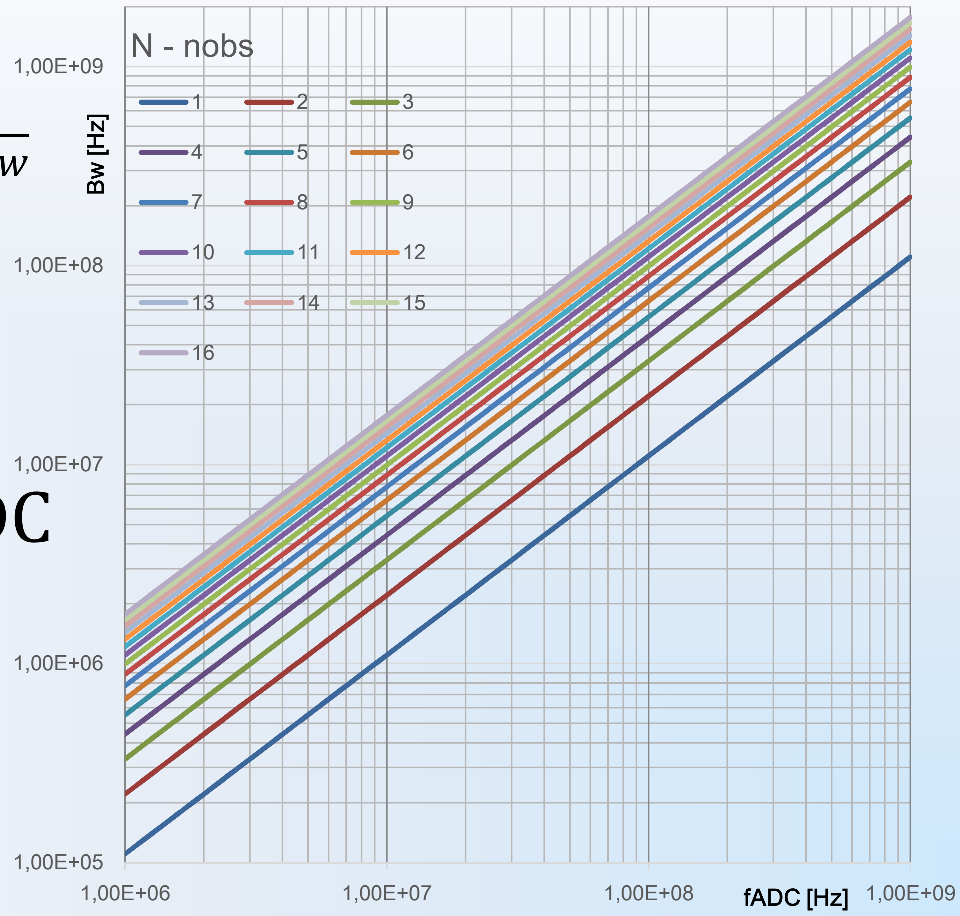
$$2^{-n} \leq e^{-\frac{t}{\tau}}$$

The required bandwidth *Bw* becomes:

$$Bw \geq \frac{\ln(2)}{2\pi} \cdot n \cdot f_{ADC}$$

In case of AGIPD:

- Digitising 2 values/pixel (gain & amplitude)
- 1024 pixel/port
- @ 33MHz
- ⇒ 16 kHz frame rate



