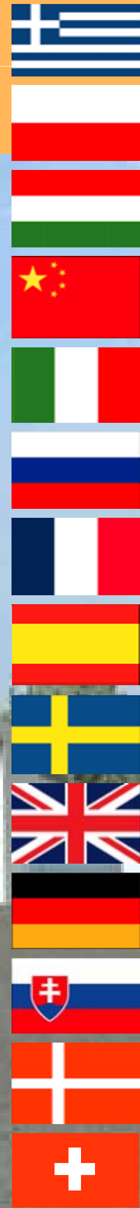
The European XFEL Project



Ulrich Trunk
Deutsches Elektronen-Synchrotron DESY

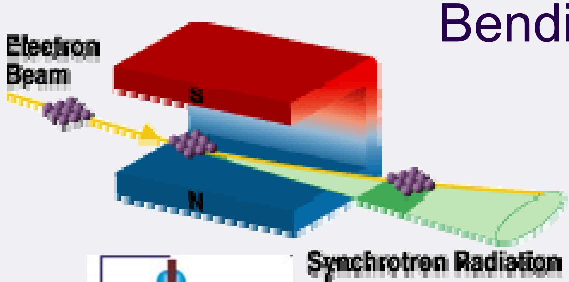
Outline

- The XFEL Machine
  - Electron Accelerator
  - Undulator Sources
- Experiments
  - XPCS Photon Correlation Spectroscopy
  - XCDI Coherent Diffraction Imaging
- 2D Area Detectors
  - Large Pixel Detector (LPD)
  - DEPFET Active Pixel Sensor (DEPFET-APS)
  - Hybrid Pixel Array Detector (HPAD)

X-Ray Sources

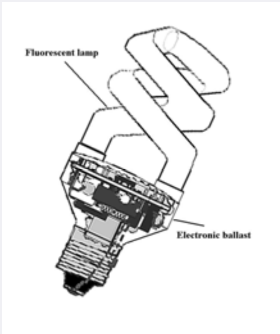
Light bulb

incoherent,
white spectrum

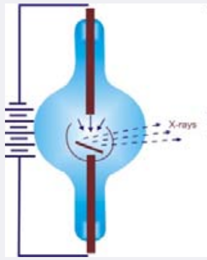


Bending magnet

Fluorescent lamp
(e.g. Hg, Ne)

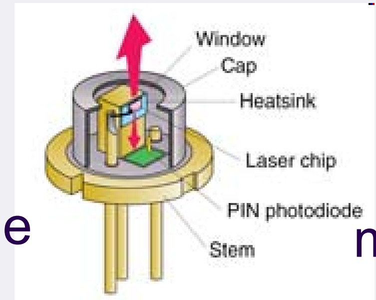


incoherent,
Line spectrum

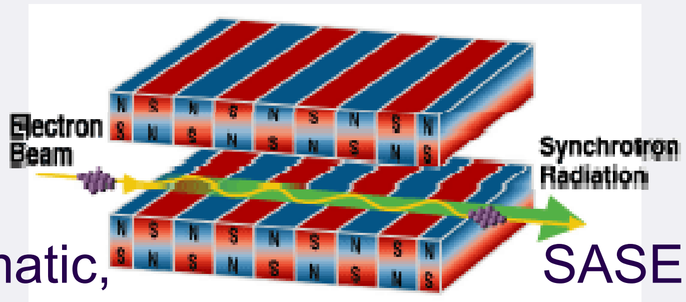


X-ray tube

Laser diode

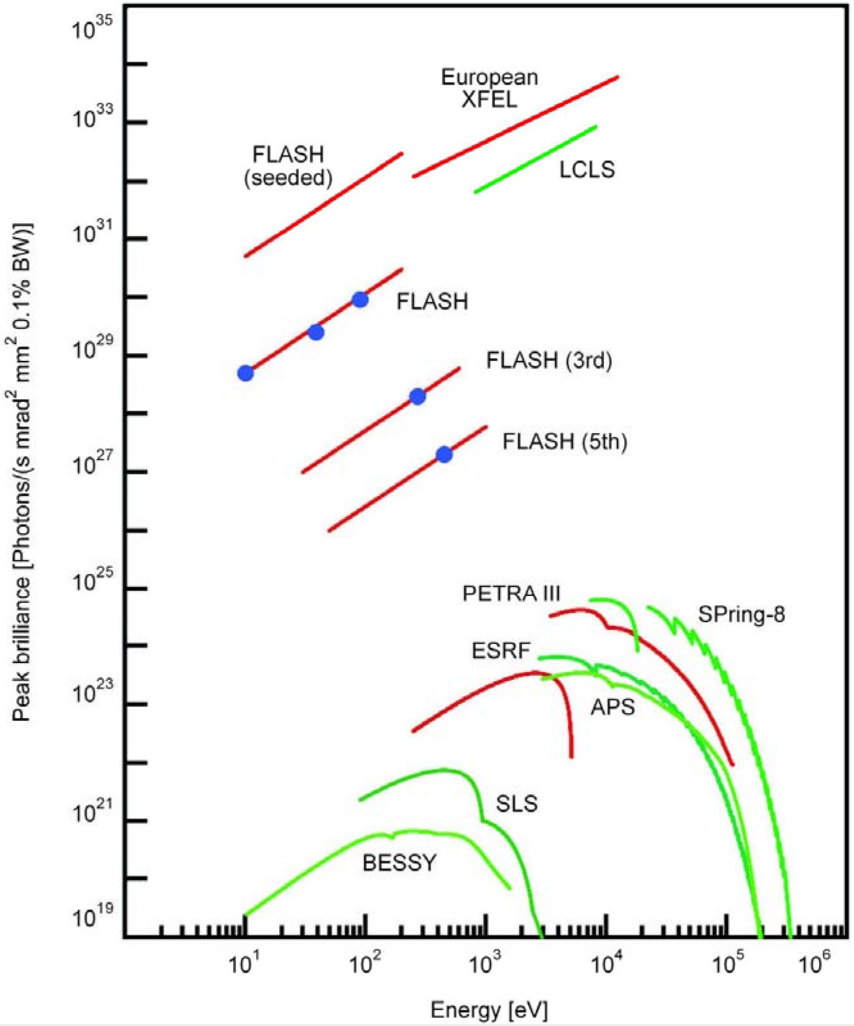


monochromatic,
coherent



SASE undulator

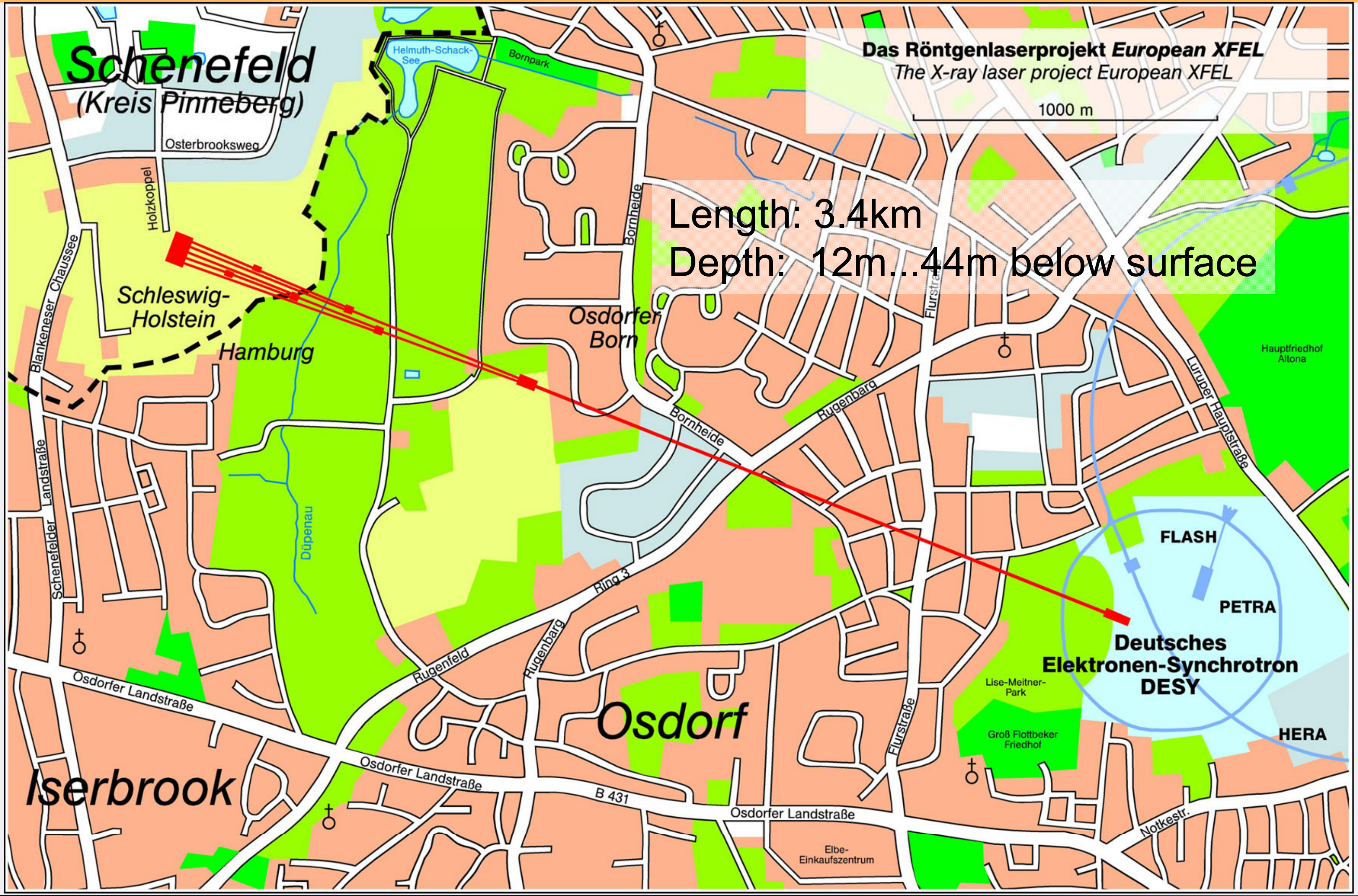
The European XFEL Key Parameters



- Superconducting linac driven
- SASE undulators
- 10^{33} ph/(s mm^2 mrad^2 0.1%BW) peak brilliance
  - 10^9 wrt. 3rd gen. synchrotrons
  - 10^5 in av. brilliance
- $E\gamma$=250eV…12keV
- 100fs pulse width
- 3000 pulses@5MHz

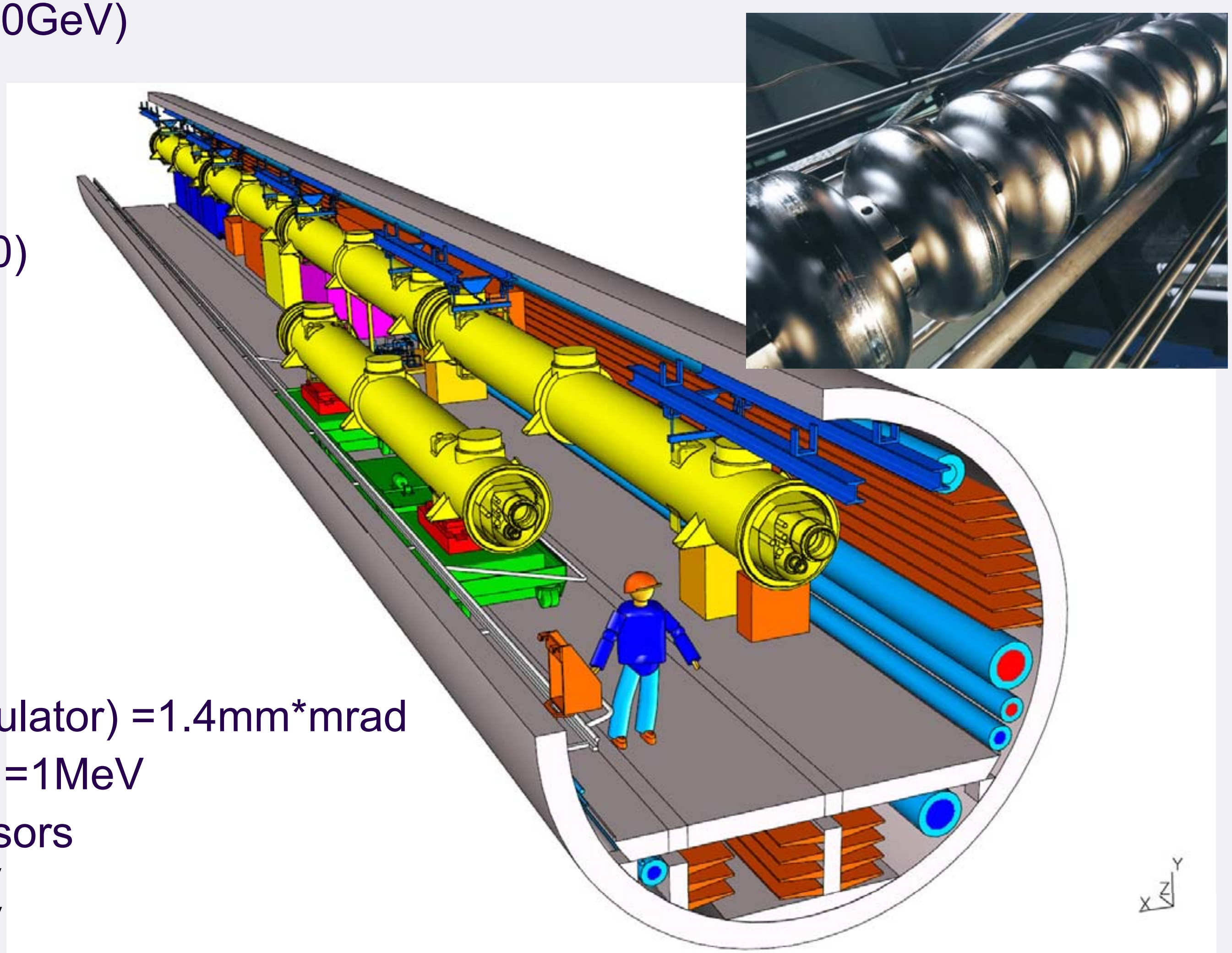
Other FEL sources: LCLS, SCSS

The XFEL Machine

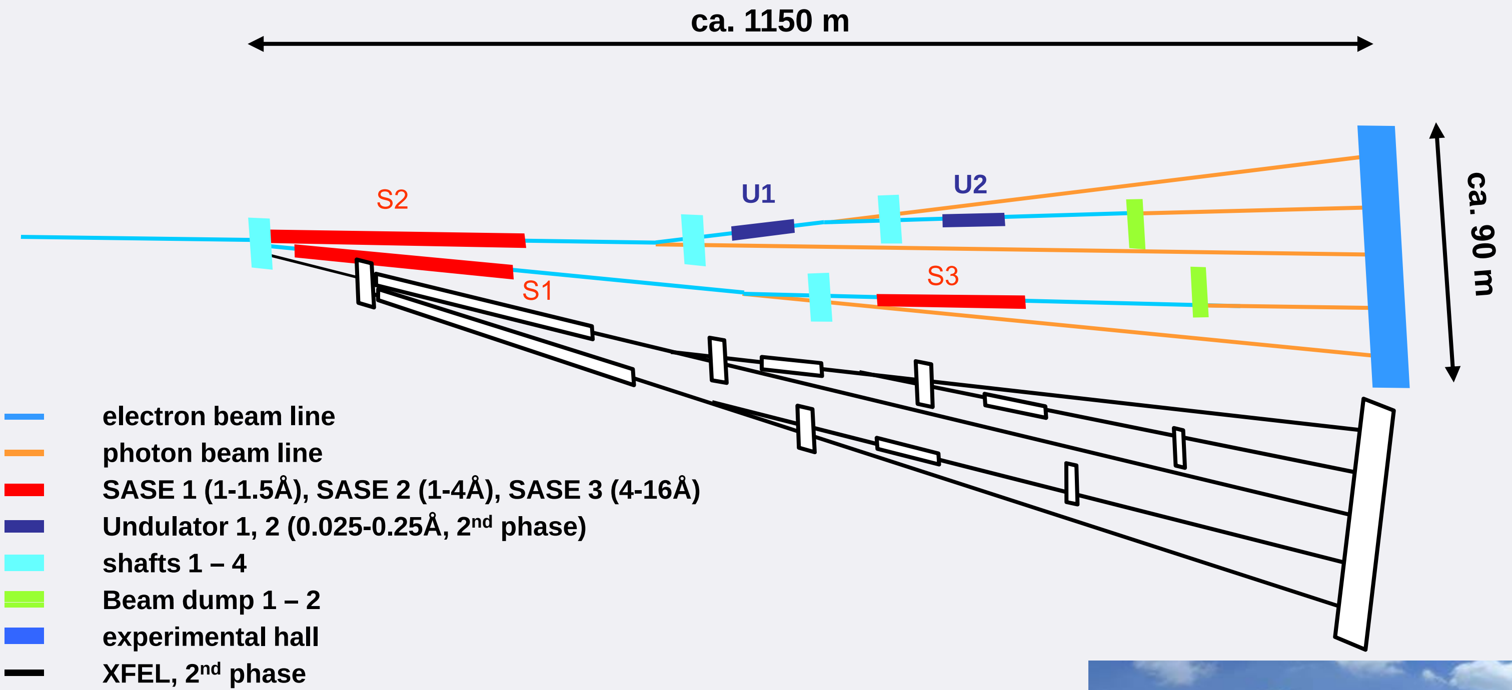


The Linac

- W_{max}=17.5GeV (20GeV)
- I_{peak}=5kA
- Q_{bunch}=1nC
- P_{beam}=600kW
- N_{bunch}=3000 (3250)
- E_{acc}=23.6MV/m
- f_{bunch}=5MHz
- f_{cycle}=10Hz
- 29 RF stations
- 928 cavities
- 116 modules
- P_{RF}=5.2MW
- Emittance (@undulator) =1.4mm*mrad
- ΔE (@undulator) =1MeV
- 2 bunch compressors
    - 1/20 @0.5GeV
    - 1/5 @2.0GeV



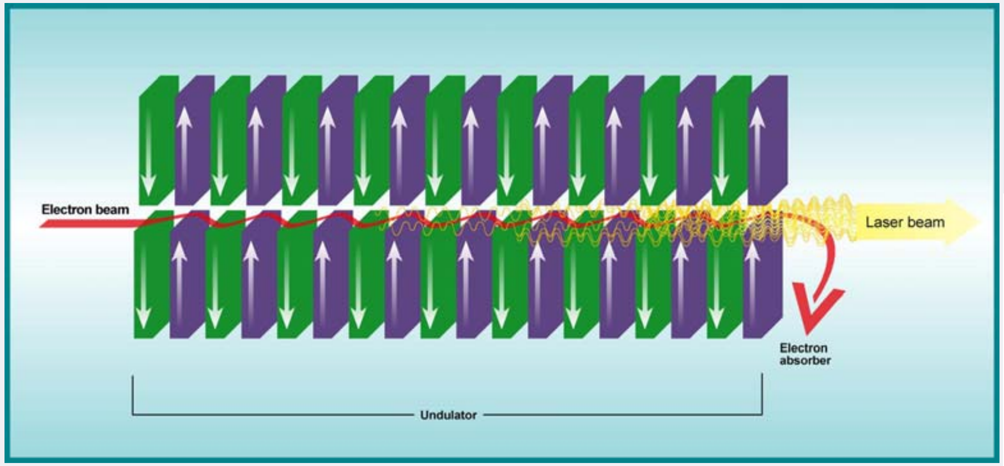
Beam Distribution

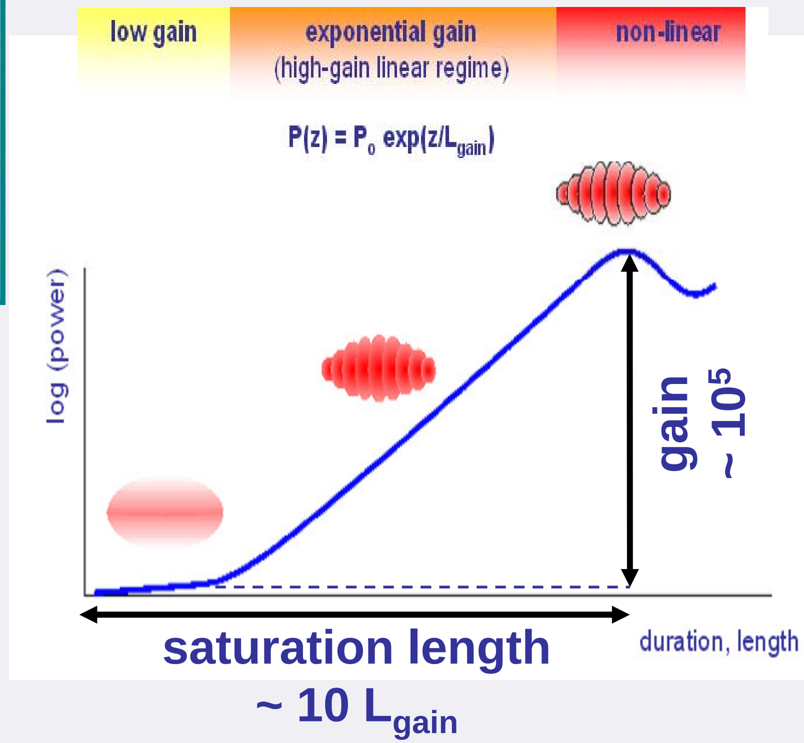


Two-stage kicker system

- Electron beam distribution among SASE undulators
- 5MHz dump kicker
  - Remove bad bunches
  - Remove bunches in the ramp phase of the flat-top kicker
- Flat-top kicker
  - Switch between S1/S3 and S2 beamlines

