The Detector Development Program for the European X-ray Free Electron Laser

Markus Kuster

for the XFEL detector collaboration

September, 14 2011

The 9th International Conference on Position Sensitive Detectors

Aberystwyth

Overview

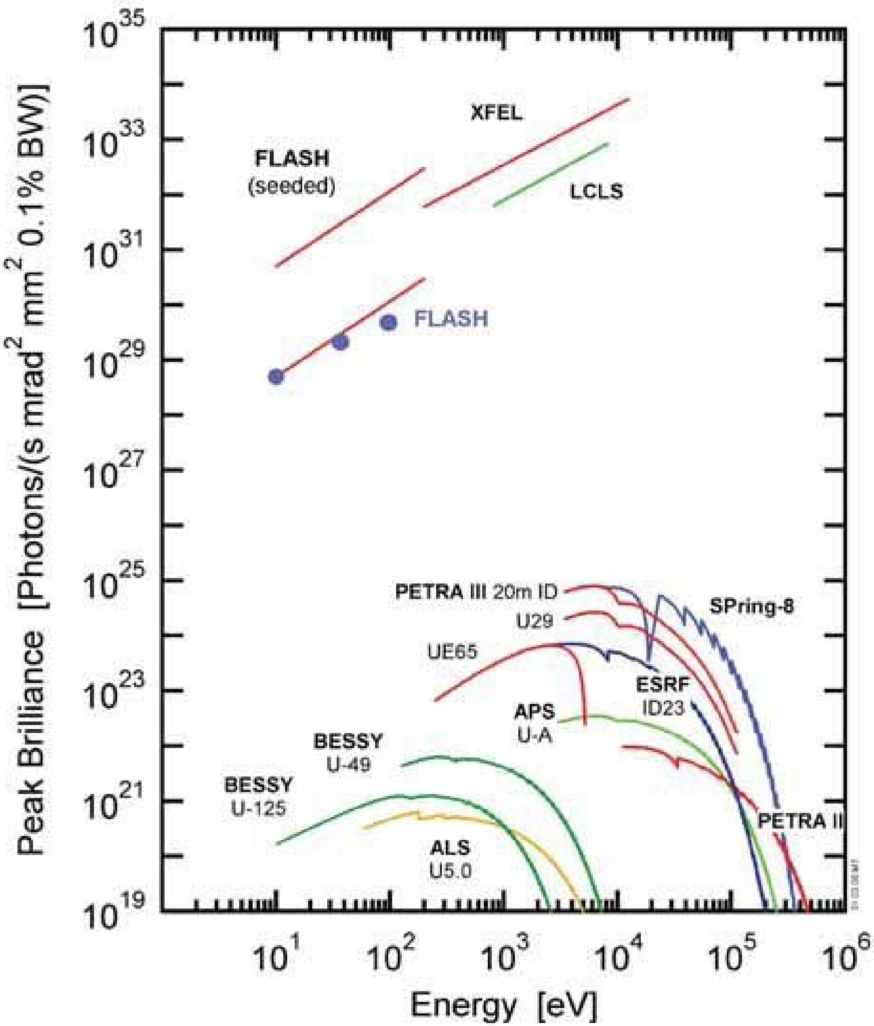
- Introduction to the European XFEL
- Detector requirements for EuXFEL
- XFEL detector development program
  - 2D Imaging detectors
    - Adaptive Gain Integrating Pixel Detector – AGIPD
    - DEPFET Sensor with Signal compression – DSSC
    - Large Pixel Detector – LPD
  - 1D detectors and small area 2D imaging detectors
- DAQ, data management and data processing
- Conclusions and outlook

The European XFEL Limited Liability Company

- Founding of the European XFEL GmbH
  28.09.2009
- Signature of convention
  30.11.2009
- Research institutes of different countries joined as shareholders to support construction and operation
- Responsible for construction and operation of XFEL facility
- Approx. 300 employees at operation phase
- Start of operation
  Mid 2015

The European XFEL

Peak Brilliance

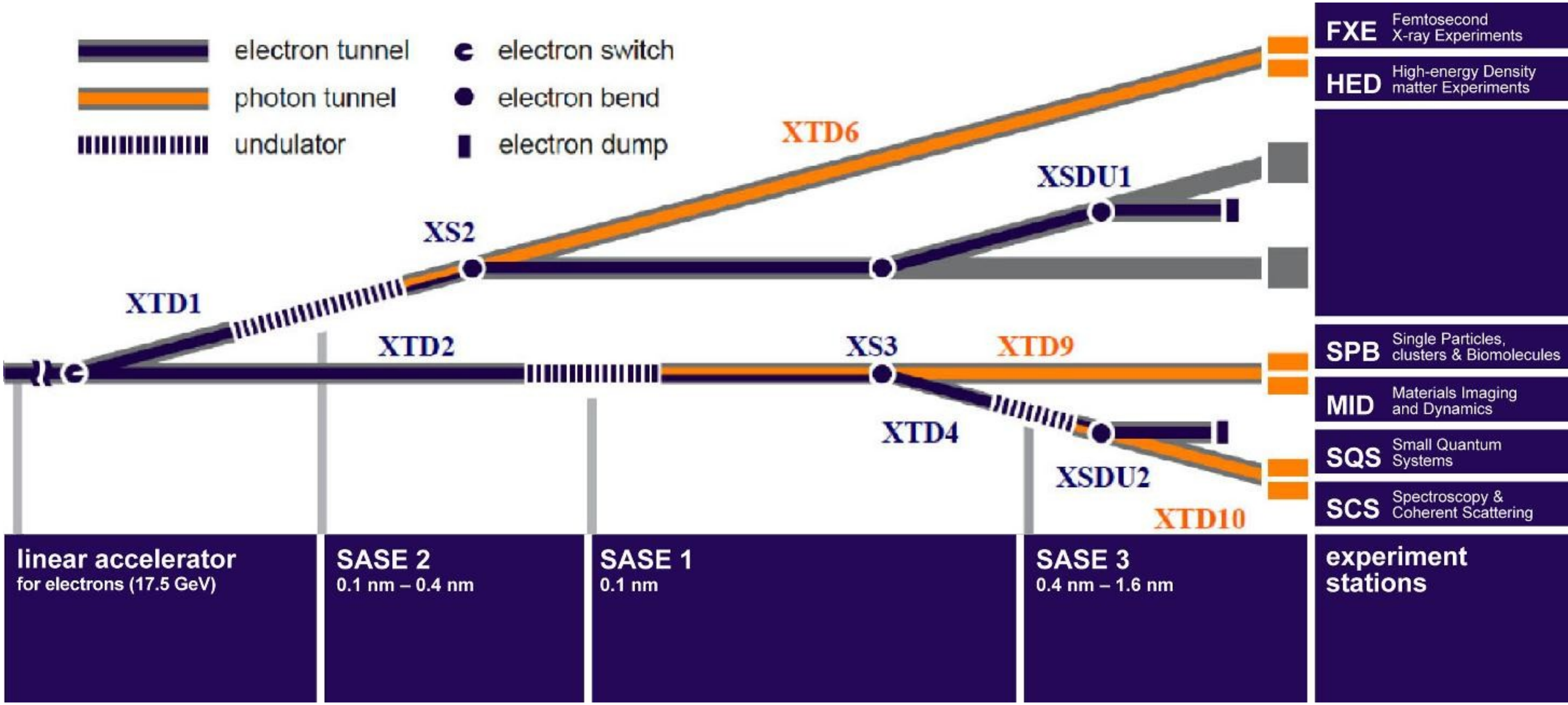


Specifications

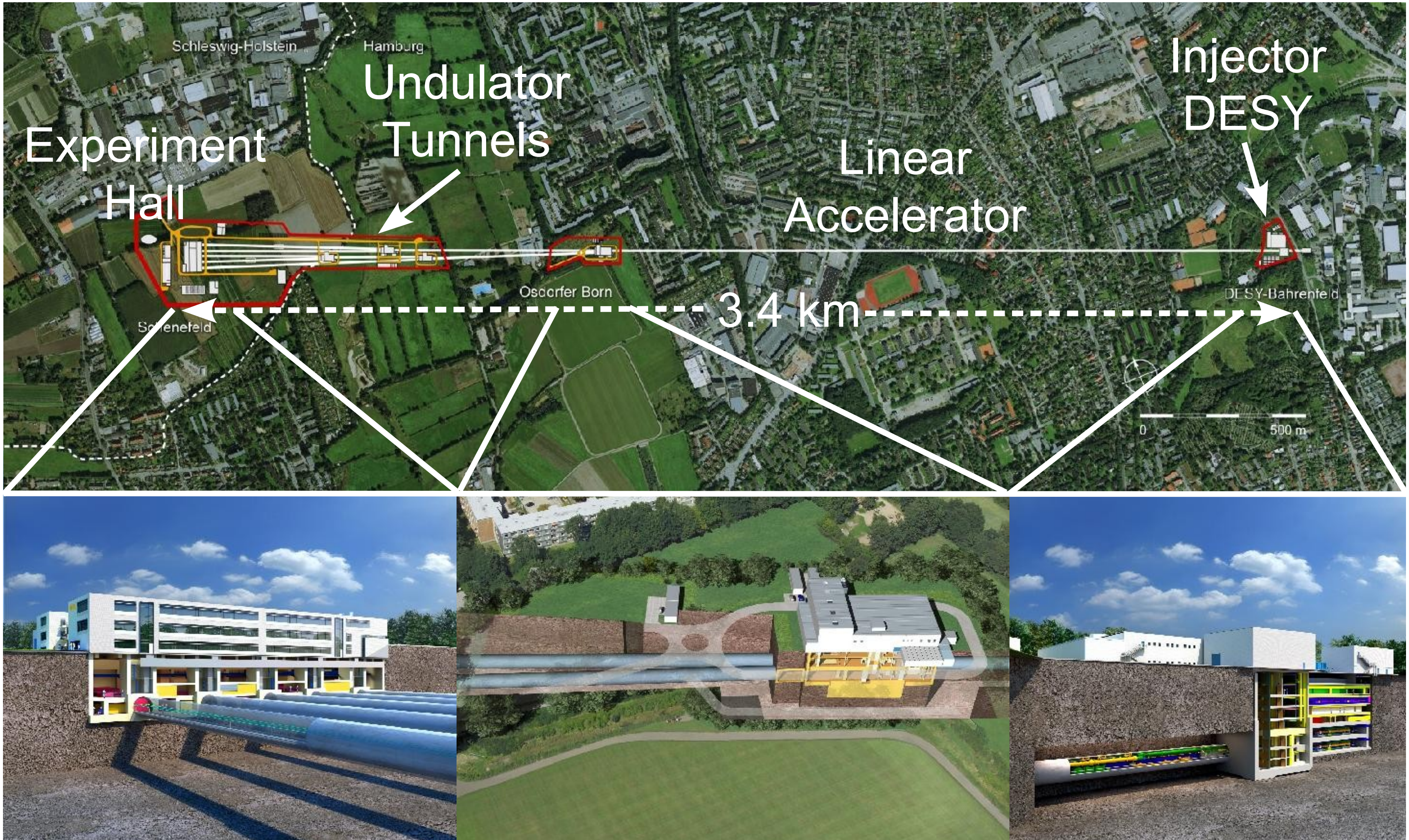
- Photon energy 0.4 – 20 keV
- Pulse duration < 100 fs
- Pulse energy few mJ
- Superconducting LINAC 14-17.5 GeV
- 10 Hz (2700 bunches/s)
- 5 beamlines / 10 instruments (start up version 3 beamlines with 6 instruments)
- Extensions possible:
  - Additional instruments
  - Additional beamlines

Start of operation 2015

XFEL Beam Line Layout



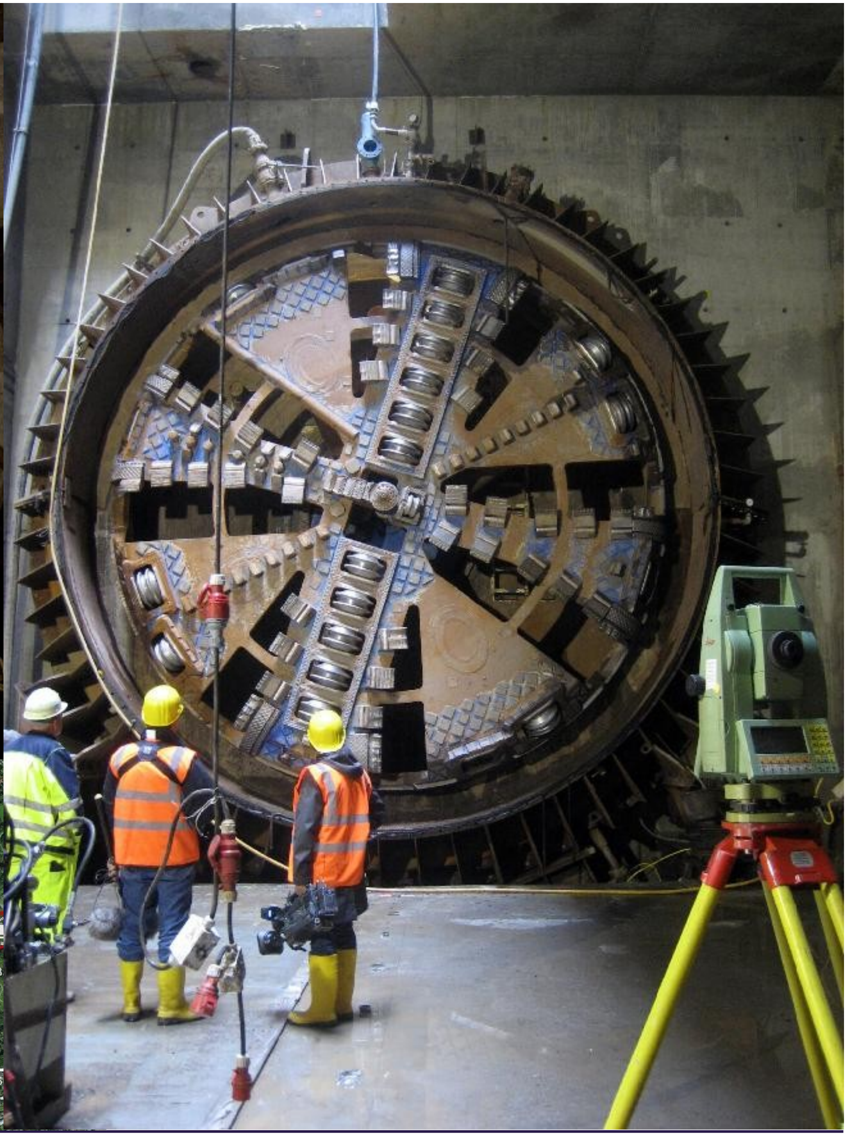
The European XFEL



Injector Shaft – DESY Bahrenfeld May 2010

Experimental Hall – Schenefeld September 2011

Accelerator Tunnel Completed – 29. July 2011



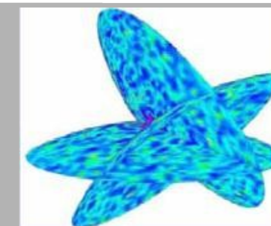
Scientific Instruments at XFEL.EU

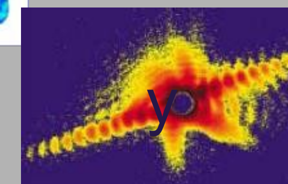
SASE 1

SASE 2

High E

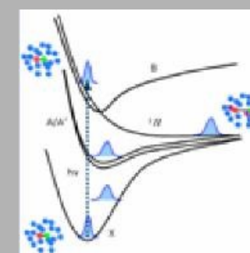
Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters and Biomolecules (SPB)
Structure determination of single particles: atoms, clusters, bio-molecules, viruses, and cells