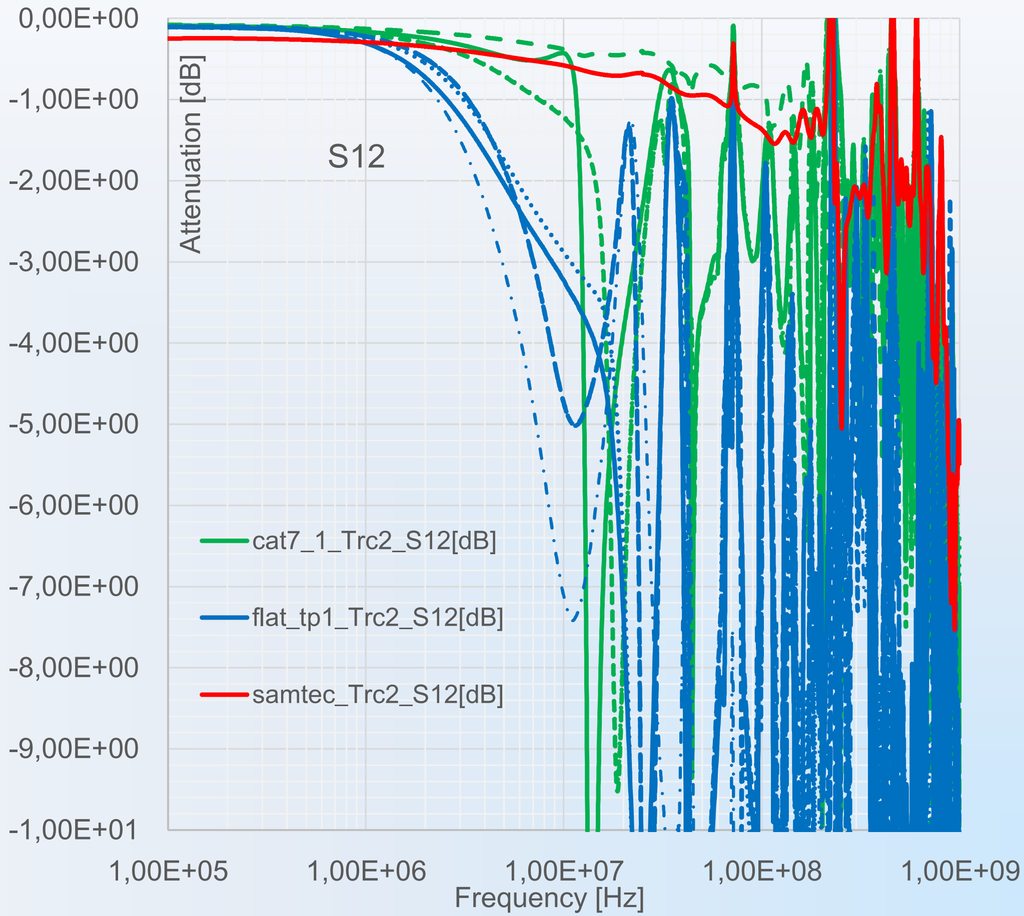
Going Faster:
Limits of Analogue Readout

2nd Order Effects:

- Skin-Effect (att.$\sim\sqrt{f}$)
  - can not be compensated with pre-emphasis ($\sim {}^{1}/_{f}$)
  - can be compensated with a digital (FIR) filter
- Reflections due to
  - Connectors
  - Bending of cables

