Detectors for the European XFEL

Markus Kuster

4th EIROforum School on Instrumentation 2015

ESO Garching

June, 18 2015

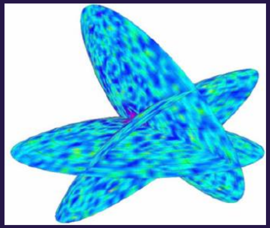
European XFEL

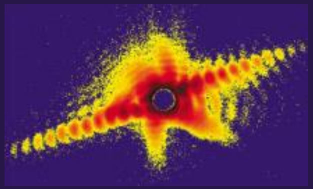
The Science Instruments at XFEL.EU

Hard X-Rays

SPB — **Single Particles, Clusters and Biomolecules and Serial Femtosecond Crystallography**

Structure determination of single particles: atomic clusters, bio-molecules, virus particles, and cells.



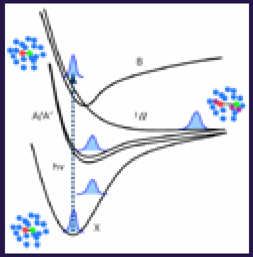


MID — **Materials Imaging & Dynamics**

Structure determination of nano-devices and dynamics at the nanoscale.

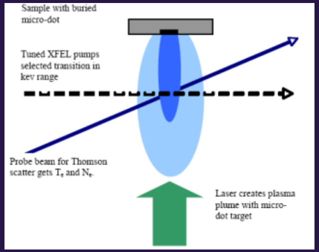
FXE — **Femtosecond X-ray Experiments**

Time-resolved investigations of the dynamics of solids, liquids, gases



HED — **High Energy Density Matter**

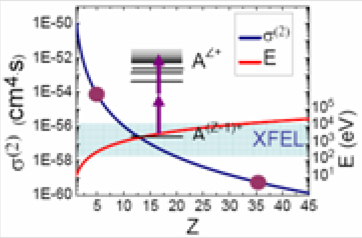
Investigation of matter under extreme conditions using hard X-ray FEL radiation, e.g. probing dense plasmas



Soft X-Rays

SQS — **Small Quantum Systems**

Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena



SCS — **Soft X-ray Coherent Scattering/Spectroscopy**

Electronic and real structure, dynamics of nano-systems and of non-reproducible biological objects

European XFEL

European XFEL Time Structure

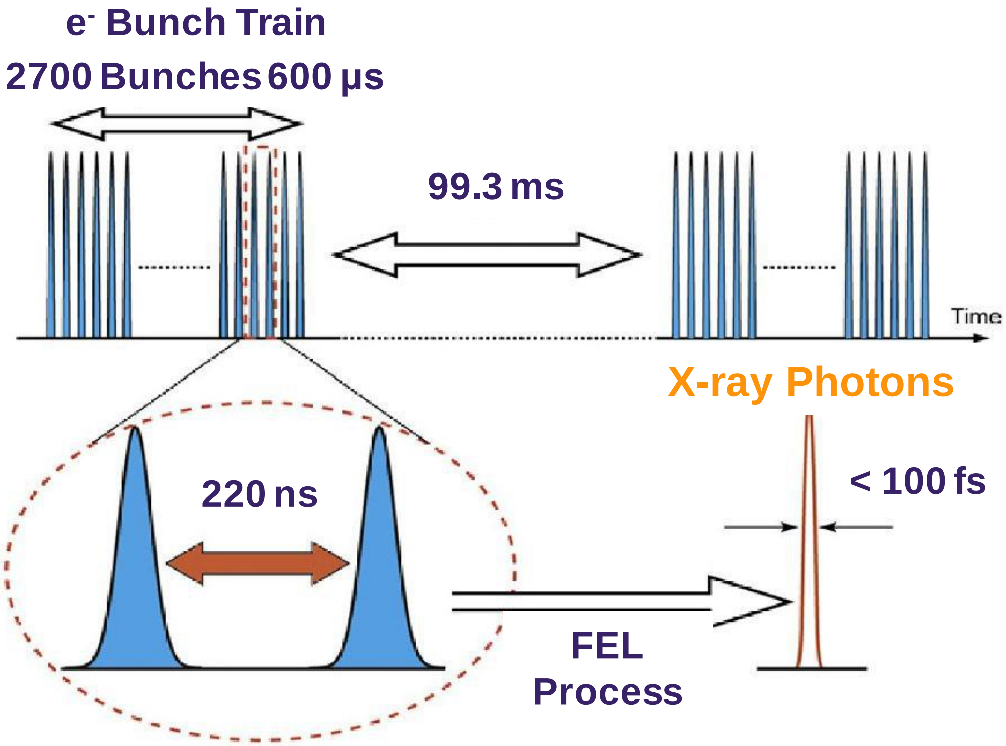
The European XFEL unique features poses strict constraints on detectors.

One of the main issues are the intensity and distinctive XFEL time structure.

Most of the time the use of commercial detectors is excluded.

Most applications require 4.5 MHz repetition rate detectors

e^- Bunch and X-ray Pulse Structure



On average up to 27.000 pulses/s

Pulse duration

< 100 fs

High peak intensities

up to 10^{12} photons/pulse

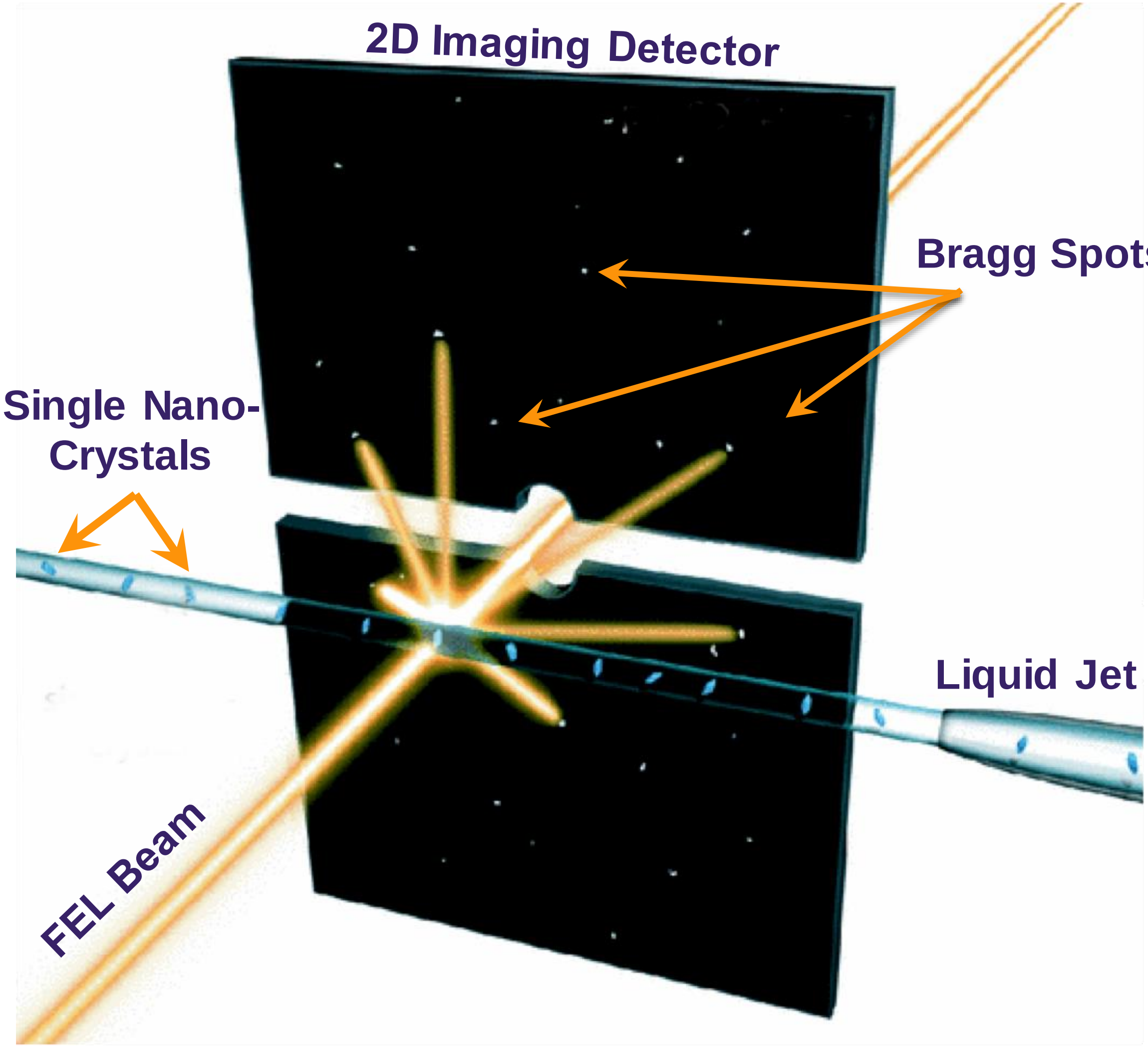
Various different pulse patterns possible

1 pulse per train

n pulses per train …

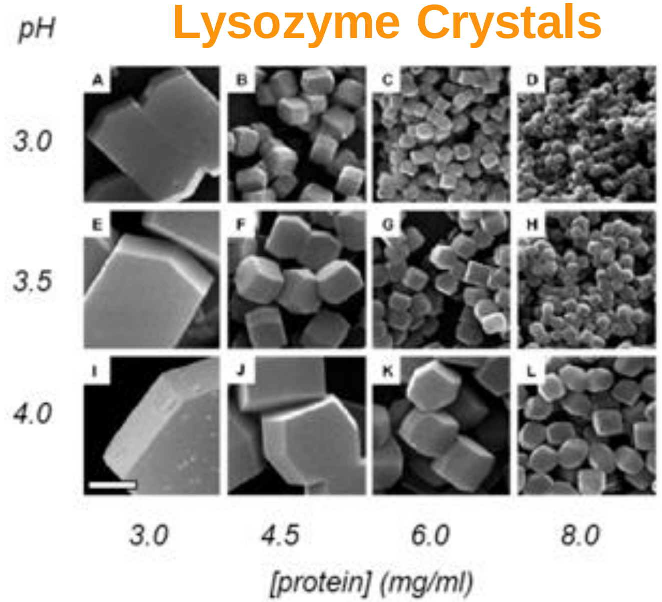
Linear, logarithmic or random distribution

SPB/SFX-I: Serial Femtosecond Crystallography



After Lukas Lomb *et al.*, Phys. Rev. B 84, 214111 (2011)

Lysozyme Crystals



Falkner, J. C., et al., *Chem. Mater.* **17**, 2679-2686 (2005)

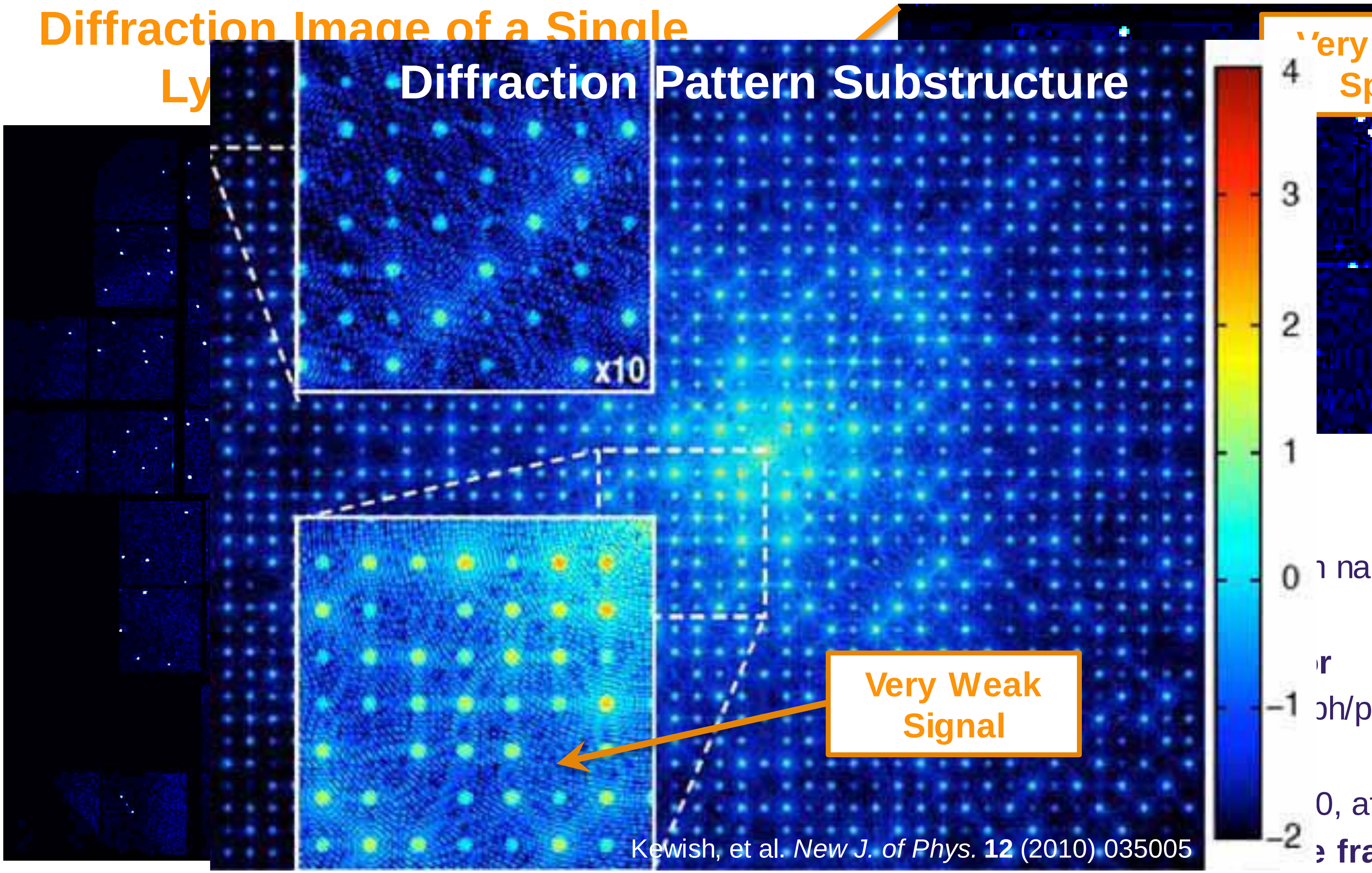
Experiment Parameters

Photon Energy Range	≈ 3 – 6 keV
Sample Size	0.1 – 2 µm
Desired max. Resolution	2 Å
Injection Method	Liquid Jets
Exp. Environment	

Vacuum $10^{-4} – 10^{-6}$ mbar

SPB/SFX-I: Serial Femtosecond Crystallography

Diffraction Image of a Single Ly



n nanocrystals

$> 10^4$

r

ph/pixel/pulse

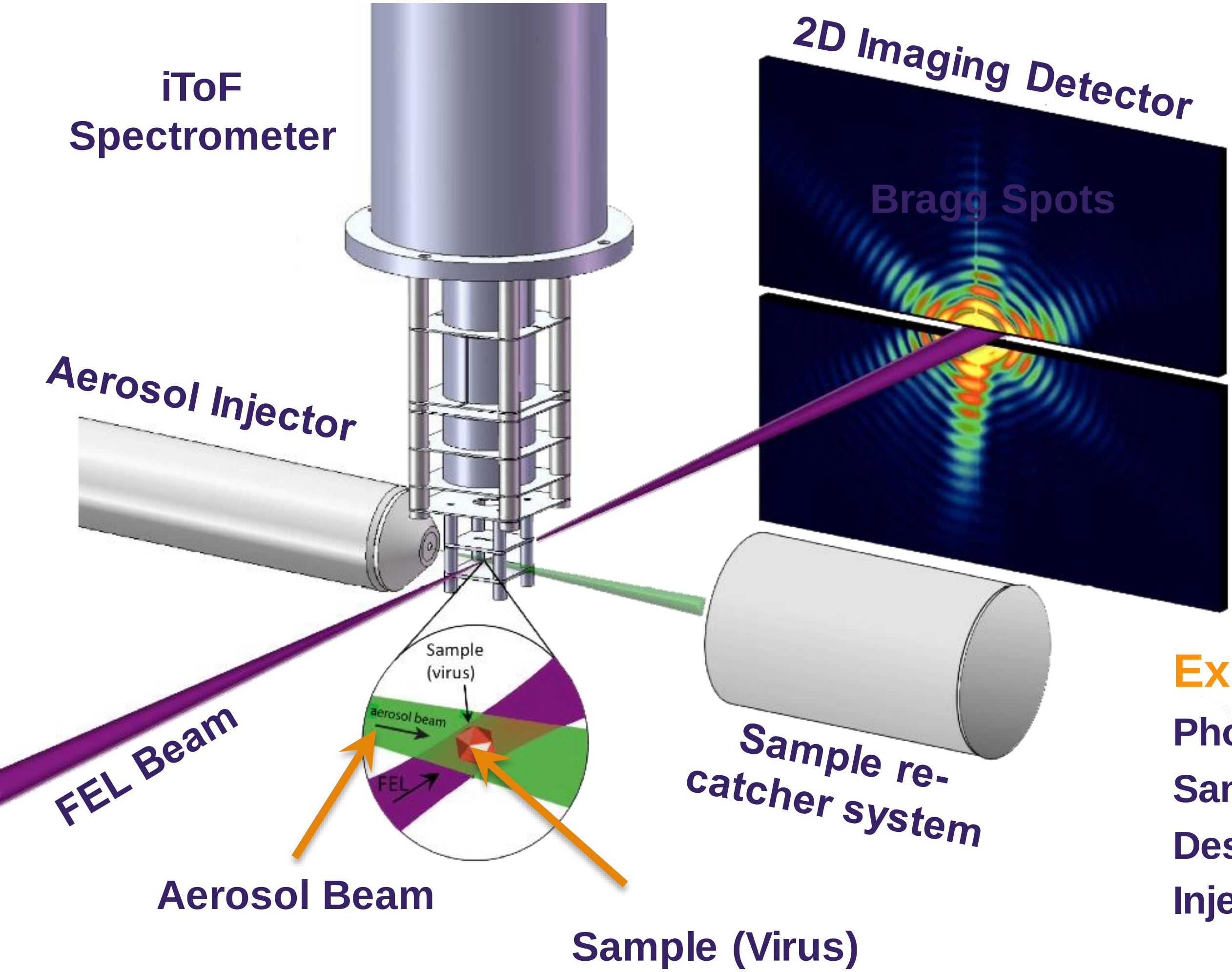
0, at least >5

e frame

Barty, A. et al. *J. Appl. Cryst.* (2014) 47, 1118-1131

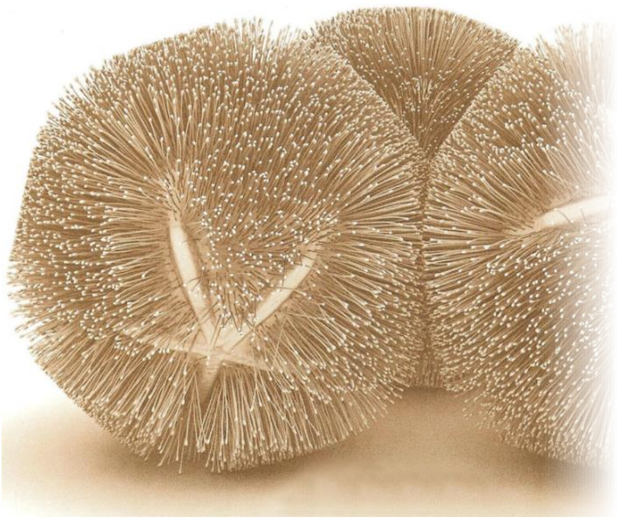
Integrated Bragg peak intensity + location