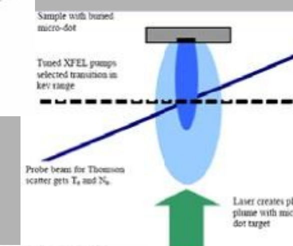


Materials Imaging & Dynamics (MID)
Structure determination of nano-devices and dynamics at the nanoscale

Femtosecond X-ray Experiments (FXE)
Time-resolved investigations of the dynamics of solids, liquids and gases.



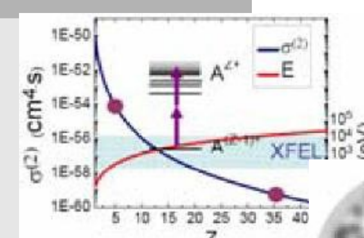
High Energy Density Matter (HED)
Investigation of matter under extreme conditions using hard X-ray FEL radiation, e.g. probing dense plasmas.



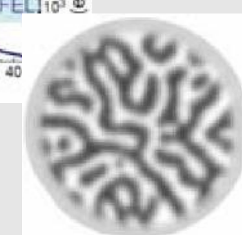
SASE 3

Low E

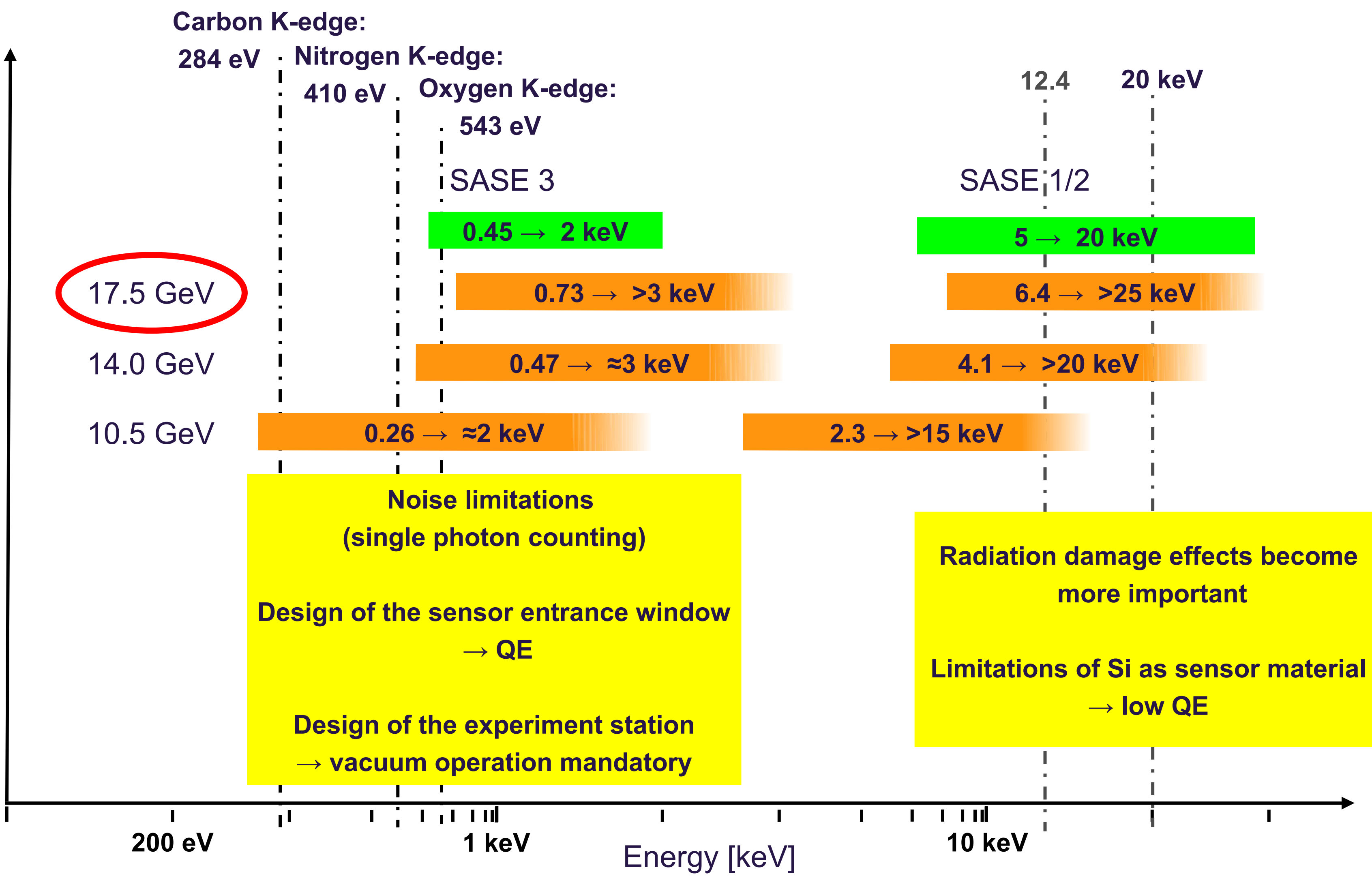
Small Quantum Systems (SQS)
Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena.



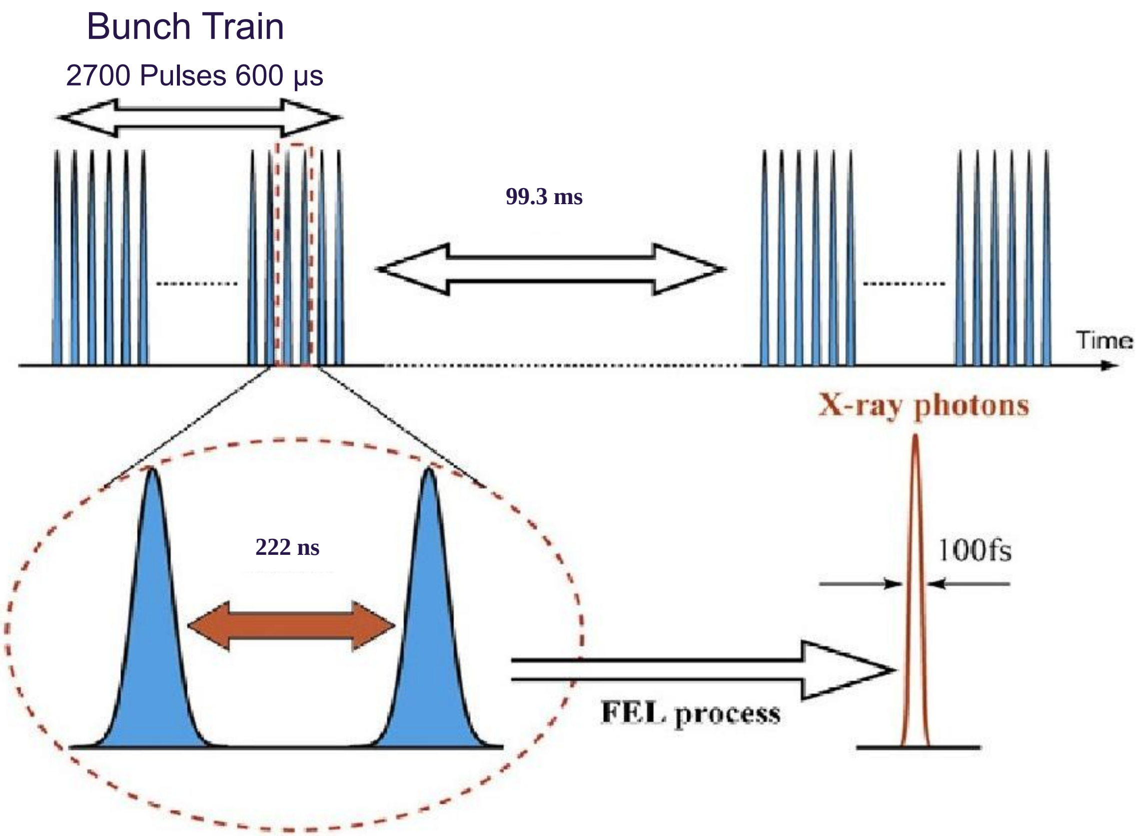
Spectroscopy and Coherent Scattering (SCS)
Structure and dynamics of nano-systems and of non-reproducible biological objects



XFEL Photon Energy Ranges



XFEL Time Structure



Unique feature of XFEL !

- High repetition rate of up to 27000 pulses/s
- Ultra short pulses < 100 fs
- High peak intensities (up to 10^{12} photons per bunch)
- Approx. 1300 pulses per bunch for SASE2 and SASE1/3
- Different pulse patterns can be realized

  1 bunch per train

  n bunches per train (linear/log/random spacing)

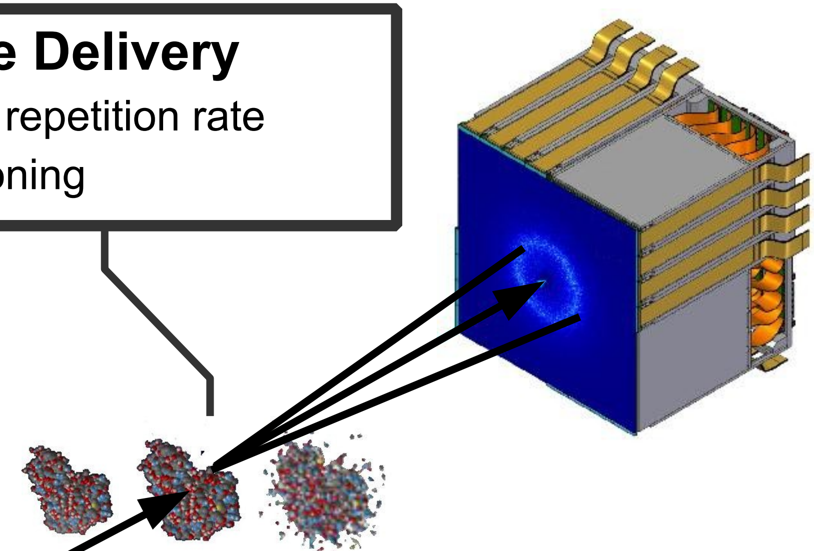
European XFEL

XFEL High Repetition Rate Challenges

Photon Diagnostics
- On-line & single-shot
- Match repetition rate

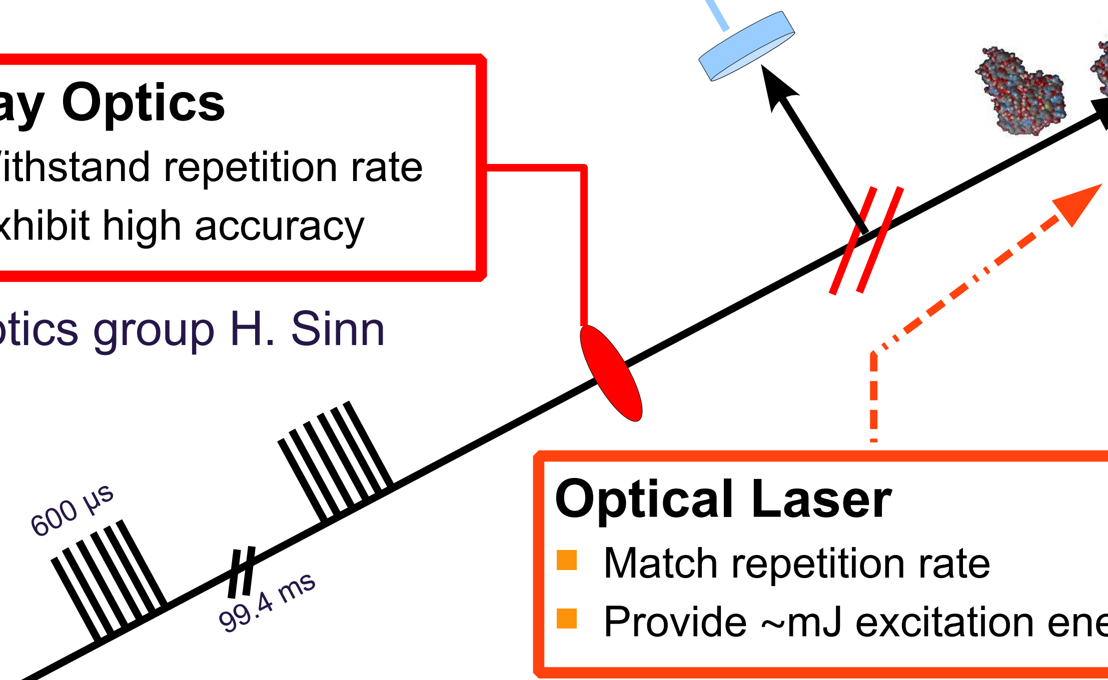
Diagnostics Group
J. Grünert

Sample Delivery
- Match repetition rate
- Positioning



X-ray Optics
- Withstand repetition rate
- Exhibit high accuracy

Optics group H. Sinn

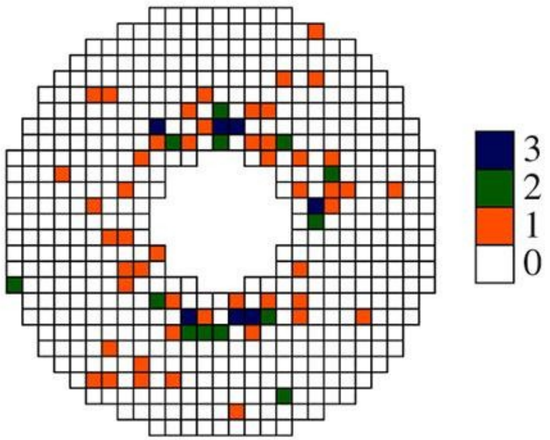


Detectors
- Match repetition rate
- Provide spatial resolution
- Withstand dose
- Data processing, management and storage
- Vetoing capabilities