Synchrotron Radiation in FELs





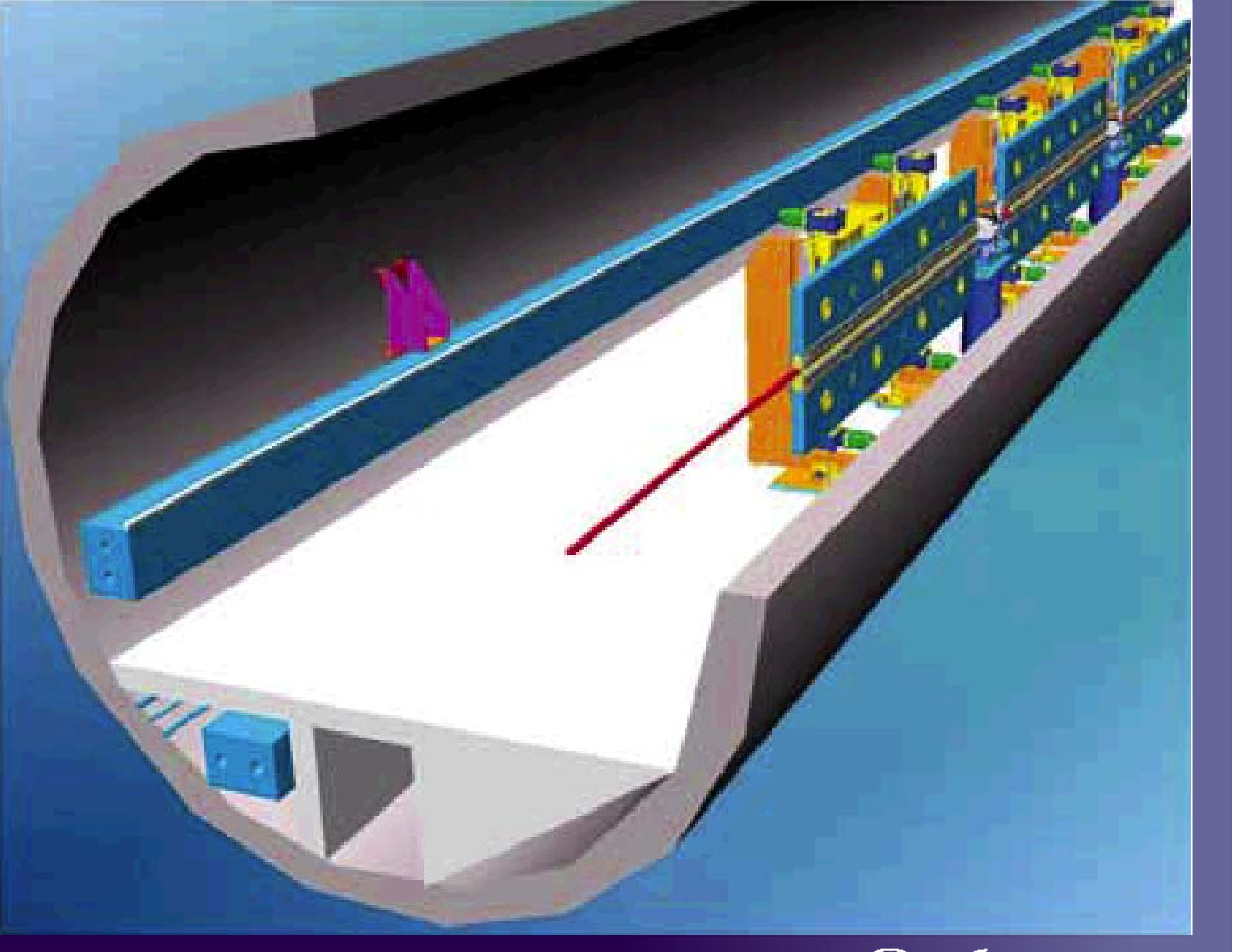
- SASE principle

(Self-Amplified Spontaneous Emission)

  - Random seed
    - Almost 100% transverse coherence
    - Limited temporal coherence
  - Tail-head phenomena
    - Microbunching
    - Exponential growth of intensity & power

Undulators

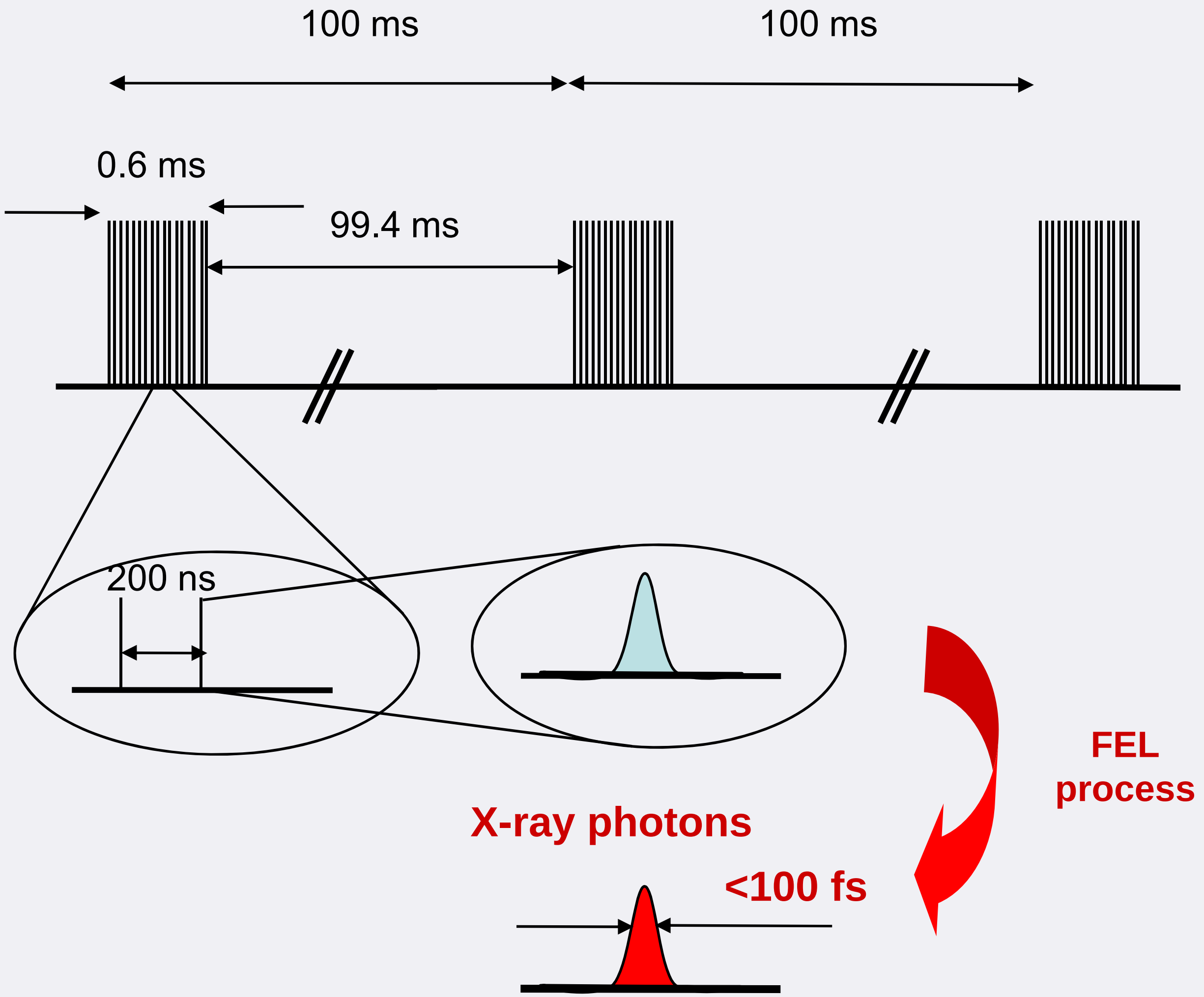
- Based on those used in FLASH
- Composed of ~5m long sections
- 21 to 42 sections per SASE source



Beamlines & Experiments

Beamline	X-ray features	Proposed instruments
SASE 1	~12 keV High coherence High flux 3 rd harmonic	PCS 1 – X-ray Photon Correlation Spectroscopy FDE 1 – Femtosecond Diffraction Experiments SPB 1 – Single Particles and Biomolecules
SASE 2	3.1 – 12.4 keV High coherence High flux	CXI 1 – Coherent X-ray Imaging HED 2 – High Energy Density XAS 2 – X-ray Absorption Spectroscopy
SASE 3	0.25 – 3.1 keV High coherence High flux 3rd harmonic	HED 1 – High Energy Density SQS 1 – Small Quantum Systems XAS 1 – X-ray Absorption Spectroscopy SQS 2 – Small Quantum Systems PCS 2 – X-ray Photon Correlation Spectroscopy CXI 2 – Coherent X-ray Imaging

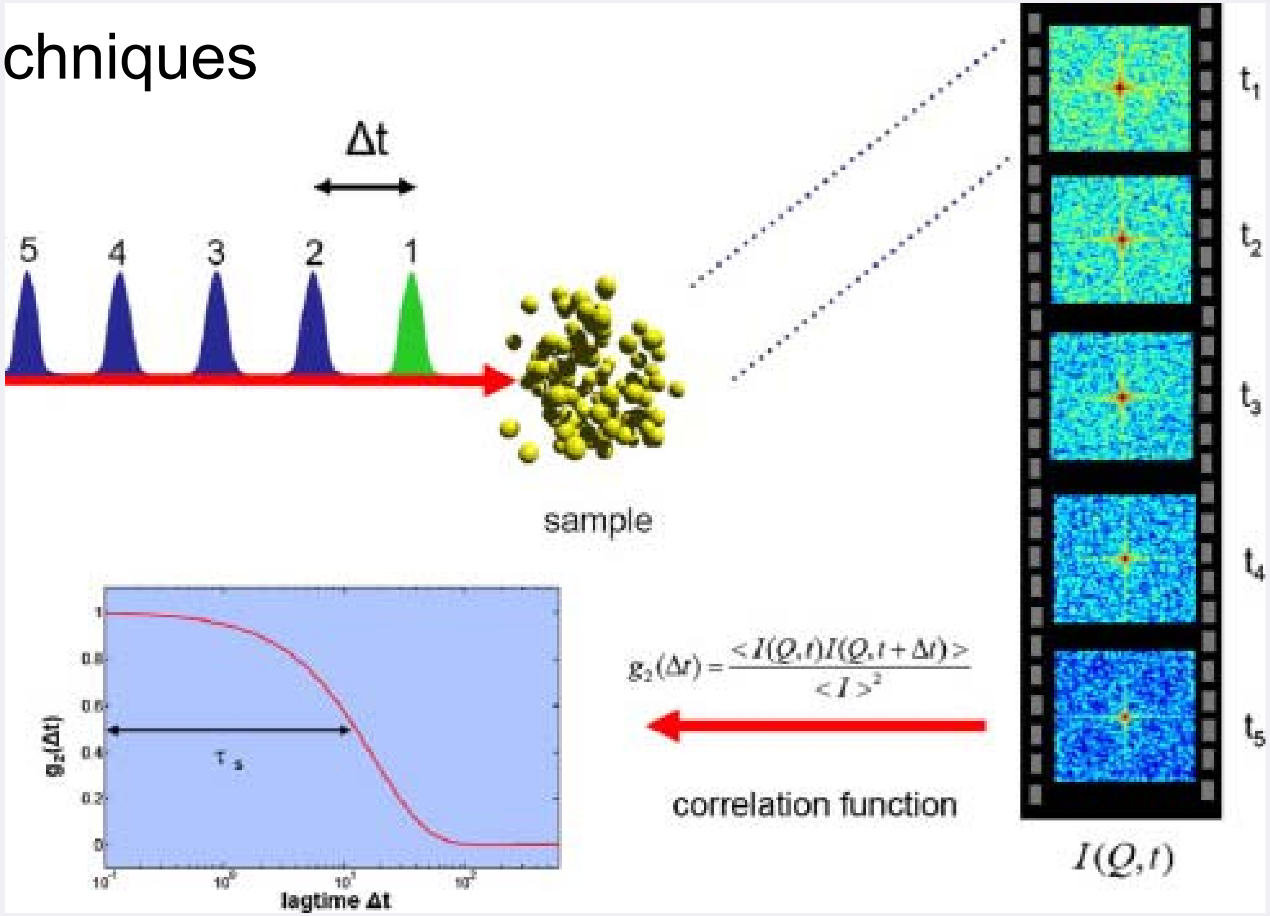
The Linac: Time Structure



av. Rate:
30kHz XFEL
120Hz LCLS
60Hz SCSS

X-ray Photon Correlation Spectroscopy

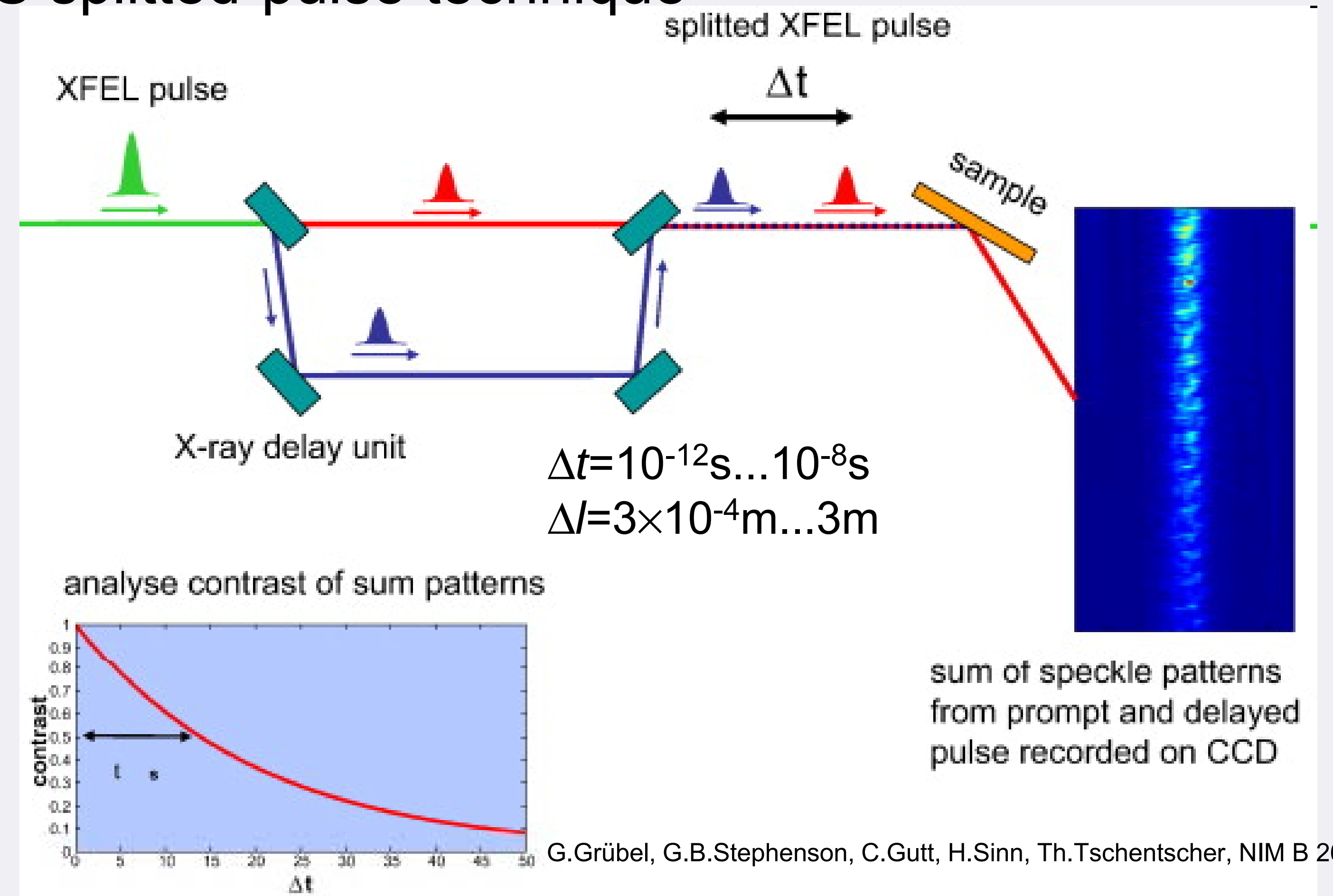
XPCS techniques



G.Grübel, G.B.Stephenson, C.Gutt, H.Sinn, Th.Tschentscher, NIM B 262 (2007)357 –367

X-ray Photon Correlation Spectroscopy

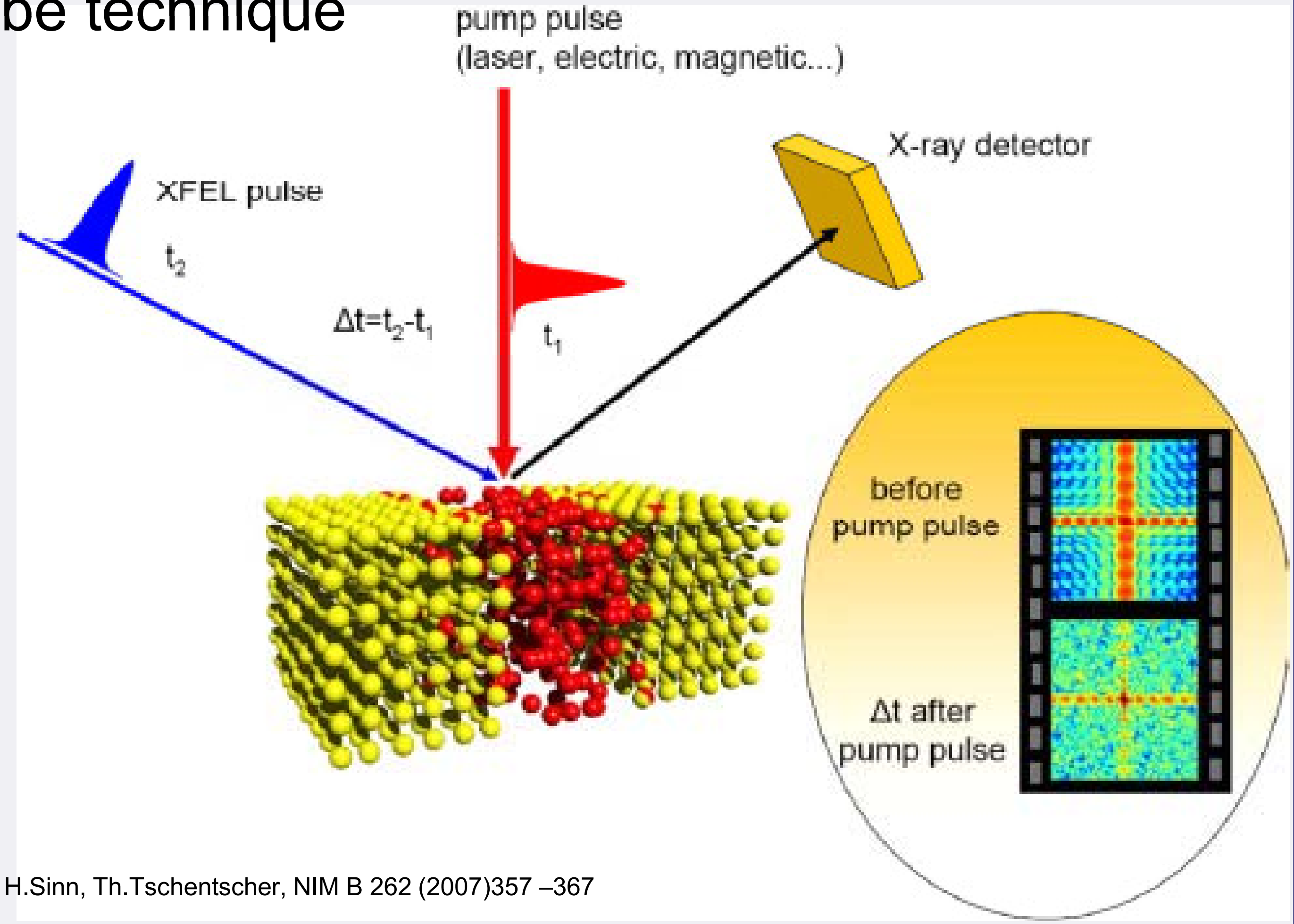
XPCS splitted-pulse technique



G.Grübel, G.B.Stephenson, C.Gutt, H.Sinn, Th.Tschentscher, NIM B 262 (2007)357 –367

X-ray Photon Correlation Spectroscopy

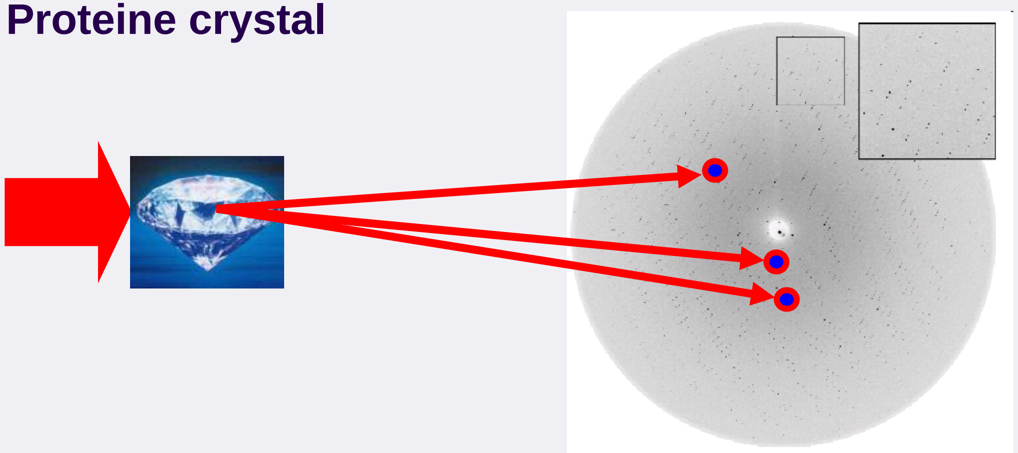
XPCS pump-probe technique



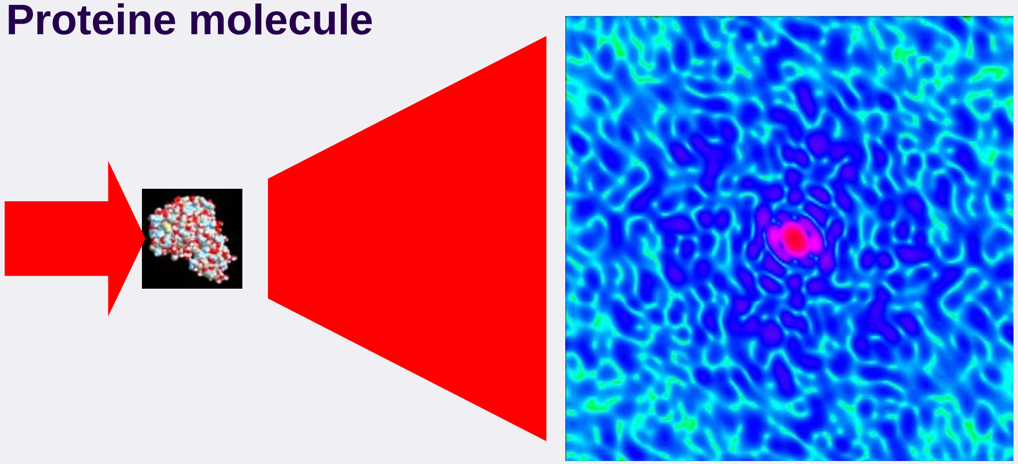
G.Grübel, G.B.Stephenson, C.Gutt, H.Sinn, Th.Tschentscher, NIM B 262 (2007)357 –367