SPB/SFX-I: 2D Single Particle Imaging



After Andreasson, J. *et al.*, *Optics Express*, *22*(3), 2497-2510 (2014)

Mimivirus



Ghigo E *et al.*. PLoS Pathog 4(6) (2008)

Experiment Parameters

Photon Energy Range ≈ 3 – 6 keV

Sample Size 0.1 – 4 µm

Desired max. Resolution 2 Å

Injection Method

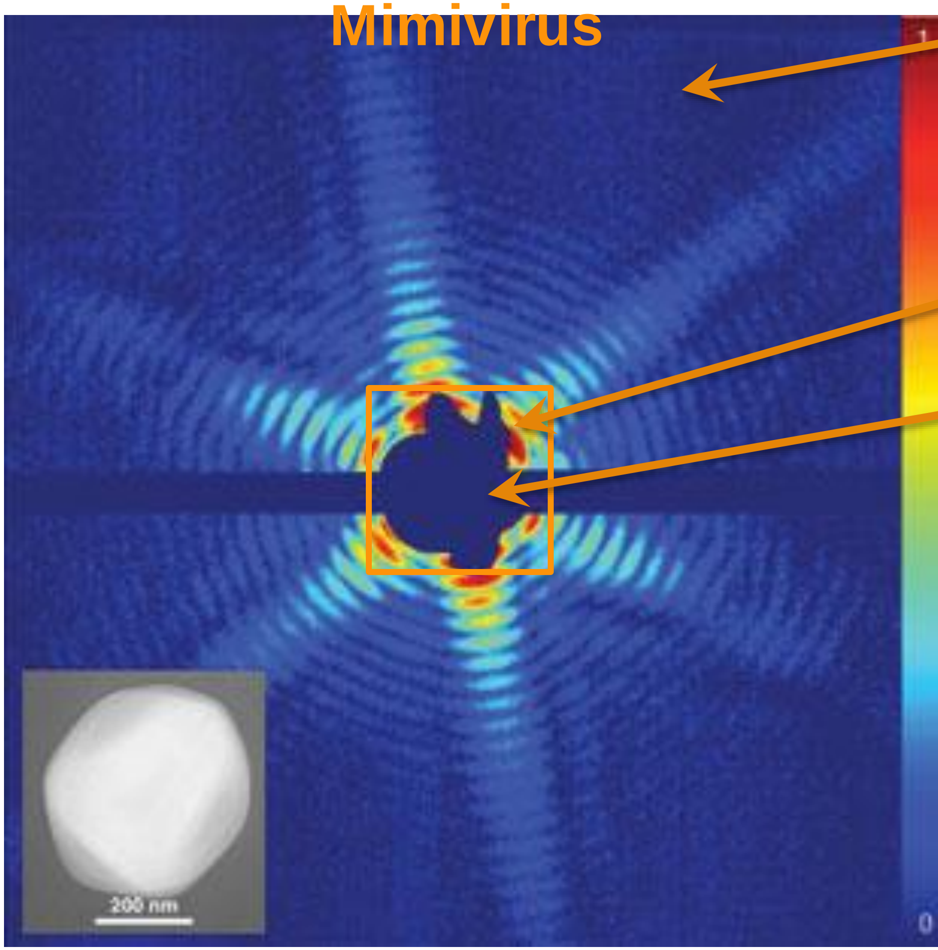
e.g. Aerosol Injector

Experimental Environment

Vacuum $10^{-4} – 10^{-6}$ mbar

SPB/SFX-I: 2D Single Particle Imaging

Diffraction Pattern of a Mimivirus



Single photon hits at high scattering angles

Very high intensity at central beam region

Hole for central FEL beam

Courtesy: J. Hajou

Experiment Parameters

Typical Samples
Biological organelles, small cells

Required #Images per Dataset 1

Signal level of interest at detector
$1 - 10^8$ ph/pixel/pulse and higher

Required sampling points per speckle >4

Information extracted from single frame
Full diffraction pattern

2D Imaging Detector Requirements

XFEL Pulse Structure

Single pulse imaging

Recoding 100 fs, readout 220 ns

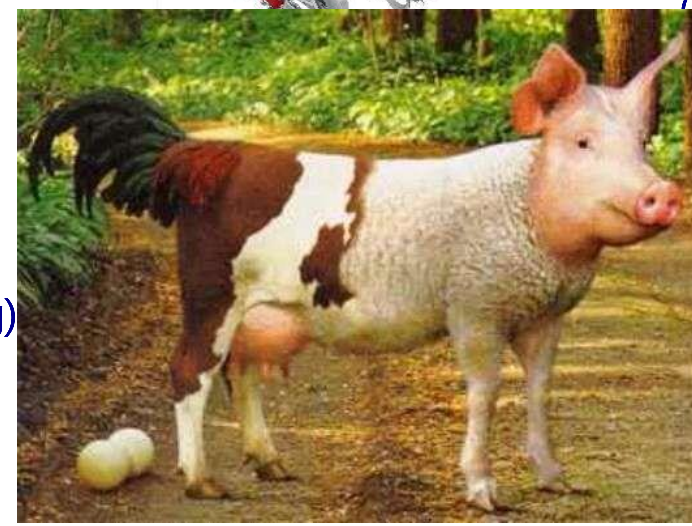
Storage of complete pulse train 2700 images

Dynamic Range

Single photon counting

(high q/single particle scattering)

Integration of up to 10^5 ph/pixel/pulse and more …



Sensitive Energy Range

0.25 (SQS, SCS) – 25 keV (MID, HED)

Ideally with same detector

Optimized entrance window for low photon energy

Radiation Hardness

Integrated energy dose over 3 years of operation

1 MGy – 1 GGy

Damage effects depend on energy range!

Graafsma, JINST 4 (2009) pp. 2011

Angular Resolution

7 mrad for FDE experiments

4 µrad for XPCS

(worst case at 10 cm distance)

Pixel size: 700 µm to 16 µm

(XPCS at 4 m distance)

Angular Coverage/ Sensor Size

ffraction experiments require solution of 0.1 nm

attering angles of 60° 20°)

Multiple detector segments

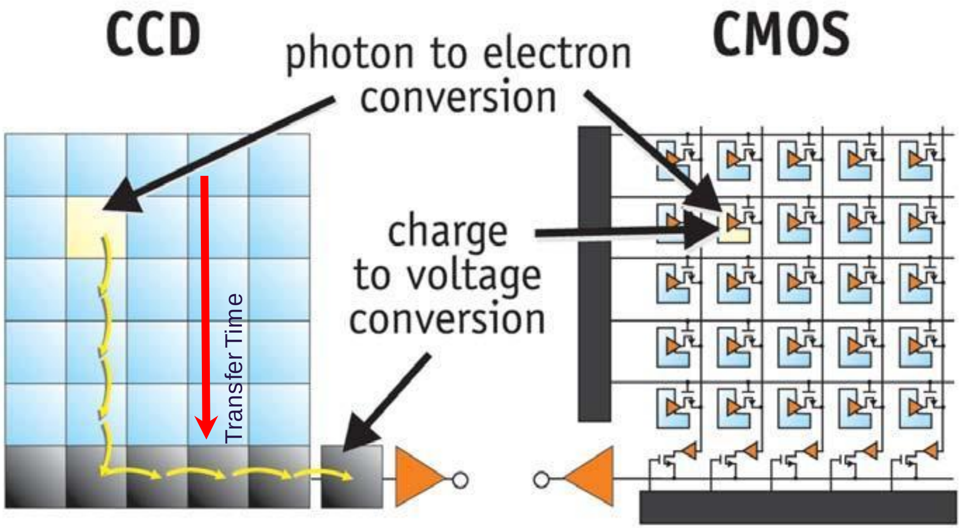
Main Scientific Applica-tions

MID, SCS, FXE, SPB and SQS

Match the environmental conditions

Vacuum ⟷ Ambient operation

Sensor Technology CMOS vs. CCD



D. Litviller, Photonics Spectra 2005

History

Both technologies developed in the late 1960s and early 1970s

Lithography limited at that time

→ CMOS performance limited

→ CCDs dominated the market

Situation changed when 250 nm, 180 nm, 130 nm processes became available

Active Pixel Sensors (CMOS)

- Fast readout up to MHz
- Reduced power consumption
- Various readout modes possible
  (any region on the sensor)
- Signal processing in pixel

→ storage, AD conversion, amplification

Charge Coupled Device (CCD)

Slow readout

few Hz to approx. 100 kHz possible

Low noise

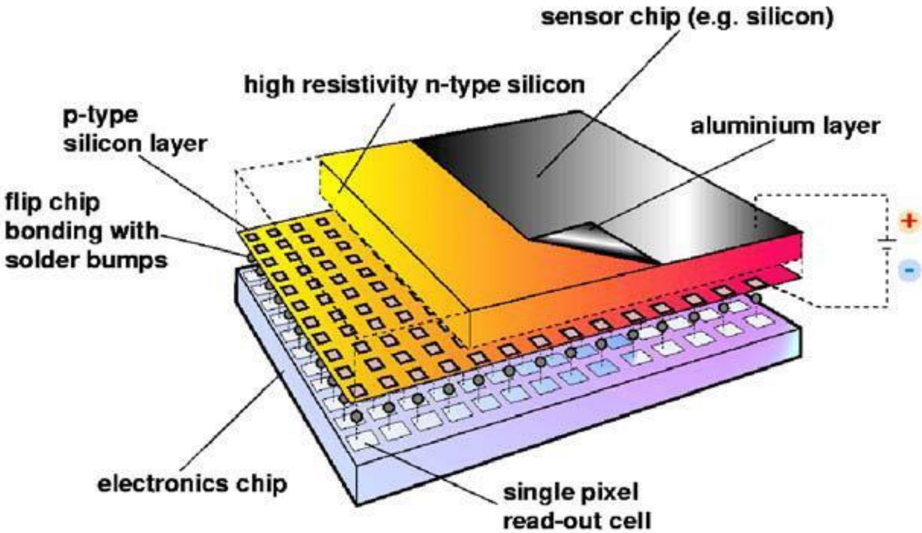
Radiation hard

(e.g. pnCCD technology)

High fill factor

Sensor Technology CMOS vs. CCD

Hybrid Pixel Sensor



History

Both technologies developed in the late 1960s and early 1970s

Lithography limited at that time

→ CMOS performance limited

→ CCDs dominated the market

Situation changed when 250 nm, 180 nm, 130 nm processes became available

Active Pixel Sensors (CMOS)

- **Fast readout up to MHz**
- Reduced power consumption
- Various readout modes possible

  (any region on the sensor)
- **Signal processing in pixel**

→ storage, AD conversion, amplification

Charge Coupled Device (CCD)

Slow readout

few Hz to approx. 100 kHz possible

Low noise

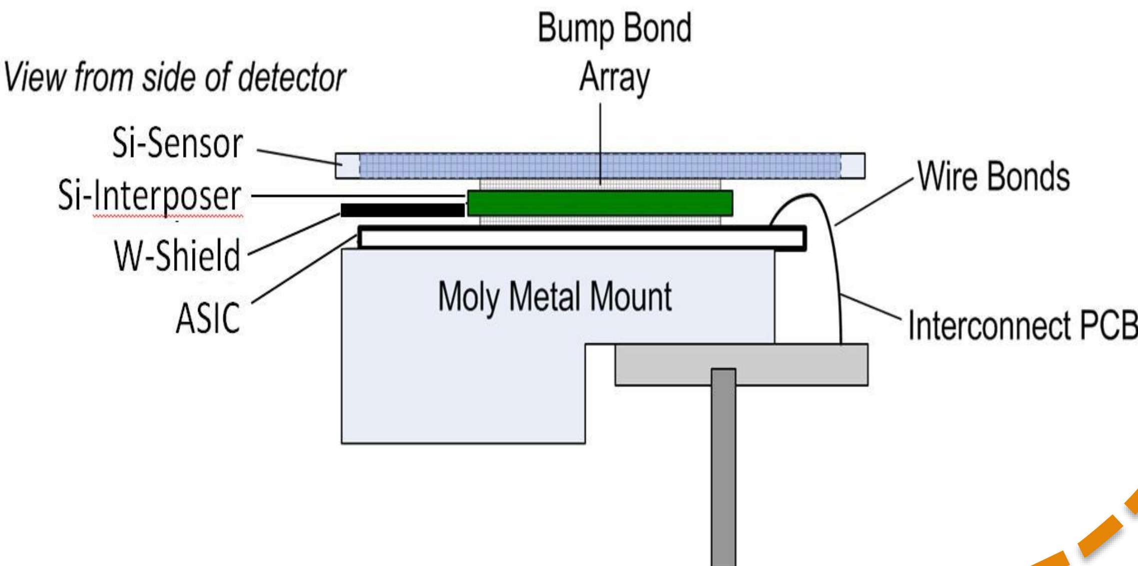
Radiation hard

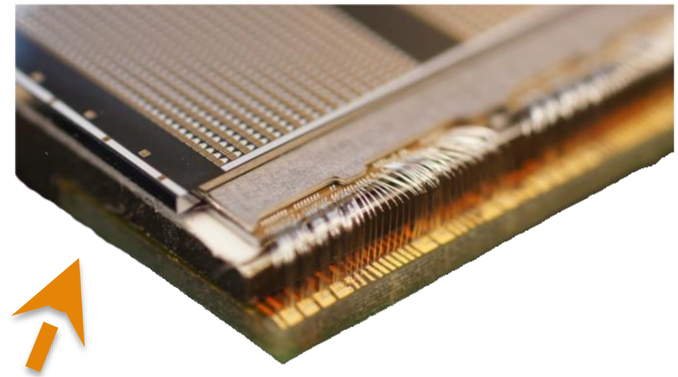
(e.g. pnCCD technology)

High fill factor

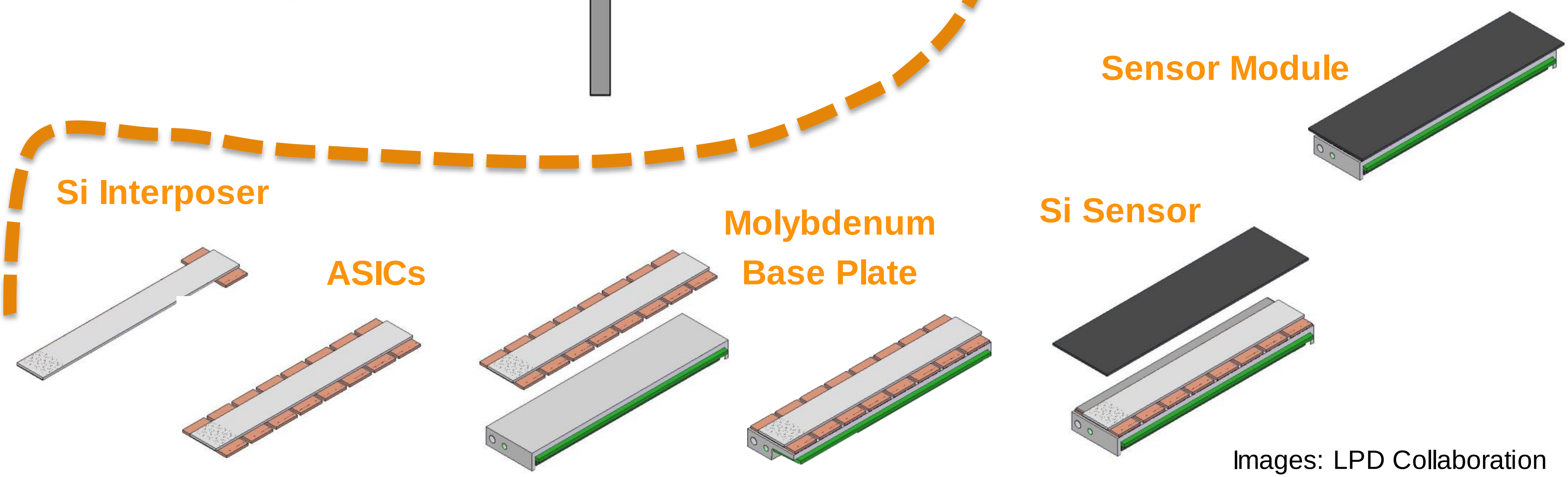
What Do You Need to Build a Sensor Module?

Example LPD Sensor Module



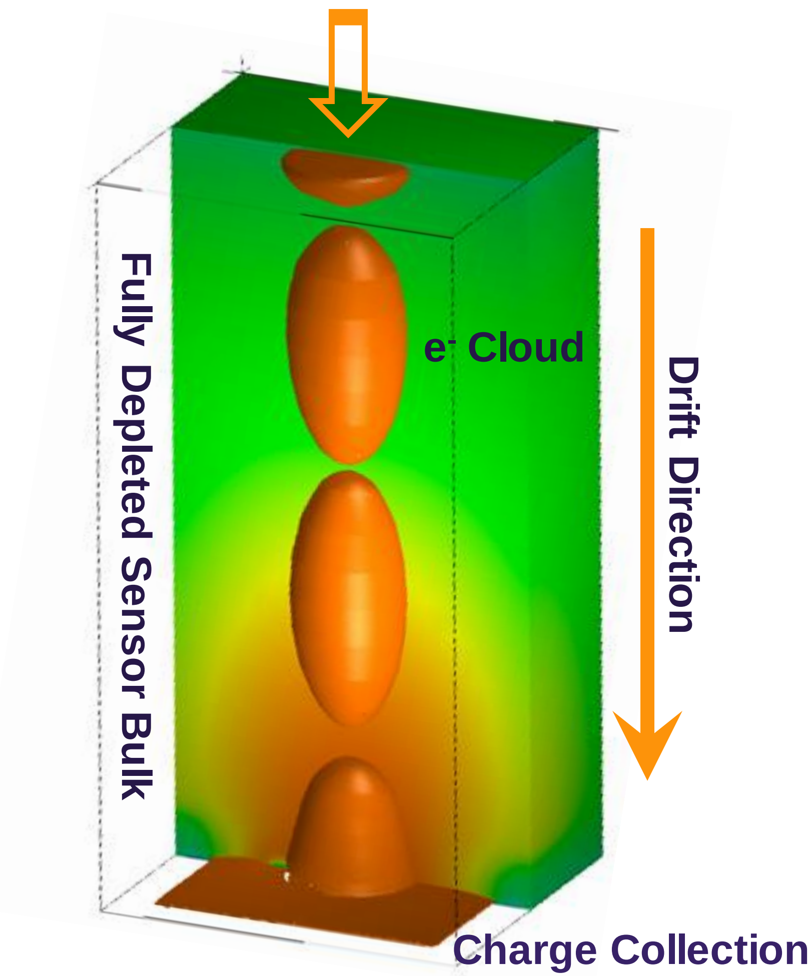


Wire bond and gold stud interconnect



Images: LPD Collaboration

Charge Transport in Silicon



Courtesy: WIAS Berlin

Electron hole pair creation at interaction point mainly through photoelectric absorption.