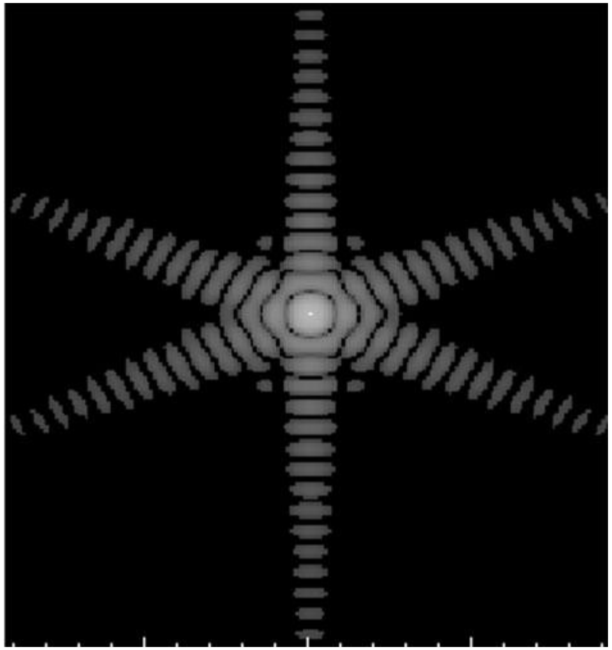
Optical Laser
- Match repetition rate
- Provide ~mJ excitation energy

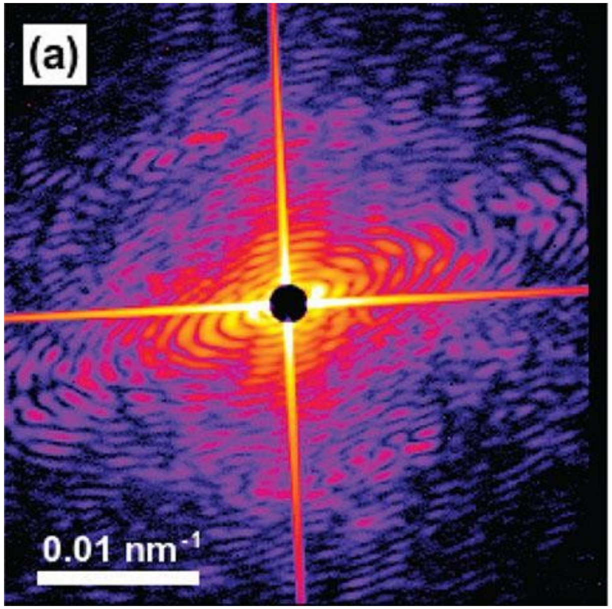
Laser Group M. Lederer

Coherent Diffraction Experiments (SPB case)



N.D. Loh and V. Elser et al. Phys. Rev. E 80 (2009)





M.P. Mancuso et al. New J. Phys. 12 (2010)

Single Particle

- Single photon counting capability
- Low noise and background

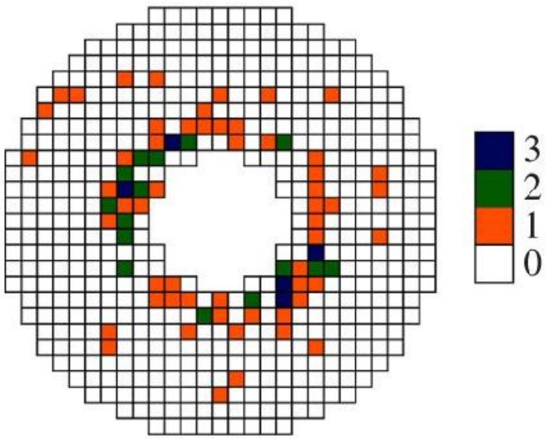
Nano-Chrystals

- Large dynamic range
- Radiation hardness
- Position resolution
- Single photon counting

Unicellular Algae

- Large dynamic range
- Large area
- Position resolution
- Radiation hardness
- Single photon counting at high q

Coherent Diffraction Experiments (SPB case)



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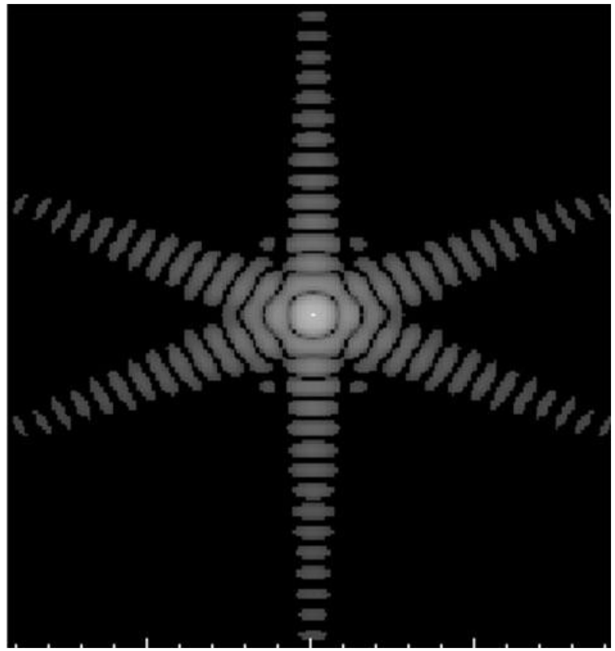

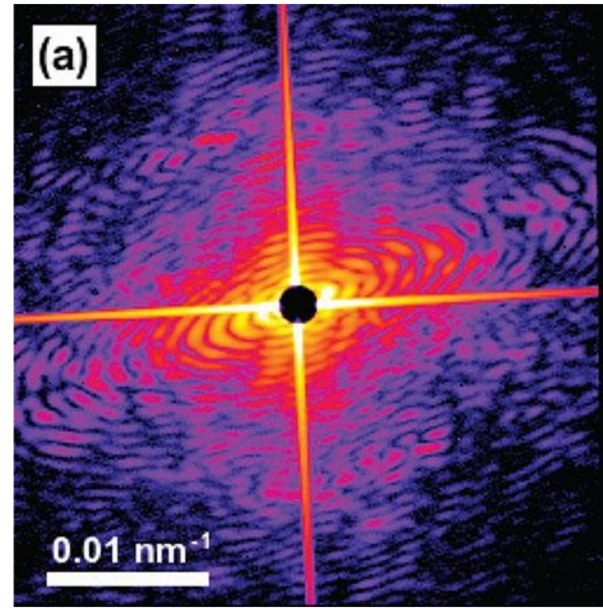

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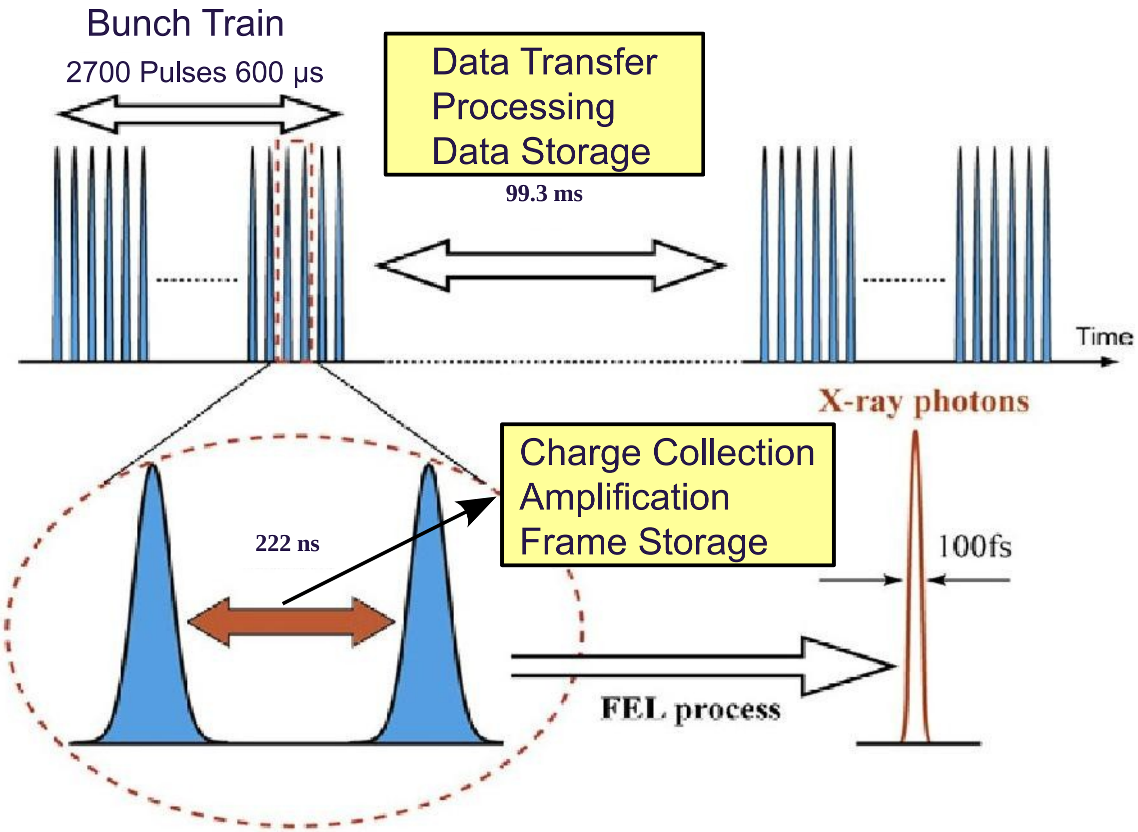
XFEL Time Structure – Read Out Concept



- High repetition rate of up to 27000 pulses/s
  Ultra fast read out and processing of the signal
  Charge settling 60-80 ns
  Charge clearing 60-80 ns
  40-80 ns left for read-out
- High peak intensities (up to 10^{12} photons per bunch)
- Pulse to pulse variation
- Pulse sequence configur-able

- Single shot imaging storage capability on sensor ideally 2700 images/train
- Data transfer and processing during bunch train gap of 99.3 ms

Requires optimized front end electronics + on pixel storage capacity!

2D Imaging Detector Requirements

XFEL Pulse Structure

Single shot imaging
(recording 100 fs, read out 200 ns)
Frame storage of complete bunch train (2700 pulses)

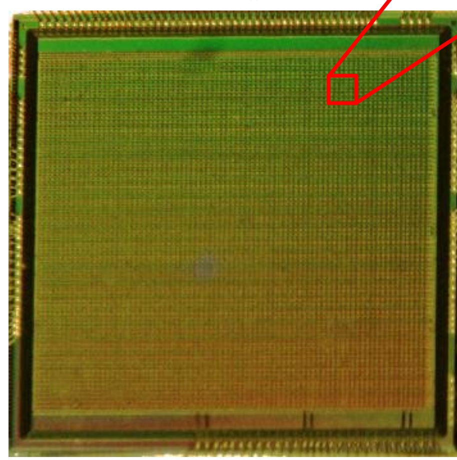
Dynamic Range

Single photon counting
(high angle/single particle scattering)
Integration of up to 10^4 ph/pixel/pulse

High accuracy at low intensity
Low accuracy at high intensity
→ different optimization of different E ranges

Sensitive Energy Range

0.25 (SCS, SQS) –25 keV (MID, HED)
Ideally with the same system
Vacuum and ambient pressure operation
Optimized entrance window for low E



Radiation Hardness

Integrated energy dose over 3 years operation
10 MGy - 1 GGy
Damage effects depend on energy range!
Graafsma JINST 4 (2009) pp. 12011

Angular Resolution

7 mrad for FDE experiments
(worst case at 10 cm distance)
4 rad for XPCS
Pixel size: 700 m to 16 m
(XPCS at 4 m distance)

Angular Coverage/ Sensor Size

Diffraction experiments require a resolution of 0.1 nm
scattering angles of 60° (120°)
(FXE, CDI, and SPB)
multiple detector segments

Main Scientific Applications

MID, XPCS, FXE, SPB and SQS

Match the environmental conditions of the experiment stations

Call for Interest 2006

- Call for interest for 2D large area pixel detectors

  30. September 2006

- Received 6 proposals from different consortia, based on different technologies
- 3 consortia were selected and asked to prepare a full proposal
- 3 projects entered first R&D phase

  AGIPD

  LPD

  DSSC

- Transition to go to production phase will be decided this year

European XFEL Project Team
c/o Deutsches Elektronen-Synchrotron DESY
in der Helmholtz-Gemeinschaft,
Notkestraße 85,
D-22607 Hamburg, Germany

XFEL
X-Ray Free-Electron Laser

Call by the:

European Project Team for the X-ray Free-Electron Laser

for:

Expressions of Interest

to:

Develop and Deliver Large Area Pixellated X-ray Detectors.

