Aldo Mozzanica
for the Swiss Light Source Detector Group

XFEL detector developments

VERTEX 2016
Outline

• Introduction to FELs
• Detector requirements at FELs
• FEL detector developments at SLAC
• Detector developments for EU-XFEL
  • LPD
  • DSSC
  • AGIPD
• The JUNGFRAU pixel detector
• PERCIVAL, a detector for low X-Ray energies
• Conclusions
Not in this talk

- CCD based systems:
  - PnCCD, used for a number experiments at LCLS
  - MPCCD, developed by e2v and SACLA
  - VL-CCD + scintillators
- SOI development at SACLA
  - SOPHIAS or MVIA
- FelPIX : recent INFN R&D
  - Please refer to poster session
- 1D: GOTTHARD
Repetition rate: 60-100-120 Hz (or bursts)
Photons per pulse (12keV): up to $1 \times 10^{12}$
Photon energy: 0.25 - 16 keV
Duration of light pulse: 1 - 100 fs
FEL detector requirements

- Imaging experiment:
  - Possibly 1 image per pulse
  - No data driven, sparse readout
- Small angular pixel size:
  - Detector source distance can be tuned
  - But with a big price in term of size and cost
  - > Megapixel systems are needed.
- Reliability: Rad Hard (for >5keV applications) and protection from accidental pulses
- Charge integrating based, PC does not work for pulsed sources
  - High dynamic range, in terms of total number of photon per pixel before saturation
  - Single photon resolution

Possibly at the same time! Different strategies, generally some kind of non linear pre. response
DR – why it is needed

- Rybosome, PILATUS 6M, 30s exposure at a Synchrotron source (SLS)
- “Worst case” example, not typical FEL measurement
CSPAD: 1st generation detector at LCLS

CXI – CSPAD 2.3M

Lysozyme structural model against its x-ray diffraction pattern using CSPAD at CXI*

Schematic of a CSPAD pixel

Koerner L J, Philipp H T, Hromalik M S, Tate M W, and Gruner S M 2009 JINST 4 P03001
Philipp H T et al. 2010 IEEE Trans Nucl Sci 57 3795
Hart P A et al. 2012 Proc SPIE 8504 85040C
Hart P A et al. 2012 IEEE NSS MIC Conference 538
Herrmann S C et al. 2012 IEEE NSS MIC Conference 520
Herrmann S C et al. submitted to JPCS (SRI 2013)
## LCLS unfulfilled needs

<table>
<thead>
<tr>
<th>CSPAD</th>
<th>High Gain</th>
<th>Low Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels per ASIC</td>
<td>194 x 185</td>
<td></td>
</tr>
<tr>
<td>Pixel Size (μm)</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Noise r.m.s. (eV)</td>
<td>1,000</td>
<td>3,500</td>
</tr>
<tr>
<td>Maximum signal</td>
<td>350</td>
<td>2,700</td>
</tr>
<tr>
<td>(8 keV equivalent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame rate (Hz)</td>
<td>120</td>
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- **High noise, high spatial resolution applications**
- **High dynamic range applications**
# 2nd generation cameras for LCLS: ePix

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<th>ePix 10k prototype</th>
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<tr>
<td>Pixels per ASIC</td>
<td>48 x 48</td>
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<tr>
<td>Pixel Size (μm)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Noise r.m.s. (eV)</td>
<td>650</td>
<td>10,800</td>
</tr>
<tr>
<td>Maximum signal</td>
<td>100</td>
<td>10,000</td>
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<td>Frame Rate (Hz)</td>
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Low noise, high spatial resolution applications: **ePix100**

High dynamic range applications: **ePix10k**

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<tr>
<td>Pixels per ASIC</td>
<td>384 x 352</td>
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<tr>
<td>Pixel Size (μm)</td>
<td>50</td>
</tr>
<tr>
<td>Noise r.m.s. (eV)</td>
<td>290</td>
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<tr>
<td>Maximum signal</td>
<td>100</td>
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<td>Frame rate (Hz)</td>
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Courtesy: G. Carini
ePix100 ASIC

- Fully analog chip
  - 50 μm x 50 μm, 352 x 384 pixels
- Columns are read sequentially
  - Allows Region of Interest (ROI) readout
- Readout speed 120 – 240 Hz
- 5 – 10 MHz pixel clock
  (4 outputs)
- SLAC ASIC Control Interface (SACI)
  - Master/slave serial interface to configure and control the chip
- ~ 12 μWatt/pixel
- TSMC 0.25 μm
ePix ONE camera – full system for one carrier module