Motion of charge carriers due to external electric field $\vec{E}$ and the resulting charge density gradient $\frac{dn}{dx}$ leads to

Drift Current Density

$$\vec{J}_n = qn\mu_n\vec{E}$$

- n Electron density
- μ_n Mobility
- $\vec{E}$ Electric field

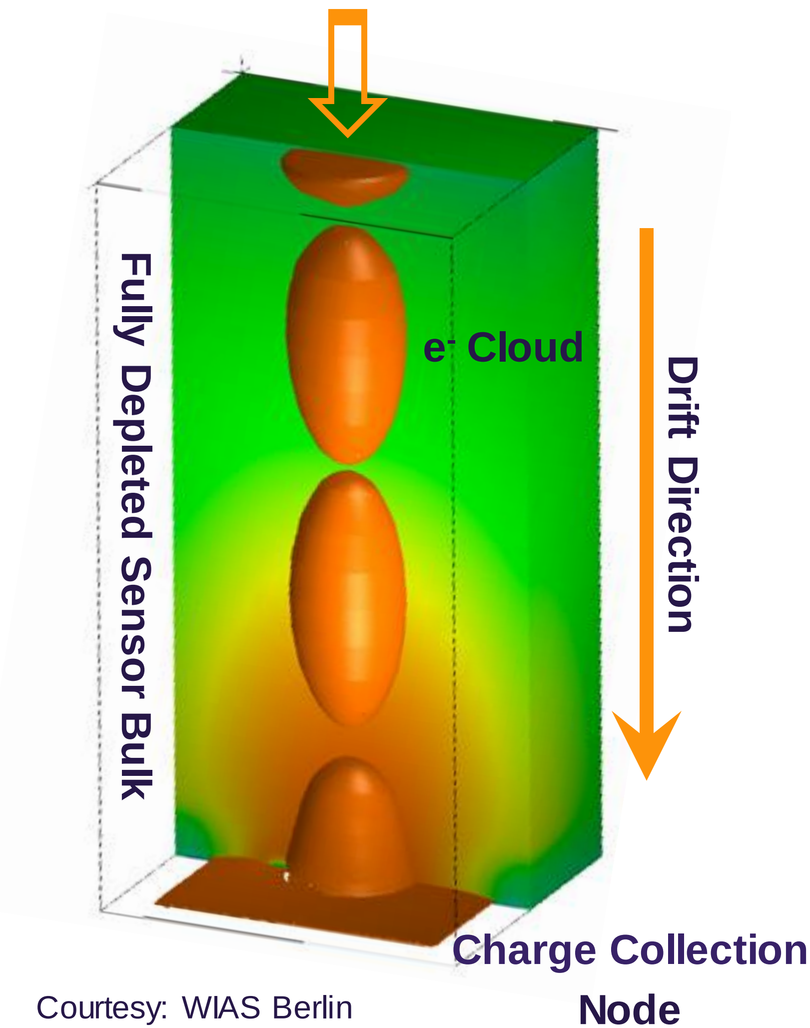
Diffusion Current Density

$$J_n = qD_n\frac{dn}{dx}$$

- D_n Diffusion constant
- $\frac{dn}{dx}$ Electron density gradient

Similar equations hold for holes, not shown here.

Charge Transport in Silicon



Courtesy: WIAS Berlin

Drift Velocity

$$\vec{v} = -\mu_n \cdot \vec{E}$$

$\vec{E}$ Electric field

μ_n Mobility

Mobility

$$\mu_n = \frac{e\tau_n}{m_n}$$

e Electron charge

τ_n Mean free time between collisions

m_n Eff. Mass of electrons

Typical values for Si at 300 K

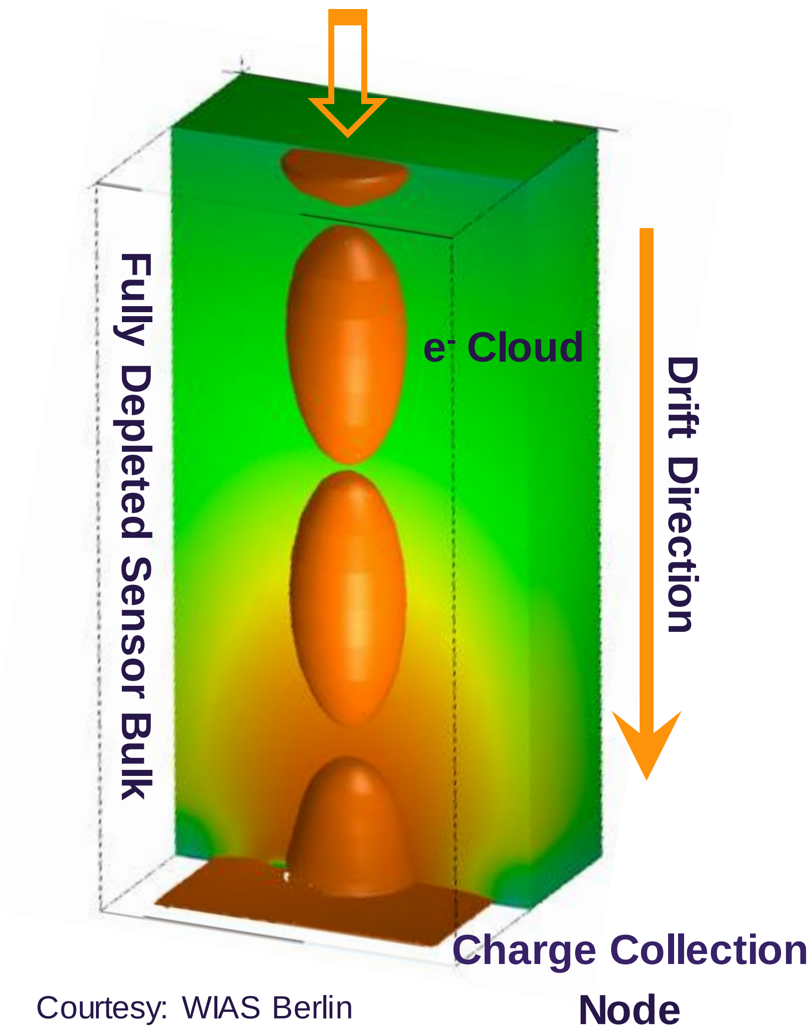
$$\mu_n \approx 1450 cm^2/Vs \qquad \mu_p \approx 450 cm^2/Vs$$

S.M. Sze, Semiconductor Devices, J. Wiley & Sons, 1985

The local drift velocity only depends on the electric field in the depleted volume.

Drift velocity defines the time until the charges reach the readout node.

Charge Collection Time



Courtesy: WIAS Berlin

Charge Collection Time

$$t(x) = \int_{x_0}^{x} \frac{1}{v(x)}\, dx$$

Typical values in n-type Si with a resistivity of 10 kΩ cm

$$t_{c,n} \approx 30 - 50 \text{ ns}$$

Approximate size of the charge cloud

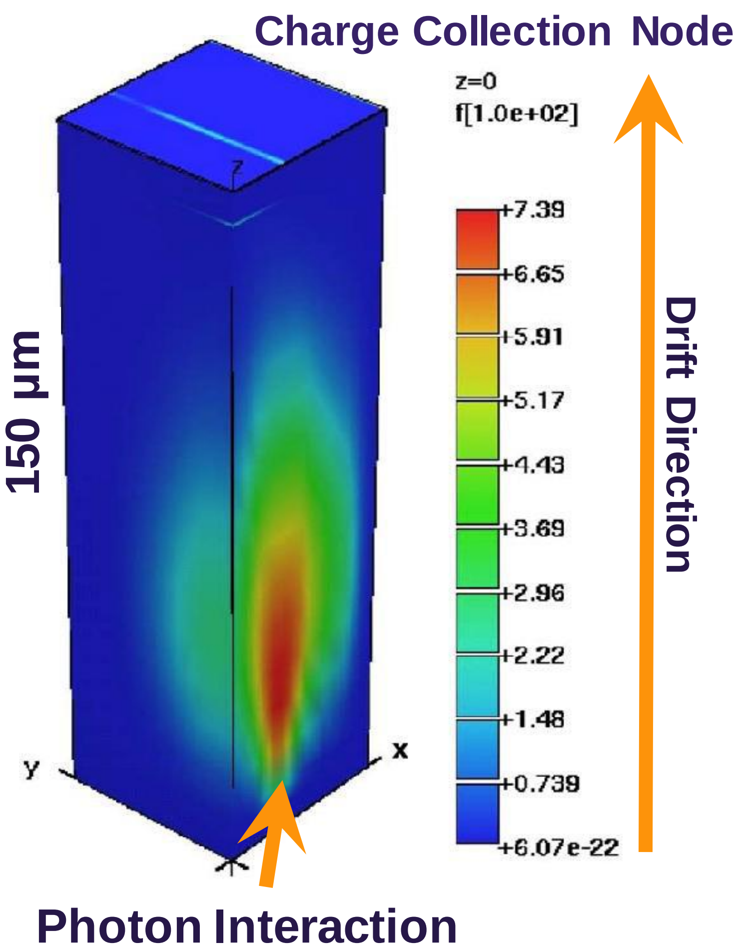
$$R_{el} \propto \rho^{-0.8} E_{el}^{1.3}$$

Typical values for a bias voltage of 300 V and 450 µm thick fully depleted sensitive volume

$$R_{el} \approx 20 - 30 \text{ µm}$$

Charge Transport in Silicon

e⁻ Charge Density



Strüder et al. NIM A (2010) vol. 614 pp. 483

Plasma Regime

XFEL pulse duration < 100 fs

→ energy deposition is instantaneous

At XFEL intensities electron hole pairs are not independent any more

→ plasma effects dominate

Plasma is quasi neutral

→ Ambipolar diffusion dominates over drift of charge carriers.

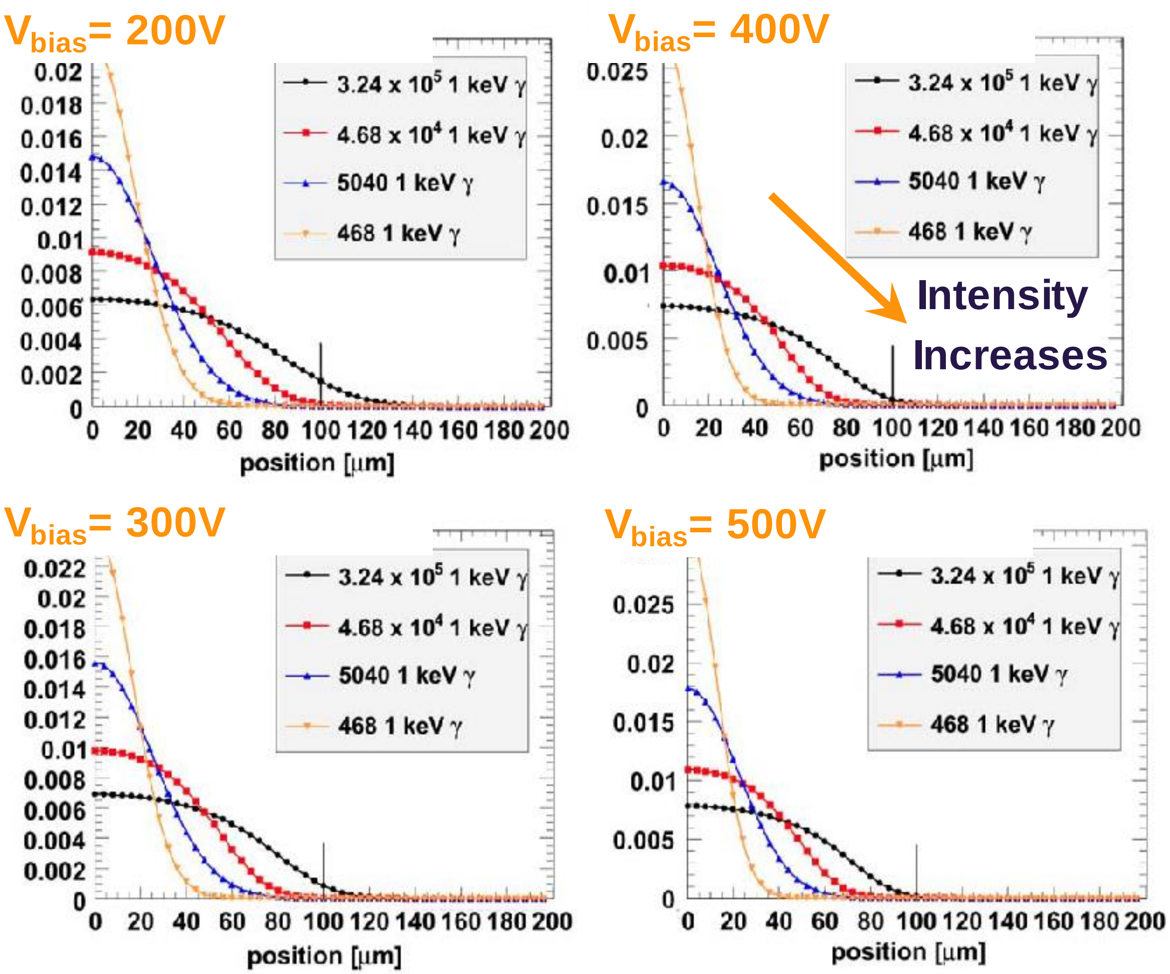
Effects dominate at high charge carrier densities, negligible at low charge carrier densities

→ **influence on PSF/charge sharing**

→ **influence on charge collection time**

Charge Transport in Silicon – Plasma Regime

1 keV Point Spread Function (I, V_{bias})



J. Becker et al. NIM A (2009) vol. 615 pp. 230

Parameter Dependance

High intensity > 10^3 ph/pix/pulse

→ more electron hole pairs

→ diameter of the PSF increases

Higher photon energy

→ more electron hole pairs

→ diameter of the PSF increases

Higher bias voltage

→ stronger electric field

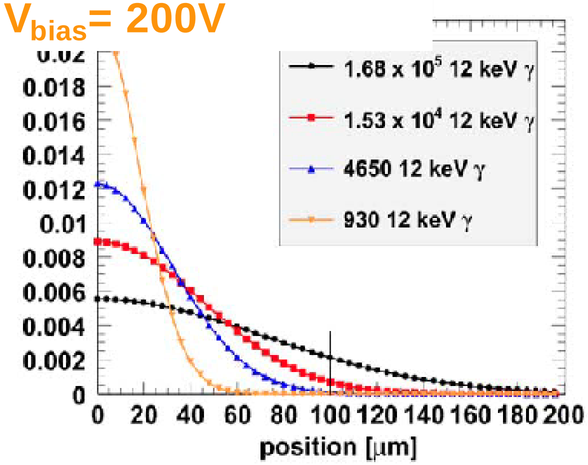
→ shorter drift time

→ diameter of the PSF decreases

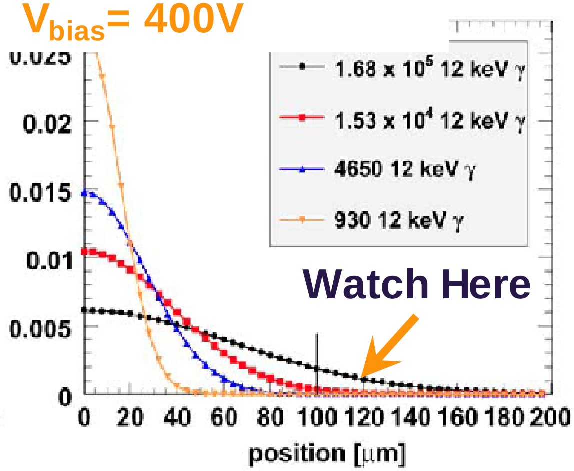
Charge Transport in Silicon – Plasma Regime

12 keV Point Spread Function (I, V_{bias})

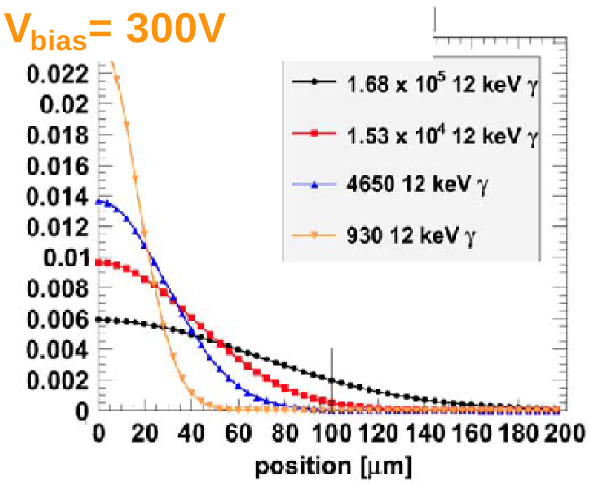
V_{bias}= 200V



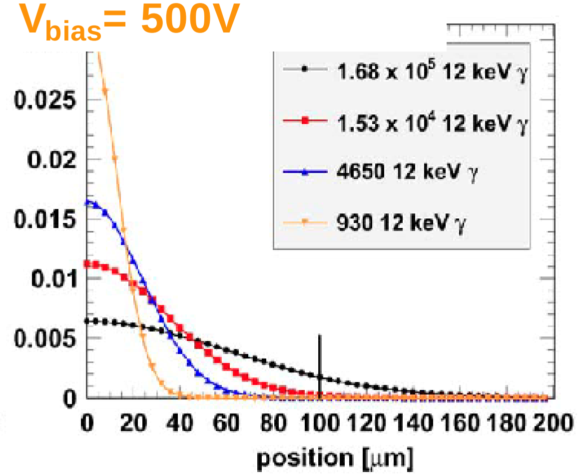
V_{bias}= 400V



V_{bias}= 300V



V_{bias}= 500V



J. Becker et al. NIM A (2009) vol. 615 pp. 230

Parameter Dependance

High intensity > 10^3 ph/pix/pulse

→ more electron hole pairs

→ diameter of the PSF increases

Higher photon energy

→ more electron hole pairs

→ diameter of the PSF increases

Higher bias voltage

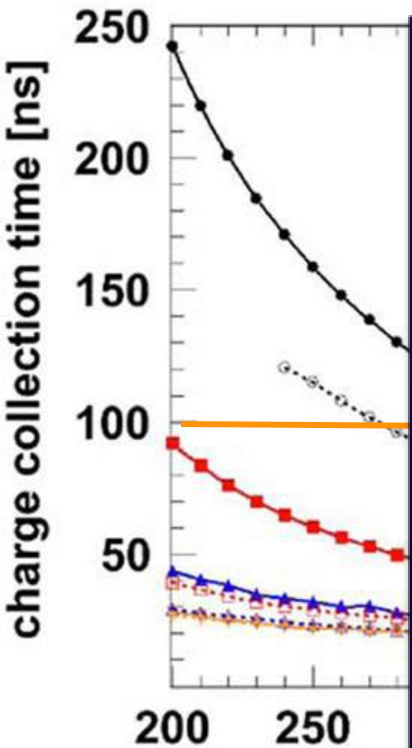
→ stronger electric field

→ shorter drift time

→ diameter of the PSF decreases

Charge Transport in Silicon – Plasma Regime

Charge Collection Time



Conclusions

→ At photon intensities > 10^3 ph/pix/pulse the spatial resolution is dominated by plasma effects not by the pixel size