Deadline: 30 September 2006
http://xfel.desy.de/xfelhomepage

XFEL 2D Imaging Detector Collaboration

AGIPD Adaptive Gain Integrating Pixel Detector Consortium (AGIPD)

Project Leader:

H. Graafsma, DESY

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

Radiation Damage Studies

Project Finished

Project Leader:

R. Klanner, Universität Hamburg

Charge Cloud Studies

Project Finished

Project Leader:

K. Gärtner, Weierstrass Institut Berlin

Large Pixel Detector Consortium (LPD)

Project Leader:

M. French, RAL/STFC

- Rutherford Appleton Laboratory/STFC
- University of Glasgow

DEPFET Sensor with Signal Compression Consortium (DSSC)

Project Leader:

M. Porro, Politechnico di Milano

- Max-Planck Halbleiterlabor Munich
- Universität Heidelberg
- Universität Siegen
- Politecnico di Milano
- Università di Bergamo
- DESY Hamburg

Radiation Damage

Problem

- We expect intensities of > 10^4 photons/pulse/pixel
- Intensity distribution across sensor depends on application
  - e.g. ... terin...
  - → ir...
- Assum...
- Share...
- Data ta...

→ 1250 hours/year

→ 10^{16} cm^{-2} absorbed photons in 3 years or 1 GGy (worst case)

(12 keV 500 µm sensor)

Consequences

- Radiation hard sensor and ASIC design is mandatory
  → e.g. larger structures (contradicts small pixel size)
  ... pro-
  ...tion

Project Leader:

R. Klanner, Universität Hamburg

Irradiation tests + simulations

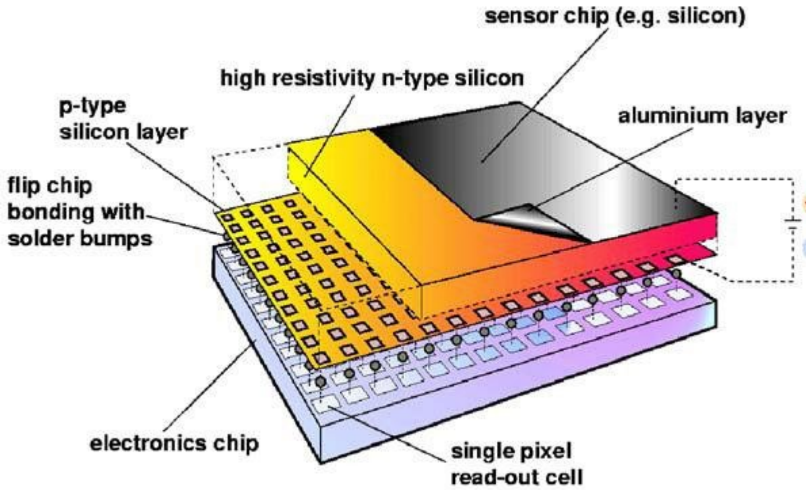
→ feedback for designers

Joern Schwandt, University of Hamburg

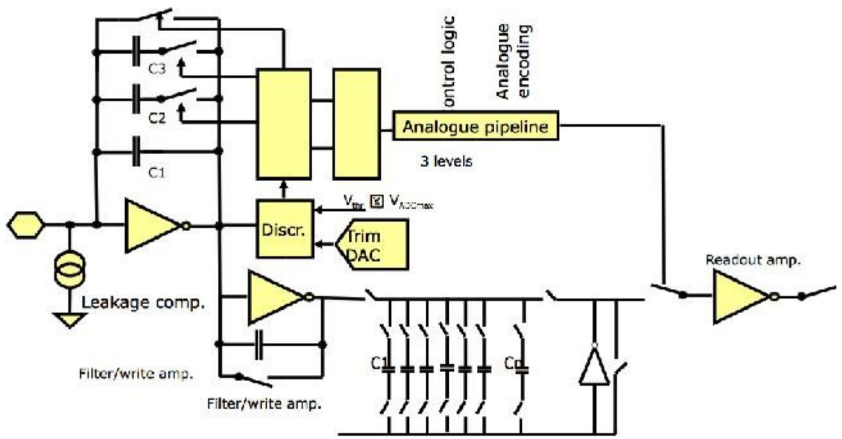
Optimization of Silicon Pixel Sensors for the high X-ray Doses of the European XFEL

AGIPD - Adaptive Gain Integrating Pixel Detector

Hybrid Technology



AGIPD Pixel ASIC



Key Detector Parameters

- Energy range
  3 – 13 keV
- Dynamic range/pixel/pulse
  10^4 @12 keV
- Single photon sensitivity
  5 σ @ 12 keV
- Number of storage cells 250-300
- 200 µm x 200 µm pixel size

Front End ASIC

- Wide dynamic input range
- 3 fold switchable dynamic gain
- Analog and ana. encoded pipeline

AGIPD Status

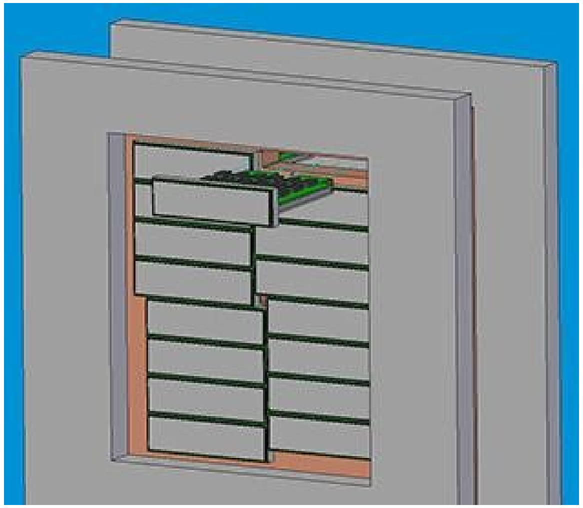
More about AGIPD

Julian Becker, DESY

AGIPD, the Adaptive Gain Integrating Pixel Detector:
A 4.5 MHz camera for the European XFEL

- Go/No-Go evaluation: **Go**
- Full system expected for com-missioning end of 2013

AGIPD 1Mpix Module



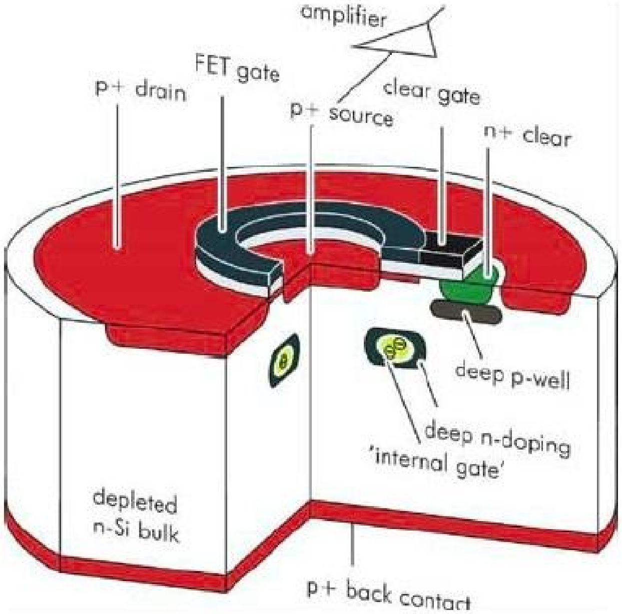
Radiation Damage

- Noise and gain tested to 1MGy → within specs
- Pre-amp successfully tested to 10 MGy
- Radiation damage studies ongo-ing

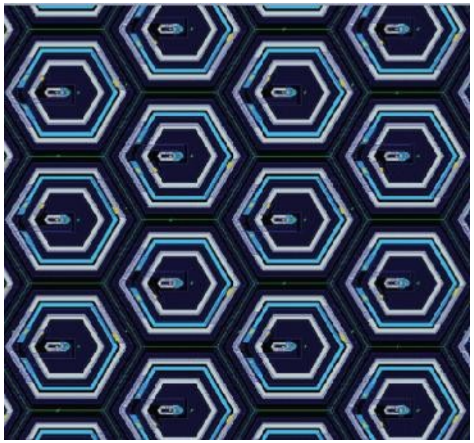
DSSC - DEPFET Sensor with Signal Compression

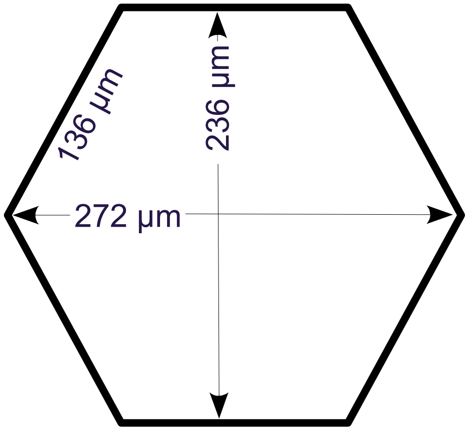
Pixel Cell

- DEPFET combined with Silicon drift detector
  → scalable pixel size
- Low noise
  → Good energy response down to 500 eV



Pixel Geometry

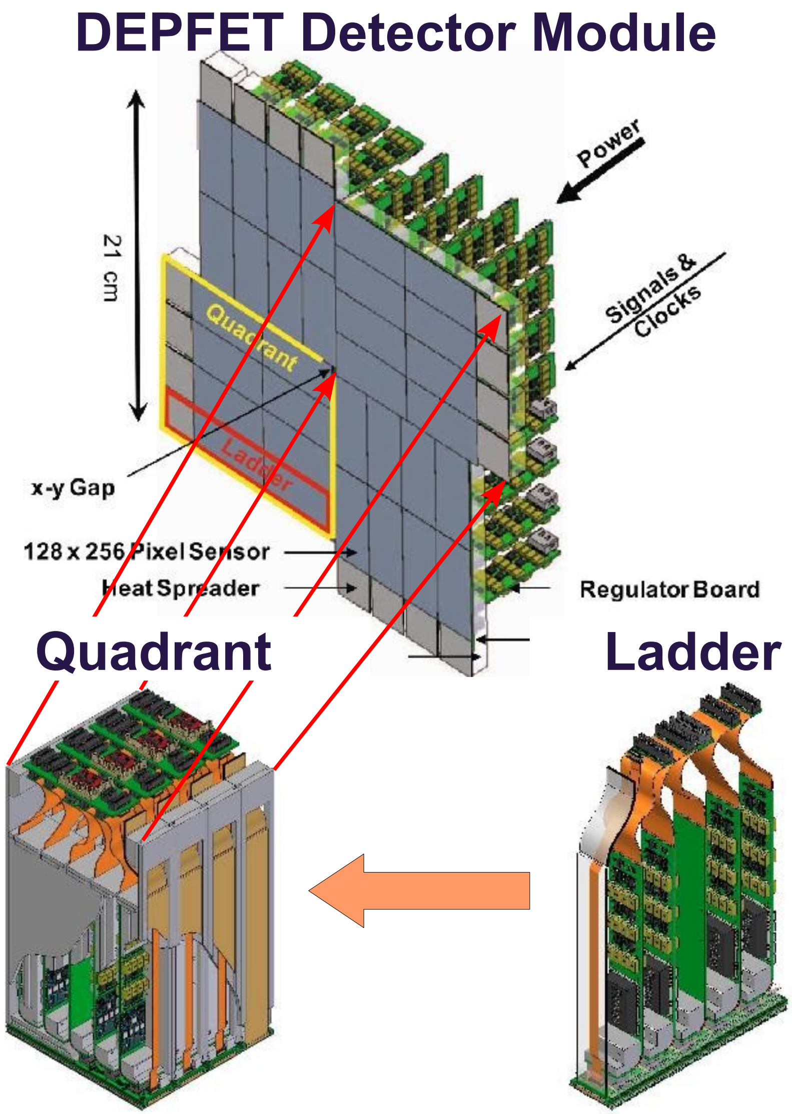




Porro et al. NIM A (2010) vol. 624 pp. 509

- Hexagonal pixels
  → more homogeneous drift field
  → minimize charge collection time
  → less charge sharing (split events)
- Per pixel ADC/digital storage pipeline
  → no charge leakage
- 576 9 bit SRAM storage cells per pixel

DSSC 1 MPixel Detector Module

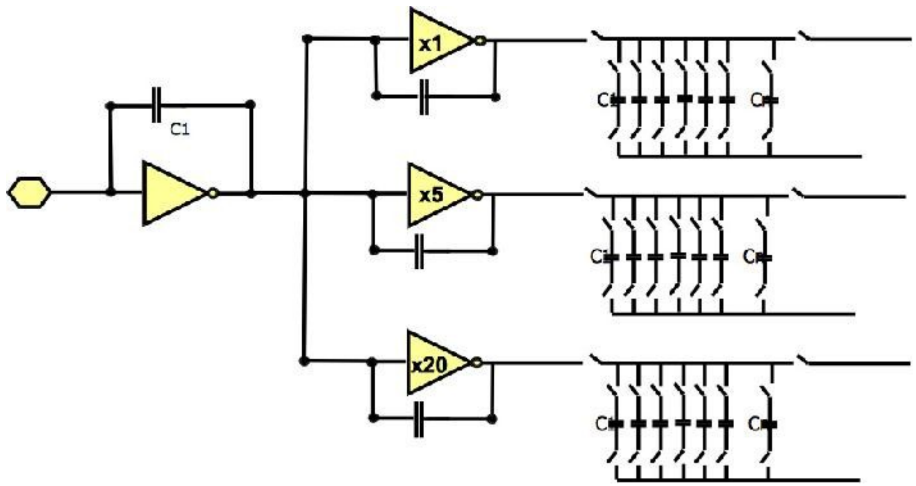


Key Detector Parameters

- Goal: Single photon sensitivity
  5 σ @1 keV and 4.5 MHz
- Energy range
  0.5 – 25 keV
  (0.5 – 4 keV optimized for)
- Dynamic range
  > 6000 photons/pixel/pulse @1 keV
- Single photon sensitivity
  5 σ @ 1 keV (5 MHz)
  5 σ @ 0.5 keV (2.5 MHz)
- Number of storage cells 576
- Smallest detector unit “ladder
  128 x 512 pixels
- 4 ladders built on quadrant
- 4 quadrants = 1k x 1k detector