- **Very compact camera** 52 mm x 52 mm x 155 mm
- Lightweight interface
  - DSUB-26 connector for power, triggers
  - Fiber pair for data and communication
- Vacuum compatible design
- Water cooled baseplate between analog and digital PCB
  - High power PCB components cooled by baseplate
- TEC cooling for detector assembly
- Detector hoody can be N2 purged

Courtesy: G. Carini
• Speckle patterns were acquired from powder of silica nanospheres (diameter of 150 nm) under small angle scattering geometry.
• Data were collected with full SASE spectrum ($\Delta E/E \approx 10^{-3}$) at 8.34 keV.
• Spot size at sample location (3 microns by 3 microns) was controlled by using beryllium compound refractive lenses.
• Higher harmonics were suppressed with the help of pair of silicon mirrors.
• Multiple series of speckle patterns were collected for various levels of the averaged pulse fluence.
Bunch structure of the European XFEL

The European XFEL facility is being built in Hamburg and Schleswig-Holstein and expected to be operational in 2017.

- **Bunch structure:**
  - 10 Hz operation, 27000 pulses/sec
  - Detectors need to operate at a maximum speed of 4.5 MHz

- **Three 2D Detector Developments at the European XFEL (coordinator: M. Kuster)**
  - DEPFET Sensor with Signal Compression Consortium (DSSC)
    - (Project Leader: M. Porro)
  - Large Pixel Detector Consortium (LPD)
    - (Project Leader: M. French)
  - Adaptive Gain Pixel integrating Pixel Detector Consortium (AGIPD)
    - (Project Leader: H. Graafsma)
## DSSC – Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy range</td>
<td>optimized for 0.5 ... 6 keV</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>Sensor Pixel Shape</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Sensor Pixel pitch</td>
<td>~ 204 x 236 µm²</td>
</tr>
<tr>
<td>Dynamic range / pixel / pulse</td>
<td>~5000 ph @ 0.5 keV</td>
</tr>
<tr>
<td></td>
<td>&gt; 10000 ph @ E≥1 keV</td>
</tr>
<tr>
<td>Resolution</td>
<td>Single photon detection also @ 0.25 keV</td>
</tr>
<tr>
<td>Frame rate</td>
<td>0.9-4.5 MHz</td>
</tr>
<tr>
<td>Stored frames per Macro bunch</td>
<td>800</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20°C optimum, RT possible</td>
</tr>
</tbody>
</table>

### 1 Mpixel camera with:

- Single photon sensitivity event at 0.25 keV
- High-dynamic range (>10000 ph/pixel)
- Frame rate up to 4.5 MHz (1 image every 220 ns)

Spectroscopy & Coherent Scattering (SCS Instrument)

Small Quantum Systems (SQS Instrument)

Ultra fast X-ray Coherent diffraction imaging (SPB instrument)
Non Linear DEPFET reminder

DEPFET vs Mini-SDD

DEPFET
- floating int. gate -> low Cin ~60 fF
- Low DEPFET gm ~ 60 - 100 μS
- The internal gate provides intrinsic signal compression

![Diagram of DEPFET circuit](image)

\[ ENC^2 \sim \frac{1}{gm} \cdot A_1 \cdot C_{IN}^2 \]

MiniSDD
- Passive anode bump-bonded to an external PMOS -> Cin ~300-500 fF
- Higher cross-talk
- High PMOS gm > 1 mS
- non-linear response has to be implemented on the ASIC front-end

![Diagram of MiniSDD circuit](image)


F. Erdinger et al. “The readout ASIC for the DSSC camera for the European XFEL”, FEE 2016, KRAKÓW, Poland
ASIC Analog Readout Channel

- **47 digital control bits per pixel.** Random R/W access to individual pixels
- Pixel filter with **15 different gain settings** (4 feedback capacitors)
- **6 ADC ramp current (gain) trim bits**
- **4 ADC Offset trim bits per pixel**
- Several test injection & monitoring possibilities for both front-end types

Gain and offset can be adjusted pixel-wise
Offset must be adjusted with a precision 10 times better than ADC resolution
### DEPFET vs Mini-SDD: Preliminary Estimate