Single Molecules & Coherent X-ray Imaging

Proteine crystal



Proteine molecule

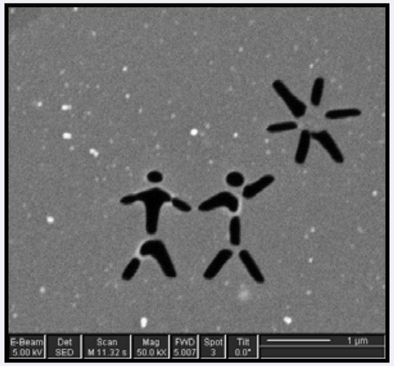


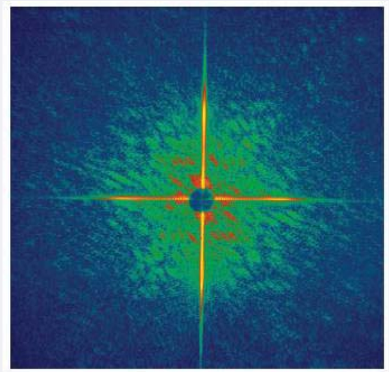
(Simulated images)

Single Molecules & Coherent X-ray Imaging

FLASH (32nm 25fs 10^{14}W/cm^2)

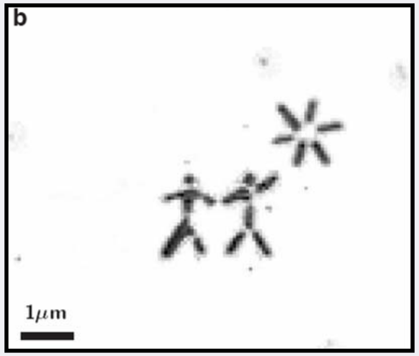
**TEM picture
of original structure**

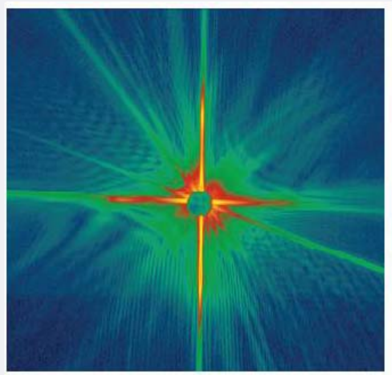




**Diffraction pattern
from first pulse**

Reconstructed picture



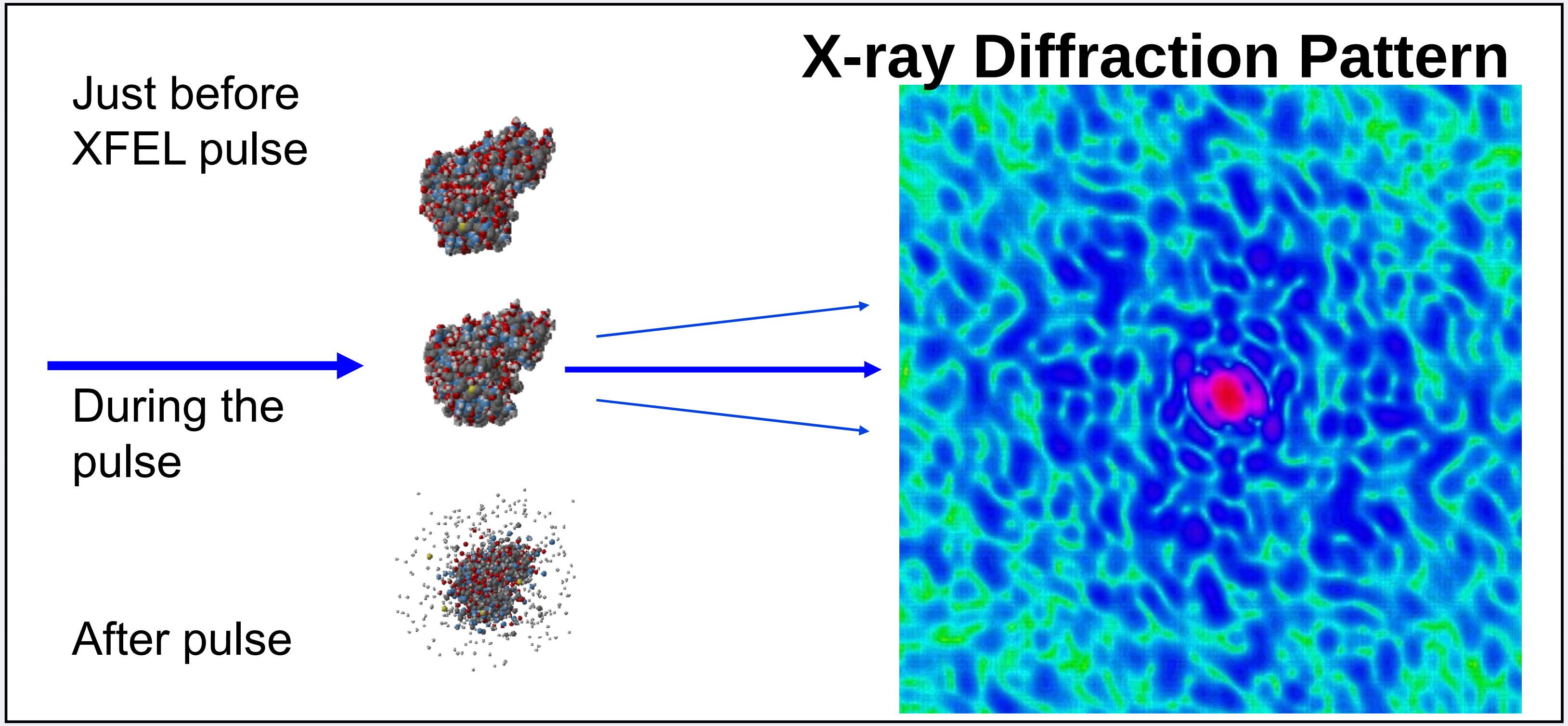


**Diffraction pattern
From second pulse**

H. Chapman, J. Hajdu et al.

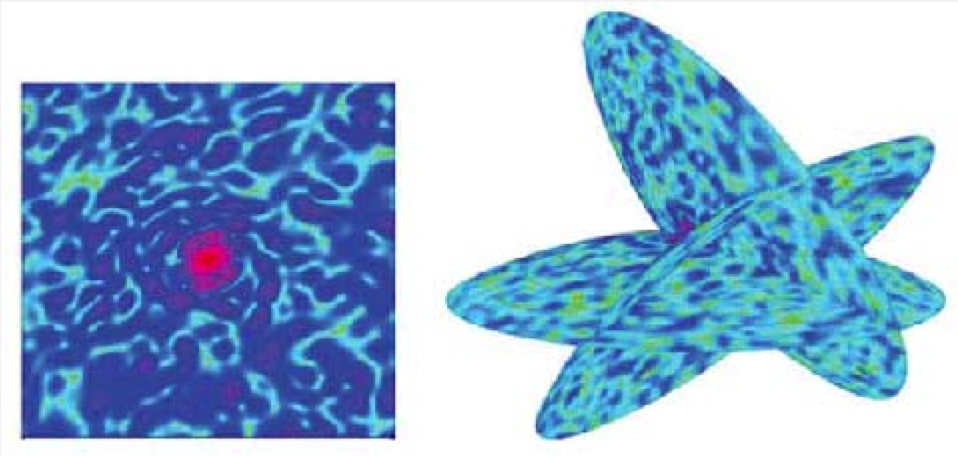
Single Molecules & Coherent X-ray Imaging

Single Molecule Imaging



Henry Chapman, *DESY*
Janos Hajdu, *Uppsala University and Stanford*

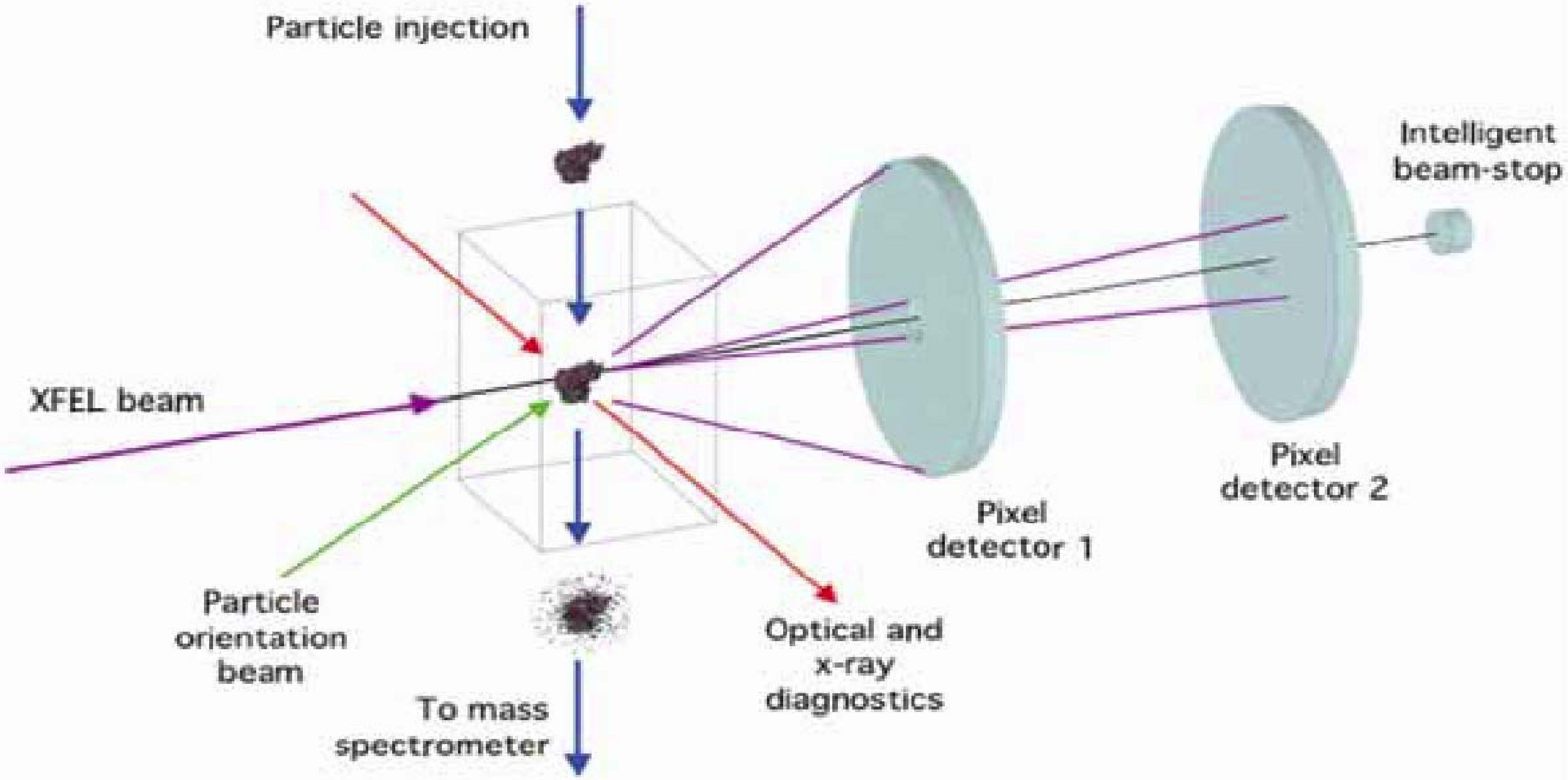
Single Particles & Coherent X-ray Imaging



Aligning the patterns along common axis allows full 3D reconstruction of the molecule

Single Particles & Coherent X-ray Imaging

Experimental setup



XFEL Detector Challenges

Time structure of the photon signals

High radiation dose at small angles: 10^4 photons per pixel per shot

➔ over 3 years 1 GGy

- Radiation damage of silicon sensor
- Radiation damage of underlying electronics

➔Program for radiation damage studies needed

High radiation dose at specific pixels: 10^5 photons in 10µm x 10µm ("charge explosion")

- 10^5 photons of 12 keV create: $(10^5 \times 12{\times}10^3)/\ 3.6 =$

  3 x 10^8 electron-hole pairs

➔"plasma effect" gives shielding of drift field

➔ diffusion before drift

➔peak broadening (space and time).

Despite that, three consortia (DEPFET-APS, HPAD, LPD) took up the challenge to build pixel detectors for the XFEL

XFEL Detector Requirements

- Energy 0.8..15keV
- No energy resolution
- High efficiency (>0.8)
- High dose 1GGy/3a
- Low dead area <10%
- High dynamic range
- XFEL Timing compliant
- Low noise (<1 ph)
- Low crosstalk
- Vaccuum compatible
- Central hole

	PPnX	PPX	CDI	SPI	XPCS
E (keV)	6–15	12	0.8-12	12.4	6 – 15
ΔE/E	No	No	No	No	No
QE	>0.8	>0.8	>0.8	>0.8	>0.8
Rad Tol	10^{16} ph	10^{16} ph	2×10^{16} ph	2×10^{15} ph	2 10^{14} ph
Size	200 deg	120 deg	120 deg	120 deg	0.2 deg
Pixel	7 mrad	100 μm	0.1 mrad	0.5 mrad	4 μrad
# pixels	500 × 500	3k × 3k	20k × 20k	4k × 4k	1k × 1k
tiling	<20%	<10%	See text		<20%
L Rate	5×10^{4}	3×10^{6}	10^{5}	10^{4}	10^{3}
G Rate	3 x10^{7}	10^{7}	10^{7}	10^{7}	10^{6}
Timing	10Hz	10Hz	5MHz	10Hz	5MHz
Flat F	1%	1%	1%	1%	1%
Dark C	<1 ph	<1 ph	<1 ph	<1 ph	<1 ph
R Noise	<1 ph	<1 ph	<1 ph	<1 ph	<1 ph
Linearity	1%	1%	1%	1%	1%
PSF	1 pixel	100 μm	1 pixel	1 pixel	1 pixel
Lag	10^{-3}	10^{-3}	7×10^{-5}	10^{-3}	10^{-3}
Vacuum	No	No	Yes	Yes	No
Other	Hole	Hole			Hole

XFEL Detector Concepts

	DEPFET-APS	LPD	HPAD
# Pixels	1k × 1k	1k × 1k	1k × 1k
Pixel size	200µm × 200µm	500µm × 500µm	200µm × 200µm
Sensor	DEPFET array	Si-pixel	Si-pixel
Dynamic range	$>10^4$ ph	2×10^4 ph (10^5 ph)	2×10^4 ph
Noise	$\sim 15 \times 10^{-3}$ph ~50e	0.21ph (0.93ph) 700e (3100e)	$\sim 45 \times 10^{-3}$ph ~150e
Concept	DEPFET nonlinear gain compression Per-pixel ADC	Multiple gain paths On-chip ADC	Adaptive gain switching (preset gain option)
Storage	8bit DRAM	3-fold analogue	2bit digital + analogue
Storage depth	≥256	512	>200
Challenges	Linearity & calibration In-pixel ADC DRAM refresh Power budget Pixel area	Preamplifier: noise, dynamic range & PSRR Feedback discharge Anlogue storage	Dynamic gain switching Charge injection Analogue storage Pixel area
	Radiation hardness		

XFEL Detectors: Obstacles, Difficulties & Challenges

Common Issues:

Droop due to leakage of

- Capacitors
  - Tunneling of electrons
- Switches (FETs)
  - Short-channel effects
  - Tunneling of electrons

Radiation hardness

CMOS Technology

IBM cmrf8sf DM (130nm CMOS)

- Proposed by all 3 XFEL 2D detector consortia
- De-facto standard for LHC upgrades
    - Choice mainly based on excellent experience with cmos6sf (0.25µm) technology
- Proven radiation hardness >10Mrad
- Foundry access via CERN as a second source besides MOSIS
- Long-term availability
- Permits sufficiently high integration density
- (dual) MIMCAPS can be employed as a (fallback) solution for storage caps

All 3 projects agreed on this technology and will share the development of some common blocks like LVDS IOs, enclosed std. cells etc.

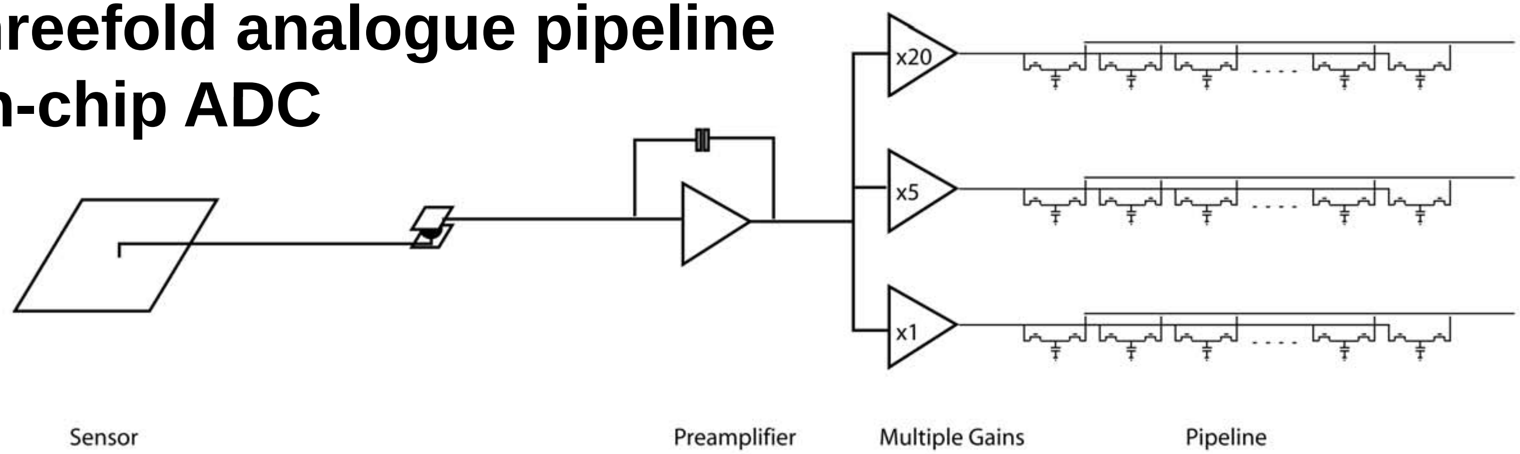
The Large Pixel Detector (LPD) Project (STFC)

Multi-Gain Concept

Dynamic Range Compression required
Experience with calorimetry at CERN
Relaxes ADC requirements
Fits with CMOS complexity