LPD - Large Pixel Detector

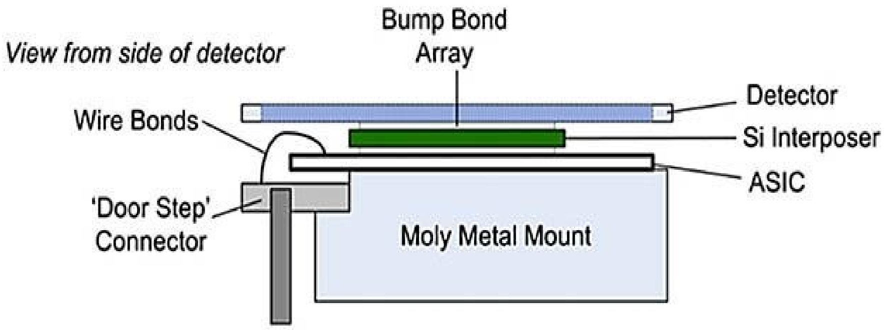
LPD Pixel Cell

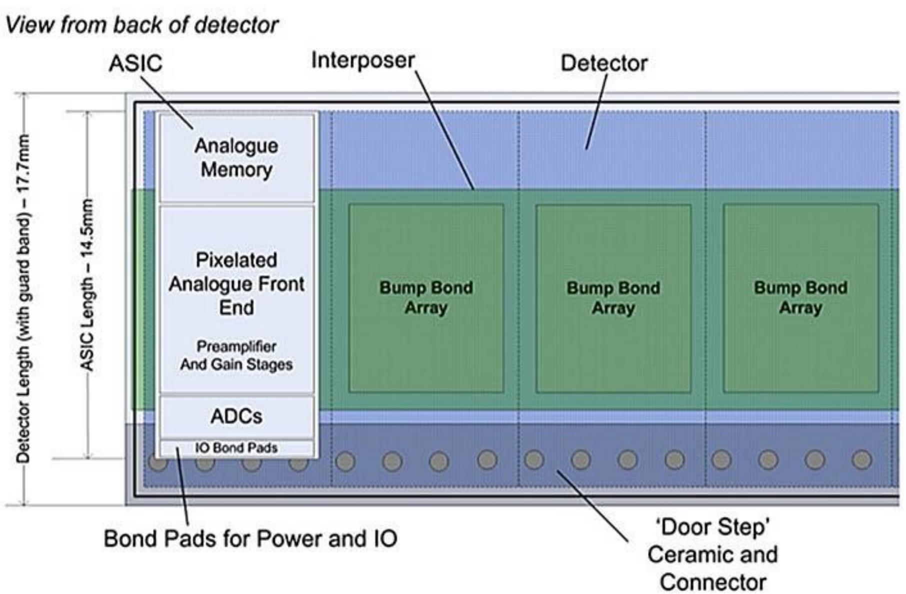


Front End ASIC

- 3 fold multi-gain concept and analog storage pipeline
- 512 channels per ASIC
- 16x 12 bit on chip ADC
- Design IBM 130 nm technology

LPD ASIC and Sensor

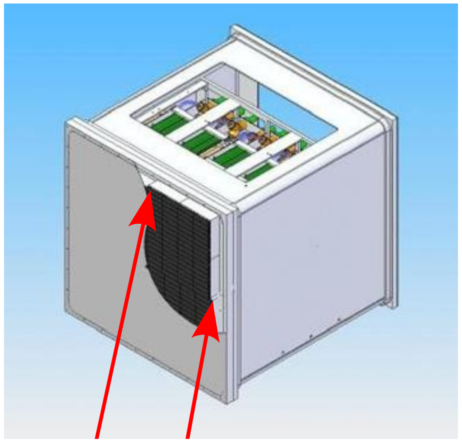




Provided by the LPD consortium

LPD – 1 Mpix Detector Module

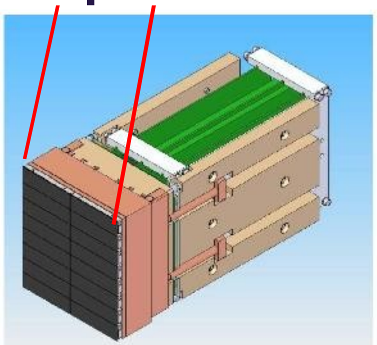
LPD Detector Module



2048 Chips, 1 048 576 pixels
Scale = 12.8 cm

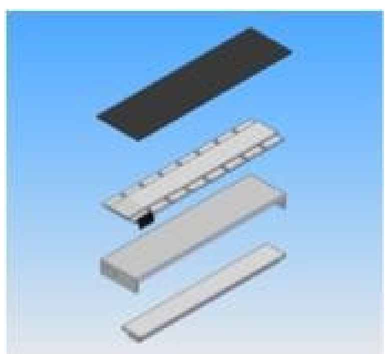
Cooling

Super Module



128 Chips, 65 536 pixels
Scale = 12.8 cm

Sensor Tile

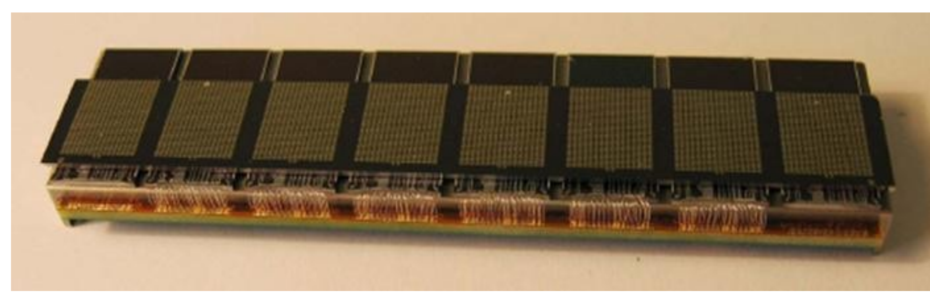


8 Chips, 4 096 pixels
Scale = 6.4 cm

Key Detector Parameters

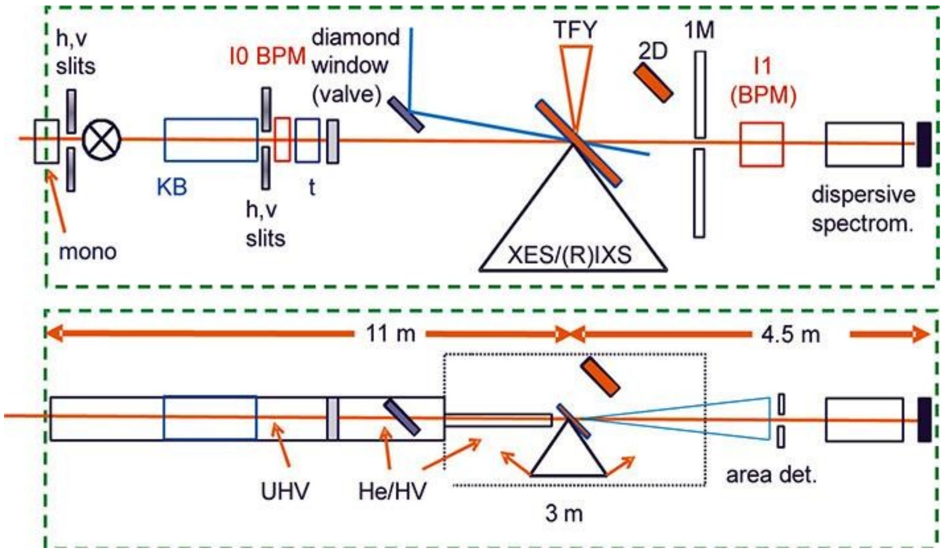
- Energy range
  1 – 24 keV
- Dynamic range
  1 – 10^5 photons/pixel/pulse
- Single photon sensitivity
  Yes
- Pixel size
  500 µm x 500 µm
- Number of storage cells 512

ASIC Module



FXE/SQS - Detector Requirements

Femtosecond X-ray Experiment



Experimental Techniques

- X-ray emission spectroscopy
- X-ray absorption spectroscopy
- X-ray diffraction (SAX, WAX, Bragg)
- eTOF, iTOF, VMI, ...

Status

- Conceptual design of SQS and FXE end-stations have been finished April 2011
- Detector requirements for SQS/FXE stations have been defined
- Technical designs ready till 2012
- Conceptual design reports for SPB and MID are in progress
  deadline September 2011
- XFEL detector R&D road map in preparation
  → technology review
  → definition of next R&D projects

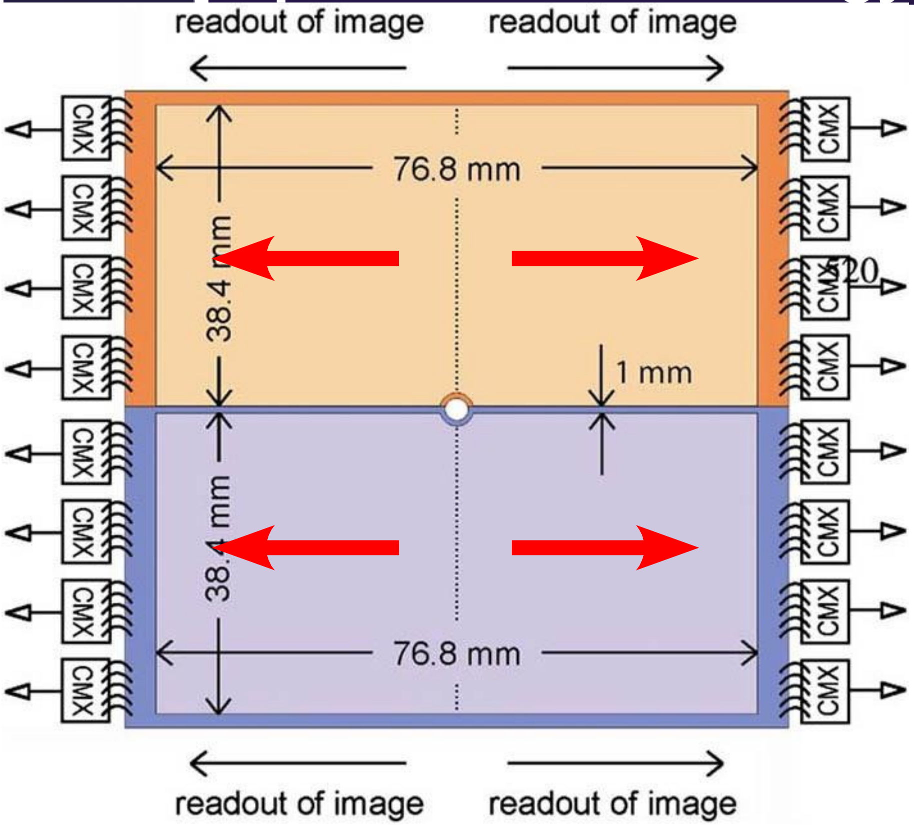
C. Bressler et al. XFEL.EU TN-2011-05

FXE Detector Requirements

Parameter	Diffuse Scattering	XES Analyzer	Solid State Bragg	Time Domain Monitor
Technology	2D Pixel	2D Pixel/1D Strip	2D	2D
Energy Range	3-20 keV	3-20 keV	3-20 keV	UV/Vis
Energy Resolution	No	200 eV @ 7 keV (single photon counting)	No	No
Frame Rate	4.5 MHz	4.5 MHz	4.5 MHz	4.5 MHz
Pixel Size/Strip Size	< 500 x 500 μm^2	100 x 100 μm^2 100 μm	100 x 100 μm^2	< 100 x 100 μm^2
Sensitive Area	22 x 22 cm^2	2 x 6 cm^2	up to 10 x 10 cm^2	1 x 1 cm^2
# Pixels	1k x 1k	200 x 600	≥ 200 x 600	100 x 100
Sensor Material	Si	Si	Si	Si
Sensor Thickness	500 μm	500 μm	500 μm	N/A

Additional information is available online at
http://www.xfel.eu/documents/technical_documents/

Option for Low Energy/Low Rep. Rate

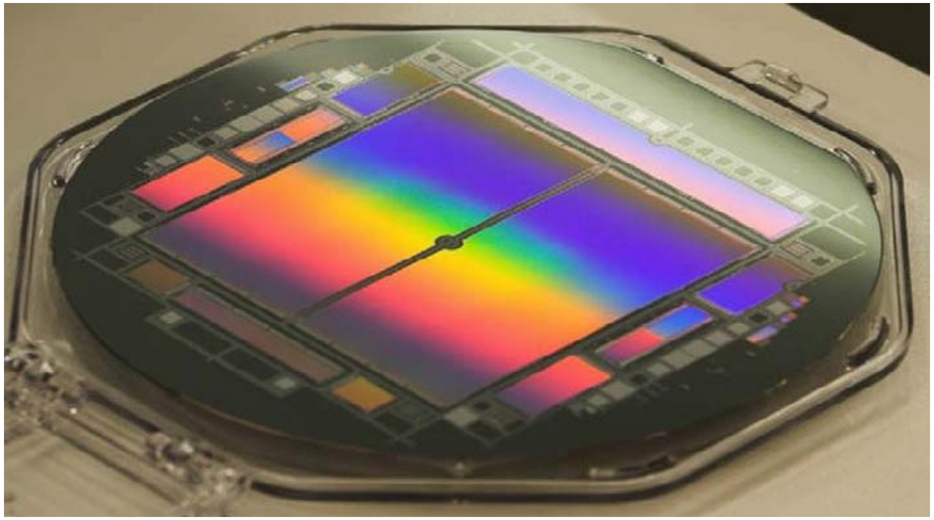


Read Out Concept

- 1 or 2 Mpix device
- Pixel size 75 µm x 75 µm
- Max. frame rate up to 200 Hz
- Highly parallelized read out
- Low noise 2 e^- high gain/20 e^- low gain

On Chip Amplifier

- Pre-amplification, multiplexing, line driving, signal filtering
- 16x 14 bit ADCs, 10 MHz



Strüder et al. NIM A 614 (2010) 483

DAQ – Data Management – Data Analysis (WP-76 C. Youngman, K. Wrona)