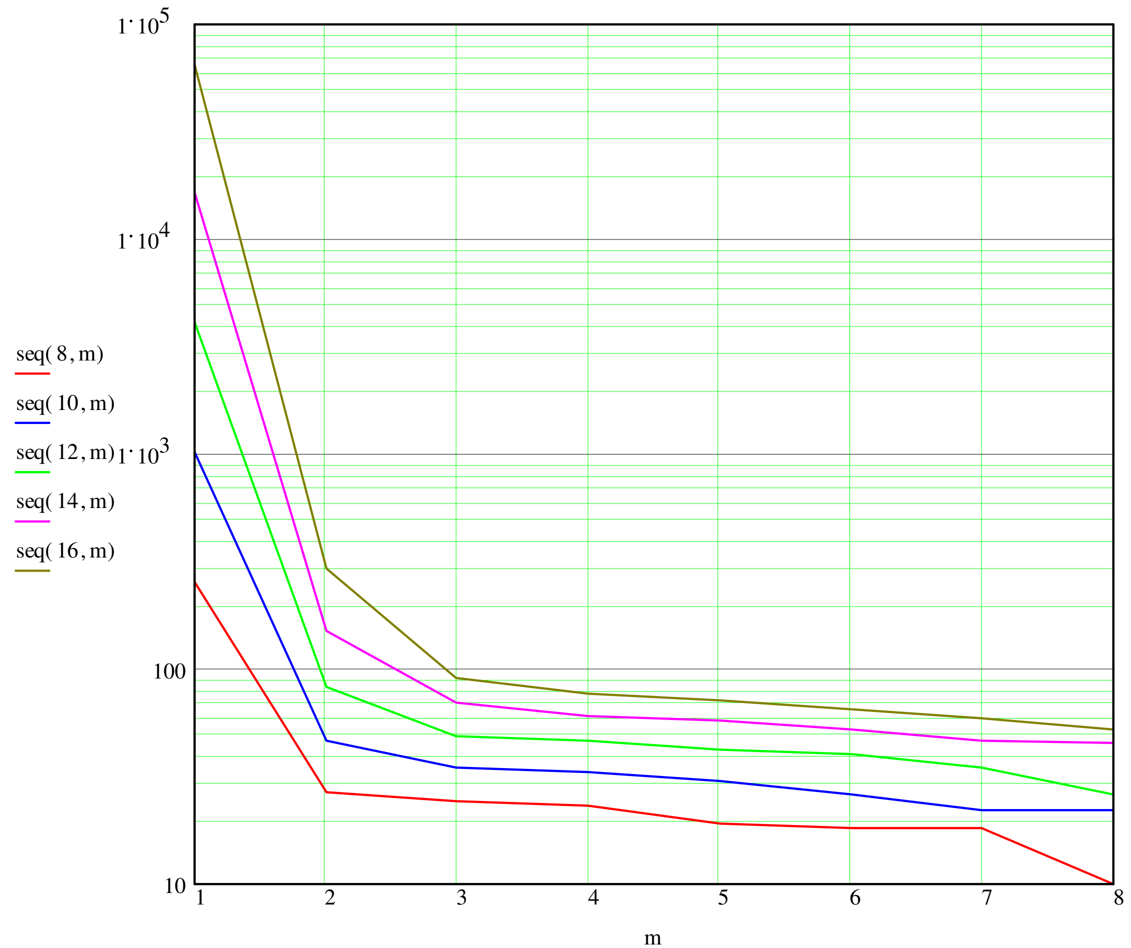
⇒ Very delicate above a few 10MHz

⇒ the same transmission line would be OK for the resulting digital data



Going Faster:
Going Digital

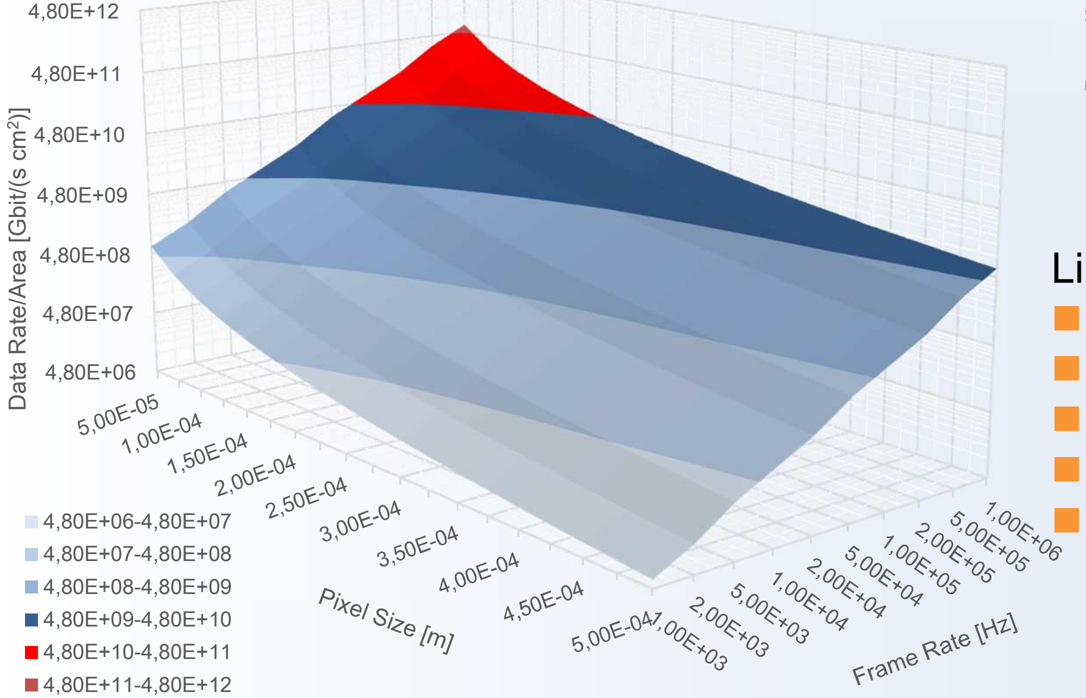
In-pixel digitisation architectures

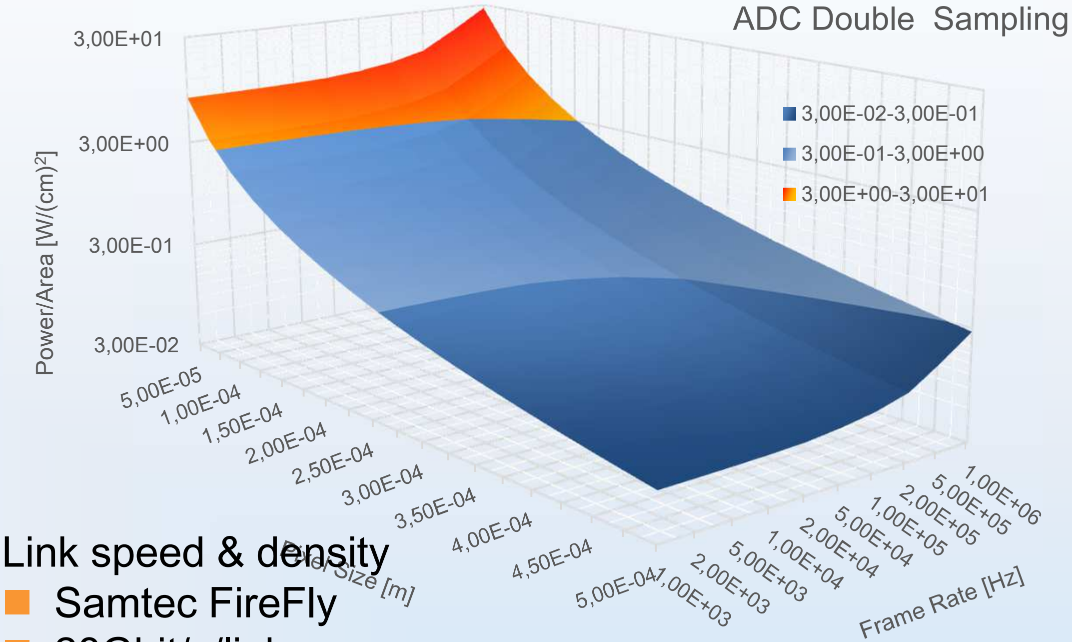


n^{th} Order Bitstream (ΔΣ)
16
f_{frame}
$\geq \sqrt[n]{2^{NoB}} \times f_{frame}$
$\geq \sqrt[n]{2^{NoB}} \times f_{frame}$ (before decimation filter)
Intrinsic
??(overhead)
(yes, digital)
Decimation filter, gain, (pulse shape analysis)
Simple analogue circuit, Low/no matching issues, noise shaping possible
Speed requirements, clock distribution, readout bandwidth

Going Faster:
Speed Limits

Power/area
- Dynamic gain switching
- Pixel size 50µm…500µm
- Digitisation with 16 bits
- at a frame rate of f_{ADC}
- Assumption: P=200µW+500pW/Hz



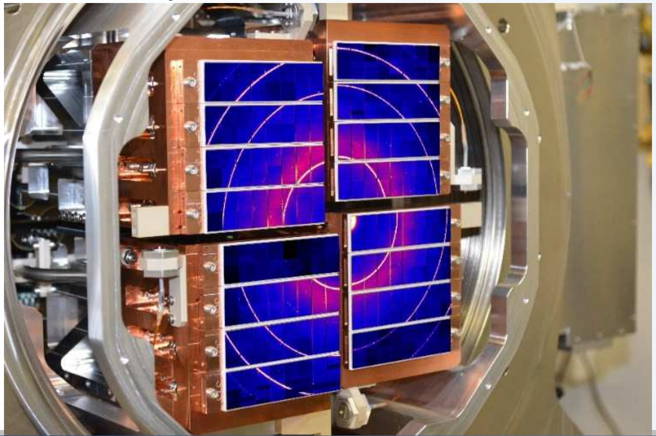


Link speed & density
- Samtec FireFly
- 28Gbit/s/link
- 24Gbit/s/link (net)
- 12 links/unit
- Footprint 20 x 30 mm²
  - 48Gbit/(s cm²)
  - 3Gs/(s cm²) (16bit/sample)
  - DAQ and analysis become „Big Data“ challenges

Summary & Outlook

AGIPD 1.1 (SPB/MID)
- System fulfils all requirements, esp. in terms of