→ Charge collection time is significantly longer in comparison to low intensity regime

→ Operating at higher bias voltage can partially compensate for the observed effects

→ For pixel sizes > 200 x 200 μm^2 observed effects are not critical, fine tuning is possible

Parameter Dependance

High intensity > 10^3 ph/pix/pulse
→ more electron hole pairs
→ diameter of the PSF increases

Higher photon energy
→ more electron hole pairs
→ diameter of the PSF increases

Higher bias voltage
→ stronger electric field
→ shorter drift time
→ diameter of the PSF decreases

Remember

Due to XFEL time st

$t_{collection} + t_{amplification} + t_{storeage}$ = 220 ns

J. Becker et al. NIM A (2009) vol. 615 pp. 230

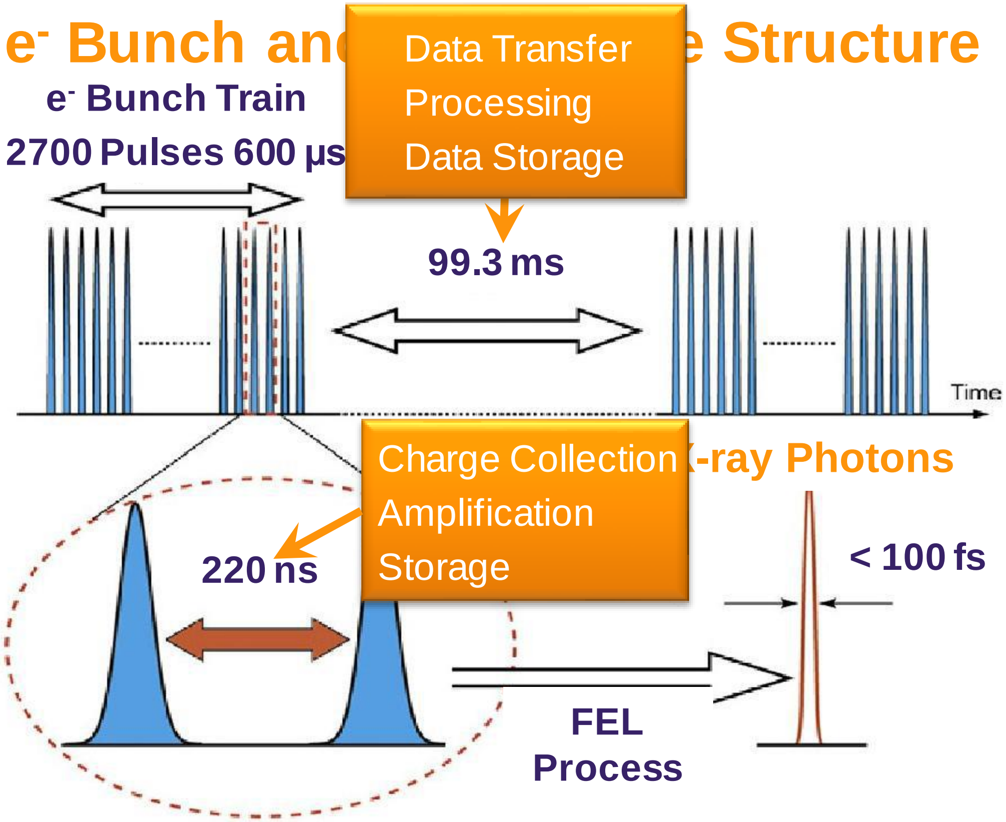
European XFEL Time Structure

The European XFEL unique features poses strict constraints on detectors.

One of the main issues are the intensity and distinctive XFEL time structure.

Most of the time the use of commercial detectors is excluded.

Most applications require 4.5 MHz repetition rate detectors



Single shot imaging requires ultra fast read out and processing of the signal:

Charge collection

60-70 ns

Charge clearing

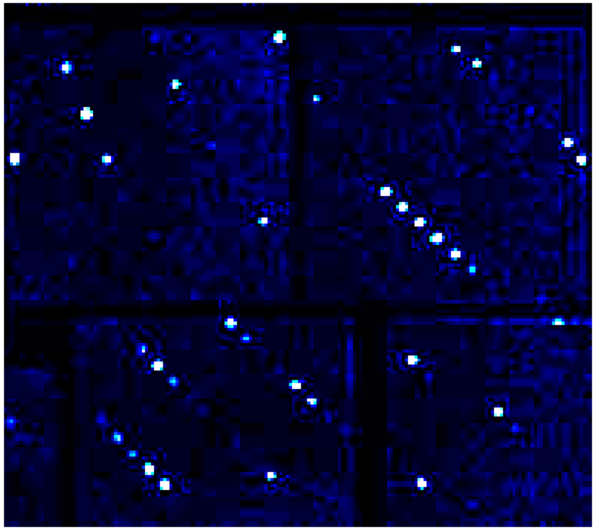
60-70 ns

Read-out

40-70 ns

On sensor electronics + memory

Dynamic Range



Ability of a detector system to record simultaneously very low signals alongside very intense signals.

Definition

$$D = \frac{S_{max}}{\sigma_{Tot}}$$

S_{max} Maximum detectable signal

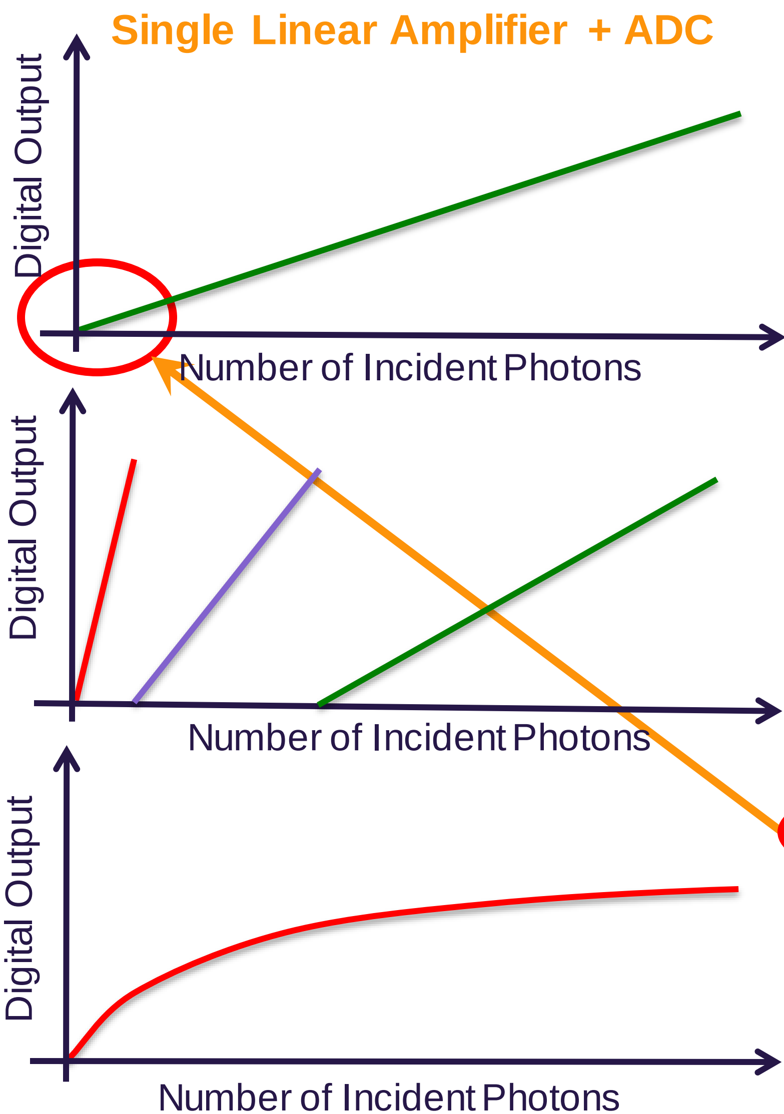
σ_{Tot} Total noise

Noise performance determines dynamic range at low intensities and full well capacity at high intensities.

Typical Values

Detector	Full Well Capacity [e⁻]	Read Noise [e⁻]	Dynamic Range
Human Eye			10^2 (stat) 10^{14} (dyn)
Modern CCDs	30.000-500.000	2 – 25	≈1.000 – 50.000

The Dynamic Range



The Problem

Measure single photons and high intensities (10^4-10^5 ph/pixel/pulse) in the same image at the same time (no averaging).

Single Linear Amplifier + ADC

Adjust output voltage range of amplifier to input of ADC.

→ equidistant sampling of whole dynamic range

Example: detect 1 and 10.000 photons

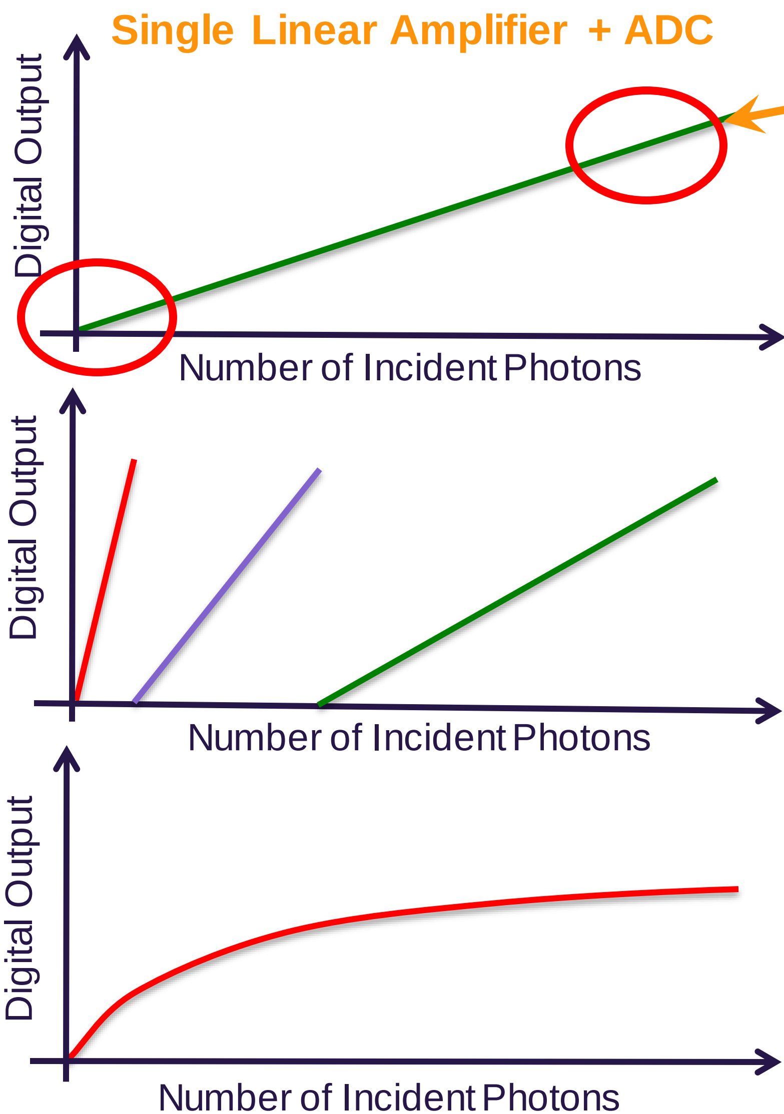
Use a 12 Bit ADC → 4096 sampling steps

Low Intensities

Tune amplifier such that LSB corresponds to 1 photon and bin width = 1 photon

→ saturation at max. of 4096 photons

The Dynamic Range



Example (continued …)

High Intensities

Tune amplifier such that MSB corresponds to 10.000 photons

Since large signals are dominate by Poissonian/shot noise $s_{Stat} \mu \sqrt{n}$

→ use bin width corresponding to 100 photons

→ problem at low end of the dynamic range

Conclusion

- Small signals need to be measured with high precision

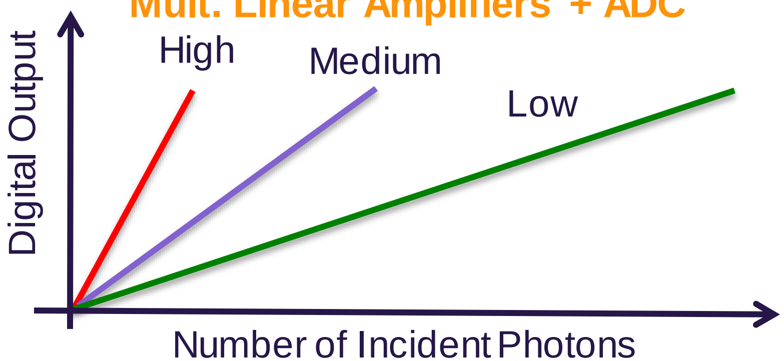
  distinguish 1, 2, 3, 4 … photons

- Large signals need to be measured with low precision not better than $\mu \sqrt{n}$

The Dynamic Range

Possible Solutions

Mult. Linear Amplifiers + ADC



Multiple parallel amplification stages

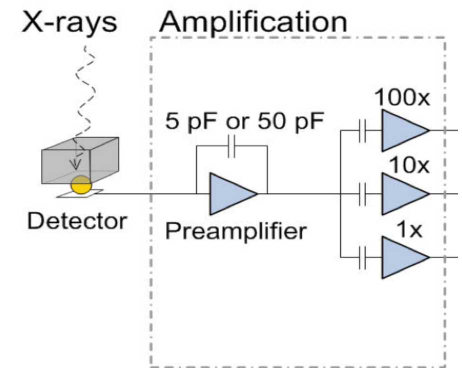
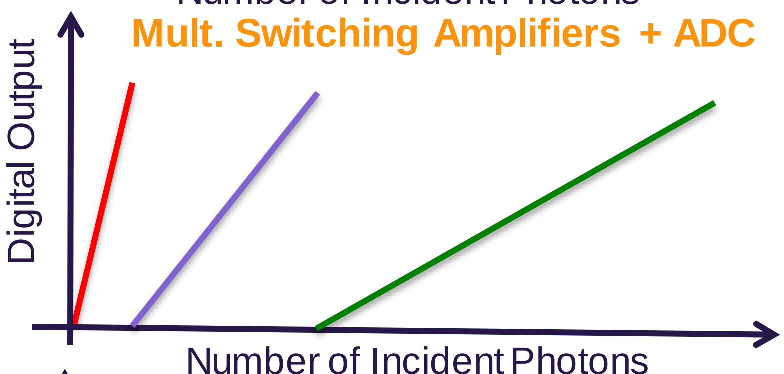


Image:RAL

Mult. Switching Amplifiers + ADC



Gain switching or charge resetting mechanism

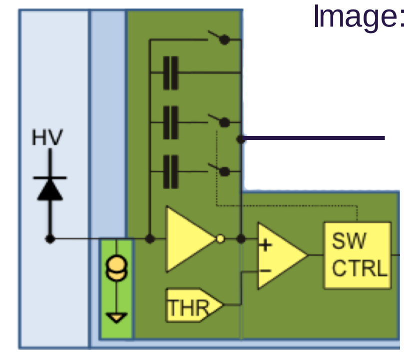
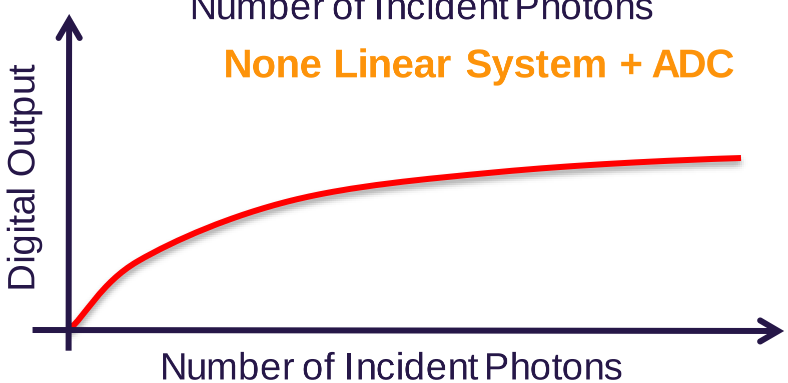


Image: AGIPD Collaboration

None Linear System + ADC



Non linear component on front-end or sensor level (sensor, preamplifier)

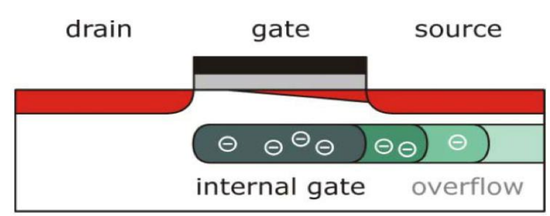
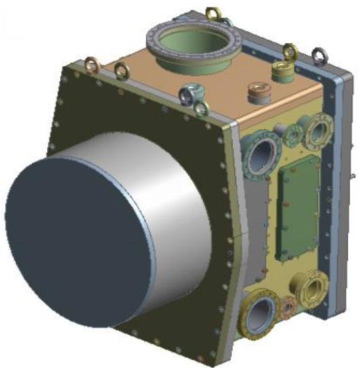


Image: DSSC Collaboration

Detectors for Day One Operation at XFEL.EU

Adaptive Gain Integrating Pixel Detector (AGIPD)



Energy Range 3 – 13 (25) keV

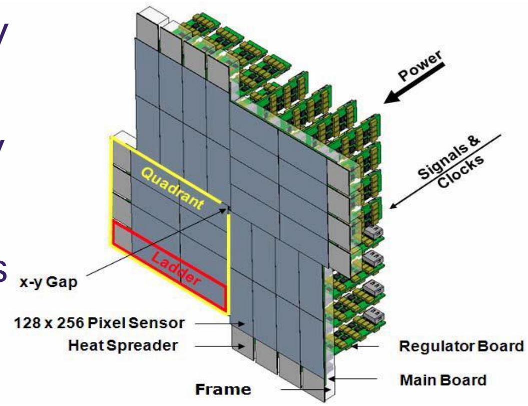
Dynamic Range 10^4 ph/px/pulse@12 keV

Single Photon Sens. Yes

Memory ≈380 images

Pixel Size 200 × 200 µm²

DePFET Sensor with Signal Compression (DSSC)



Energy Range 0.5 – 6 (25) keV

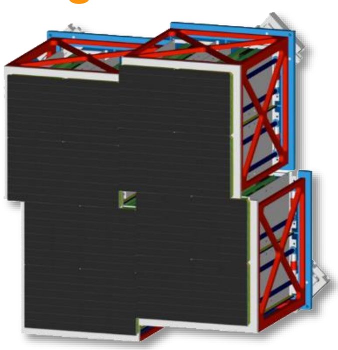
Dynamic Range 6000 ph/px/pulse@1 keV

Single Photon Sens. Yes

Memory ≈800 images

Pixel Size 236 × 236 µm²

Large Pixel Detector (LPD)



Energy Range 3 – 13 (25) keV

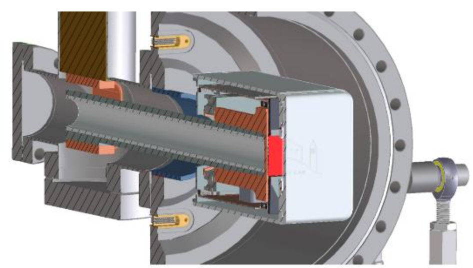
Dynamic Range 10^5 ph/px/pulse@12 keV

Single Photon Sens. Yes

Memory ≈512 images

Pixel Size 500 × 500 µm²

FastCCD



Energy Range 0.25 – 6 keV

Dynamic Range ≈100 ph/px/pulse@0.5 keV

Single Photon Sens. Yes

Memory No

Pixel Size 30 × 30 µm²

Detectors for Day One Operation at XFEL.EU

Adaptive Gain Integrating Pixel De-

AGIPD Adaptive Gain Integrating Pixel Detector Consortium (AGIPD)