Data Volume

- Data rate 2D imaging detectors

  average 13 GB/s peak up to 30 GB/s

  → >10 PB/year storage capacity

Data Handling

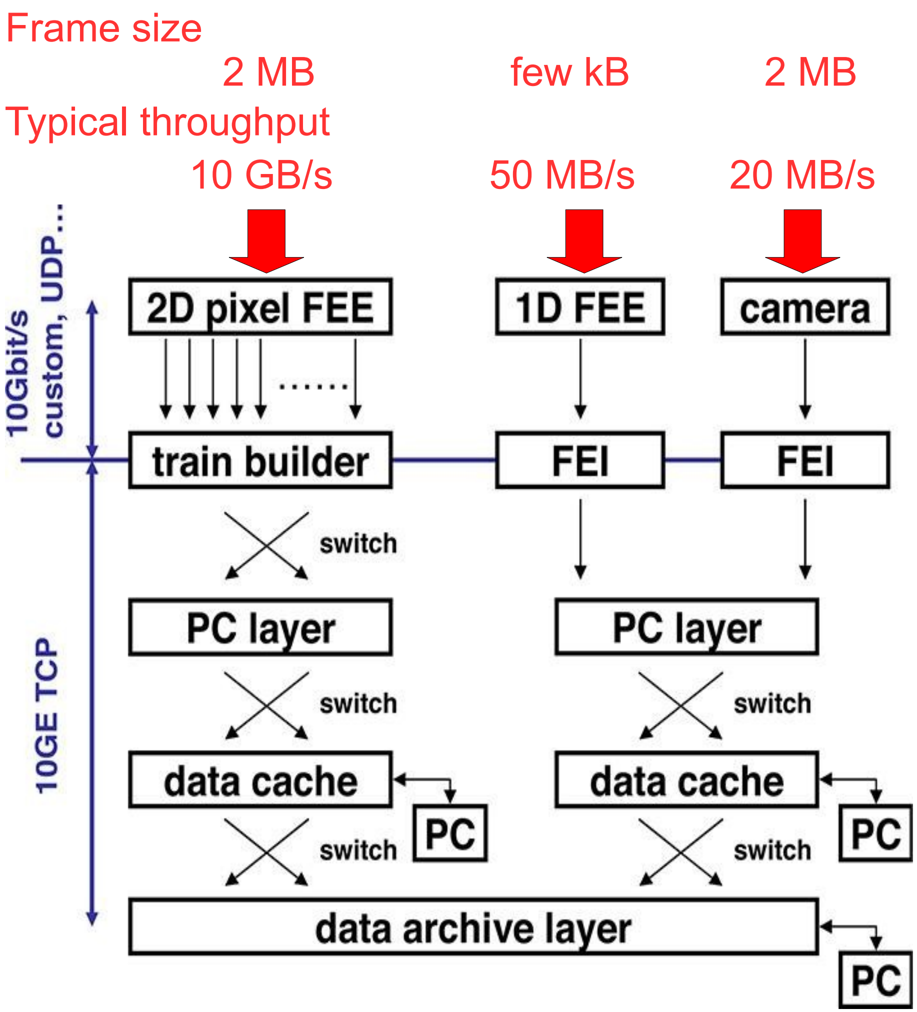
- Data processing and reduction on site (online/off ine)
- Eff cient data reduction concepts required (vetoing, compression)
- Provide storage infrastructure with optimized access

Data Analysis

- Centralized on-site data analysis frame work (scalable, modular, expandable)

DAQ Architecture (C. Youngman WP-76)

EuXFEL Readout Architecture



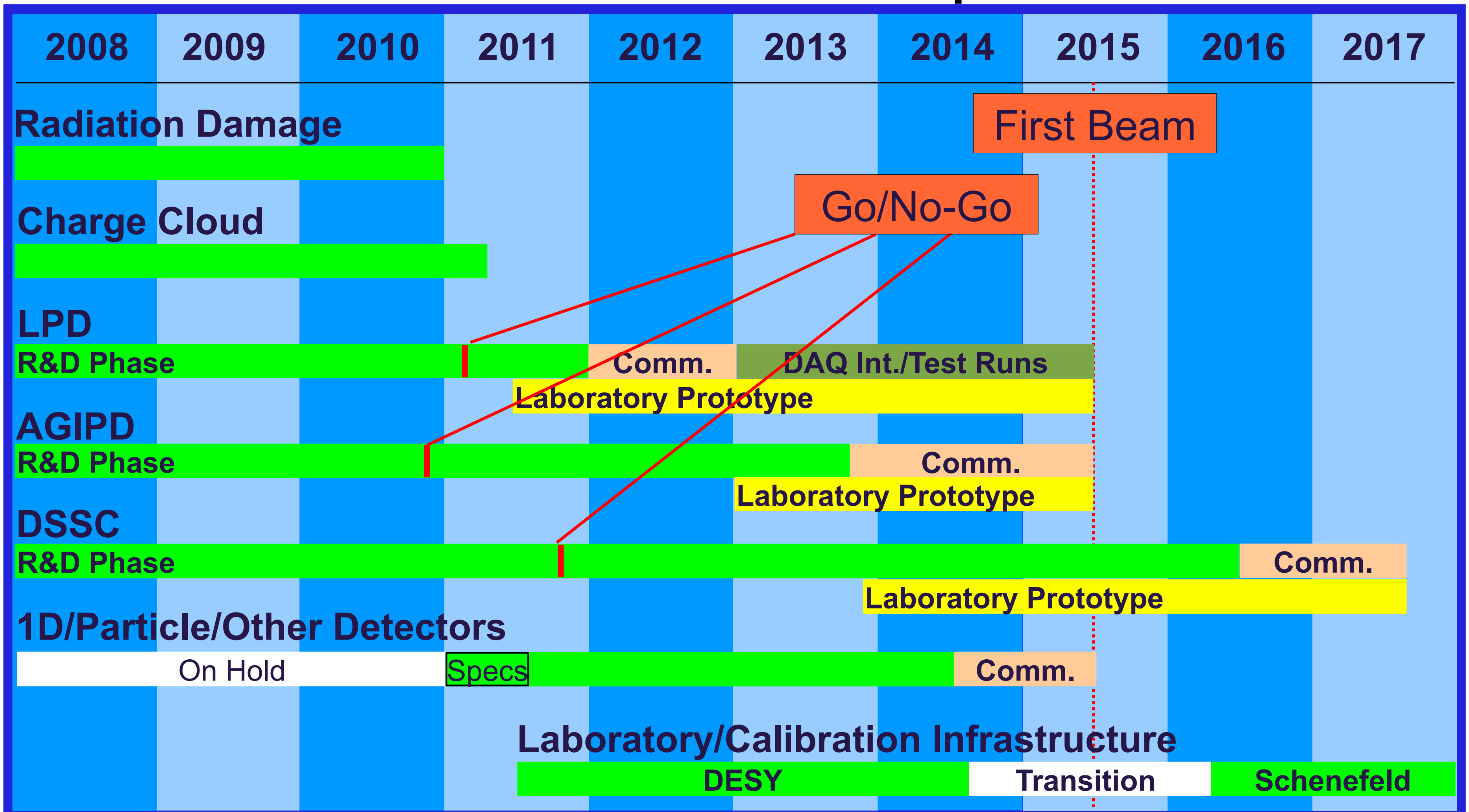
Architecture Layers

- FEE (ASIC+ADC+Data link)
  Data forwarding (all) and formatting (2D)
- FEI (data readout + control)
  formatting, train building, pedestal correction, zero suppression, frame tagging
- Train builder
  formatting, frame/train building, pedestal correction, zero suppression, pixel counting + region of interest finding & tagging …
- PC layer = interface to data cache
  monitoring for control purposes, tagged frame and train rejection, additional analysis and further rejection and/or compression, file size optimization …
- Data cache= temporary storage
  processing
- Data archive = disk & tape storage
  analysis and processing

Courtesy Chris Youngman WP-76 EuXFEL

WP-75 Schedule till 2015

Timeline Detector Development



Summary and Conclusions

- All 2D detector projects are on track and progressing well
- Test measurements with ASICs and prototype sensors are progressing well
- Radiation tolerance measurements and optimization is ongoing
- We look into alternative 2D detector technologies for low energy, high energy and low repetition rate applications
- Evaluation of 0D/1D, small area imaging and particle detector requirements is ongoing
- Next in depth review: DSSC in October

We have an exiting and challenging time ahead of us!

XFEL 2D Detector Collaboration

AGIPD Adaptive Gain Integrating Detector Consortium (AGIPD)

Project Leader:

H. Graafsma, DESY

- PSI/SLS Villingen
- Universität Bonn
- Universitä...
- DESY

Large Pixel Detector Consortium (LPD)

Project Leader:

M. French, RAL/STFC

- STFC/Rutherford Appleton Lab.
- University of Glasgow

Radiation

Project Leader:

R. Klanner, Universität Hamburg

...nal ...n (DSSC)

M. Porro, Politechnico di Milano

- Max-Planck Halbleiterlabor Munich
- Universität Heidelberg
- Universität Siegen
- Politechnico di Milano
- Università di Bergamo
- DESY Hamburg

Charge Cloud Simulations

Project Leader:

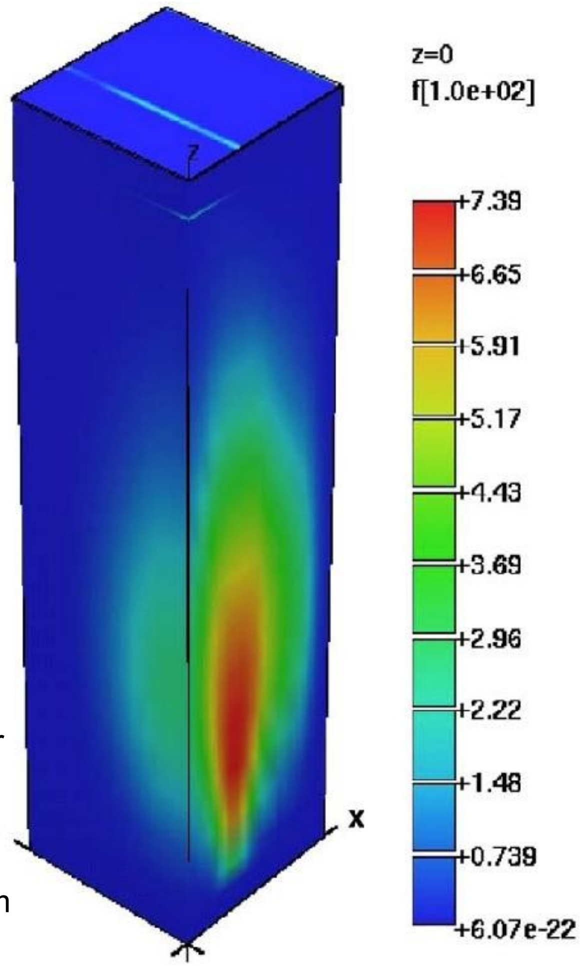
K. Gärtner, Weierstrass Institut Berlin

Thanks to all collaboration members for their contributions !

Backup Slides

Charge Explosion Effects

Charge Evolution Cloud in Si



1.5 ns after generation

Initial diameter 5 µm

Final size 25 µm x 65 µm

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

Plasma Effects in Si

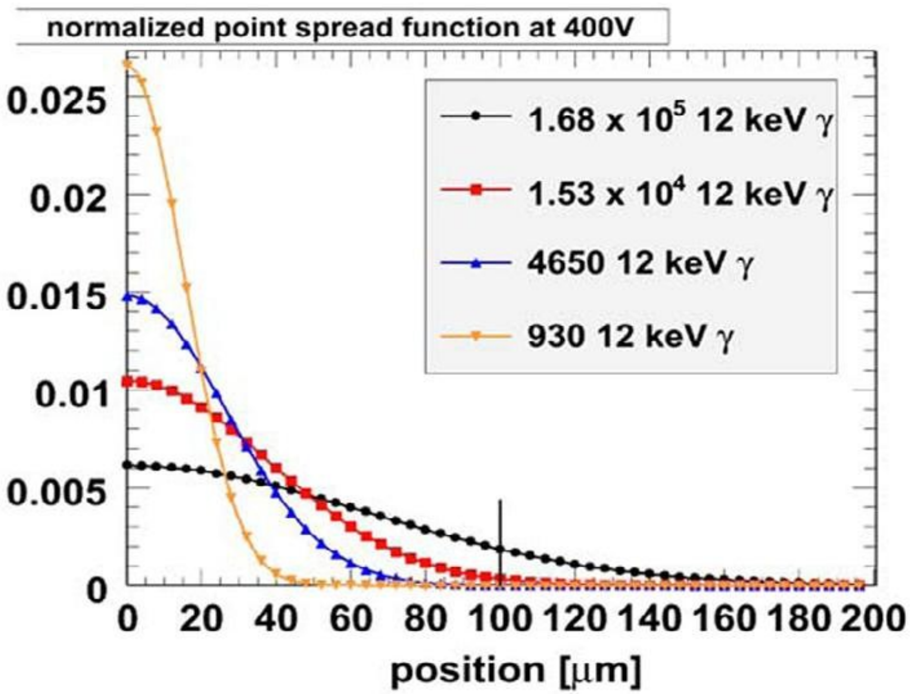
- At XFEL intensities 10^4 photons/pixel/pulse electron hole plasma effects dominate in sensor
- Plasma modifies the electric field in the sensor
- Ambipolar diffusion dominates over drift of charge carriers
- Effects dominate at high densities, negligible at low densities

  → **affects PSF/charge splitting**

  → **affects charge collection time**
- Plasma effects decrease with increasing electric field strength (bias voltage)

Point Spread Function

Point Spread Function - PSF



Parameter Dependency

- Bias voltage → electric field
- Photon energy
- Photon intensity/spot size

Collaboration Partners

- Simulations K. Gärtner WIAS
- Measurements J. Becker, R. Klanner et al. Universität Hamburg