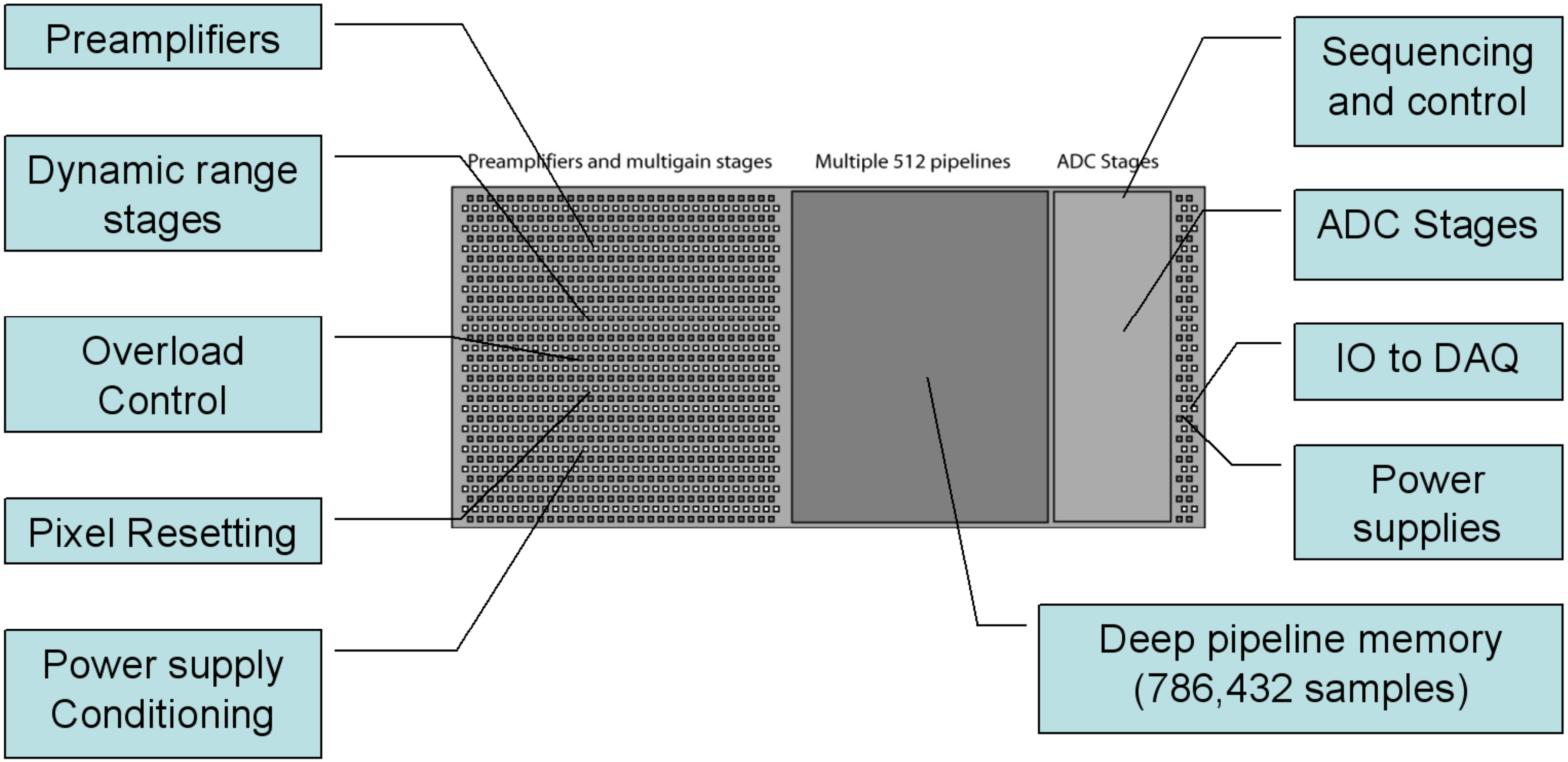
Threefold analogue pipeline

On-chip ADC



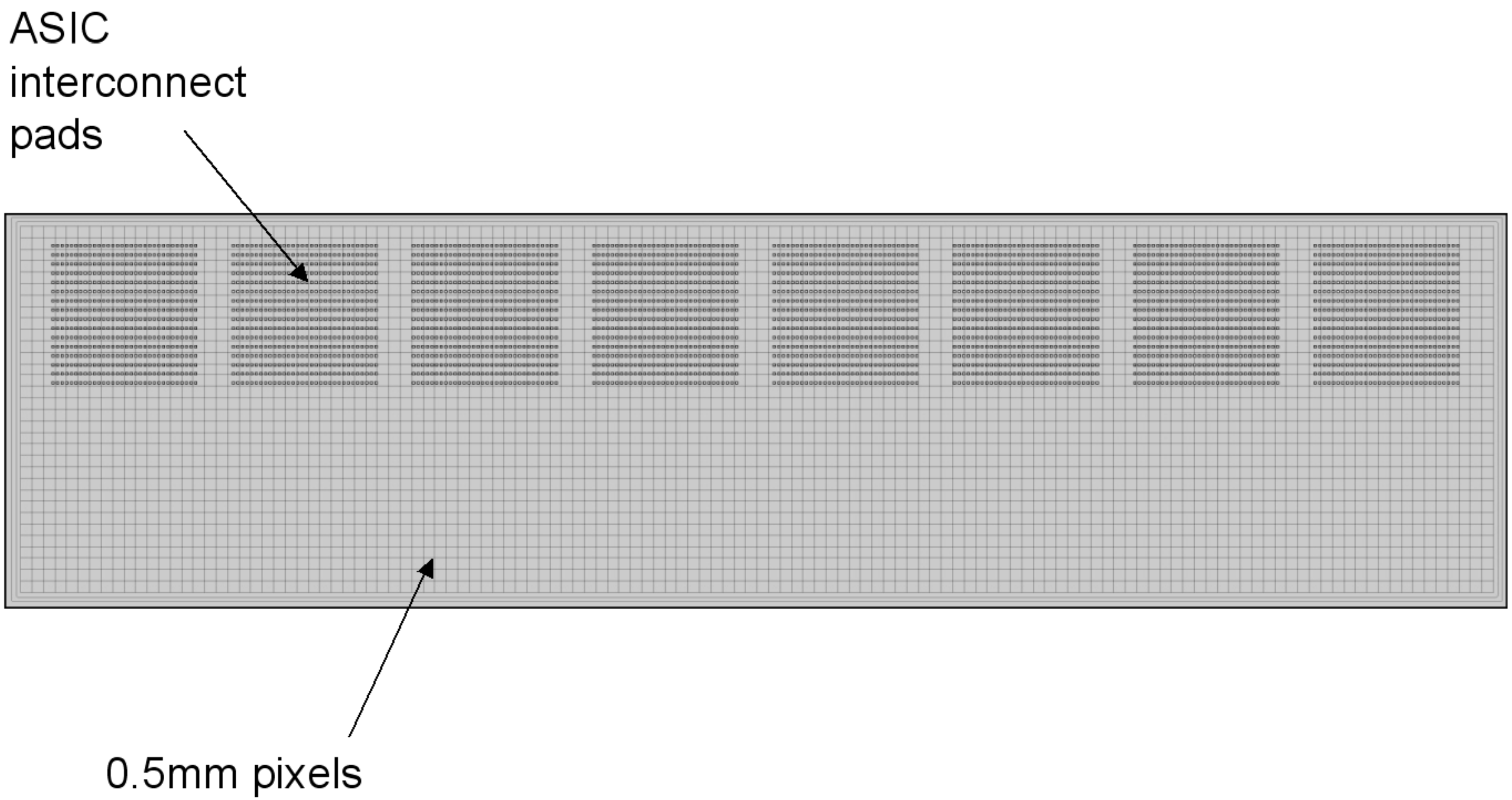
(M. French, STFC)

LPD Chip Layout (STFC)



(M. French, STFC)

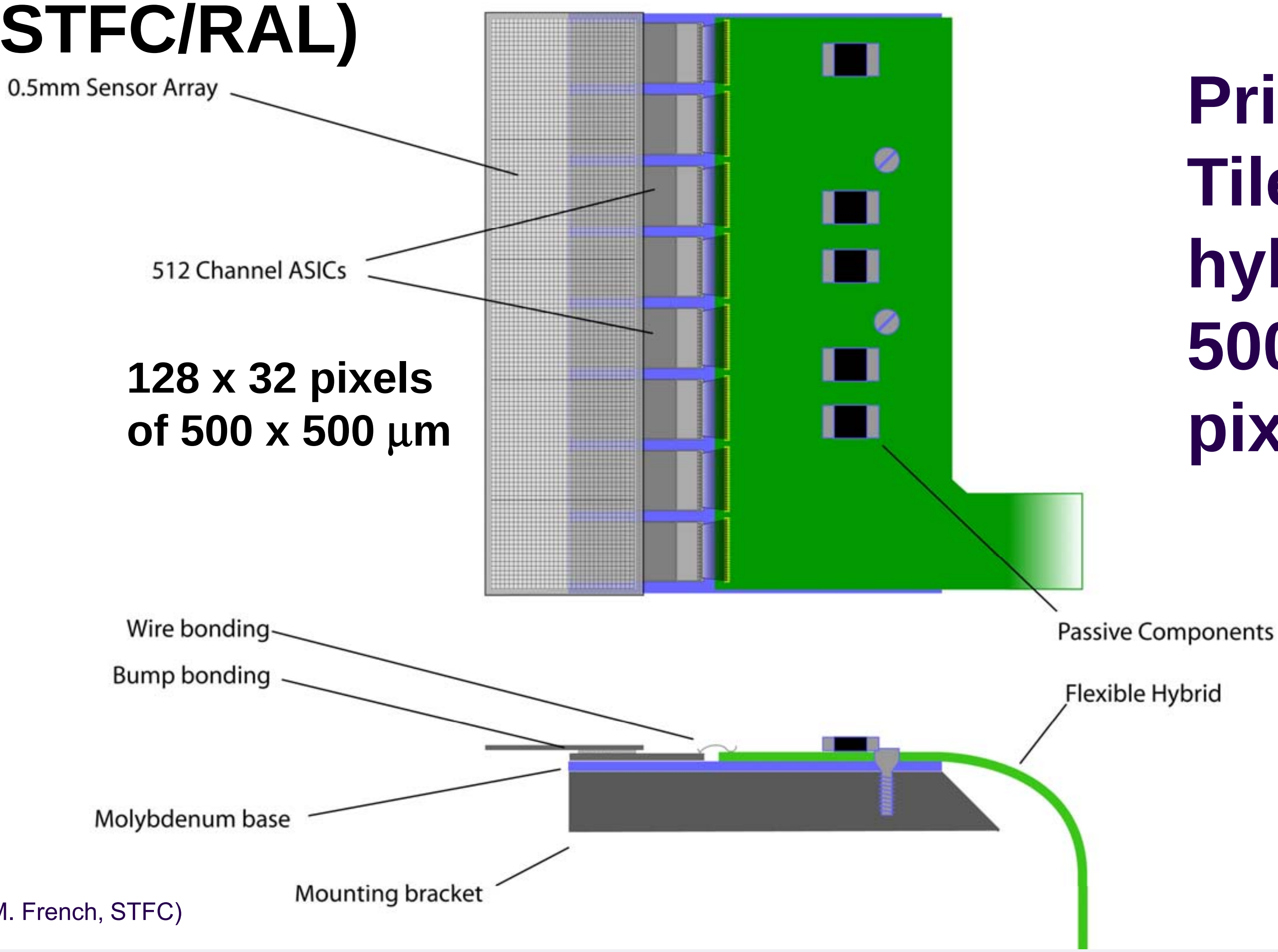
LPD Sensor Layout (STFC)



(M. French, STFC)

The Large Pixel Detector (LPD) Project (STFC)

(STFC/RAL)



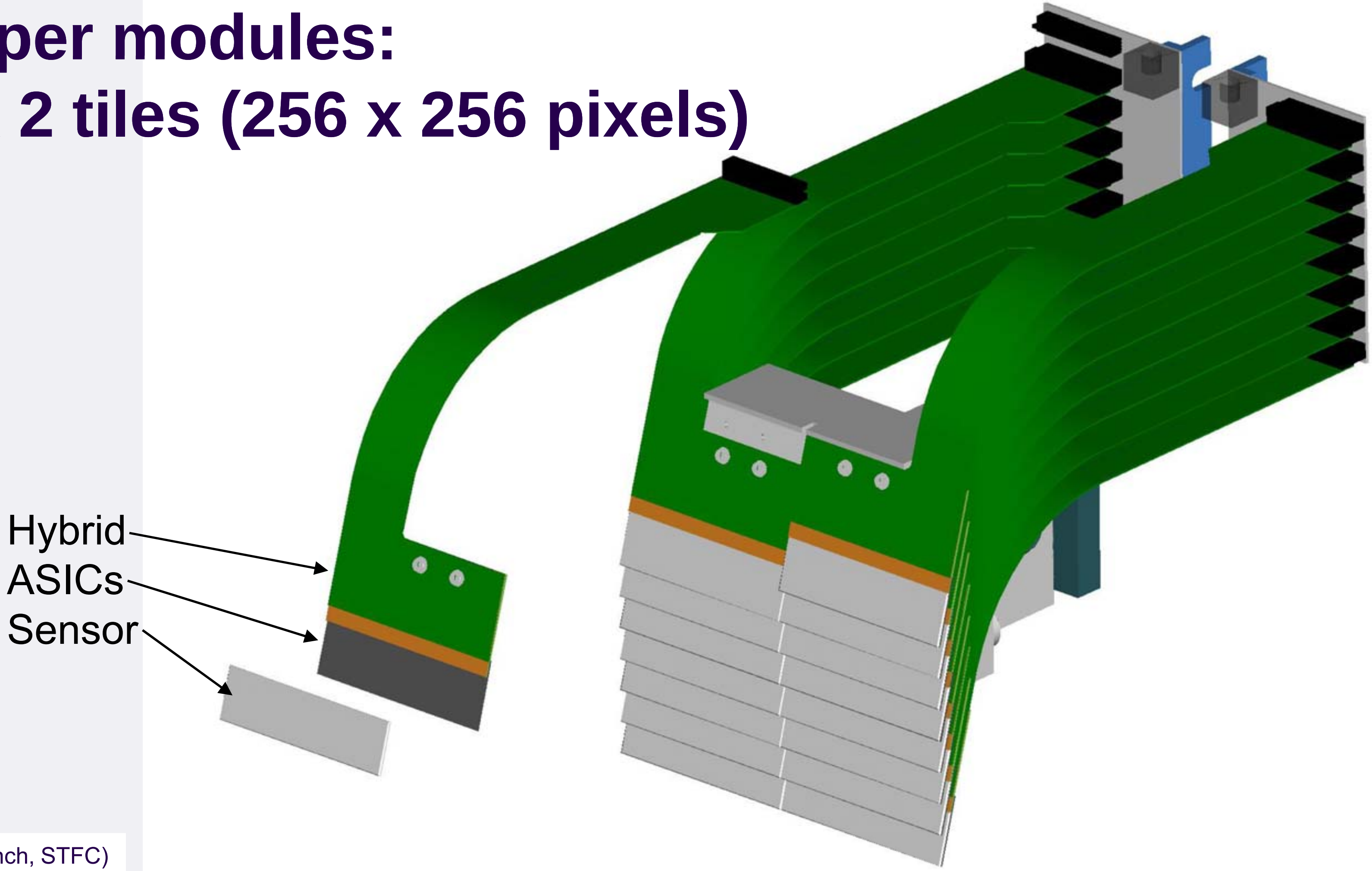
128 x 32 pixels of 500 x 500 µm

Principle: Tiled hybrid with 500 µm pixels

(M. French, STFC)

The Large Pixel Detector (LPD) Project (STFC)

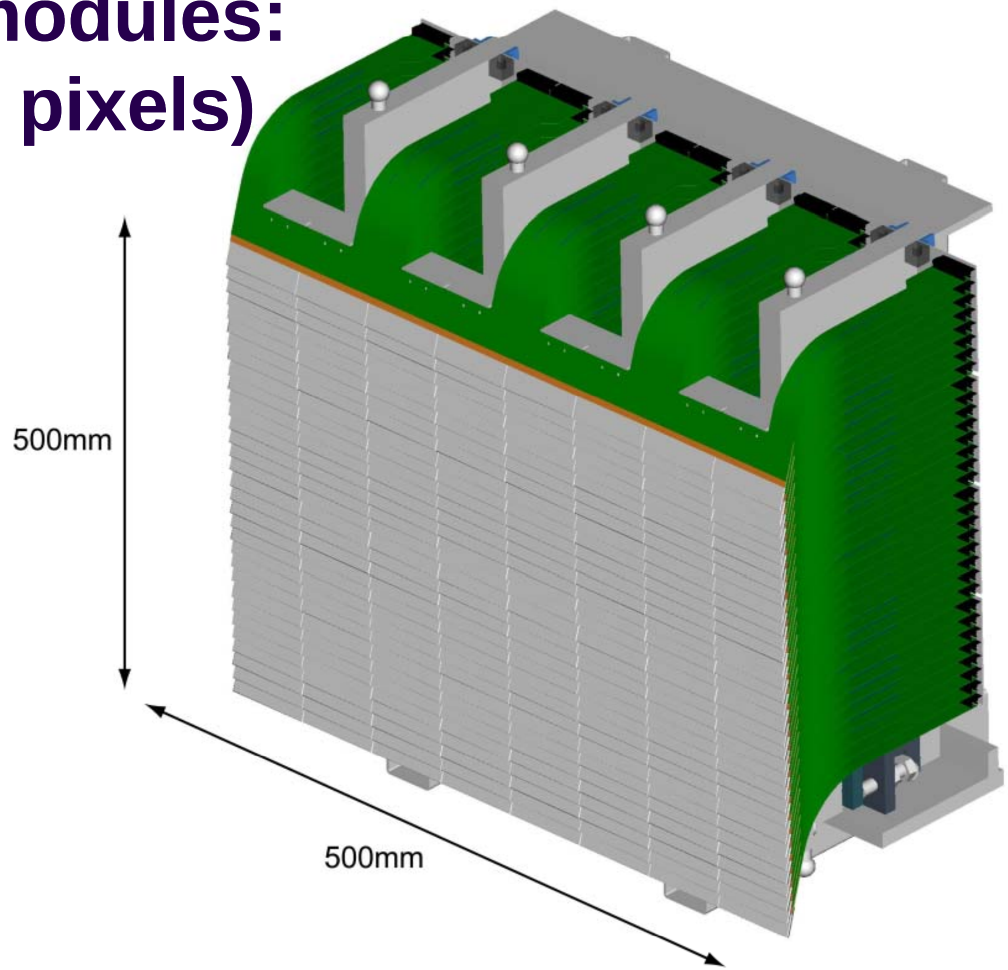
Super modules:
8 x 2 tiles (256 x 256 pixels)



(M. French, STFC)

The Large Pixel Detector (LPD) Project (STFC)

4 x 4 Super modules:
(1024 x 1024 pixels)



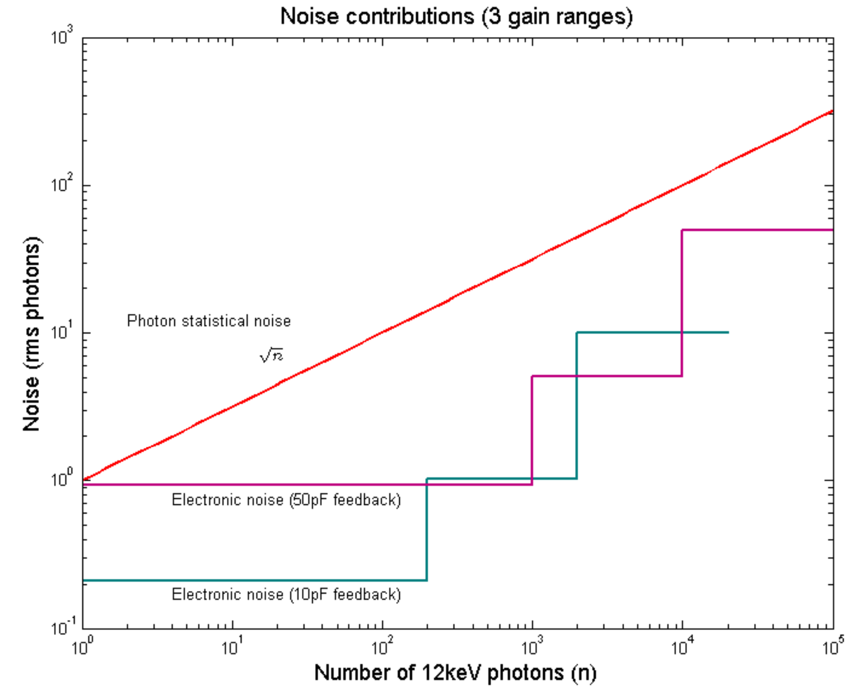
(M. French, STFC)

Noise contributions

LPD Noise & Gain (STFC)

Pre-amplifier feedback capacitor	10pF			50pF		
Gain factor	100	10	1	100	10	1
Dynamic Range (12keV photons)	2×10^2	2×10^3	2×10^4	10^3	10^4	10^5
Pre-amp noise	0.13	0.13	0.13	0.47	0.47	0.47
Gain-stage noise	0.13	0.19	-	0.63	0.99	-
Pipeline noise (100fF storage)	0.038	0.38	3.8	0.19	1.9	19
ADC noise (12-bit resolution)	0.092	0.92	9.2	0.46	4.6	46
Total noise	0.21	1.02	9.95	0.93	5.1	50

Simulation for different Feedback caps

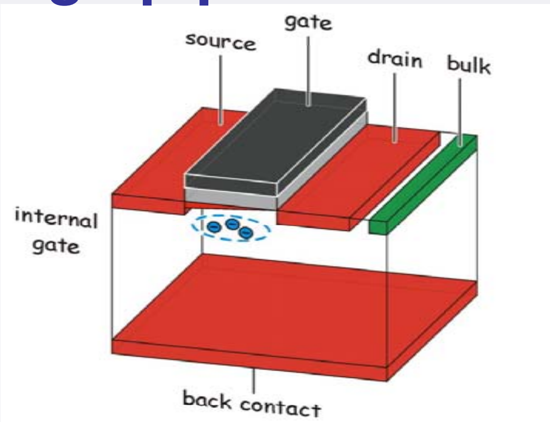


(M. French, STFC)

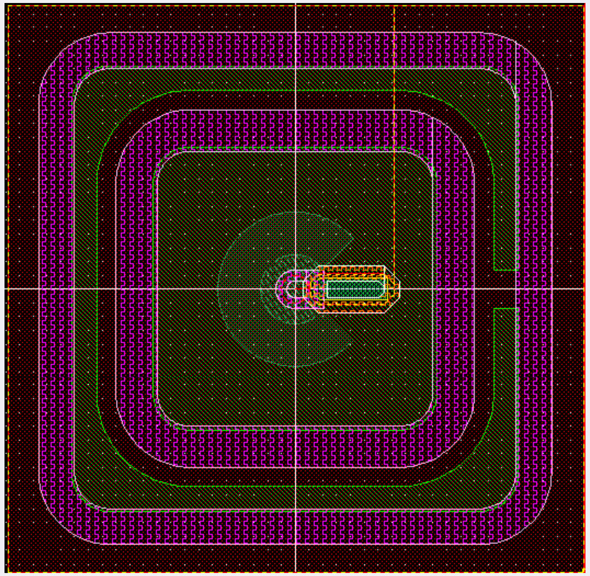
DEPFET Active Pixel Sensor Detector (MPI-HLL)

- DEPFET per pixel
- Very low noise (good for soft X-rays)
- non linear gain (good for DR)
- per pixel ADC
- digital storage pipeline

MPI-HLL, Munich
Universität Heidelberg
Universität Siegen
Politechnico di Milano
Università di Bergamo
DESY, Hamburg

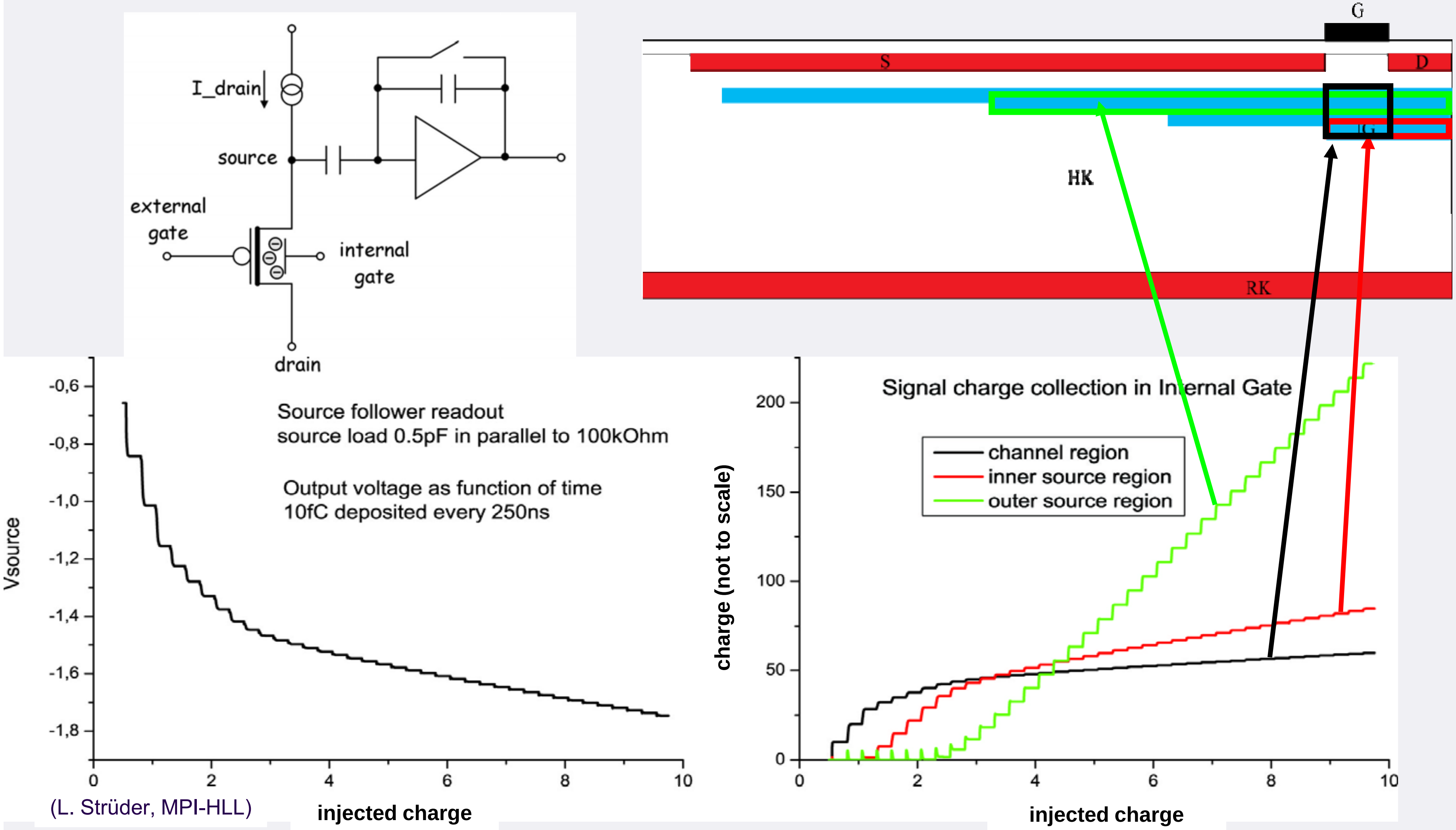


200µm x 200µm pixel combines DEPFET with small area drift detector (scaleable)