Project Leader: H. Graafsma, DESY

PSI/SLS Villingen, Universität Bonn, Universität Hamburg, DESY

Yes

Memory ≈380 images

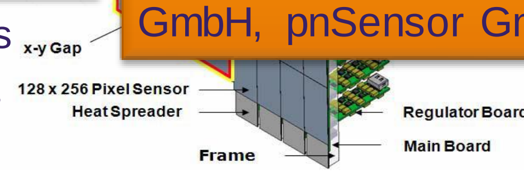
Pixel Size 200 × 200 µm²

DePFET Sensor with Signal Compre-

DEPFET Sensor with Signal Compression Consortium (DSSC)

Project Leader: M. Porro, MPE

Università Heidelberg, Politecnico di Milano, Università di Bergamo, DESY, European XFEL GmbH, pnSensor GmbH



Memory ≈800 images

Pixel Size 236 × 236 µm²

Large Pixel Detector (LPD)

Large Pixel Detector Consortium (LPD)

Project Leader: M. French, RAL/STFC

Rutherford Appleton Laboratory/STFC

University of Glasgow

Memory ≈512 images

Pixel Size 500 × 500 µm²

FastCCD

Fast CCD

Peter Denes, John Joseph, Dionisio Doering, Nord Andersen LBNL

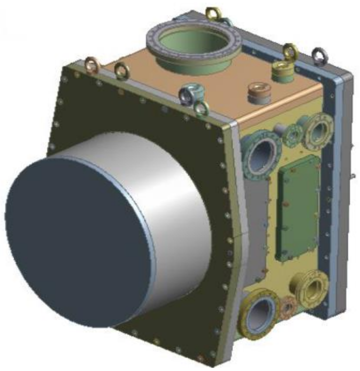
Single Photon Sens. Yes

Memory No

Pixel Size 30 × 30 µm²

Detectors for Day One Operation at XFEL.EU

Adaptive Gain Integrating Pixel Detector (AGIPD)



Energy Range 3 – 13 (25) keV

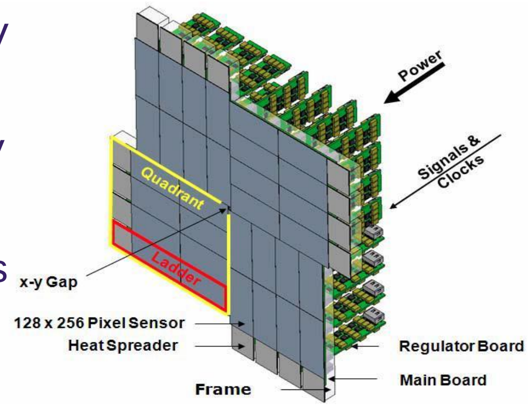
Dynamic Range 10^4 ph/px/pulse@12 keV

Single Photon Sens. Yes

Memory ≈380 images

Pixel Size 200 × 200 µm²

DePFET Sensor with Signal Compression (DSSC)



Energy Range 0.5 – 6 (25) keV

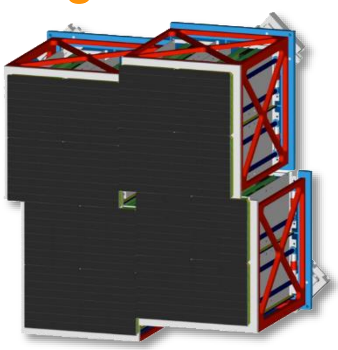
Dynamic Range 6000 ph/px/pulse@1 keV

Single Photon Sens. Yes

Memory ≈800 images

Pixel Size 236 × 236 µm²

Large Pixel Detector (LPD)



Energy Range 3 – 13 (25) keV

Dynamic Range 10^4 ph/px/pulse@12 keV

Single Photon Sens. Yes

Memory ≈512 images

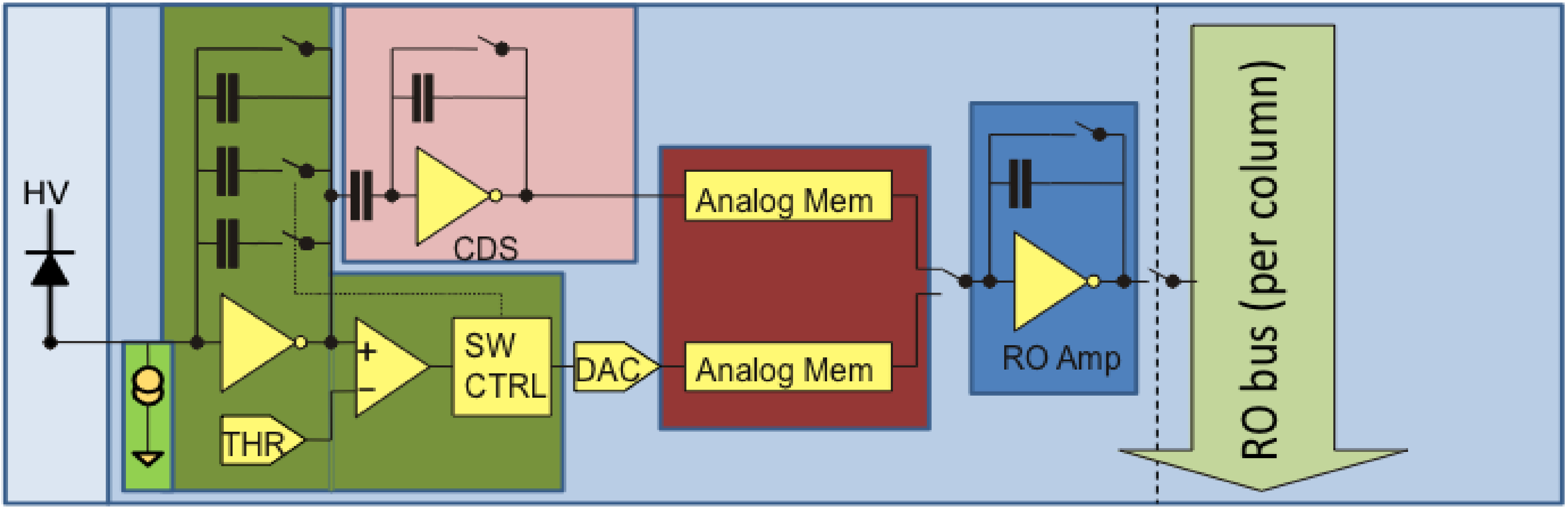
Pixel Size 500 × 500 µm²

Other Detectors

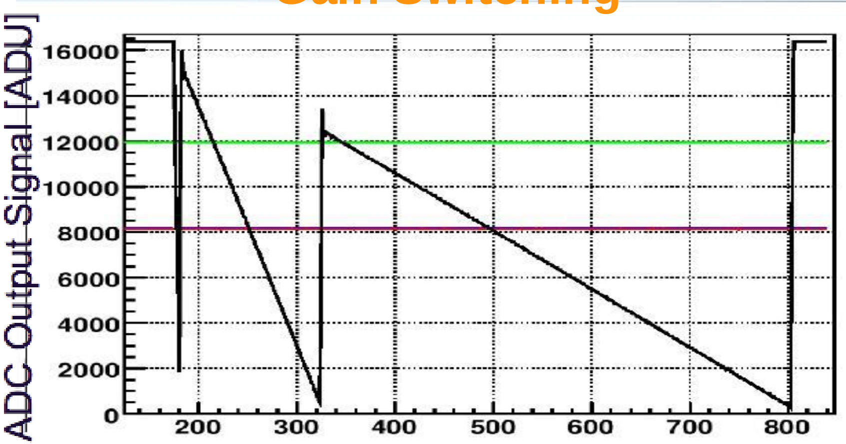
- 1D detectors for high repetition rate applications
- Small area, low repetition rate, low energy 2D detectors
- CCDs for low speed imaging
- Point like detectors for veto applications

European XFEL

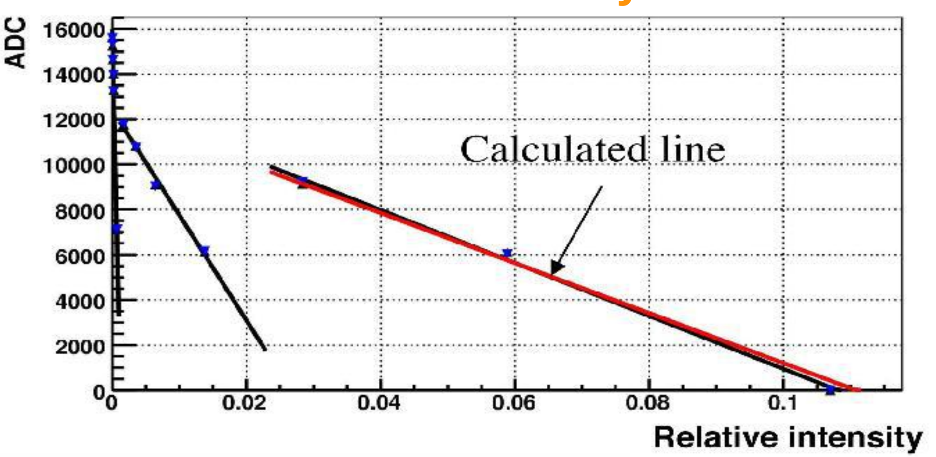
AGIPD – Gain Switching Concept



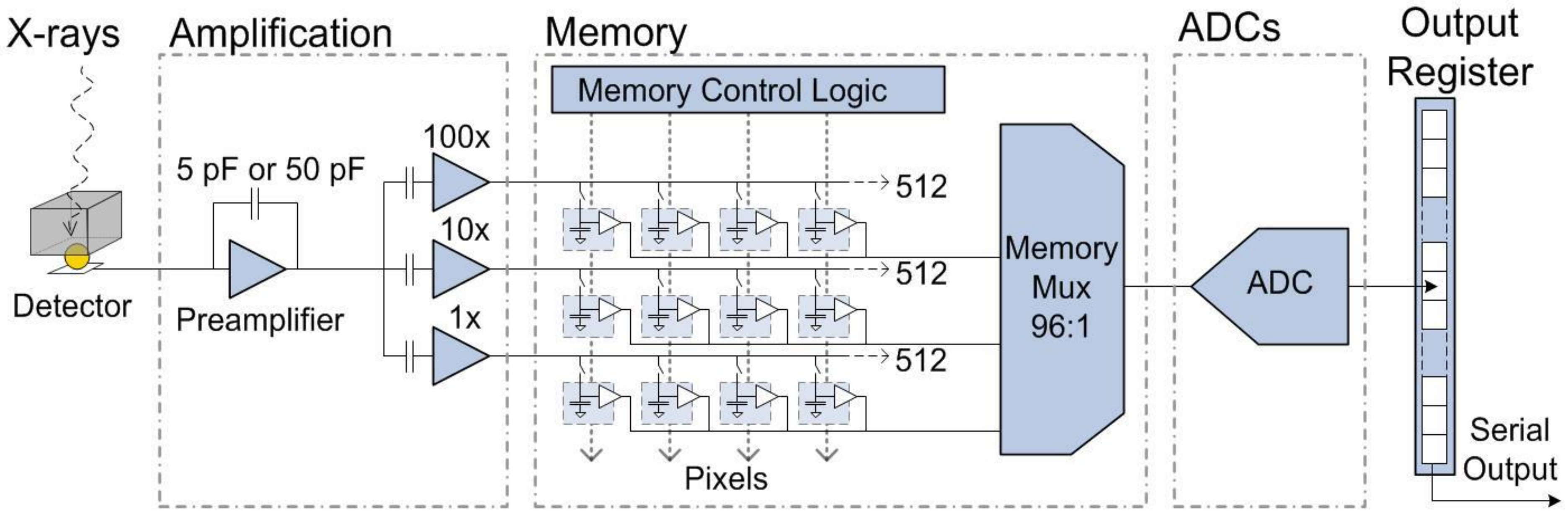
Gain Switching



Gain Linearity

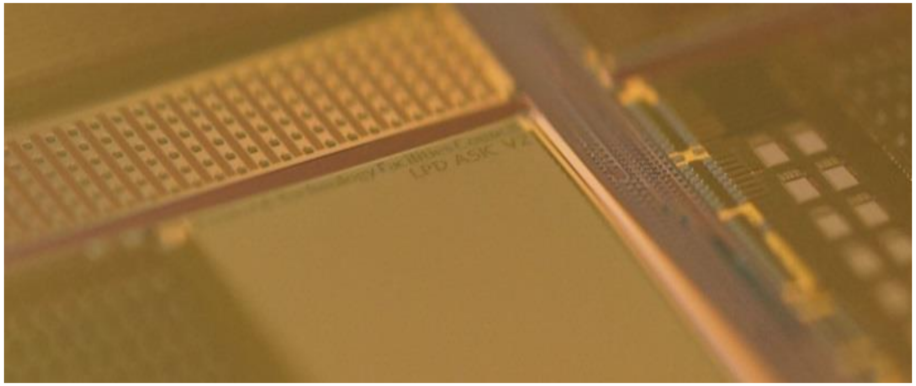


Large Pixel Detector – Pixel Cell and ASIC



LPD ASIC V2

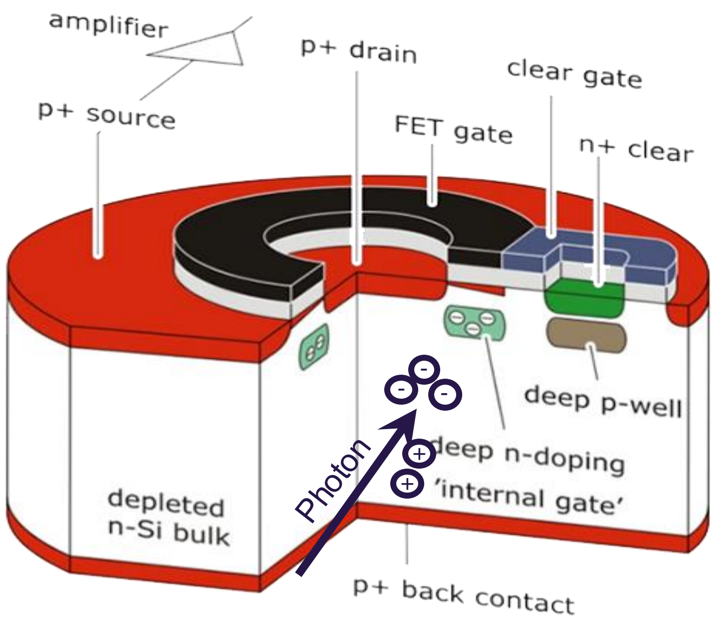
- Adjustable dynamic range
- 3 fold multi-gain concept and analog storage (1x,10x,100x)
- 512 images memory depth with veto (trigger)
- 16x 12 Bit on chip ADCs



Images: LPD Collaboration

Standard DePFET without Signal Compression

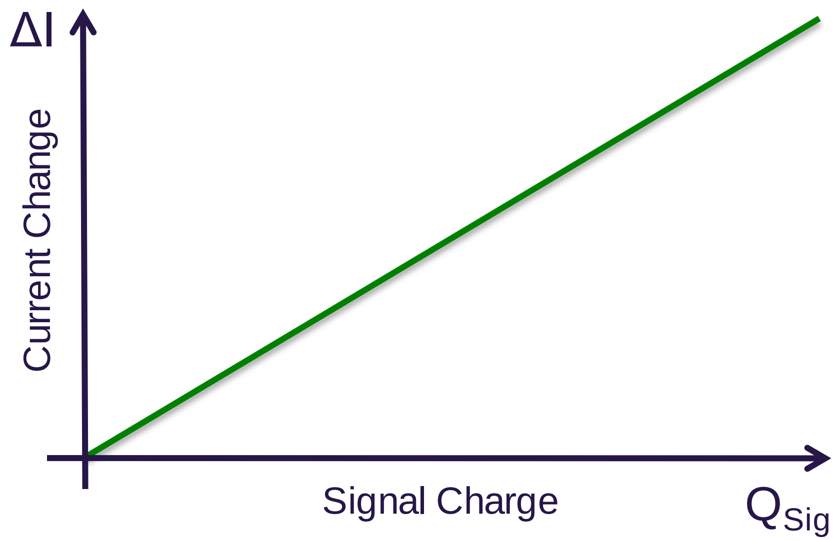
DePFET Working Principle



J. Kemmer G. Lutz, *NIM A*. 253, Nr. 3,1987

- Source drain current is steered by the amount of free charge carriers in the external gate
- Incident photon produces electron hole pairs
- Electrons drift to potential minimum at internal gate, holes to back contract
- Mirror charges created in external gate steer I_{SD}

Linear System Response



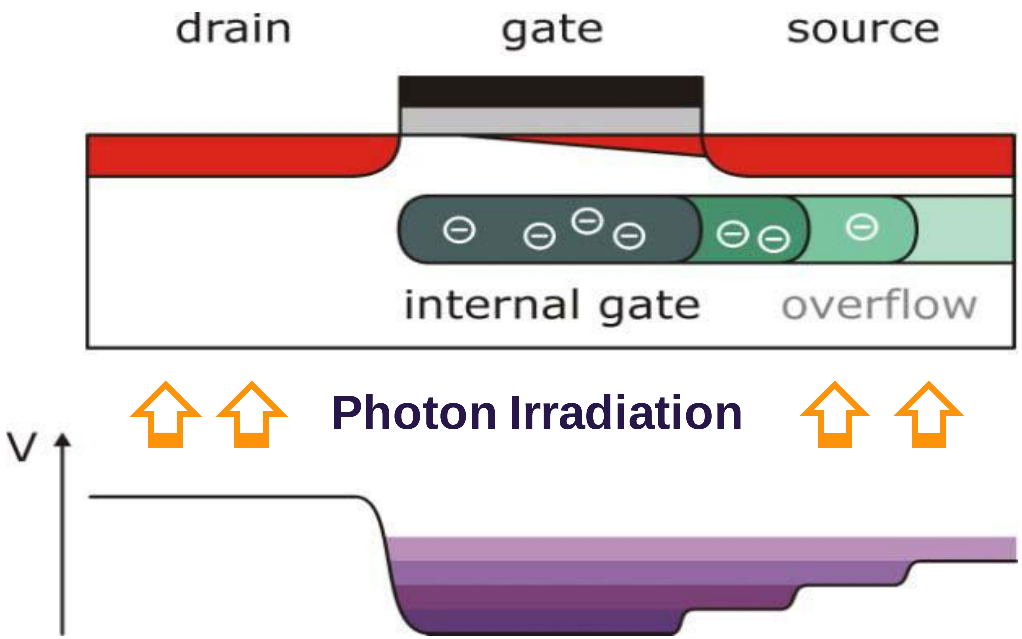
- Measure I_{SD} which is proportional to the signal charge
- Signal clearing is required to remove signal e^- and e^- from leakage current