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>DEPFET px-8</th>
<th>mini-SDD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dynamic range [ph.]</td>
<td>ENC [el.]</td>
</tr>
<tr>
<td></td>
<td>4.5 MHz</td>
<td>2.2 MHz</td>
</tr>
<tr>
<td>0.25</td>
<td>480</td>
<td>NA</td>
</tr>
<tr>
<td>0.3</td>
<td>615</td>
<td>NA</td>
</tr>
<tr>
<td>0.5</td>
<td>1116</td>
<td>18.4</td>
</tr>
<tr>
<td>0.7</td>
<td>1905</td>
<td>21.7</td>
</tr>
<tr>
<td>1</td>
<td>3270</td>
<td>26</td>
</tr>
<tr>
<td>&gt; 4000</td>
<td>21.1</td>
<td>13.9</td>
</tr>
<tr>
<td>&gt; 7000</td>
<td>24.4</td>
<td>16</td>
</tr>
<tr>
<td>&gt; 10000</td>
<td>19.5</td>
<td>19.5</td>
</tr>
</tbody>
</table>

- \( \text{Noise}_{\text{SDD}}/\text{Noise}_{\text{DEPFET}} \sim 3 \)
- \( S/N > 5 \) only with DEPFET for \( E \leq 1 \) keV
  - For \( S/N = 5 \), \( P(1|0) \sim 6 \times 10^{-3} \)
- Dynamic range of DEPFET for \( E \leq 1 \) is almost the double for DEPFET

LPD Introduction

Large Pixel Detector

- Built by the Science and Technology Facilities Council, Rutherford Appleton Lab for the European XFEL
- 1 Megapixel - 500um pixels
- 4.5MHz frame rate
- High dynamic range, 1 to 1x10^5 photons per pixel per pulse. Using parallel gain stages.
- 512 frame memory depth continuously stores images, overwriting whenever a veto is received.
- Output data rate ~10GB/s per megapixel

Contact: Matthew.hart@stfc.ac.uk
LPD Readout ASIC

- 512 Channels per ASIC
- Preamplifier with 50pF feedback – $10^5$ 12keV photons
  - An additional 5pF high gain mode gives sub photon noise performance at the expense of some dynamic range.
- 100x, 10x and 1x parallel gain stages
  - The best gain for each pixel is selected by the DAQ system during readout.
- 512 frames of memory for each channel and gain
  - Veto System used to make best use of memory
- 16 ADCs – 12 Bit SAR
- 100MHz digital output
- Built on IBM 130 nm
LPD In Action

- The LPD system has been successfully tested at a range of facilities LCLS, PETRA III, Diamond Light Source, ESRF and the Central Laser Facility @ Harwell.

- Tests using the Diamond Light Source Hybrid mode showed that LPD can resolve photon peaks. Allowing measurement of gain and noise performance.

- Noise $\sigma = 0.3$ photons (18keV)

- Test with ESRF Hybrid mode were intense enough to capture single shot diffraction patterns with LPD running at full speed.
The AGIPD Concept

3-fold dynamically gain switching preamplifier

CDS stage (2 selectable gains)

Pixel buffer (charge sensitive)

Column buffer (interleaved, precharging signal to bus)

Reading Section
Used during the gap of 99.4ms

Offchip driver (Fully differential Amplifier)
## AGIPD: 1M System

<table>
<thead>
<tr>
<th>AGIPD1.0</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Module</strong></td>
<td>8 x 2 chips = <strong>65 kpixel</strong></td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td>102.4 x 25.6 mm²</td>
</tr>
</tbody>
</table>

### Upstream

| **Quadrant** | 4 modules = **256 kpixel** |
| **Overall pixel count** | **1 Mpixel** |
| **Active area** | ~22 x 22 cm² |
| **Central hole** | Adjustable |

### Downstream

| **Modules** | 2 (side-by-side) = **128 kpixel** |

| **System** | |
| **Heat dissipation** | 1 kW / Mpixel system |
| **Cooling** | Liquid cooling (silicone oil) |
| **Cooling power** | 1.5 kW (-60 °C) 0.5 kW (-80°C) |
| **Operating Temp.** | -20 °C |

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1M System will be delivered to XFEL.EU in August 2016
AGIPD: 1M System

AGIPD Quadrant
AGIPD1.0
Dynamic Range Scan: IR Pulsed Laser

LOW gain range
(x12.4 keV): 7000 (+3000)

HIGH gain range (x12.4 keV): 40

MED gain range
(x12.4 keV): 1000
- 75um pixel pitch
- UMC 110nm technology
- Design similar to AGIPD and GOTTHARD
- << power consumption probably (budget of ~25uA/ch)
- plenty of space for circuit, filled with SC
- Space for MiM feedback capacitor limited, low gain from 13pC (AGIPD,GOTTHARD)->7.5pC
  - precharge of feedback capacitors
- Enclosed gate layout for most analog sections
500k pixel module