(L. Strüder, MPI-HLL)

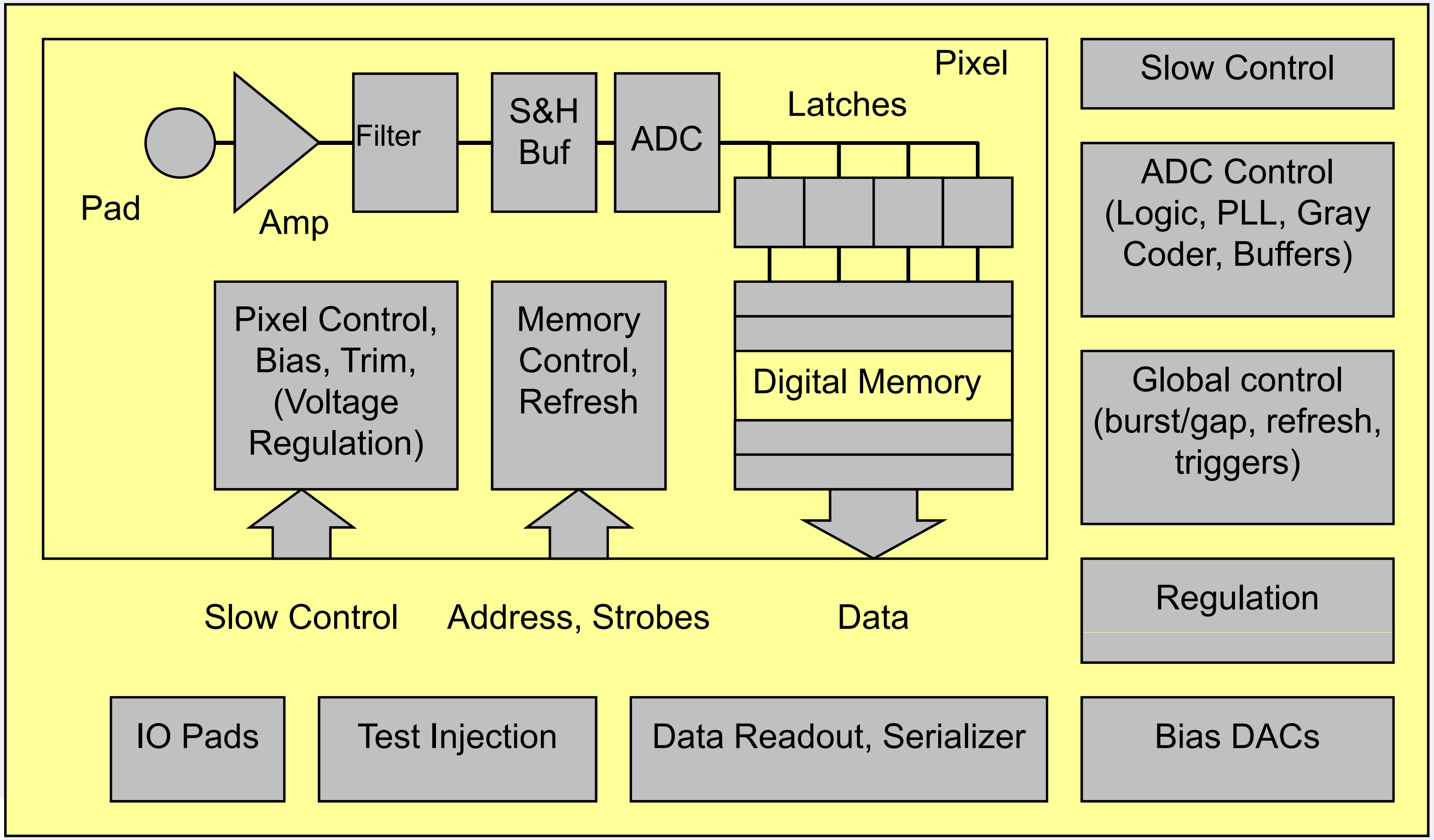
DEPFET Nonlinear Gain (MPI-HLL)



(L. Strüder, MPI-HLL)

DEPFET Active Pixel Sensor Detector (MPI-HLL)

Block Diagram



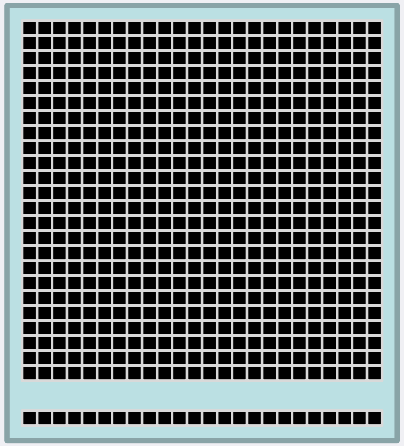
(L. Strüder, MPI-HLL)

DEPFET Active Pixel Sensor Detector (MPI-HLL)

Dynamic range challenge is relaxed by non-linear sensor characteristics

Baseline approach:

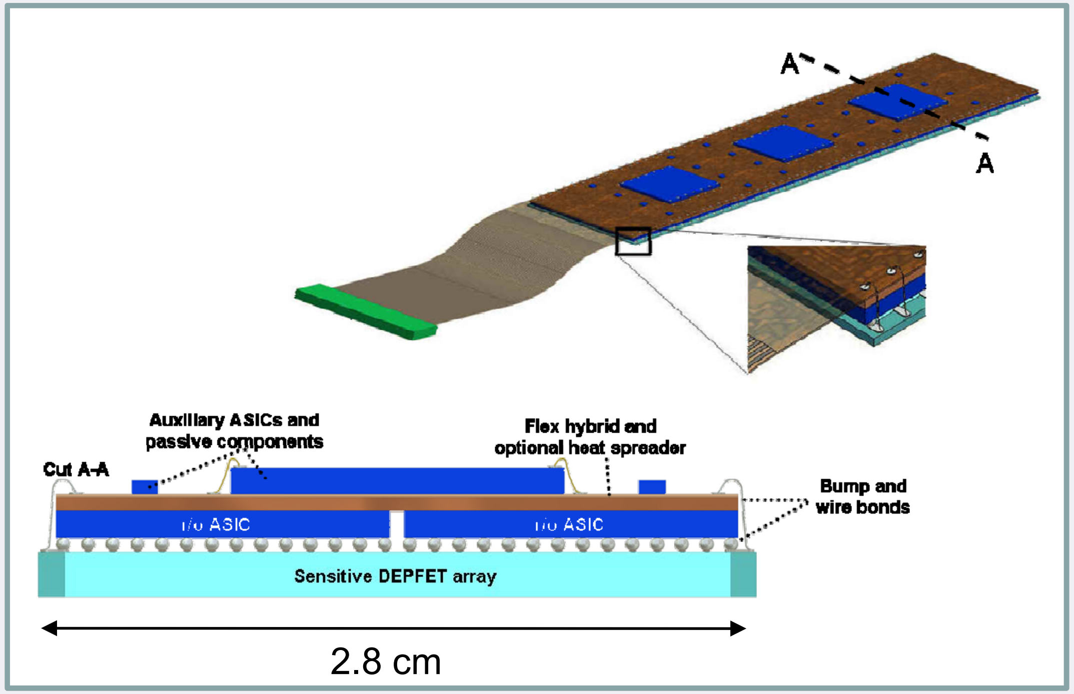
- **Double correlated Sampling** (read voltage or current, tbd.)
- **ADC** in every pixel (200ns, 8Bit)
- **Digital storage** in every pixel (DRAM w. refresh)
- Serial digital readout during bunch gaps



(L. Strüder, MPI-HLL)

Key Parameters of readout ASIC	
Pixel Size	$200 \times 200\ \mu m^2$
Number of pixels	$64 \times 64 = 4096$
Chip size	~ $13 \times 14\ mm^2$, IO pads on one side
Amplification	Double corr. sampling, SF or current RO
Target noise	50 electrons
Target power per pixel	1 mW (0.01mW w. power cycling)
Digitization	per pixel, ~ 8 bit
storage	digital, per pixel, 256-512 events
trigger selection	Yes
readout	serial, daisy chain of several chips

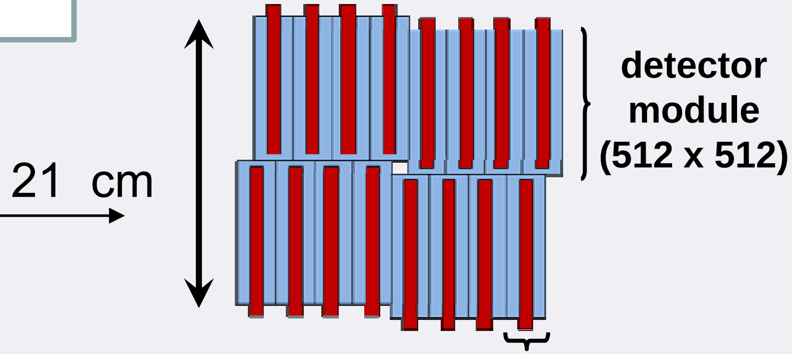
DEPFET Active Pixel Sensor Detector (MPI-HLL)



Multi Chip Modules

- DEPFET Sensor bump bonded to Readout ASICs
- Optional Heat spreader
- Flex Hybrid with passive components and auxiliary ASICs (e.g. voltage regulators)
- Sensor (512x128 pixels) 2.56x10.24 cm^2
- 16 readout ASICs (64x64)
- Dead area: 10-15%

- connect detector units to ladder
- 1 ladder = 128x 512 pixels
- 4 ladders = 1 quadrant
- 4 quadrants = 1k x 1k detector



Monolithic detector subunit (128 x 512)

(L. Strüder, MPI-HLL)

Hybrid Pixel Array Detector (HPAD) (DESY)

Basic parameters

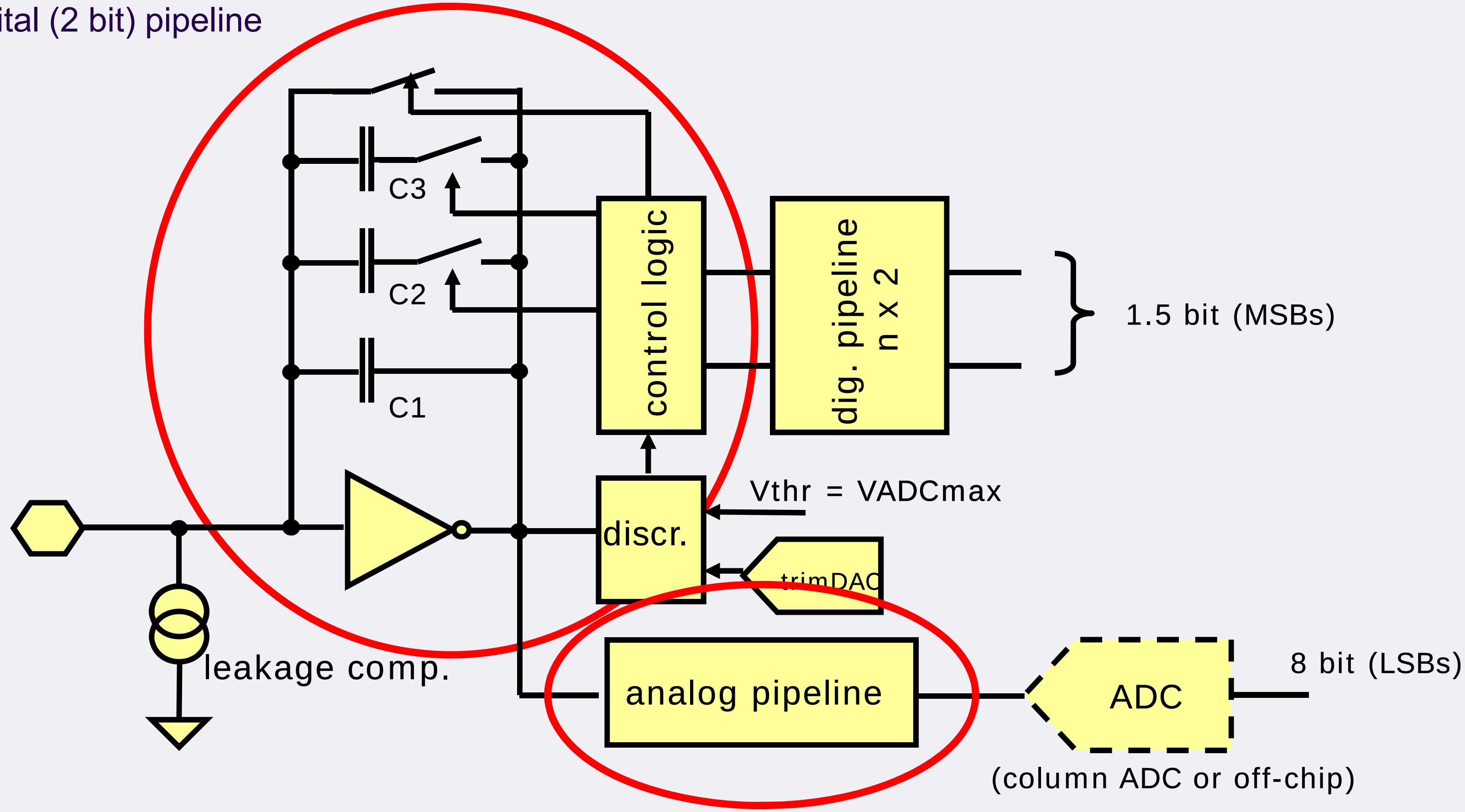
- Single shot 2D-imaging
- 200 μm x 200 μm pixels
- 5 MHz framing speed
- Single photon sensitivity at 12keV
- 2 x 10^4 dynamic range, using 3 switched gains
- >200 images storage depth
- 128 x 256 monolithic tiles
- Flat detector

The HPAD consortium:

PSI/SLS -Villingen:	chip design; interconnect and module assembly
Universität Bonn:	chip design
Universität Hamburg:	Radiation damage tests, “charge explosion” studies; and sensor design
DESY-Hamburg:	chip design, interface and control electronics, mechanics; overall coordination

Hybrid Pixel Array Detector (HPAD) Concepts (DESY)

wide dynamic input range
multiple (3) scaled feedback capacitors
reduced ADC resolution (10 bit instead of 12 bit)
analog + digital (2 bit) pipeline



HPAD Dynamic Range (DESY)

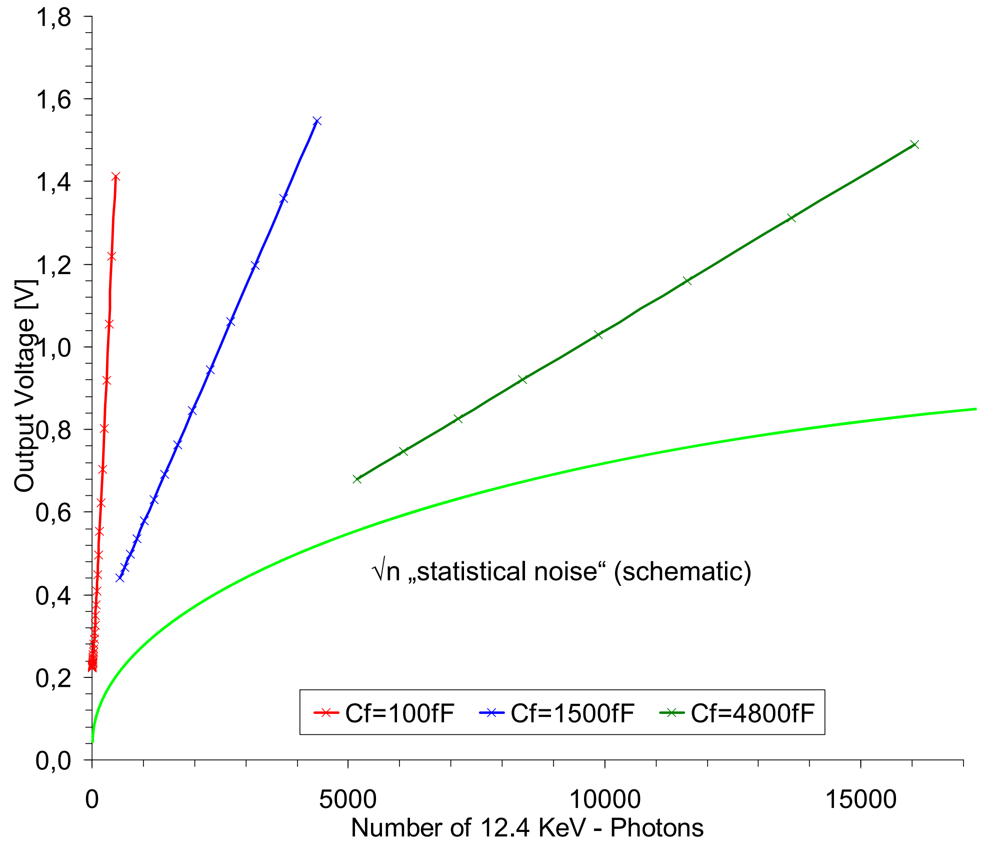
Integrator gain requirements:

Effective analog resolution ≥ 8 bit

Analogue resolution always better than "statistical noise" $\sqrt{n_{ph}}$

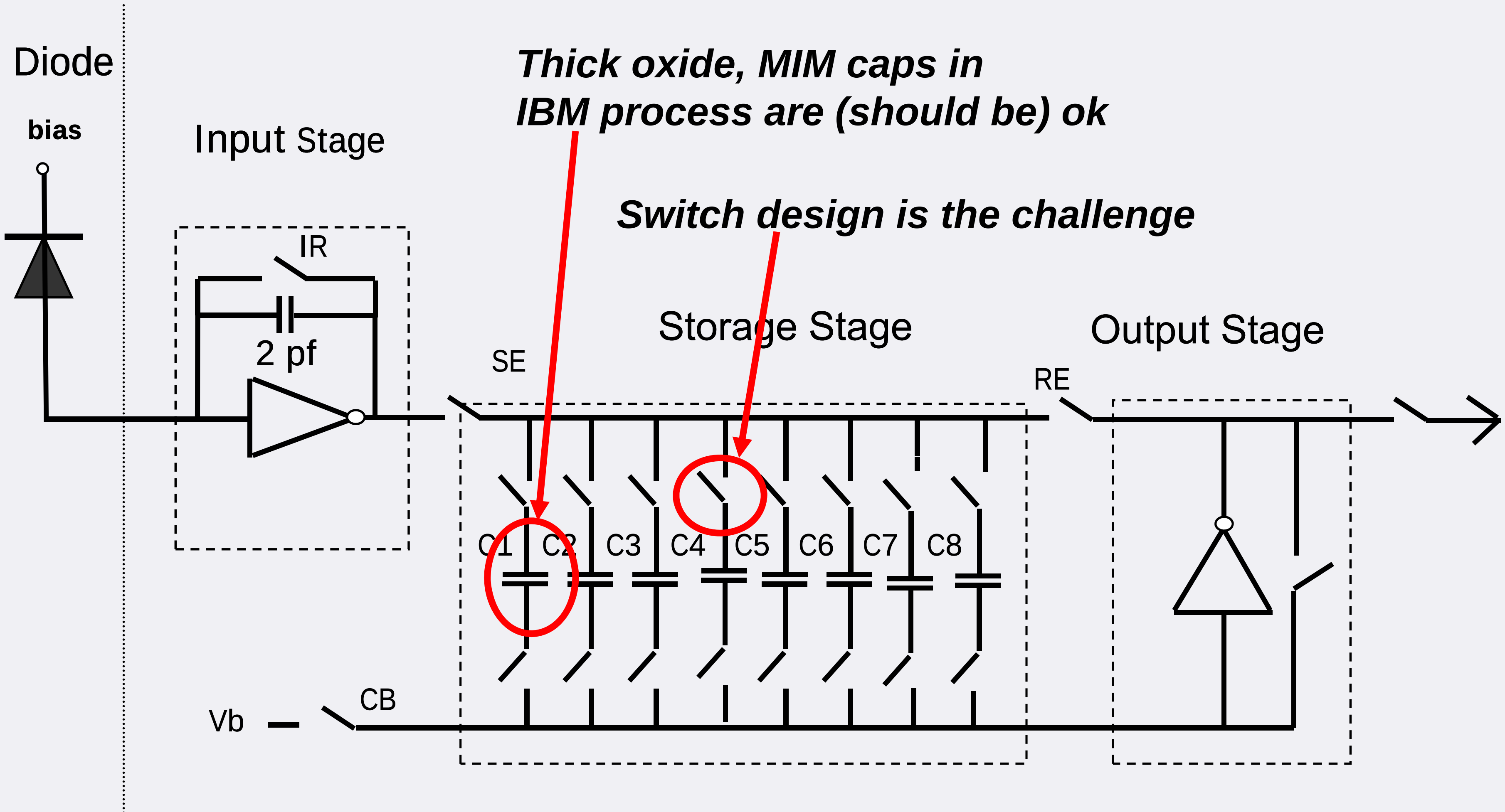
maximum signal ≥ 10^4 photons

range	norm. gain	Cf [fF]	max n_{ph}
1	1	100	256
2	1/16	1600	4096
3	1/64	6400	16384



100 msec *“loss free”* Charge Storeage in Analogue Pipeline

(DESY)