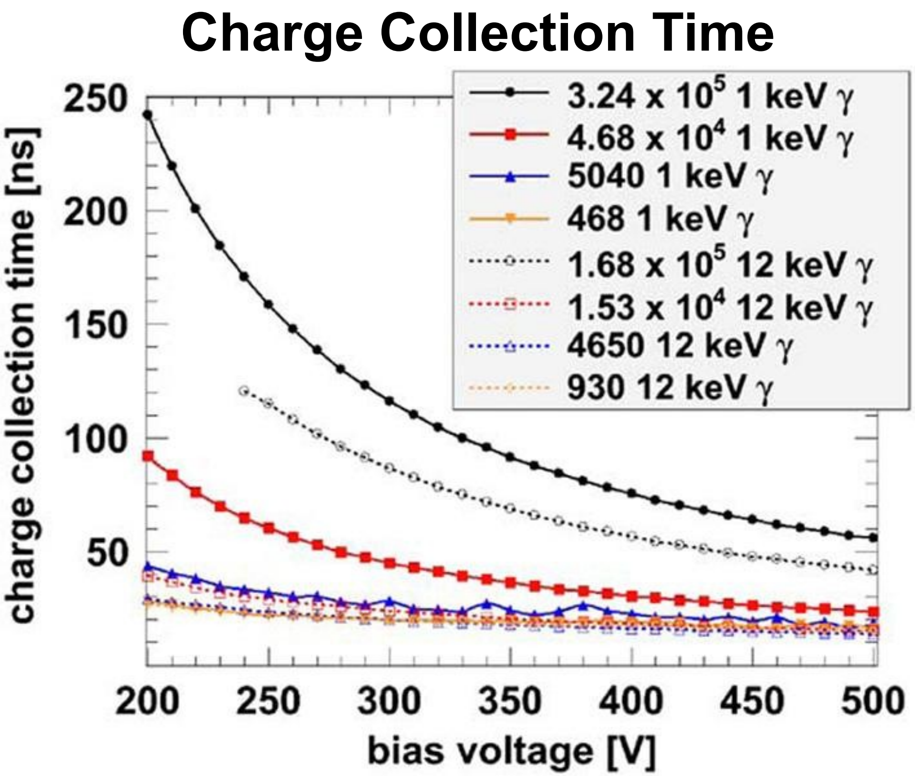
Results (AGIPD)

- For high densities/low bias voltages the charge collection time exceeds XFEL bunch rep. time
- PSF stays within one pixel size for 10^4 12 keV or 10^5 1 keV photons

Effects negligible for current design!
(200 x 200 μm^2 pixel size)

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

Charge Collection Effects



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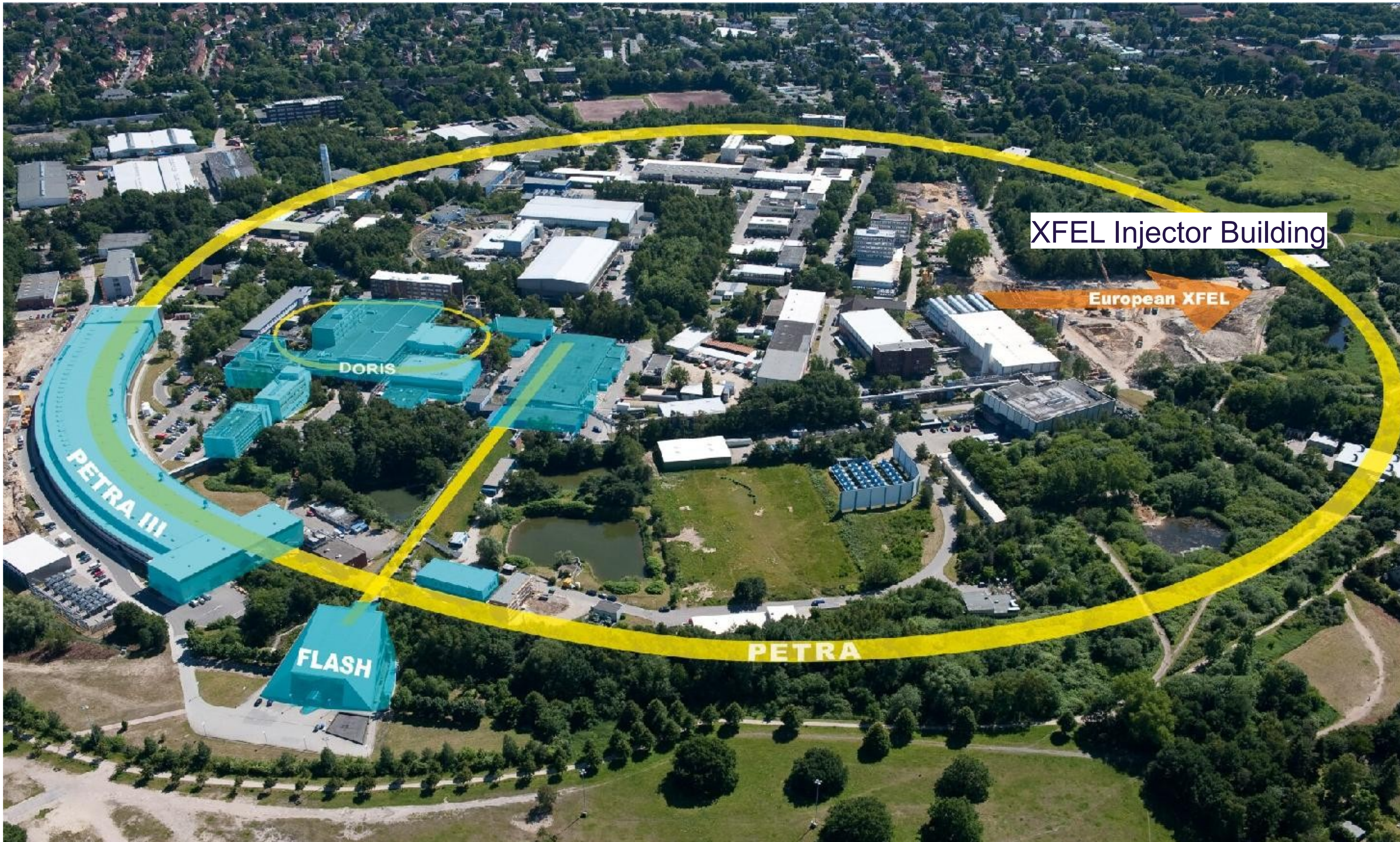
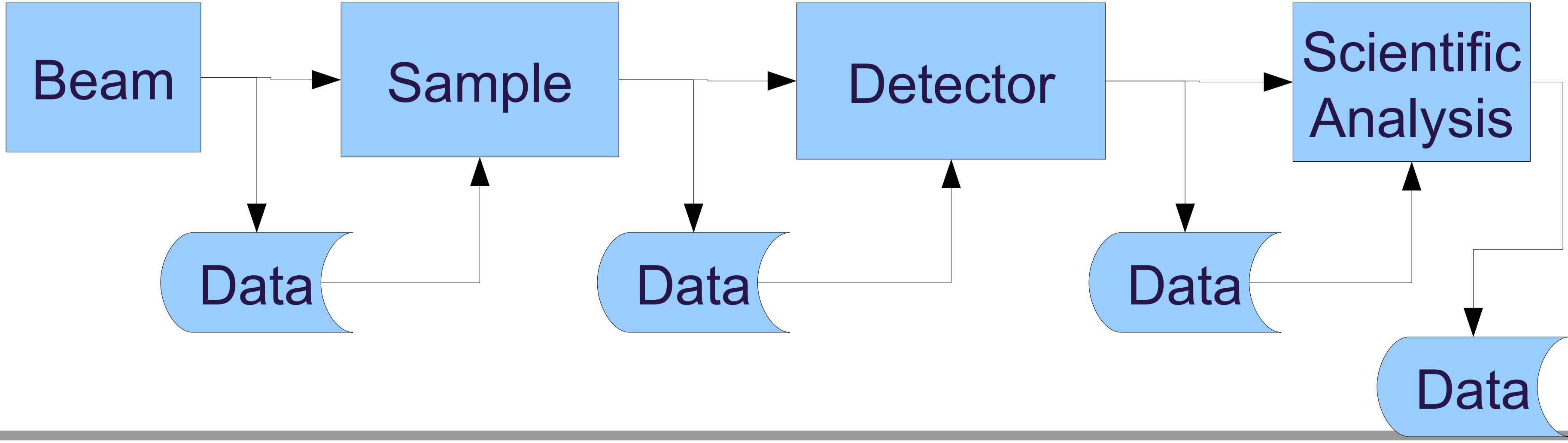
XFEL @ DESY Campus



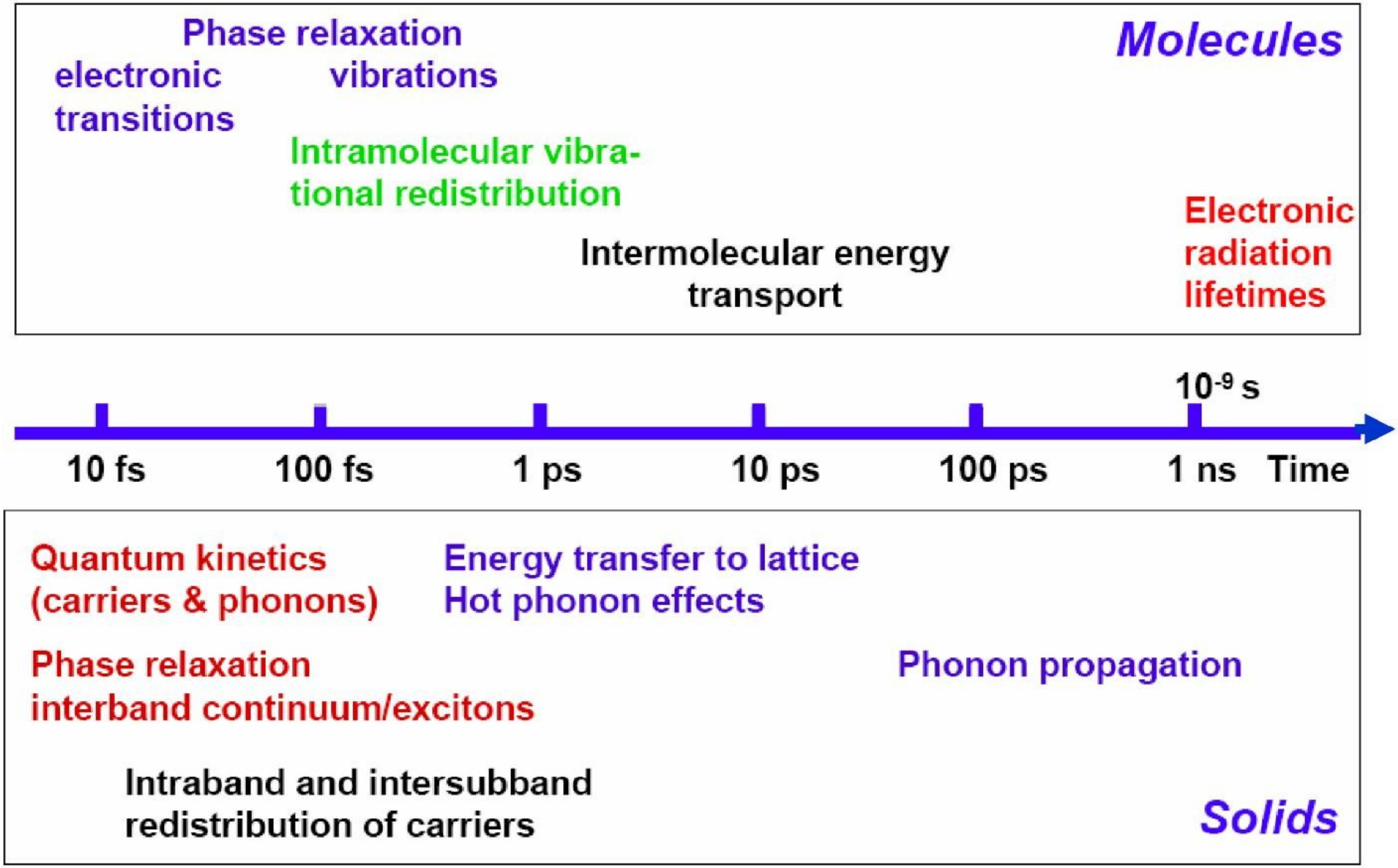
Start-to-End Simulation



Status and Goals

- Collaboration between experts in different disciplines at DESY, CFEL, XFEL + … requirement definition + conceptual design phase
- Modular, scalable and user accessible
- Experiment optimization and planning, optimization and performance simulation of sub-components, experiment planning
- Integrated into standard data analysis and management concept

Timescale of Dynamics



Smaller Pixel Size

AGIPD Feasibility Study

100 x 100 µm² possible

Price to pay

- Limited number of storage cells
  → memory depth 128(300) images
- No gain switching (low intensity)
- Radiation hardness issues

LPD Feasibility Study

250 x 250 µm² possible

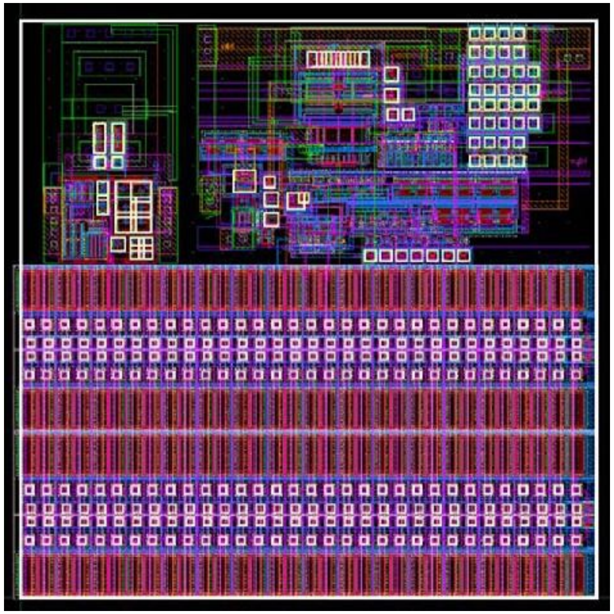
Price to pay

- Limited number of storage cells
  → memory depth 374(512) images
- Different interposer technology
- Sensor OK