Advantages

- Low internal capacitance → low noise
- Non destructive measurement

DSSC DePFET with Signal Compression

DSSC DePFET Working Principle



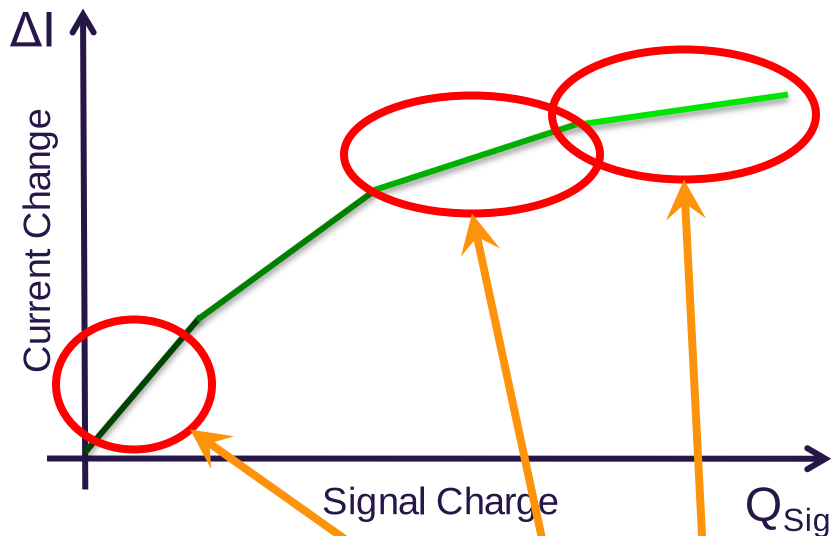
Extend internal gate towards source region

Only charges collected under external gate contribute to I_{SD}

Small Signals

All charge is collected at internal gate under the external gate

Non Linear System Response



→ full steering of I_{SD} → **high gain**

Large Signals

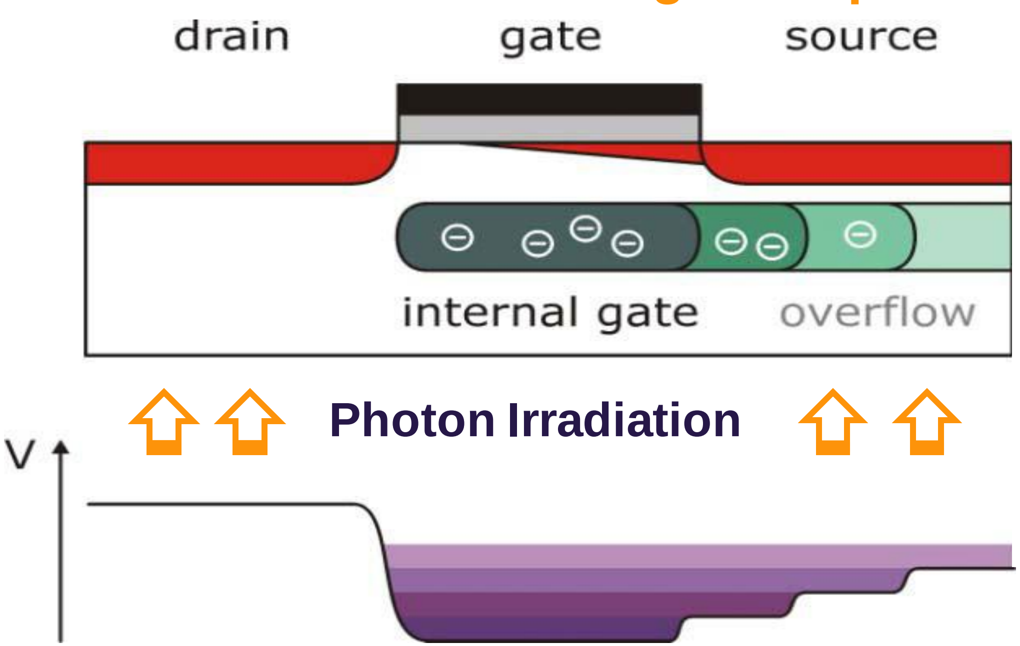
Charge spills over into extended source region

No or little contribution to I_{SD} → **low gain**

Porro et al. NIM A (2010) vol. 624 pp. 509

DSSC DePFET with Signal Compression

DSSC DePFET Working Principle



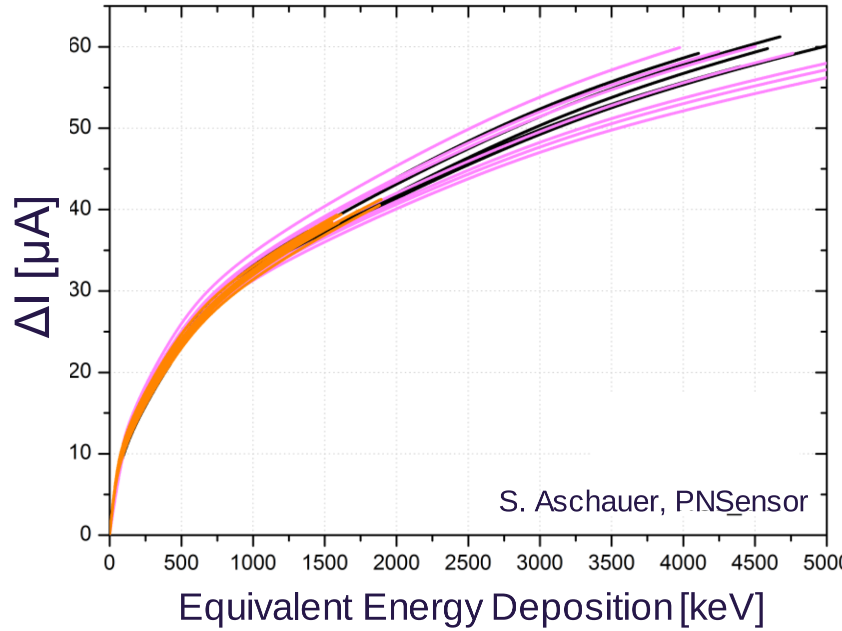
Extend internal gate towards source region

Only charges collected under external gate contribute to I_{SD}

Small Signals

All charge is collected at internal gate under the external gate

Measured System Response



→ full steering of I_{SD} → high gain

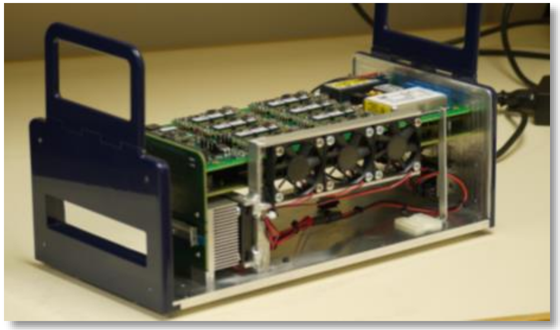
Large Signals

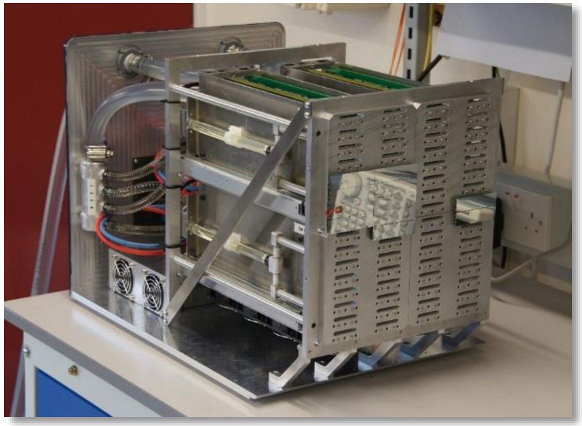
Charge spills over into extended source region

No or little contribution to I_{SD} → low gain

Porro et al. NIM A (2010) vol. 624 pp. 509

LPD – Detector Systems





16 Super Modules
256 Detector Tiles
2048 ASICs

2-Tile System	¼ Megapixel Detector	Megapixel Detector
Small flexible test system (32 x 256 pixels) Used for firmware tests, tests at beamlines, veto tests, …	Test system at XFEL.EU (512 x 512 pixels) Temp. stabilized (water cooling) Connected to XFEL DAQ system	Final system (1024 x 1024 Pixels) Movable Quadrants Currently under construction at STFC

LPD – Detector Systems

16 Super Modules
256 Detector Tiles
2048 ASICs

2-Tile System	¼ Megapixel Detector	Megapixel Detector
Small flexible test system (32 x 256 pixels) Used for firmware tests, tests at beamlines, veto tests, …	Test system at XFEL.EU (512 x 512 pixels) Temp. stabilized (water cooling) Connected to XFEL DAQ system	Final system (1024 x 1024 Pixels) Movable Quadrants Currently under construction at STFC

AGIPD – Direct Beam Measurements at PETRA III

Intensity Distribution

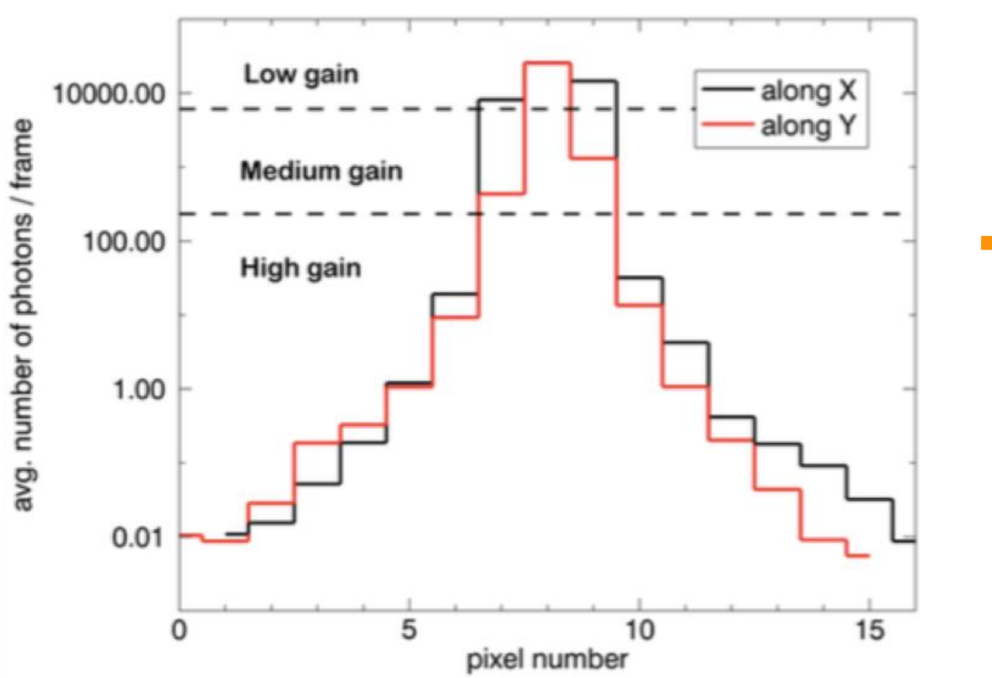
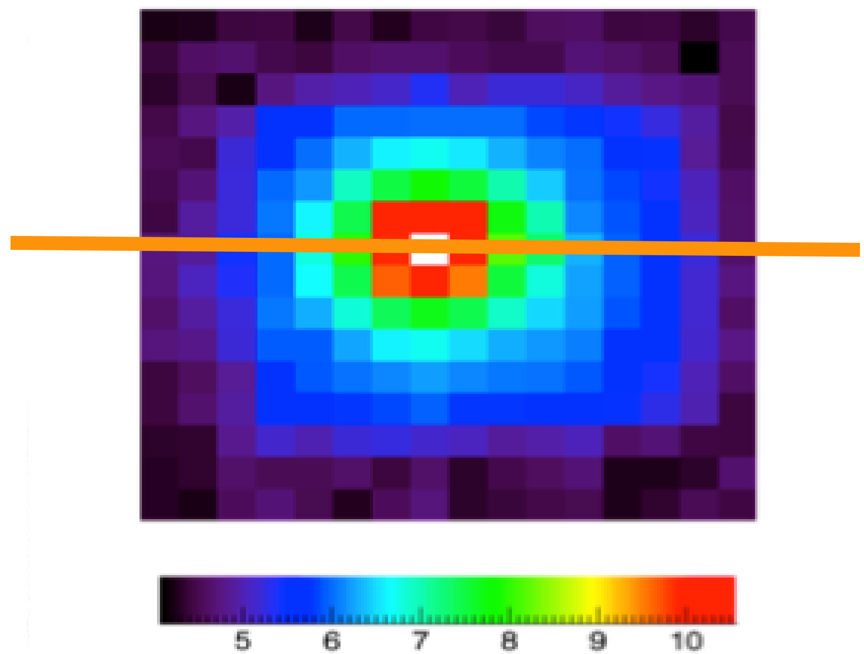


Image of the Direct Beam



Primary intensity 10^4 photons/pulse

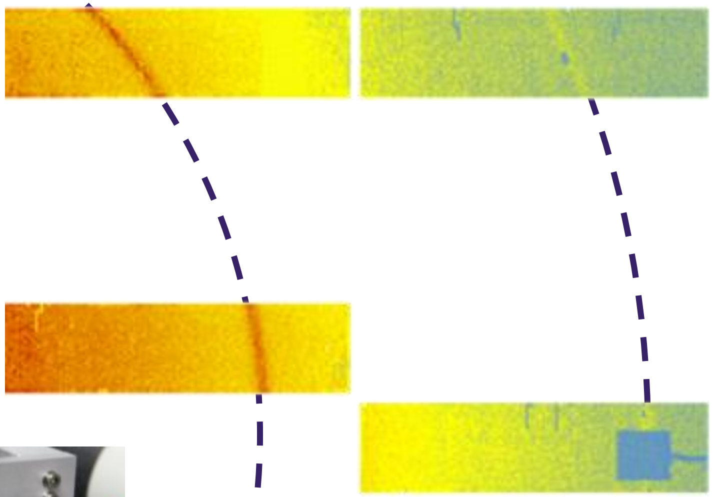
Single photon sensitivity

Operated at 4.5 MHz

J. Becker et al. arXiv 1303.2502V1

Large Pixel Detector – Performance

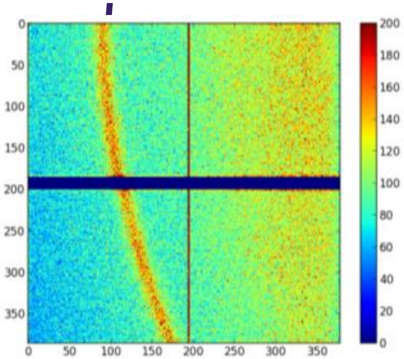
Diffraction Experiment at LCLS at 9 keV



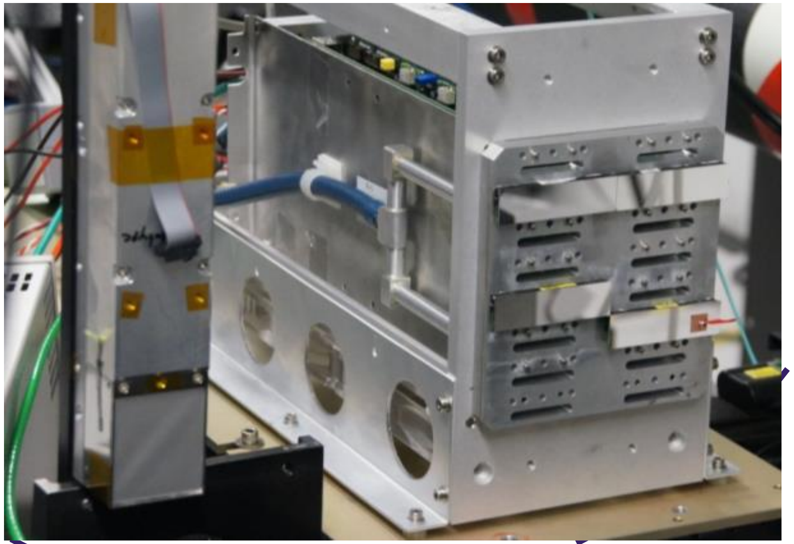
Sample Titanium dioxide (TiO_2) on Kapton

Detectors CSPAD and

LPD Two Tile system



LPD Super Module



European XFEL

Large Pixel Detector – Performance

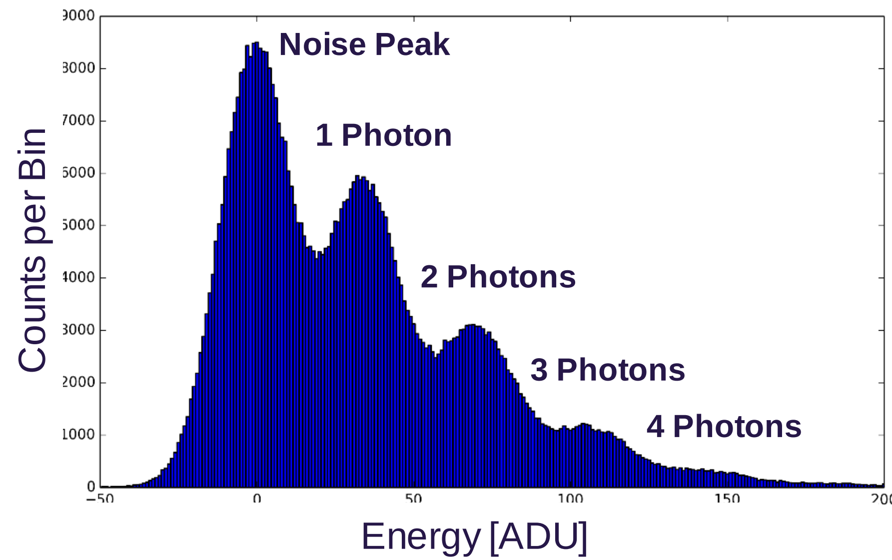
Performance tests at Diamond, LCLS, Petra III and in our Lab

Single photon sensitivity demonstrated down to 12 keV

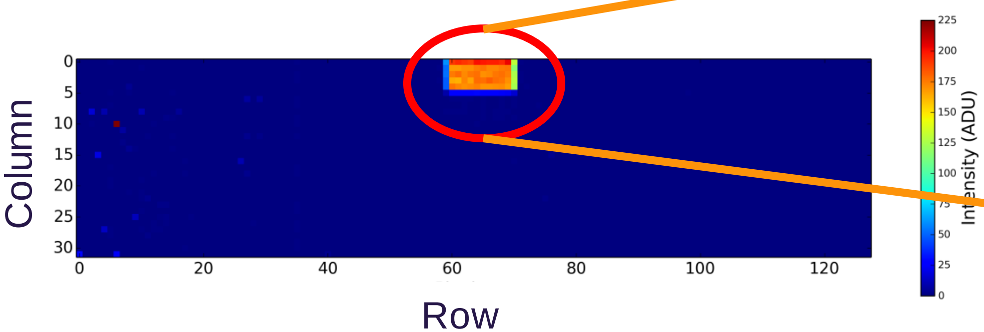
Noise 0.35 photons @ 12 keV

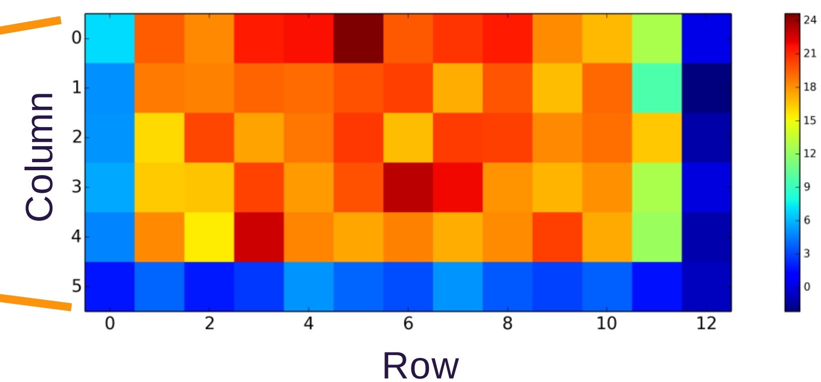
Tests with final hardware at ESRF and APS this fall