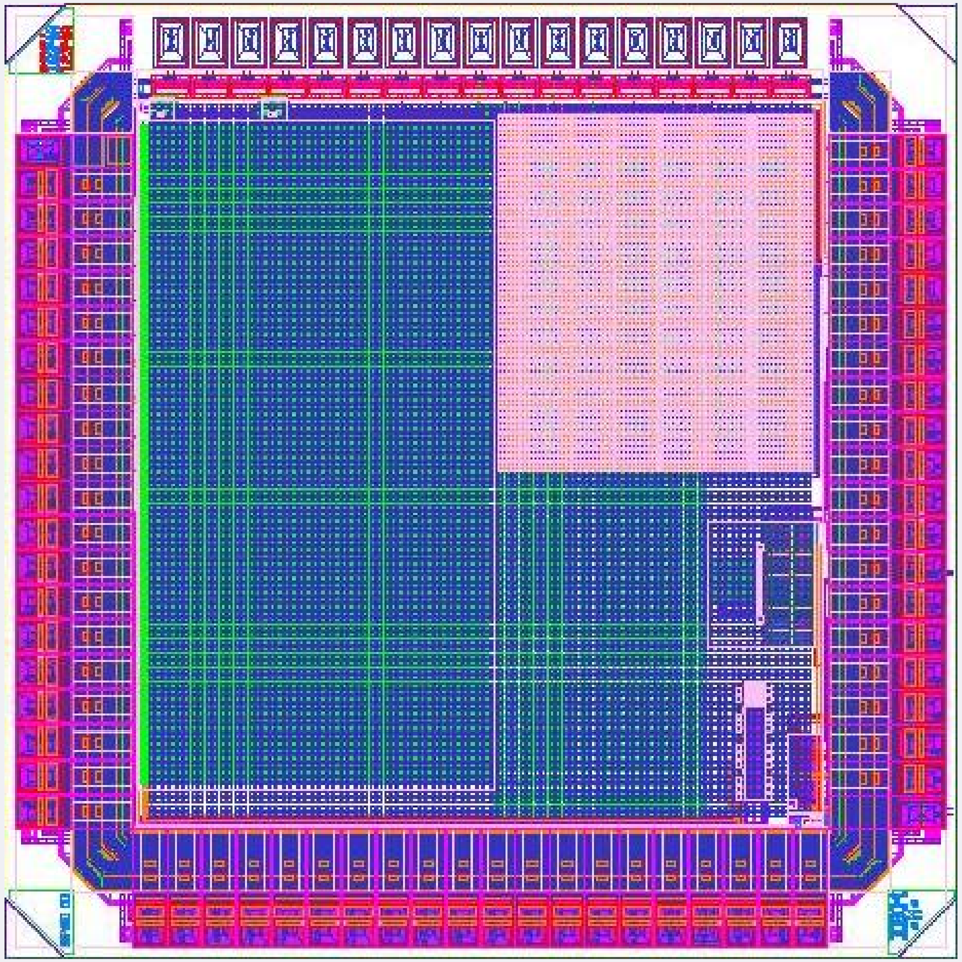
The “hpad 0.1” chip (DESY)

Intended for radiation and leakage current studies

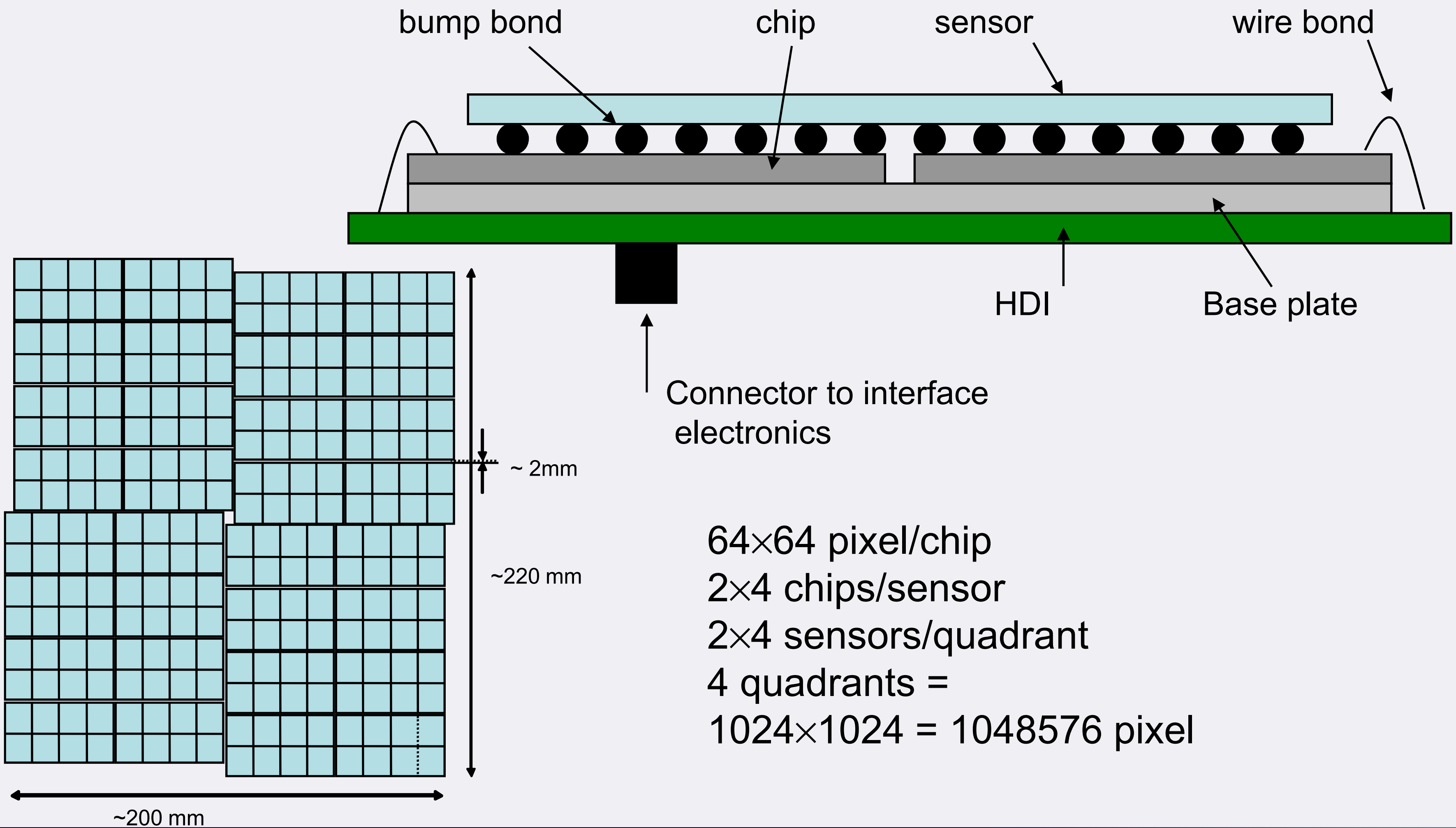
2mm x 2mm, submitted via MOSIS at 26.03.2008

Only test structures:

- Capacitors
- Switches (FETs)
- 16-cell analogue storage array
- OP-Amp & buffer amplifiers
- Minimum protection pad



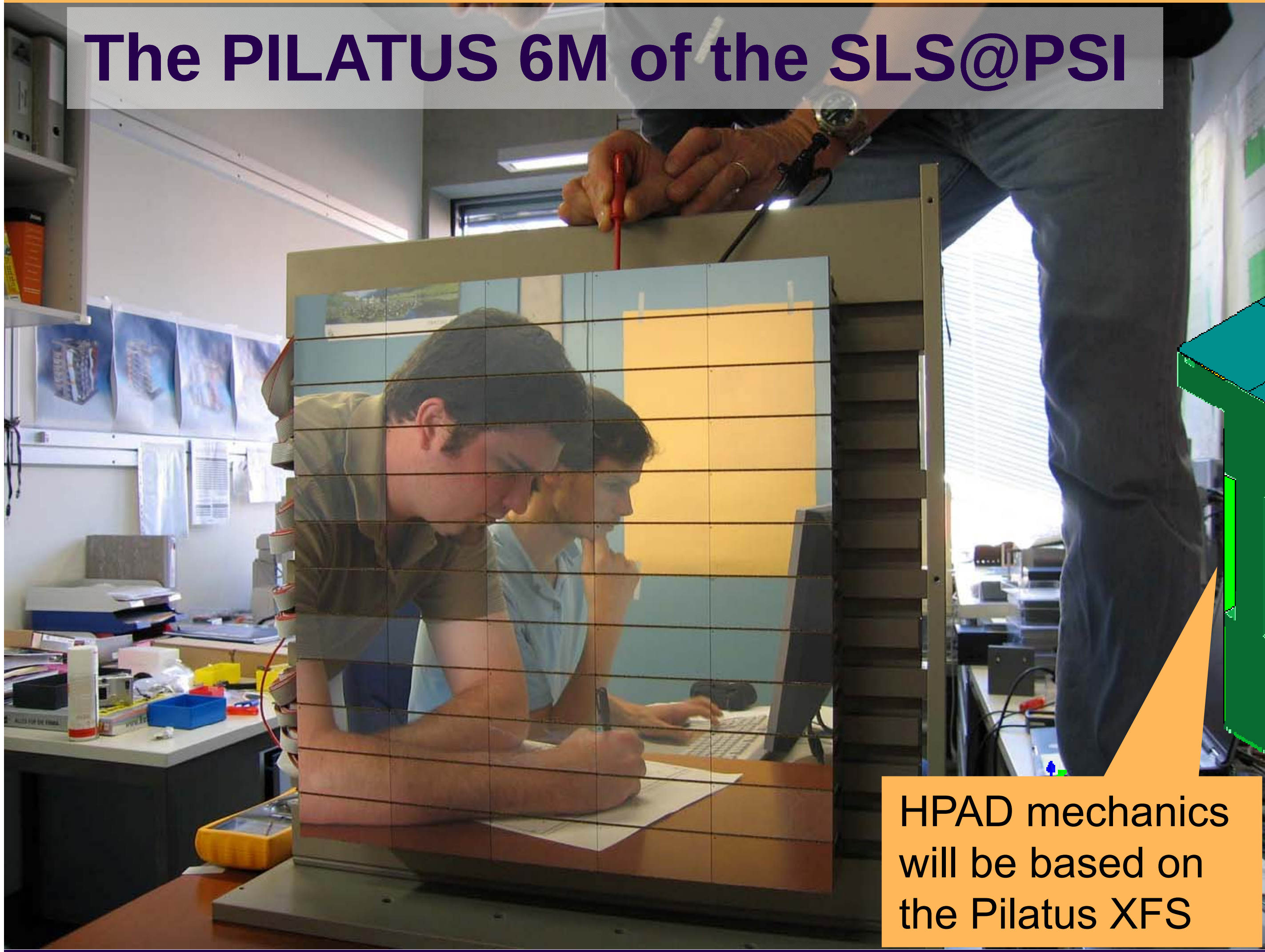
The Analogue-Pipeline HPAD (DESY)



64×64 pixel/chip
2×4 chips/sensor
2×4 sensors/quadrant
4 quadrants =
1024×1024 = 1048576 pixel

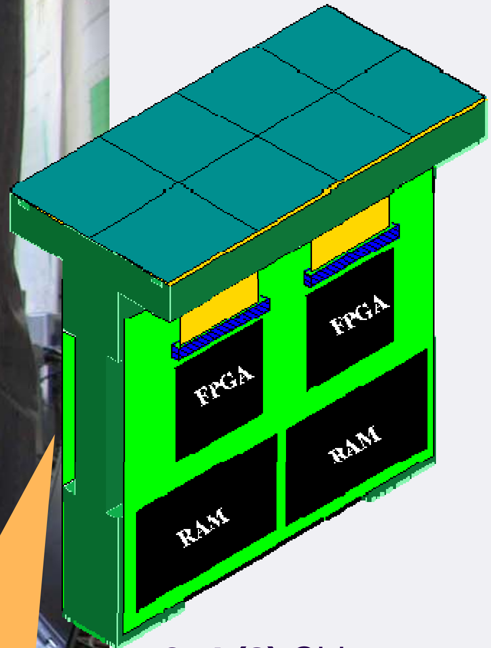
HPAD: How things will look

The PILATUS 6M of the SLS@PSI



HPAD mechanics will be based on the Pilatus XFS

Pilatus XFS Module

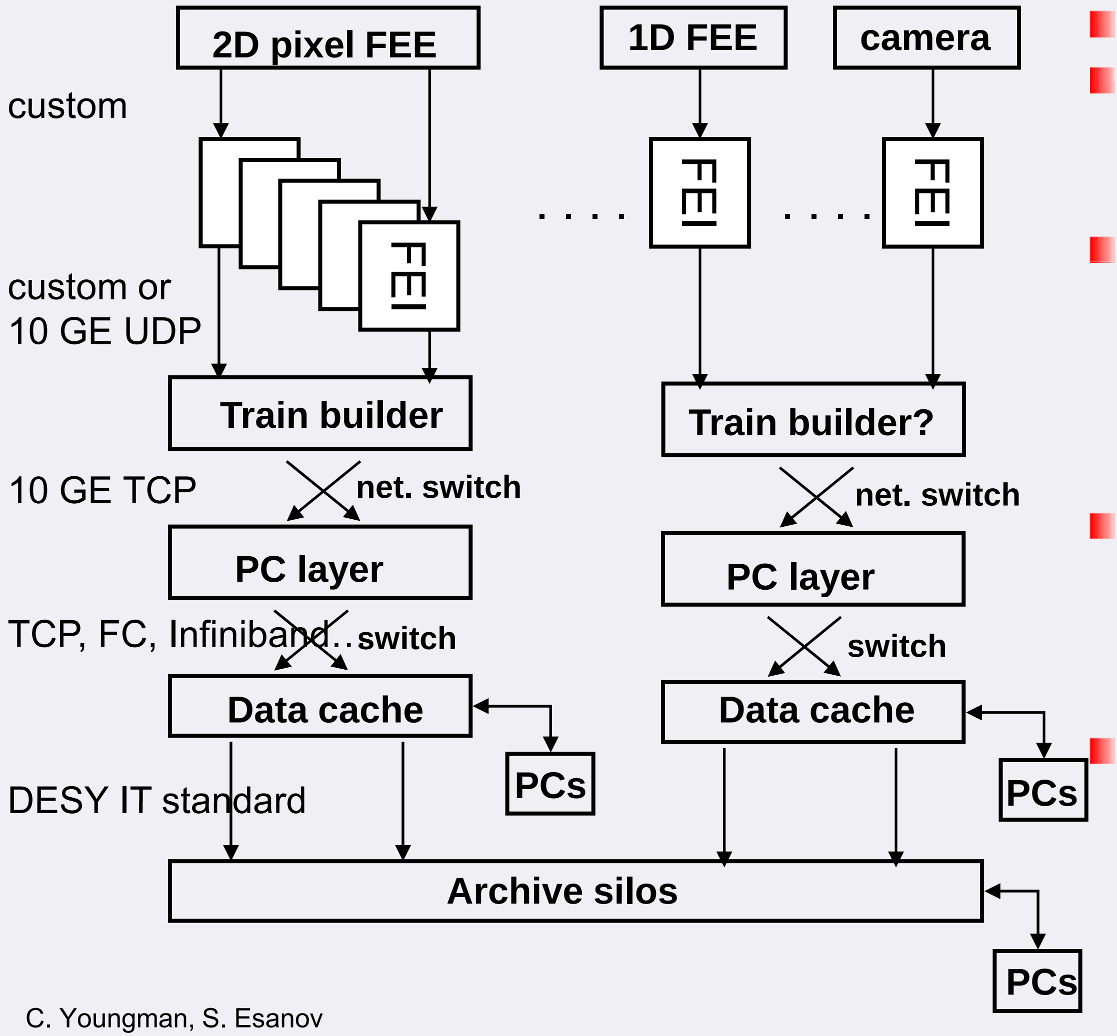


2x4 (8) Chips per Module.

~78 x 39 mm² (XFS)

~50 x 27 mm² (HPAD)

XFEL DAQ architecture (DESY)

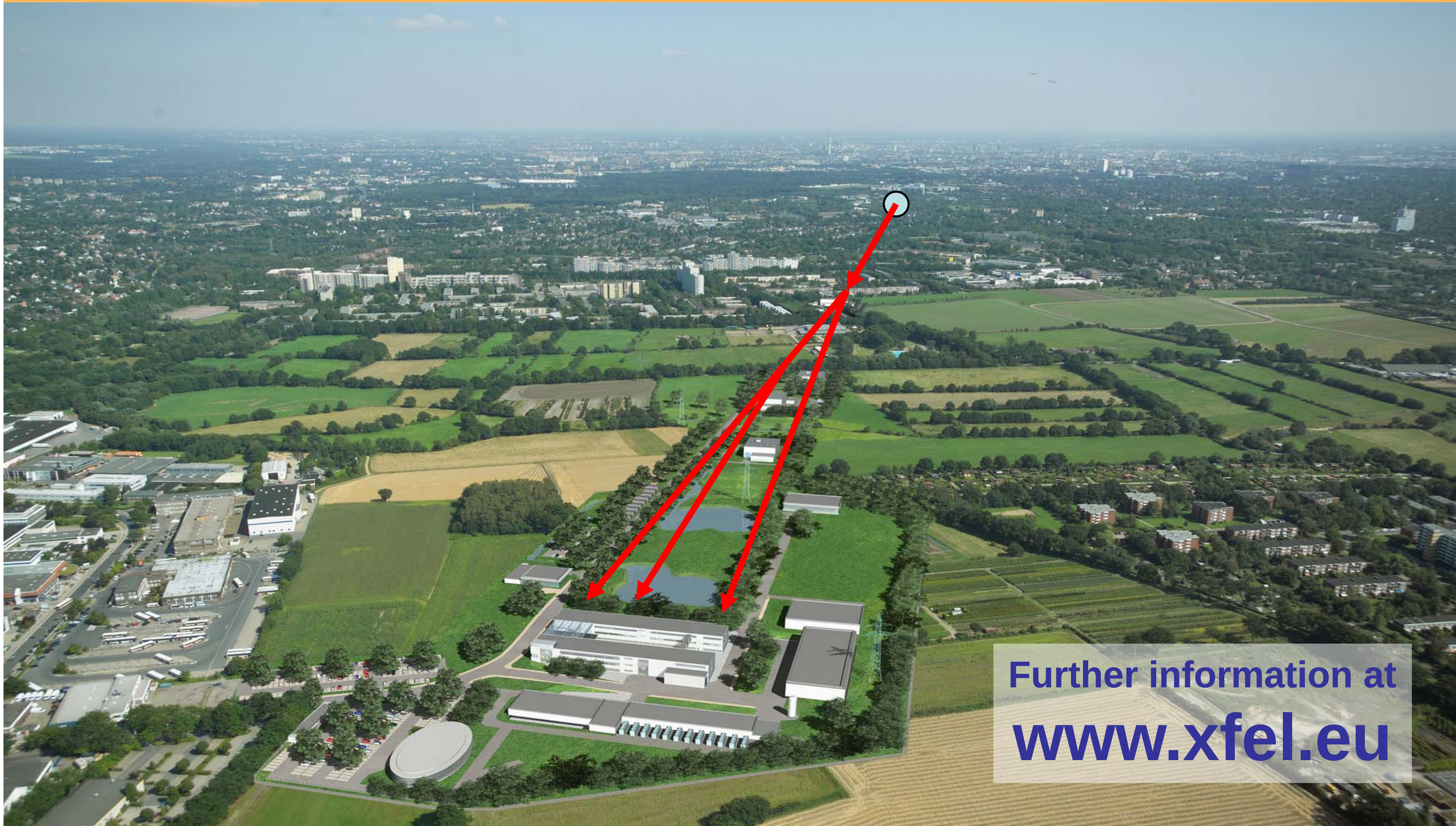


- Front End Electronics (FEE)
- Front End Interface (FEI)
  - interface to Train Builder.
  - maybe not needed by 2D
- Train builder layer
  - builds trains
  - simple data processing
  - maybe not needed by 1D and cameras.
- PC layer
  - interface to cache
  - additional train building (?)
  - more complex data process
- Data cache
  - hold, analyze, reduce and reject data
  - post processing commit to silo

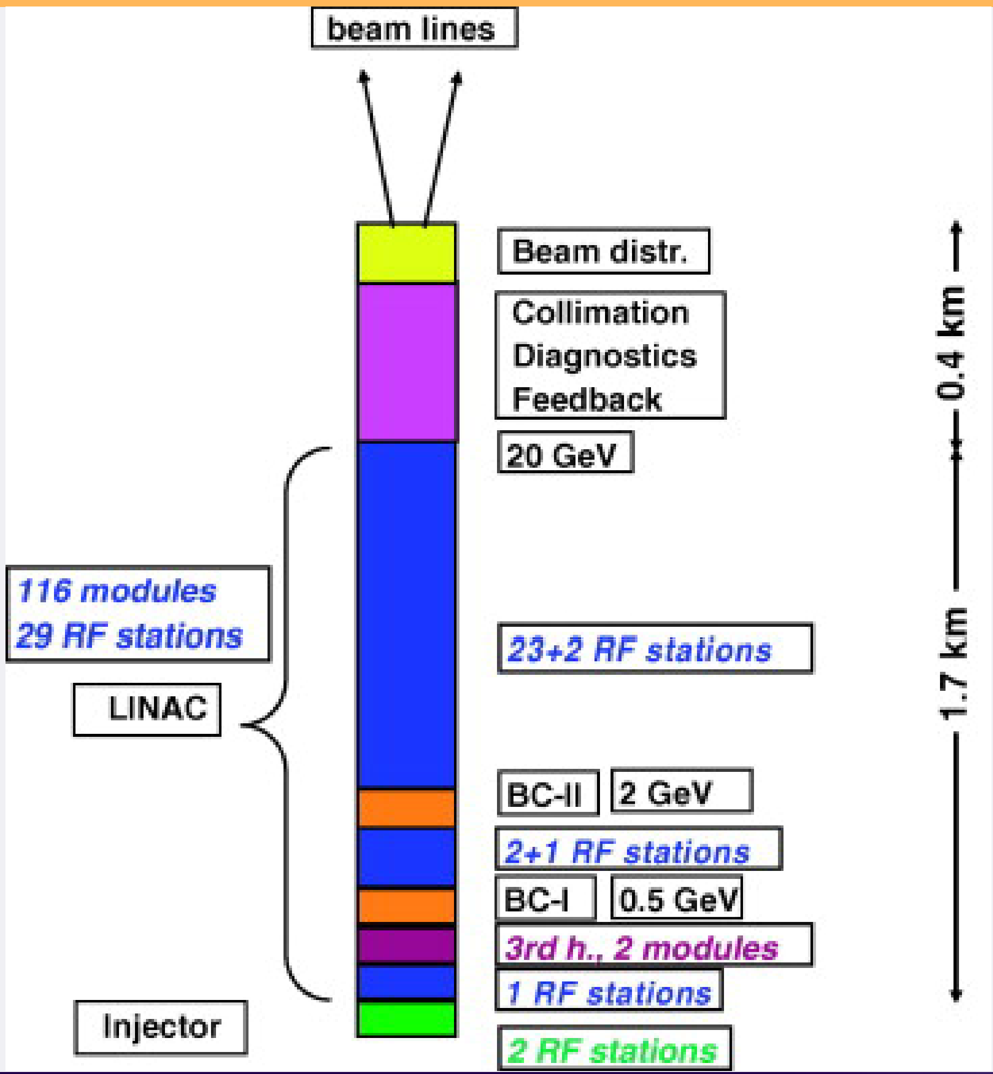
Summary & Outlook

- Signing of the Contract for the XFEL GmbH (company) scheduled for end of 2008
  - Start of civil construction scheduled for Nov. 2008
- Accelerator
  - Modules similar to FLASH/TTF
  - Successfully tested prototypes exist
- Undulators
  - Modules based on those of FLASH
- 2D area detectors
  - 3 projects
  - Individual solutions to the dynamic range challenge
- Ongoing studies on possible obstacles
  - Charge Explosion
  - Radiation hardness (test chip)
- First pixels in silicon in 2009
- Full area detectors in 2012