XPCS Requirement

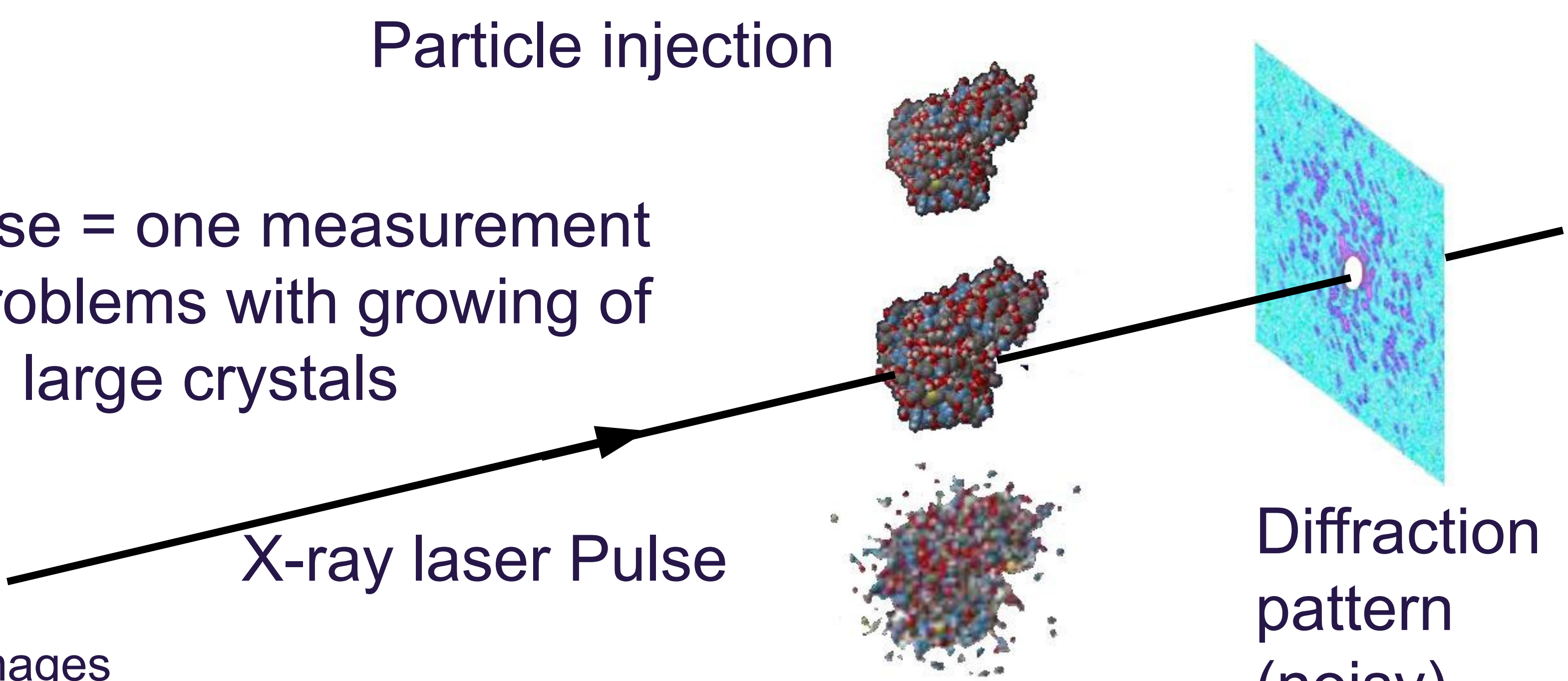
- No signal overlap between pixels, i.e. one speckle per pixel
- Pixel size < 50 µm
  ideally < 20 µm at 4 m distance

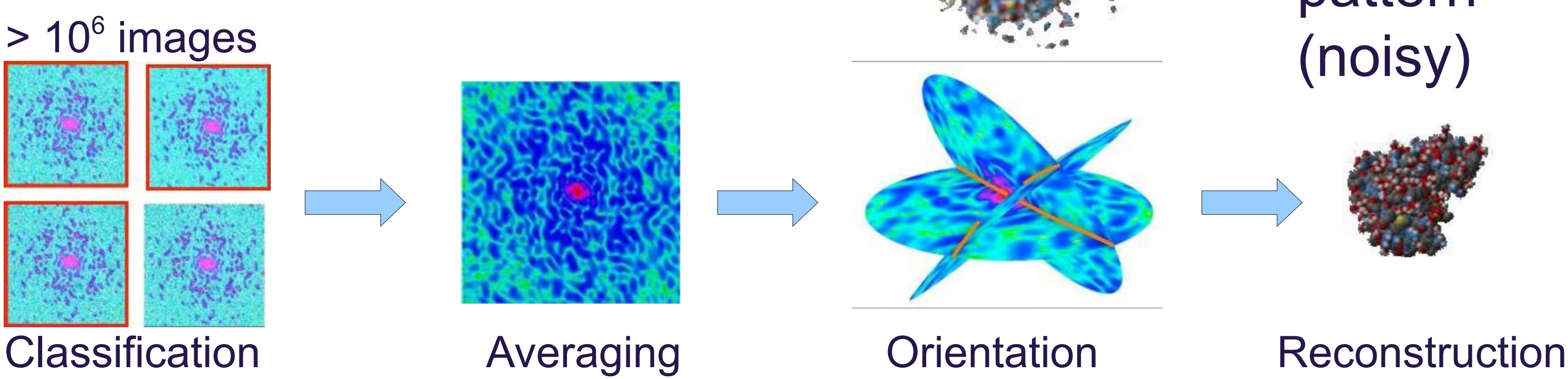
AGIPD Reduced Area Pixel Cell



Single Molecule X-ray Imaging

One pulse = one measurement
Avoid problems with growing of large crystals

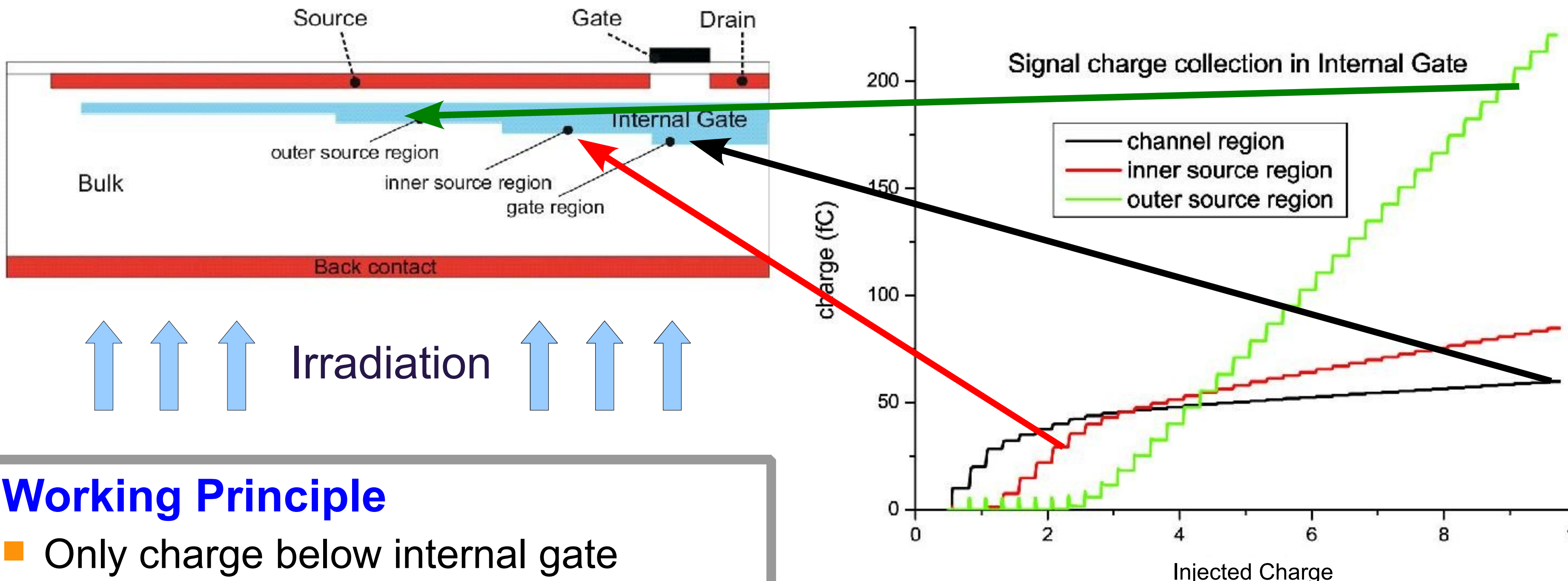




DSSC Signal Compression

Extended Internal Gate

Charge Collection at Internal Gate



Working Principle

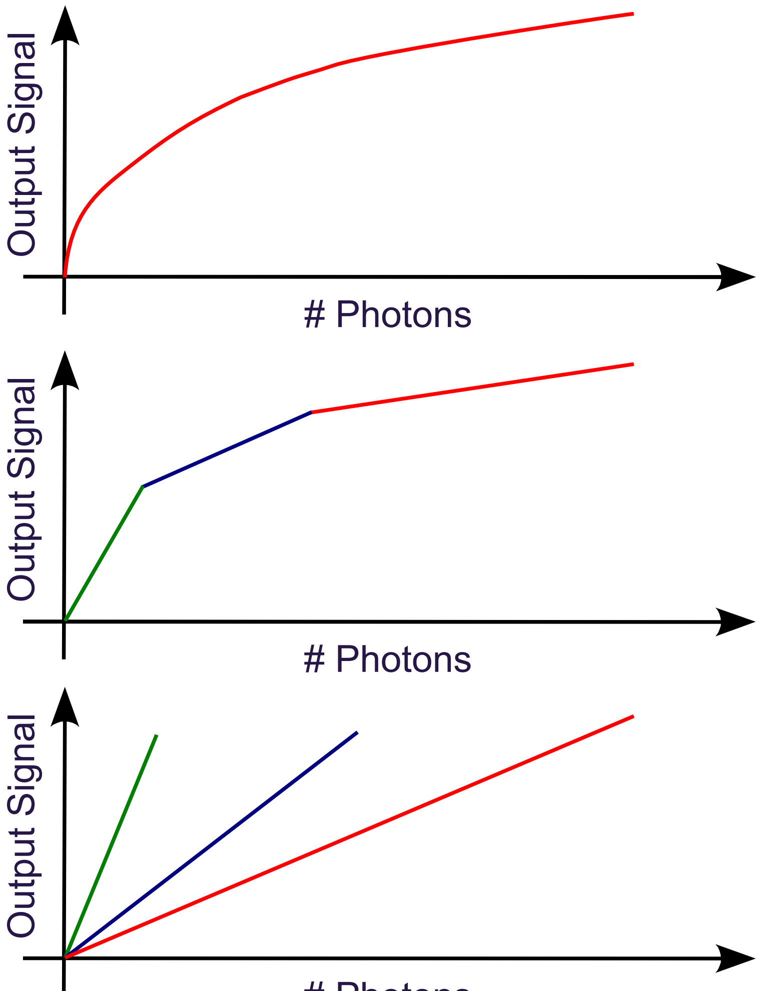
- Only charge below internal gate contributes to I_{SD}
- Small signals
  → charge collected at internal gate
  → full/most effective steering of I_{SD}

- Large Signals
  → charge spills over to source region
  → minor or no contribution to I_{SD}

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

Dynamic Range

Dynamic Range Compression



Requirements

Single photon sensitivity (5σ) and high luminosity of 10^3-10^4 ph/pixel/pulse simultaneously

- Small signals need to be measured with high accuracy
- Large signals are dominated by Poissonian noise $\propto \sqrt{n}$
  → less accuracy required

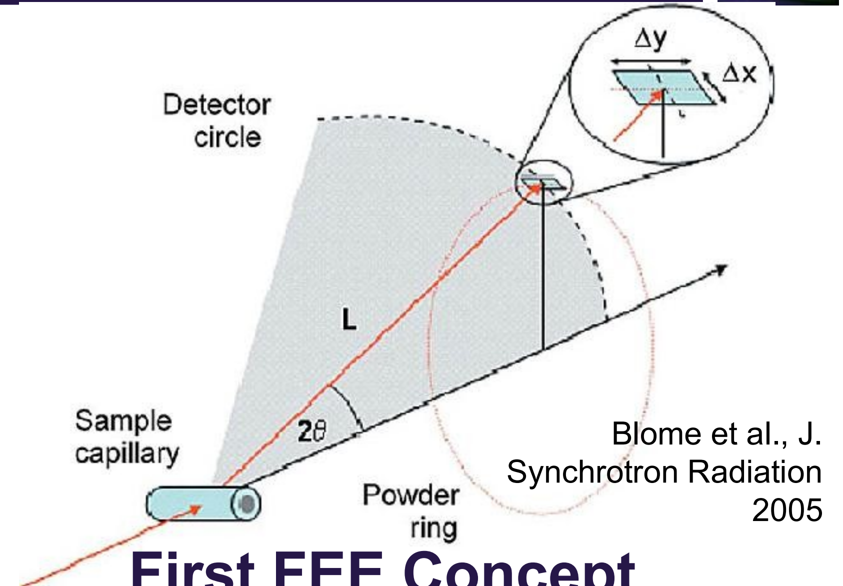
Solution

Non-linear component per pixel in sensor or front-end with decreasing gain for increasing signal levels

- Sensor intrinsic non-linear gain
- Dynamic gain switching
- Three parallel amplifier stages

1D Detectors and 2D Small Area Detectors

- First review of requirements in 2008 (I. Ramos)
- Conclusions 2009
  - Powder diffraction experiments
  - Dispersion experiments
  - Baseline sensor
    - ➔ 1D strip detector, 1024 strips, 50 µm strip pitch, 4.5 MHz readout, optimized for 12 keV
- **Further studies are presently ongoing**



Blome et al., J. Synchrotron Radiation 2005

First FEE Concept