Photon Spectrum at 18 keV



Imaging and Charge Sharing Properties





Large Pixel Detector – Performance

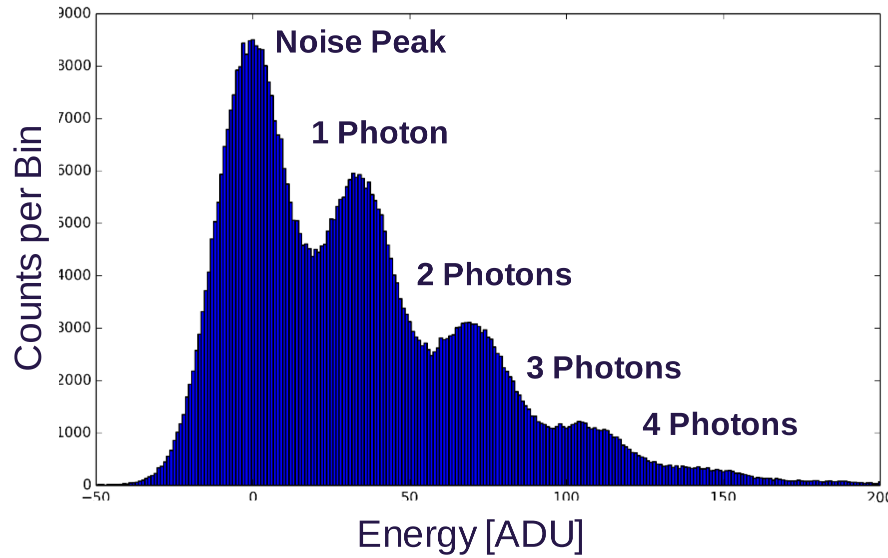
Performance tests at Diamond, LCLS, Petra III and in our Lab

Single photon sensitivity demonstrated down to 12 keV

Noise 0.35 photons @ 12 keV

Tests with final hardware at ESRF and APS this fall

Photon Spectrum at 18 keV



Spatial Resolution

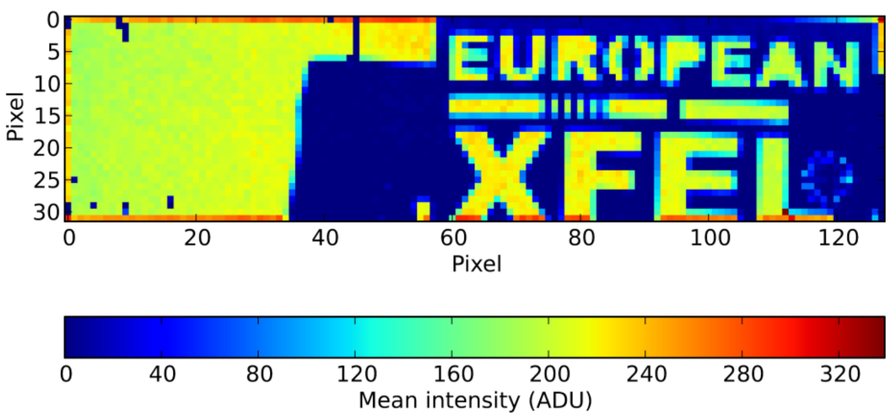


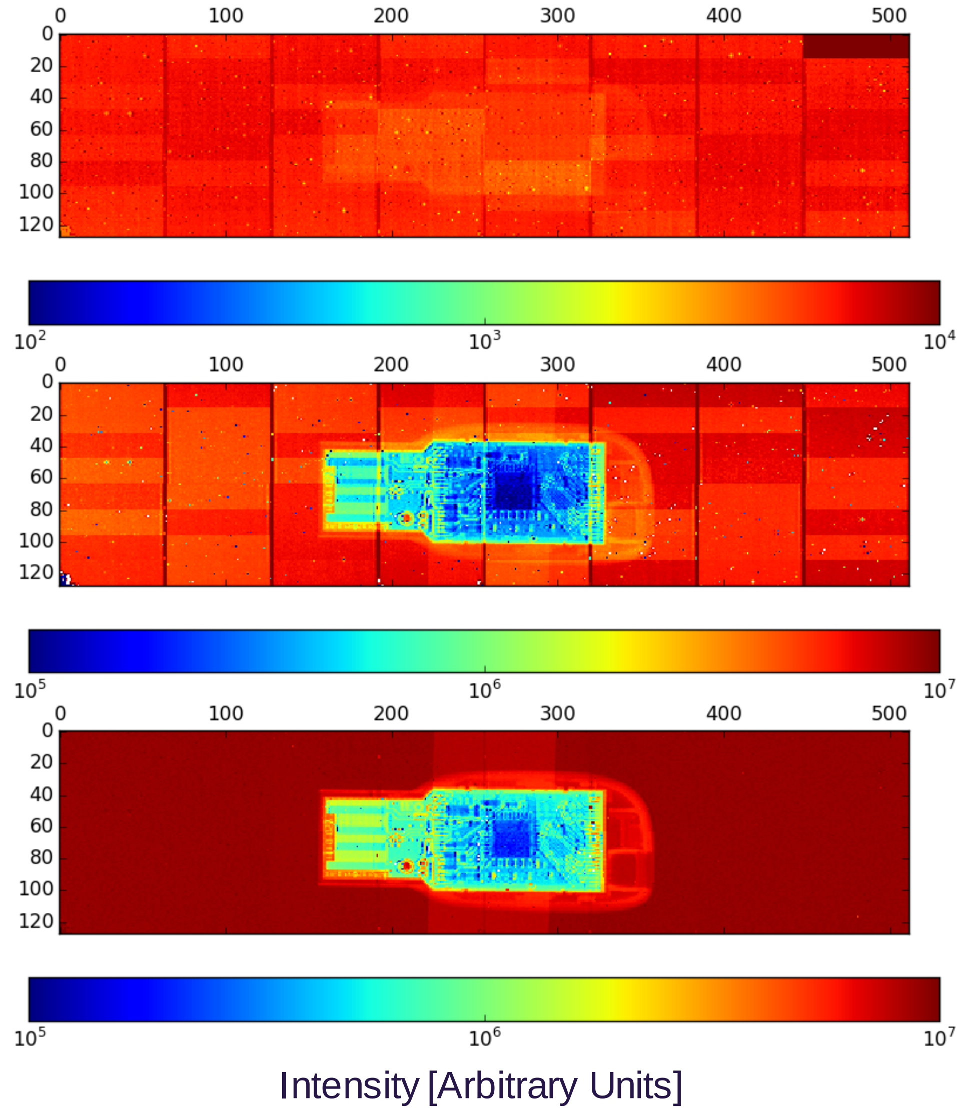
Image Corrections – Example AGIPD

X-ray of a Pen Drive

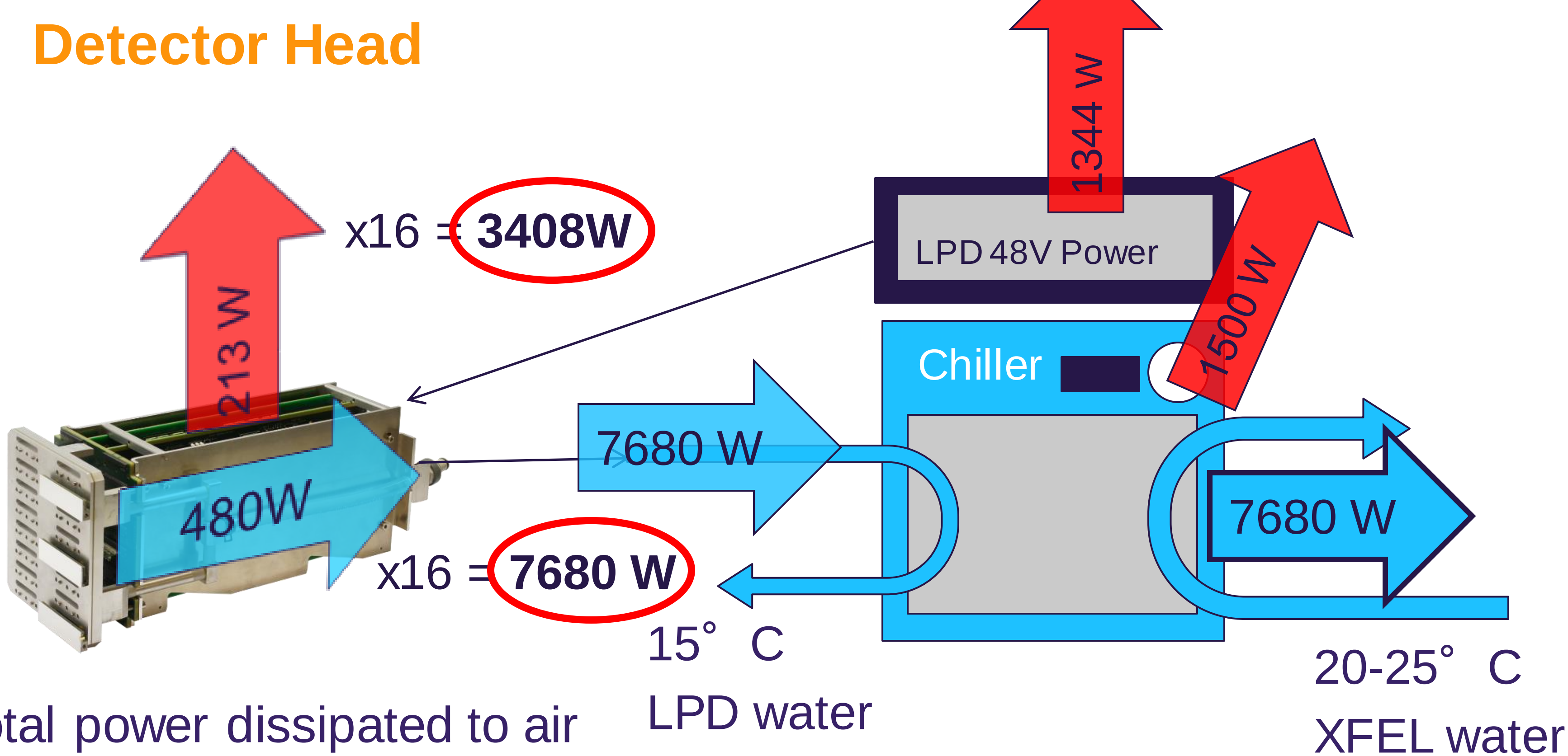
Mean of 10.000 images with an integration time of 50 μs

After dark field correction

After correcting for gain variation of different amplifiers



LPD – 1 Mpx Detector Power Dissipation



Total power dissipated to air and water

≈ 13 kW

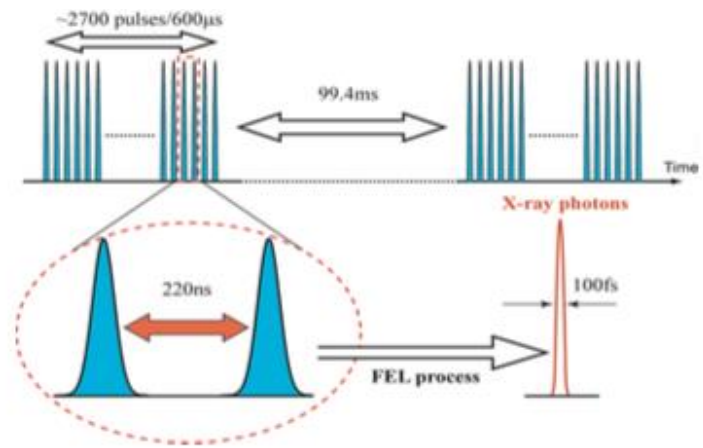
→ Liquid cooling mandatory

M. Hart, LPD Collaboration

Expected Data Rates

Readout rate driven by bunch structure

- 10 Hz train frequency
- 4.5 MHz pulse frequency in trains



Data rate driven by detector type

Detector type	Sampling	Data/pulse	Data/train	XFEL/sec	Future/sec
1 Mpxl 2D camera	4.5 MHz	~2 MB	~1 GB	~10 GB	~220 GB
1 channel digitizer	5 GS/s	~2 kB	~6 MB	~60 MB	~240 MB

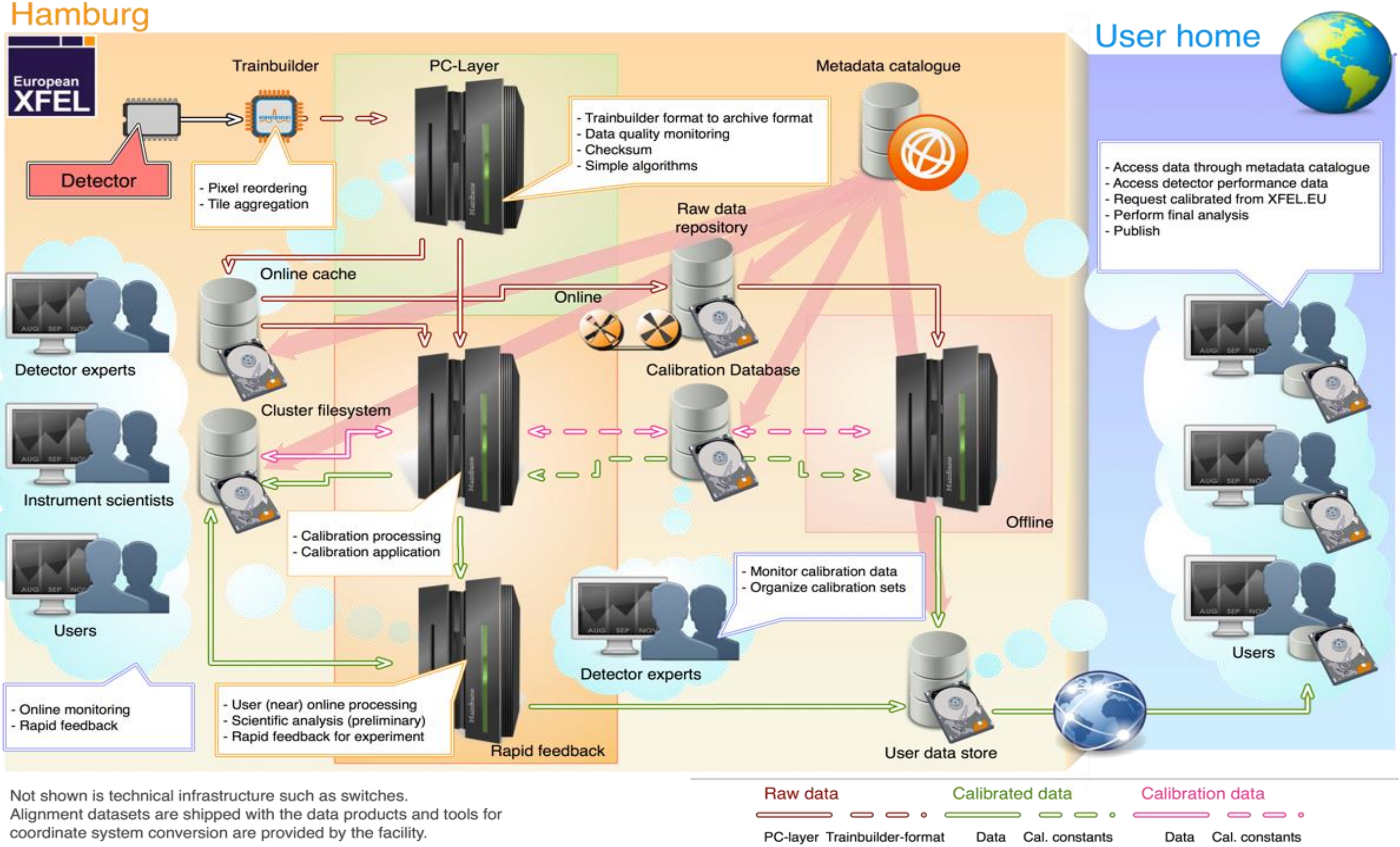
Challenges

- Gathering, calibrating and storing data of many detectors
- Data analysis, data reduction and processing
- Data long term storage and more …

Day one 2016/17 10 PB offline disk storage.

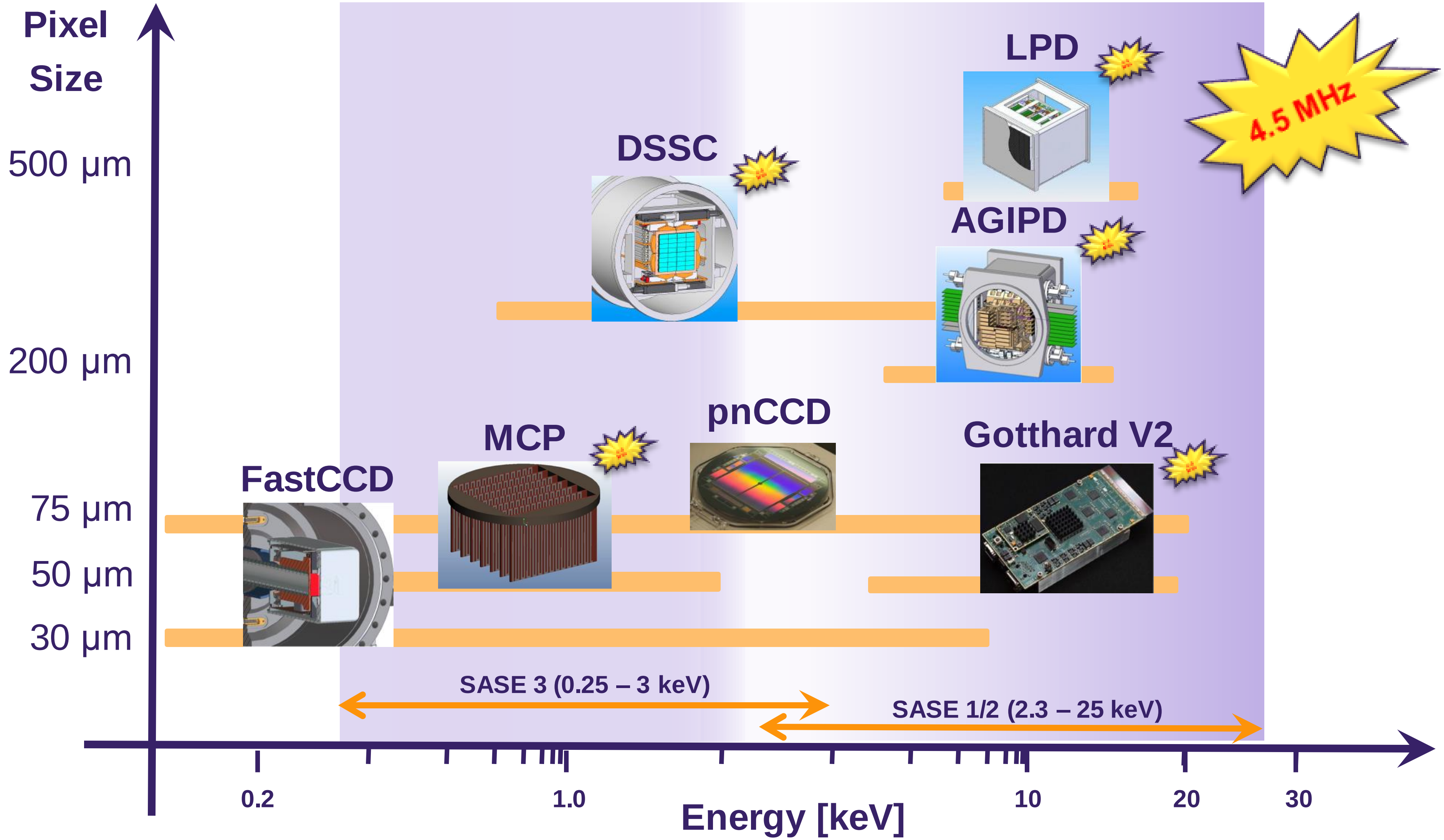
European XFEL Hamburg

Data Flow and Scientific Data Products



Not shown is technical infrastructure such as switches.
Alignment datasets are shipped with the data products and tools for coordinate system conversion are provided by the facility.