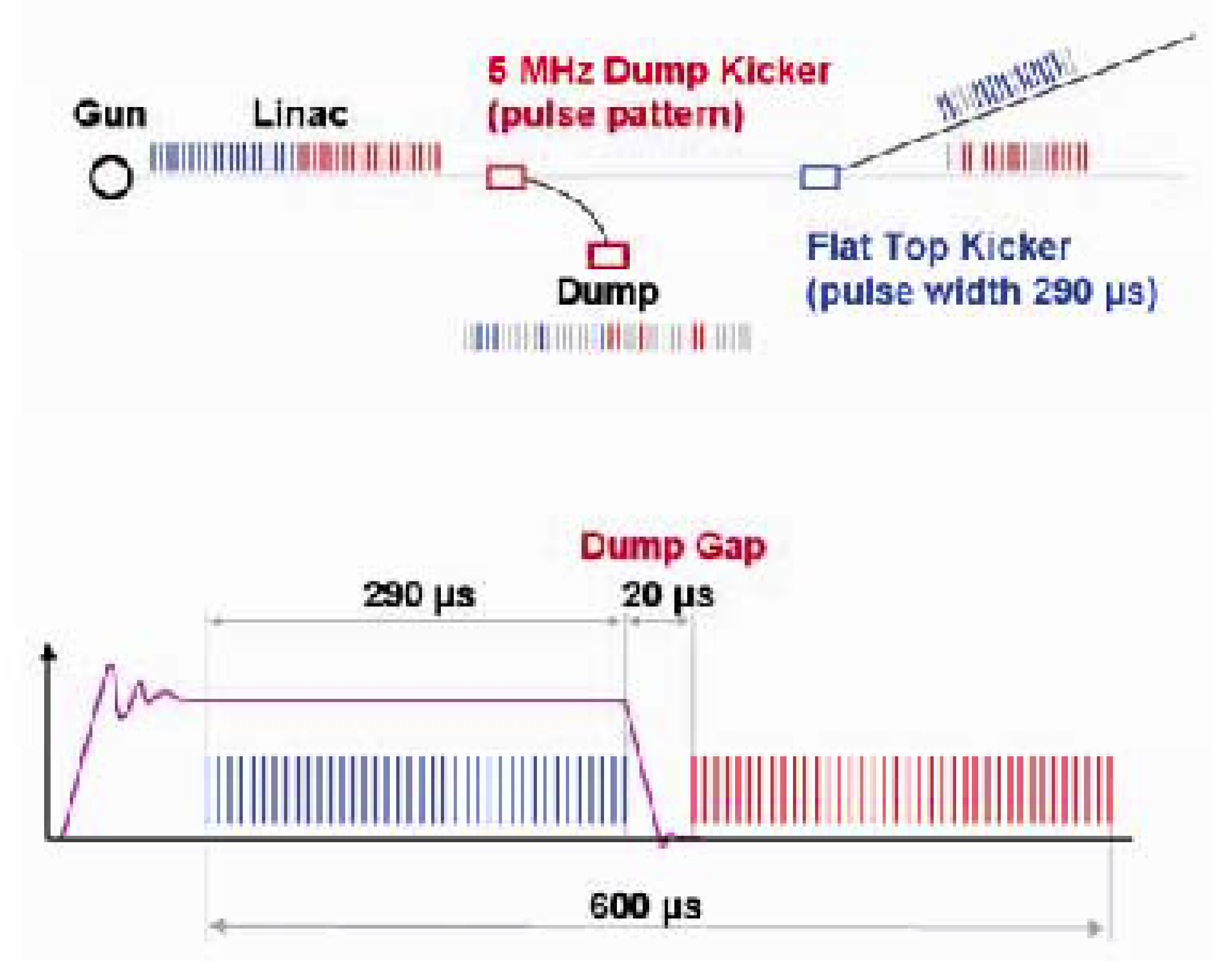
The European XFEL in 2012



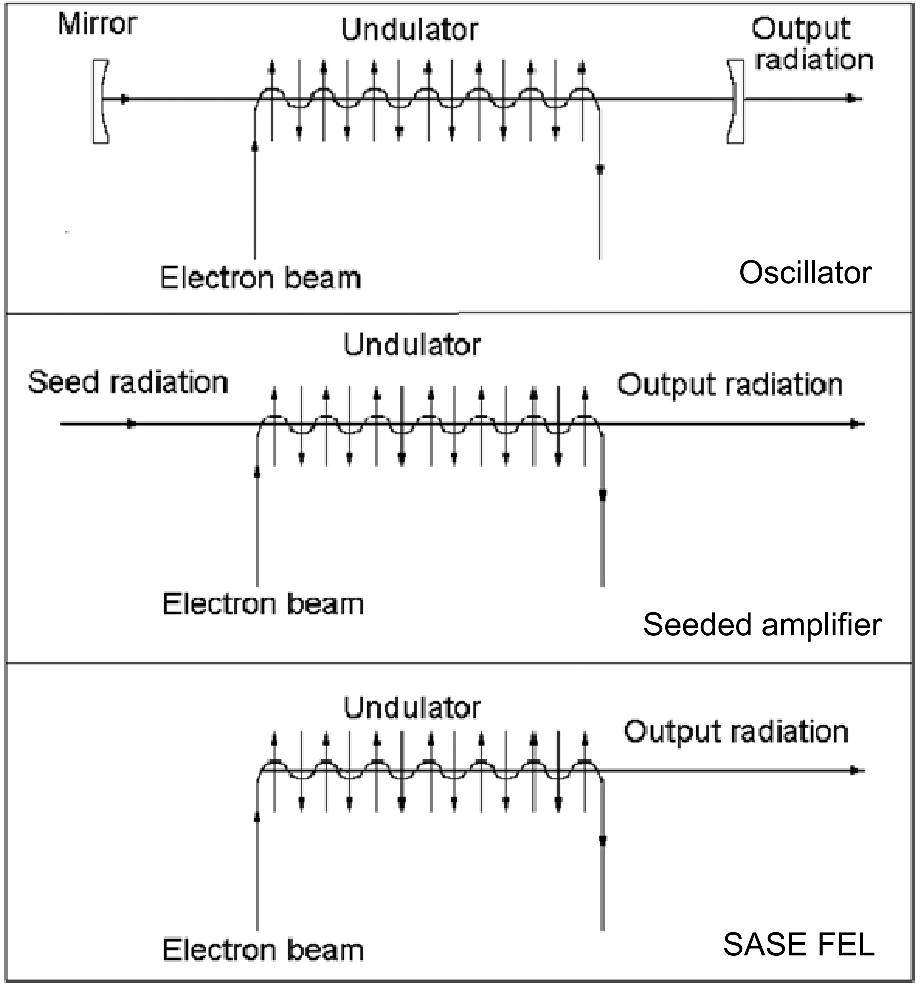
The Linac

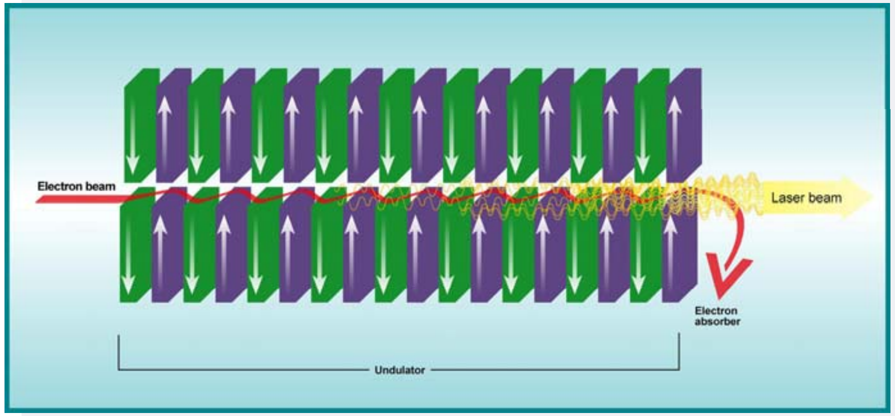

beam lines
Beam distr.
Collimation
Diagnostics
Feedback
20 GeV
116 modules
29 RF stations
LINAC
23+2 RF stations
BC-II
2 GeV
2+1 RF stations
BC-I
0.5 GeV
3rd h., 2 modules
1 RF stations
Injector
2 RF stations
0.4 km
1.7 km

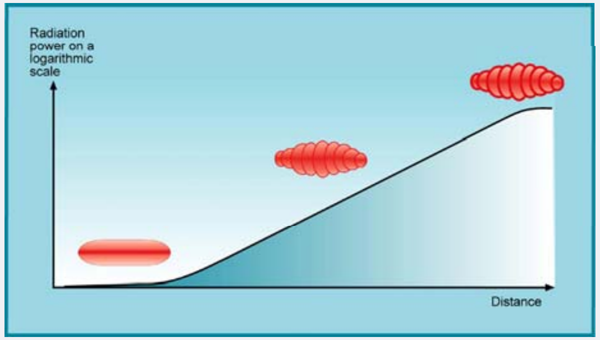
Beam Distribution Kicker System



Synchrotron Radiation in FELs

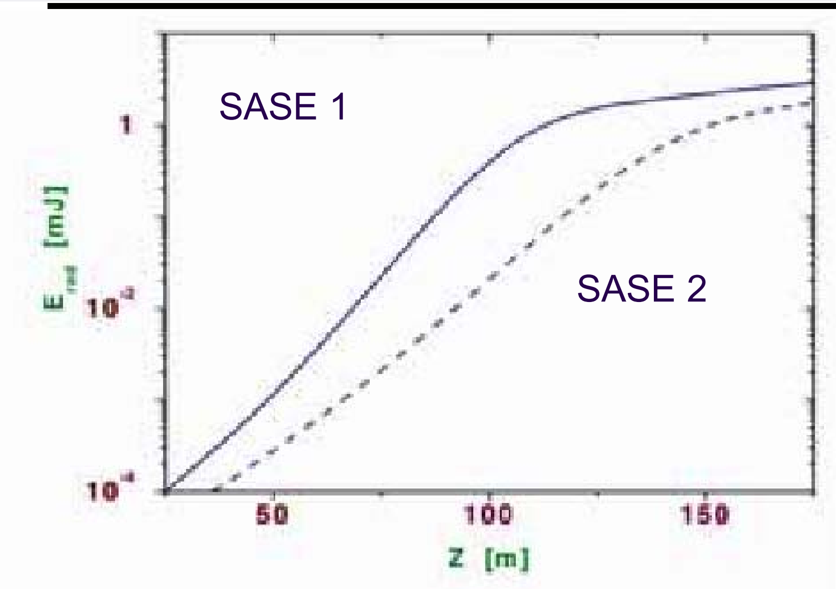


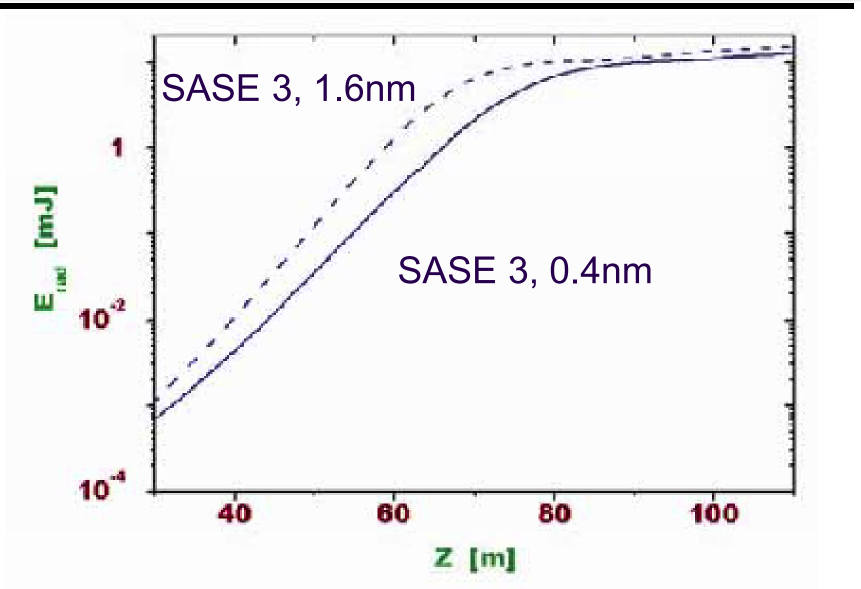




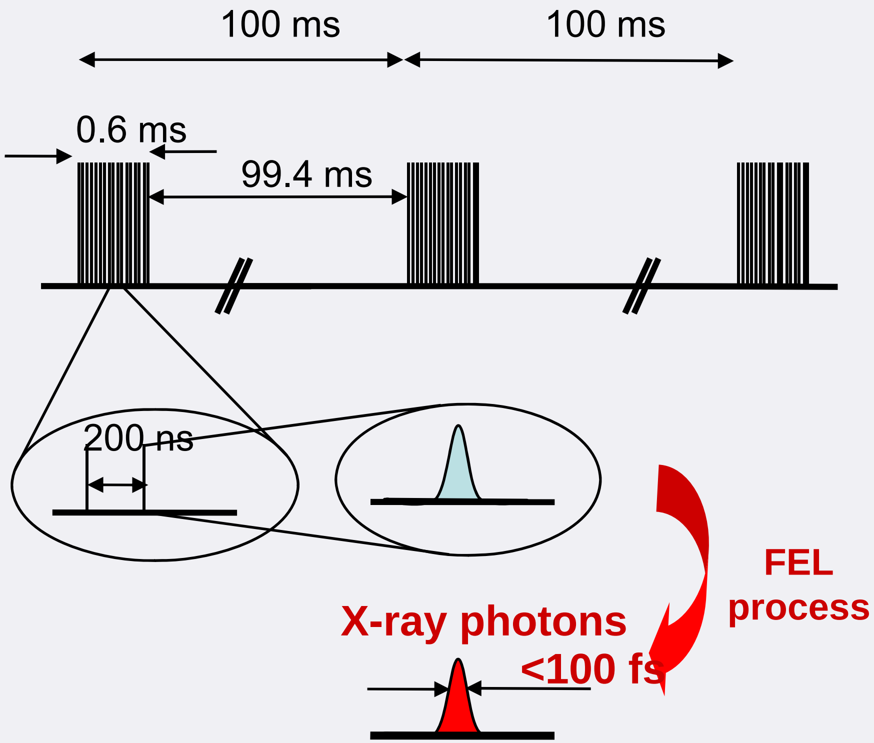
Undulators

	λ [nm]	λ_u [mm]	g [mm]	B_{max} [T]	K	β [m]	L_{sat}^{+} [m]	N_{tot}^{++} [5m]	L_{tot}^{+++} [m]
SASE 1*	0.1	35. 6	10	1.0	3.3	32	133	33	201.3
SASE 2*	0.1	48	19	0.63	2.8	46	174	42	256.2
	0.4		10	1.37	6.1	15	72		
SASE 3**	0.4	80.0	23	0.44	3.3	15	81	21	128.1
	1.6		10	0.91	6.8	15	50		

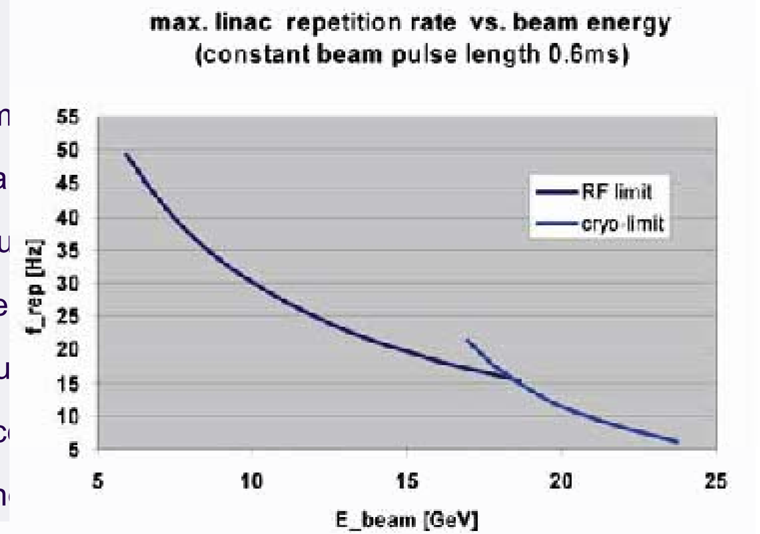


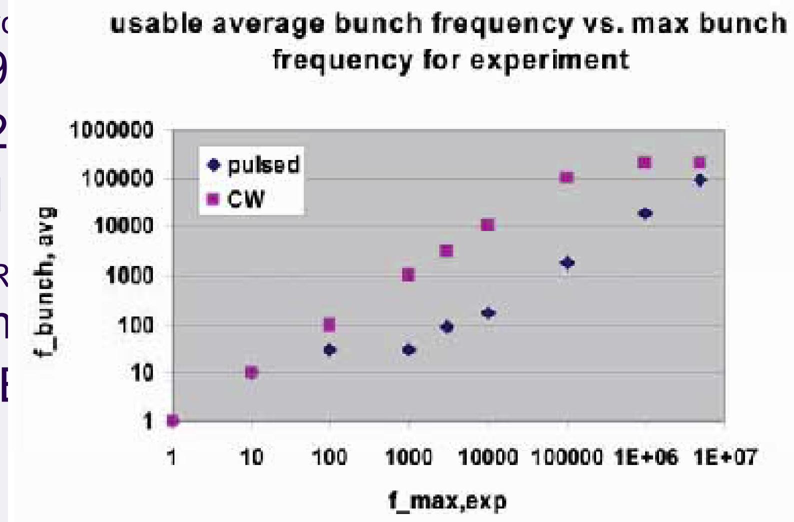


The Linac

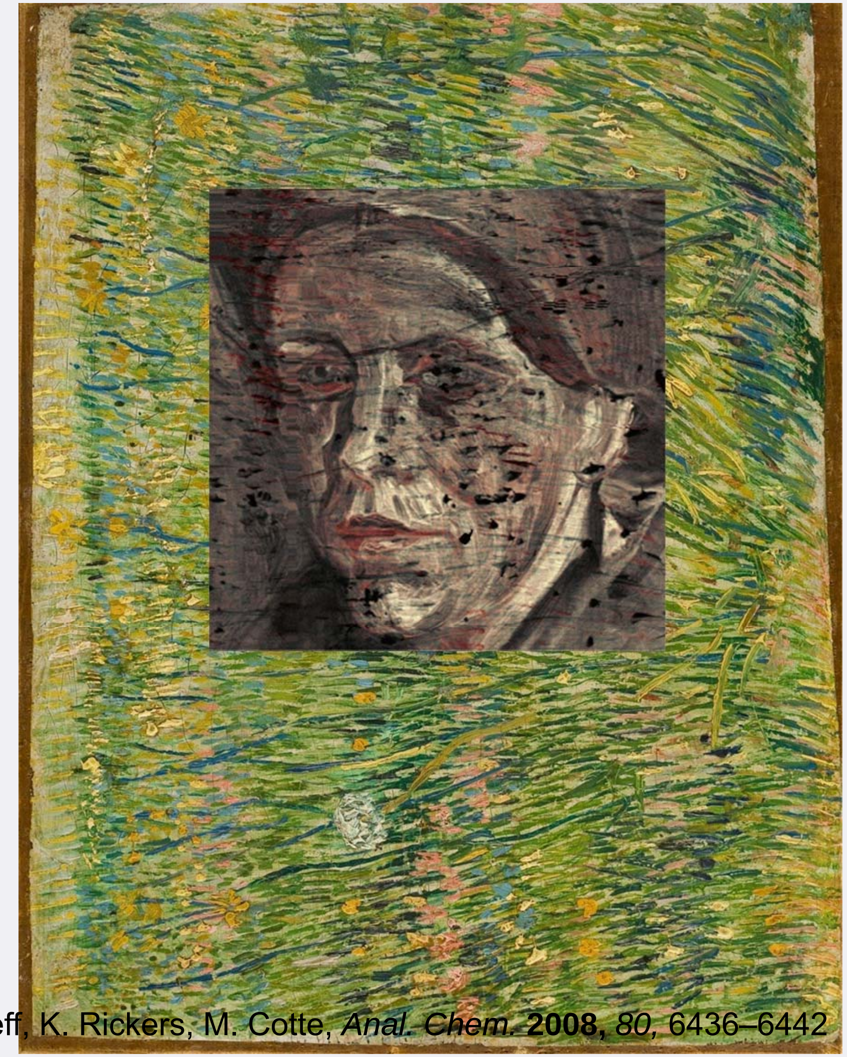


- W_{m}
- I_{pea}
- Q_{bu}
- P_{be}
- N_{bu}
- E_{ac}
- f_{bun}
- f_{cyc}
- 29
- 92
- 11
- P_{R}
- En
- ΔE





Experiments with Synchrotron Radiation



Visualization of a Lost Painting by Vincent van Gogh Using Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping

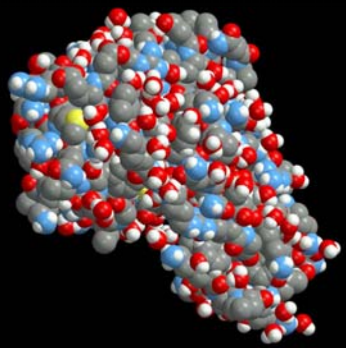
J. Dik, K. Janssens, G. van der Snickt, L. van der Loeff, K. Rickers, M. Cotte, *Anal. Chem.* **2008,** *80,* 6436–6442