  - Noise (<310e / <1.2 keV)
  - Single photon sensitivity
  - Dynamic range (>$10^4 \gamma$ @ 12.4keV)
  - Speed
- Both systems in user operation
- Issues with low/med gain discrimination
  - Mask fix (AGIPD 1.2) taped out 14. Aug. 2018
  - ≈30% better 'gain separation' in wafer test
  - Module production at IZM & ADVACAM under way

SFX AGIPD 4M and HiBEF 1M systems
- SW/FW development in progress
- Evaluation of advanced cooling concepts
- Both systems will be delivered with Silicon sensors & AGIPD 1.x ASICs



ecAGIPD for HiBEF
- Will replace Silicon sensors with High-Z ones
- Changes
  - Electron collecting preamp
  - Reversed polarity of discriminator
  - New calibration circuit
  - Use of twin wells
  - Reversed gain encoding levels
- AGIPD06
  - 16 x16 ecAGIPD prototype
  - Submitted 13.11.2017
  - Manufacturing @ GF only started end of March (30.03.18)
  - Silicon back since July
  - Working, characterisation ongoing
- Only peripheral routing missing for an 64x64 EcAGIPD

100kHz Imager for CW-XFEL and PETRA IV
- Concept studies
  - Dynamic gain switching
  - In-pixel ADC
  - High-speed serial link I/O
- More specs needed

http://photon-science.desy.de/research/technical_groups/detectors/projects/agipd