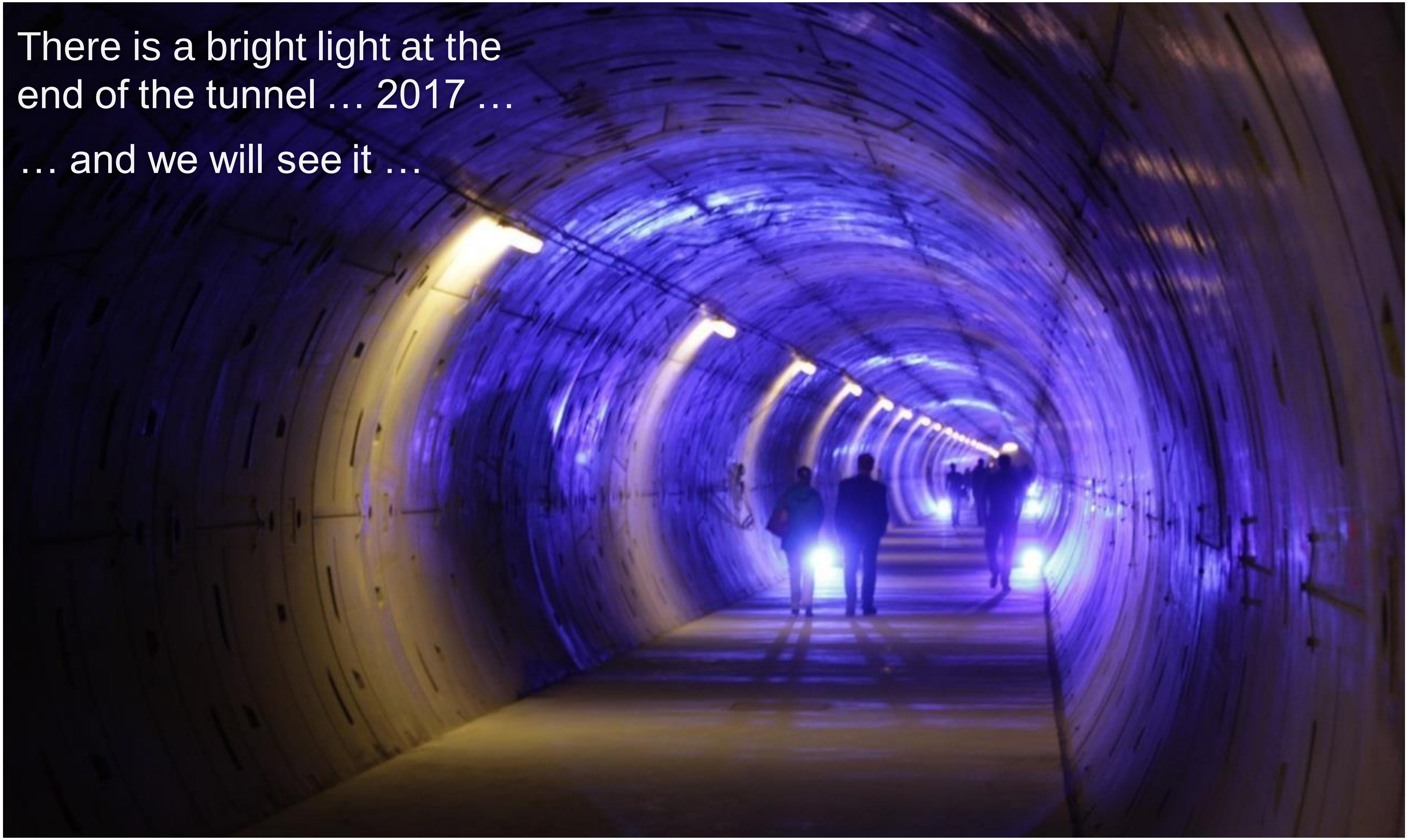
Detectors for the European XFEL



Thank you for your attention!

There is a bright light at the end of the tunnel … 2017 …

… and we will see it …



Detector Group at the European XFEL

Thank you for your attention!

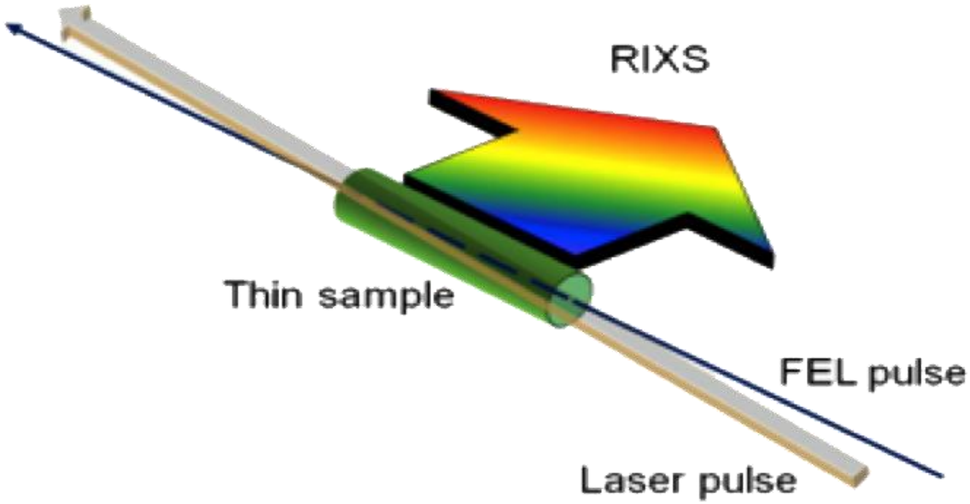
SQS: Resonant Inelastic X-Ray Scattering

Excite sample with a short laser
→ probe sample with X-rays at after
different times

Study RIXS signal in two dimensions (dispersive/beam)
→ The time evolution of a pump
laser excitation
→ Study emission from different positions along the sample (non-linear phenomena)

Requires measurement of single photons in two dimensions at 4.5 MHz

- the dispersion direction (energy)
- the beam direction along the sample (position equivalent to time)



Experiment Parameters

Photon Energy Range
≈ 0.2 – 2 keV

Sample Size 0.1 – 4 µm

Desired max. Resolution
sub eV

Experimental Environment
Vacuum 10^{-6} – 10^{-8} mbar

SQS: Soft X-ray Single Shot Spectrometer

Experiment Setup

- Rowland geometry + detector at grazing incidence
- Wolter optics design allows magnification in the imaging direction by factor ≈ 8
- Two gratings to cover different energy ranges

Experiment Parameters

Required #Images per Dataset

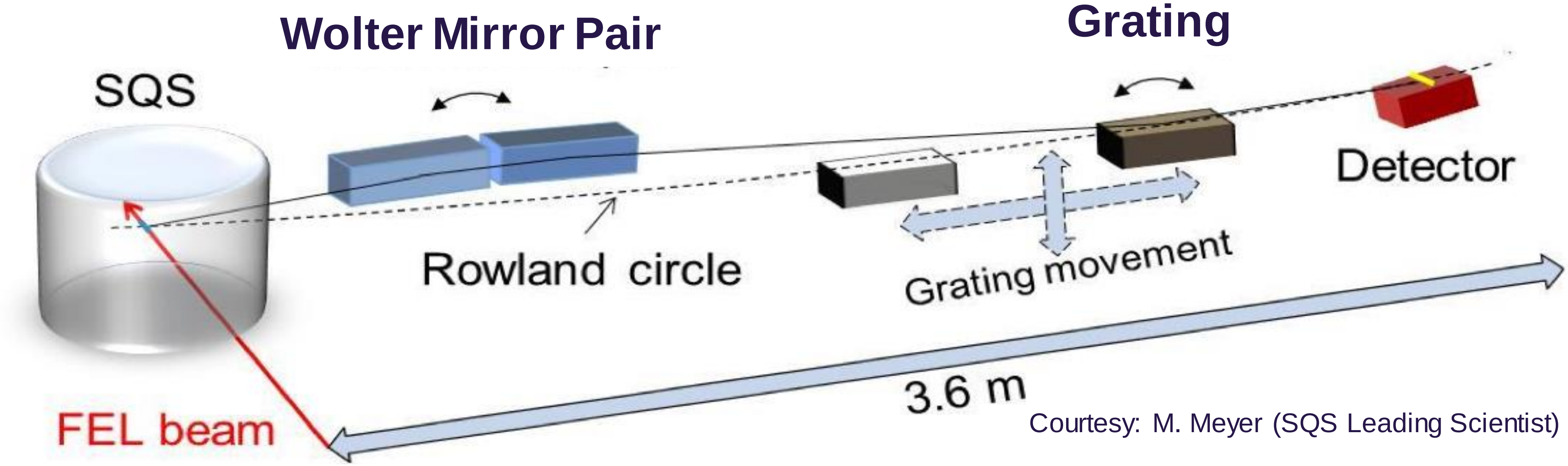
few tens

Signal level of interest at detector

$1 - 10^2$ ph/pulse

Information extracted from single frame

Full 2D spectrum



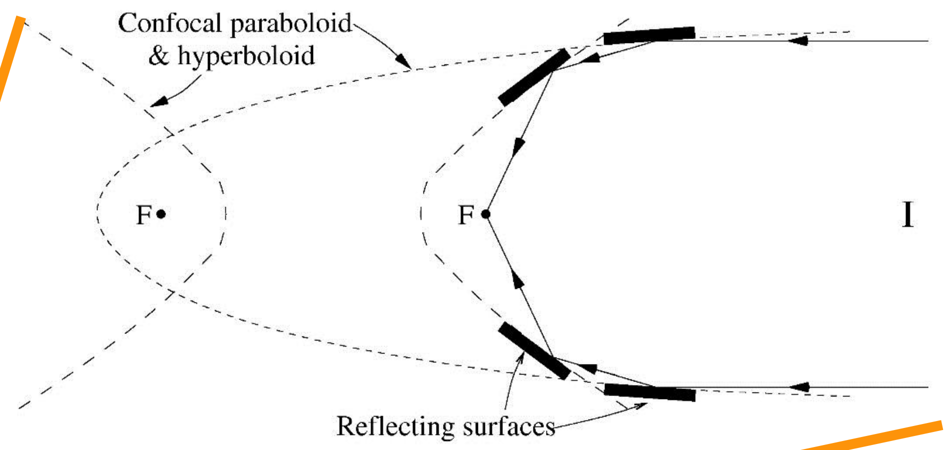
Courtesy: M. Meyer (SQS Leading Scientist)

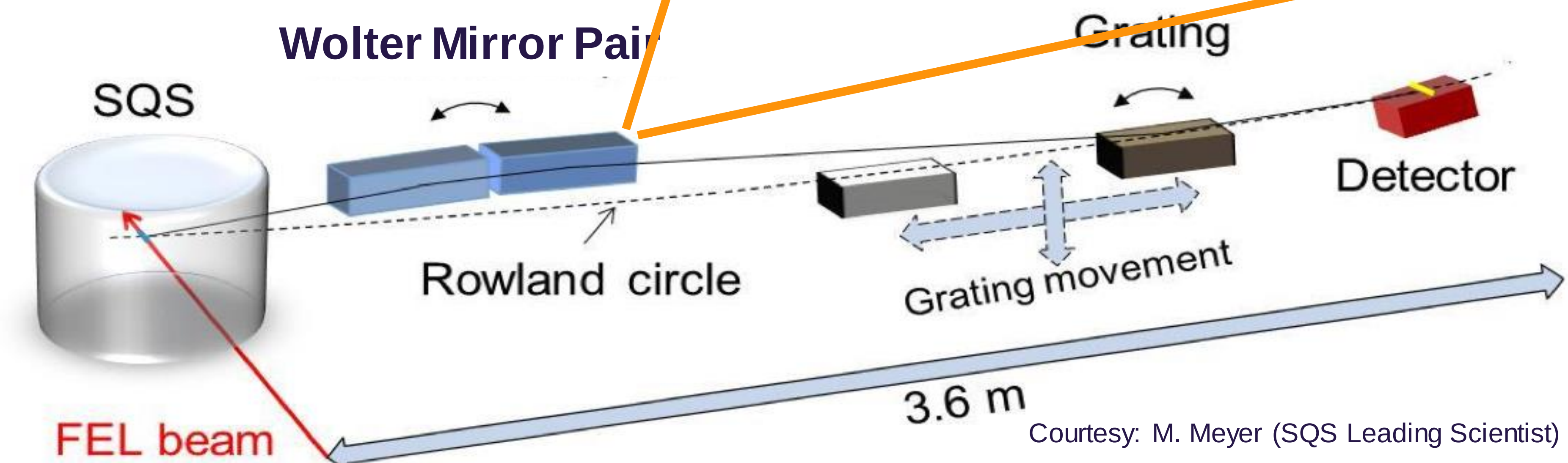
SQS: Soft X-ray Single Shot Spectrometer

Experiment Setup

- Rowland geometry + detector at grazing incidence
- Wolter optics design allows magnification in the imaging direction by factor ≈ 8
- Two gratings to cover different energy ranges

Wolter I Optics



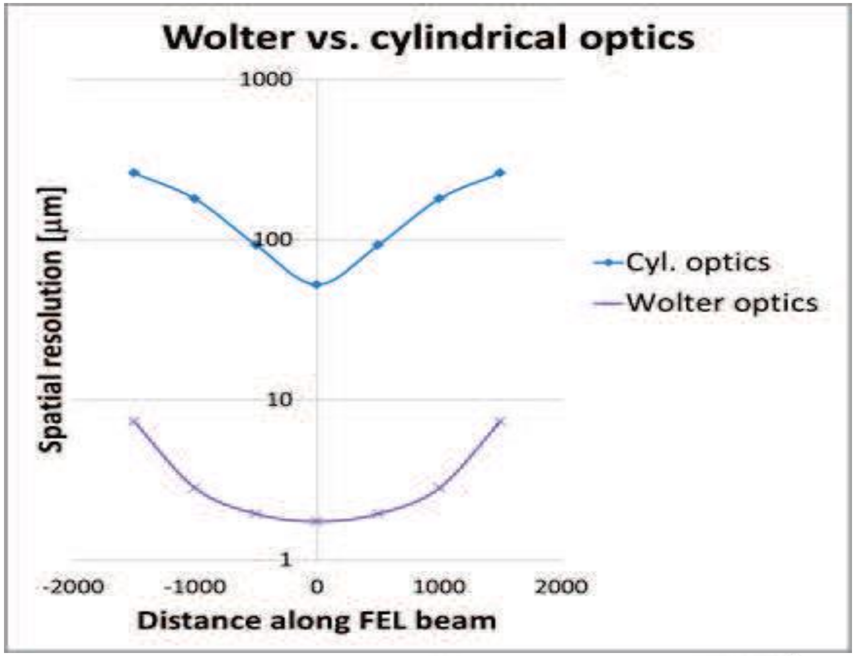


Courtesy: M. Meyer (SQS Leading Scientist)

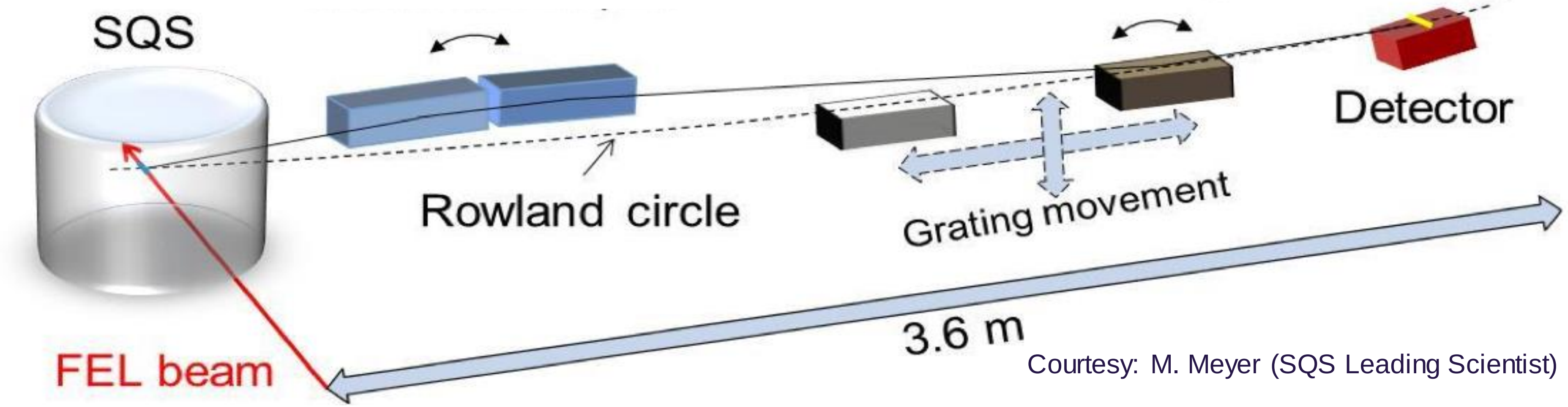
SQS: Soft X-ray Single Shot Spectrometer

Experiment Setup

- Rowland geometry + detector at grazing incidence
- Wolter optics design allows magnification in the imaging direction by factor ≈ 8
- Two gratings to cover different energy ranges



Wolter Mirror Pair



Courtesy: M. Meyer (SQS Leading Scientist)

MCP Detector with DLD Readout

MCP Detector with Delay Line Readout

4.5 MHz compatible Si based imaging detectors with pixel sizes < 100 µm are not available.

Use micro-channel plate to convert single photons to 10^3–10^4 electrons

Advantage

- Fast detector for single shot imaging
- Reasonable sensitivity
- Good spatial resolution

Limitations

Dead time of a single pore is much longer than µs

→ use Wolter optics to distribute signal

Spatial resolution

50 µm (‖ DL) x 156 µm (⊥ DL)

Working Principle of a Micro Channel Plate