X-ray Photon Correlation Spectroscopy

Circular polarised X-rays interact with the magnetisation of the sample

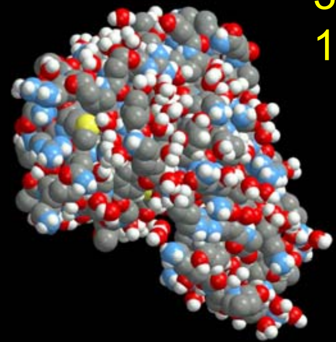
- Imaging of magnetic domains
- Studies of collective phenomena
- Investigation of phase transitions

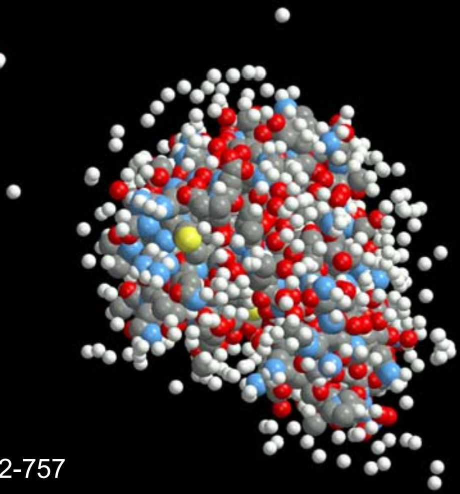
Single Molecules & Coherent X-ray Imaging



Coulomb explosion of Lysozyme

20 fs
3×10^{12} photons/100 nm spot
12 keV

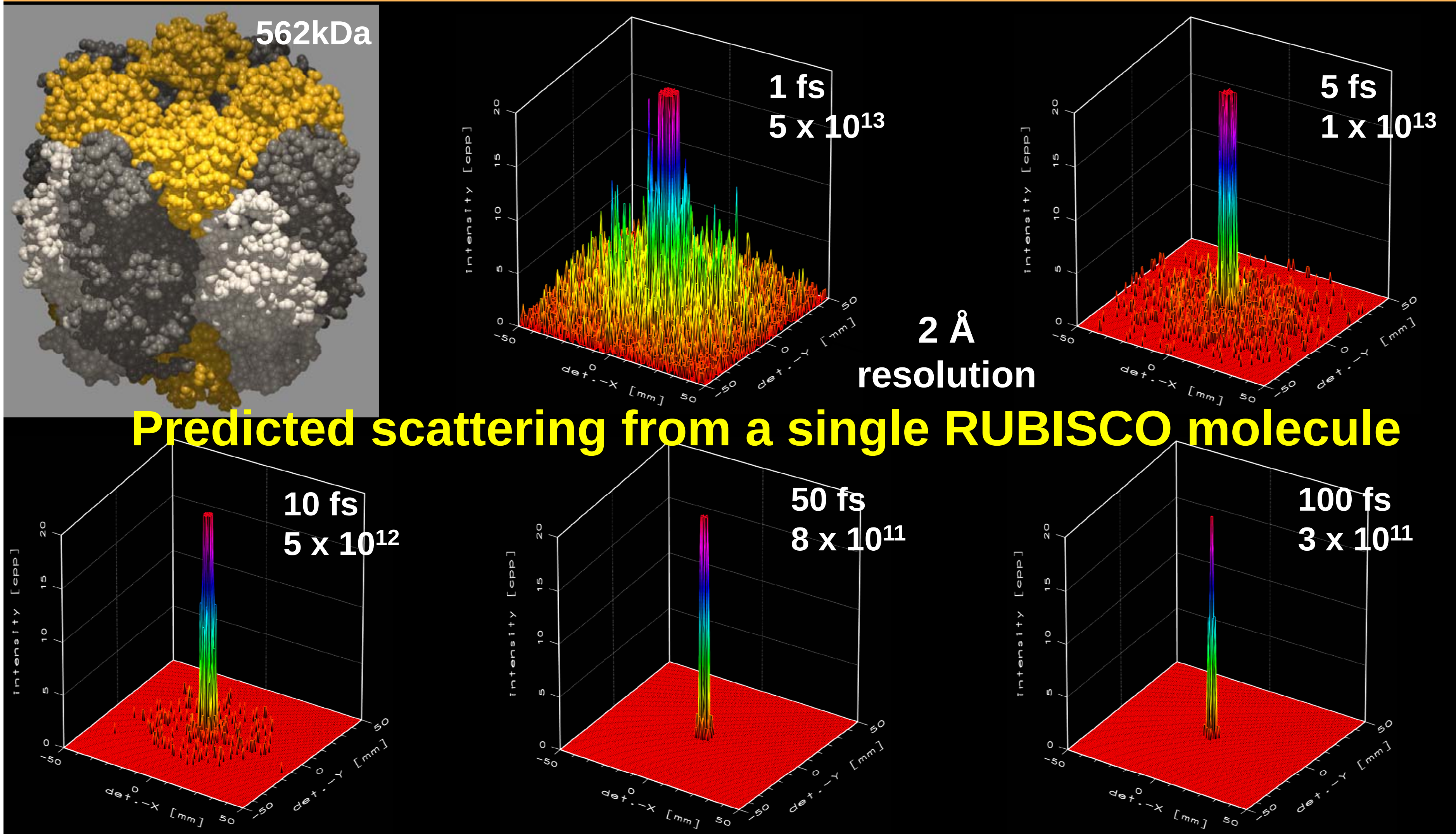




Radiation damage interferes with atomic positions and atomic scattering factors

Neutze, R., Wouts, R., van der Spoel, D., Weckert, E. Hajdu, J. (2000) *Nature* 406, 752-757

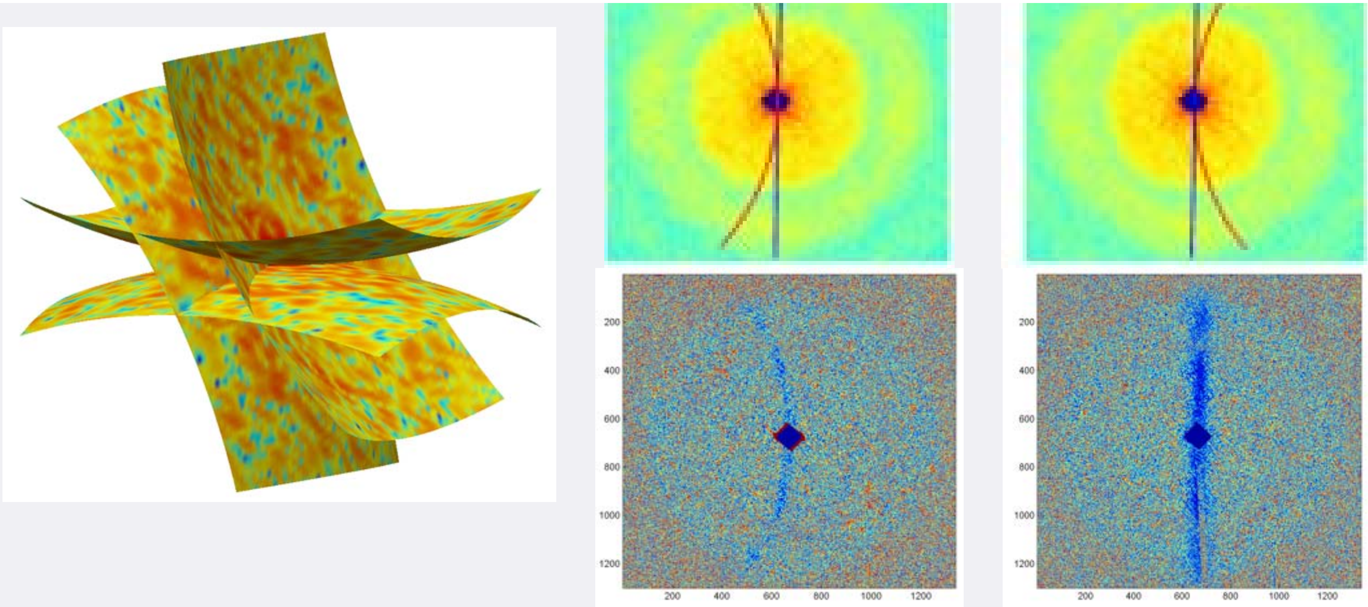
Single Molecules & Coherent X-ray Imaging



Predicted scattering from a single RUBISCO molecule

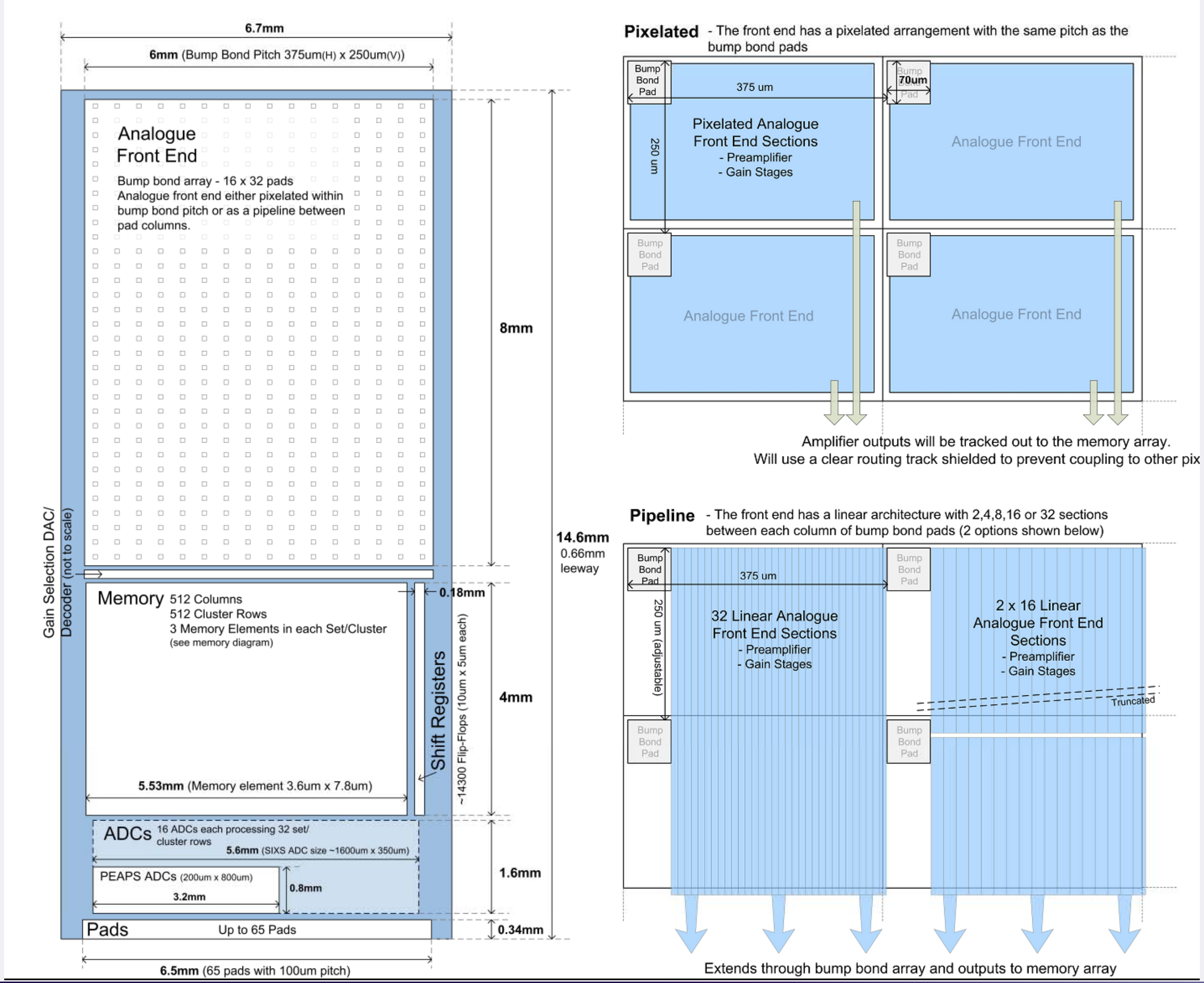
Single Particles & Coherent X-ray Imaging

Orientation, superposition & reconstruction



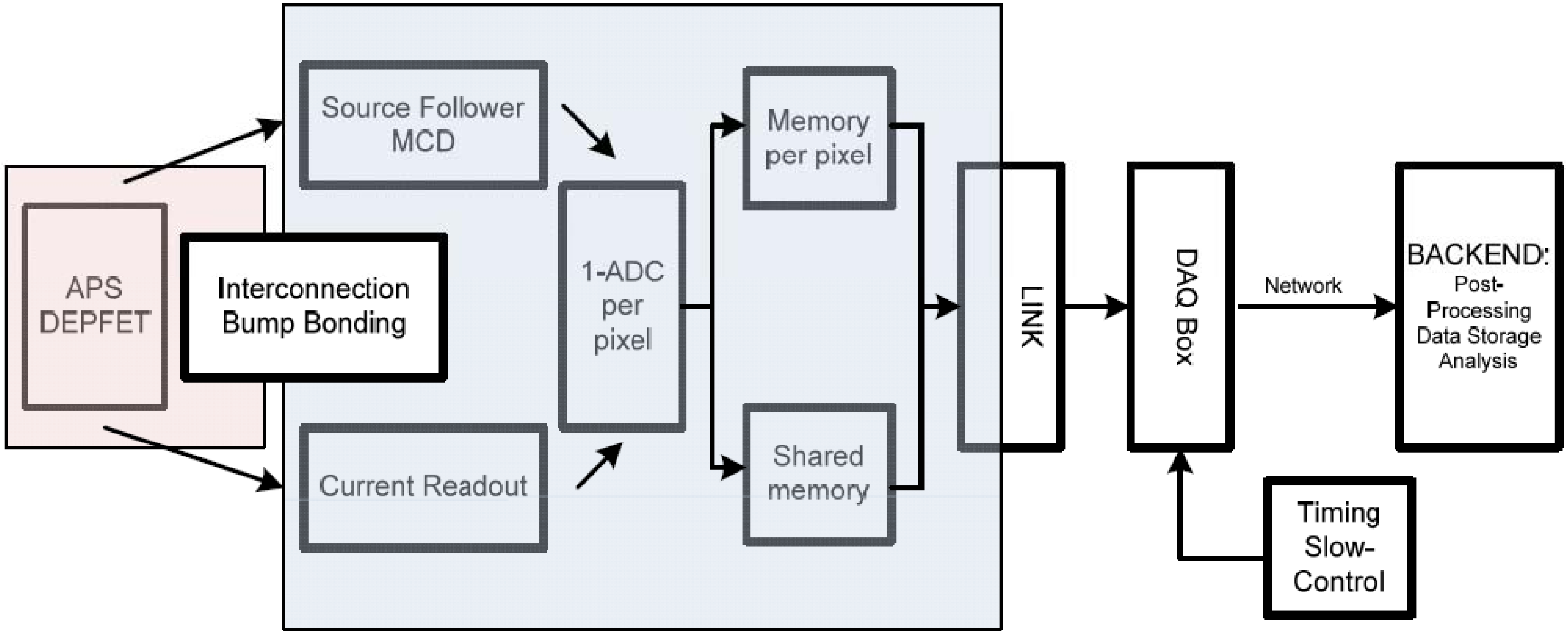
Intersection of two Ewald spheres with their centrosymmetric opposites. Centrosymmetry gives an extra intersect as there are *two* common arcs of intersection in *each* diffraction pattern (upper row). The images in the middle show the expected arcs of intersections in two diffraction patterns from the experimental pyramid x-ray diffraction data set from Figure 6.4.668. Images in the bottom row show these very lines of intersections when the experimentally obtained patterns are subtracted from each other pair wise [38].

LPD Memory Layout



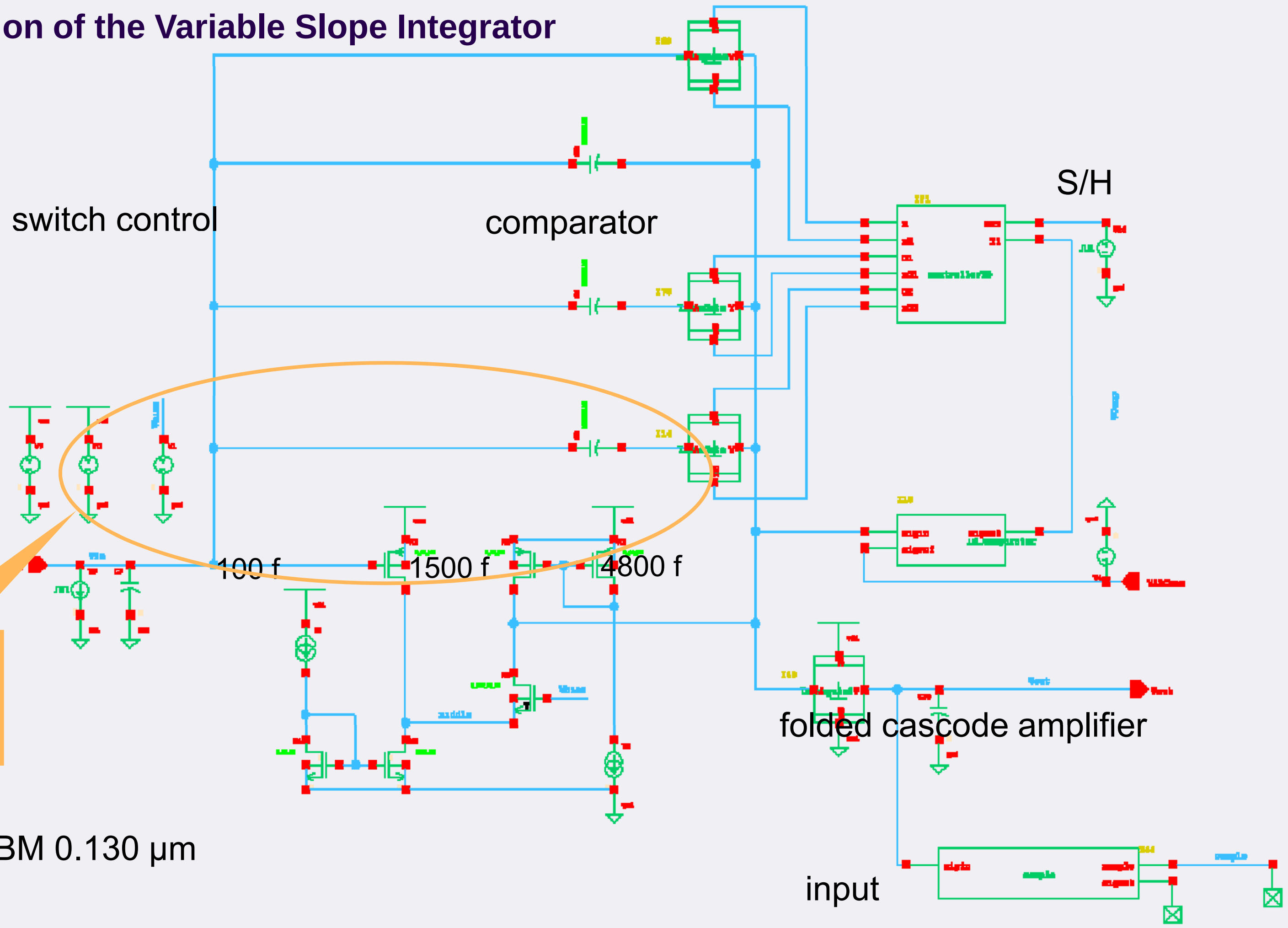
(STFC/RAL)

DEPFET Active Pixel Sensor Detector



HPAD Simulation

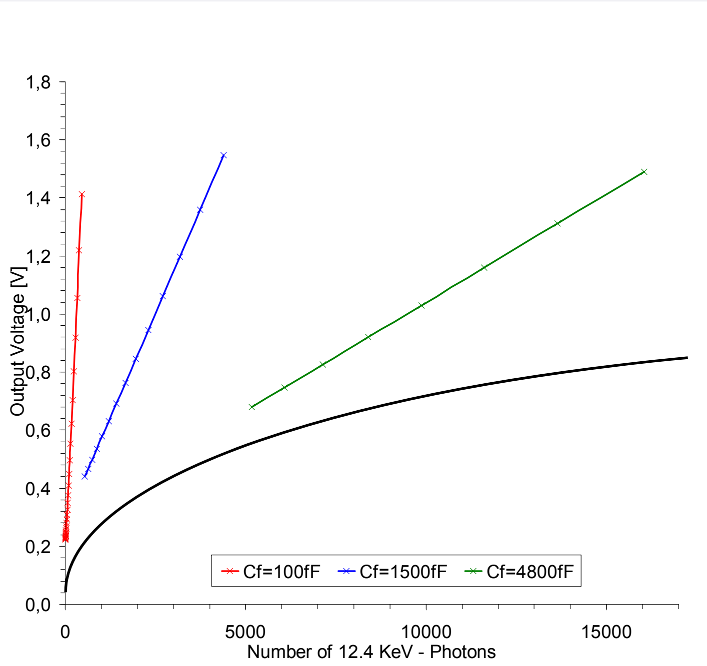
Implementation of the Variable Slope Integrator



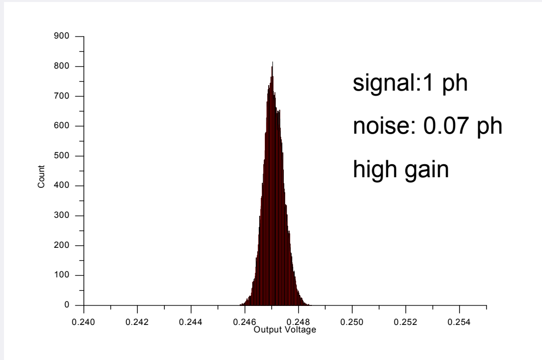
gain switching conserves signal charge

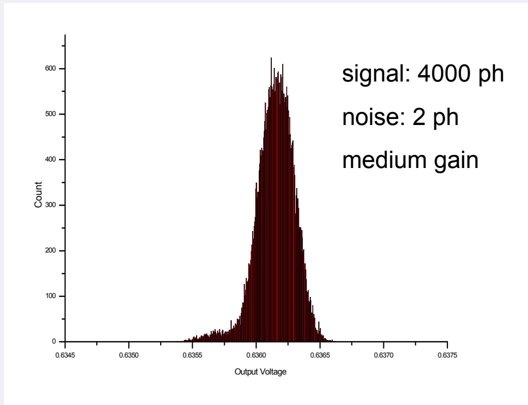
IBM 0.130 µm

HPAD Simulation Results



output voltage as a result of the dynamic gain switching





output noise for two different input signals (preliminary)