- Same geometry as an EIGER module
- 2x4 chips
- 1024x512 pixels
- 3.8x7.7 cm² silicon sensor
- Sensor thickness 320 μm
- Modular readout electronics
- Water cooling, operation at 20 °C
Noise across dynamic range

Automatic gain switching scan:

- White visible light illumination
- Requires etching of Al entrance window
- Increasing integration time
- Plots in unit of 12keV photons
- Charge injection is continuous and not pulsed
Noise across dynamic range

Automatic gain switching scan:

- White visible light illumination
- Requires etching of Al entrance window
- Increasing integration time
- Plots in unit of 12keV photons
- Charge injection is continuous and not pulsed

Gain switch

Response and noise curves

Poisson statistical limit
Single photon measurements

- X-Ray tube, W anode
- Cu Fluorescence target
- 10us integration time
- HG0
- HV=200V
- Readout at 500-700Hz
  - limited by prototype firmware
  - 20MHz ASIC readout
• In HG0 the gain is ~2x WRT G0
• Gain uniformity 2.7%
• Noise is 30% less
• Noise map uniform
• MPV < 50 e.n.c.
• Single photon resolution at 1.5keV demonstrated
1M tests at LCLS (preliminary)

- YB 66 crystal 200um diameter
- 9.5keV photon energy monochromator
- 20um focal spot on sample
- Cumulative plot over few deg. of crystal rotation
- Data from Wed. last week

Log scale (different dataset)

Gain map 1 frame

Cumulative image, linear
The Percival Sensor

> 7 ADCs (+ spare) per column ⇒ read sensor in 7-row “groups”
> 1408 columns + 32 dark ⇒ 11.5k ADCs in a 2M chip
> 12+1(overrange)+2 (gain) bits ⇒ 15 (x2 for CDS) bits/pixel/frame
> 45 LVDS output lines at 480MHz data rate for one 2M chip (20 Gbit/s)
Dynamic range: test results (TS1.2)

3 gains, “lateral overflow”

dyn. range: 3.5Me ~ 50k photons @ 250eV
reasonably low parameter dispersion between different samples (also from different wafers)
## FEL detectors comparison table

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<tr>
<th>Detector system</th>
<th>Pixel size [µm×µm]</th>
<th>Elect. noise r.m.s [e-]</th>
<th>Single ph. res. (5σ) from</th>
<th>DR: ph. per pulse per pixel @ 12kev</th>
<th># SC EU-XFEL</th>
<th>Cont. rep. rate [kHz]</th>
<th>Mod. Size [kpix] / dead area</th>
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<tr>
<td>CSPAD - HG</td>
<td>110×110</td>
<td>~330</td>
<td>5keV</td>
<td>230</td>
<td>1</td>
<td>0.12</td>
<td>140/20%</td>
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<tr>
<td>CSPAD - LG</td>
<td>110×110</td>
<td>~970</td>
<td>17keV</td>
<td>1800</td>
<td>1</td>
<td>0.12</td>
<td>140/20%</td>
</tr>
<tr>
<td>epix100</td>
<td>50x50</td>
<td>~80</td>
<td>1.5keV</td>
<td>65</td>
<td>1</td>
<td>~0.3</td>
<td>540/n.a.</td>
</tr>
<tr>
<td>epix100k</td>
<td>100x100</td>
<td>~180</td>
<td>3.2keV</td>
<td>6600</td>
<td>1</td>
<td>~1</td>
<td>120/n.a.</td>
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<td>DSSC †</td>
<td>Pitch 200‡</td>
<td>21 or 50</td>
<td>0.3keV</td>
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<td>50 (HG0)</td>
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<td>1</td>
<td>0.12</td>
<td>2000/0%*</td>
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‡hexagonal pixels  
† designed for EU-XFEL  
††12 keV operation not foreseen  
* 2 side buttable design only quads are possible  
MPCCD, pnCCD and MVIA not in table
**In the near future**

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Deployment
 Calibration
 Commissioning
### Detector system developments

**On a longer timescale**

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<td>65</td>
<td>1</td>
<td>~0.3</td>
<td>540/n.a.</td>
</tr>
<tr>
<td>epix100k</td>
<td>100x100</td>
<td>~180</td>
<td>3.2keV</td>
<td>6600</td>
<td>1</td>
<td>120/n.a.</td>
<td>32/15%</td>
</tr>
<tr>
<td>DSSC †</td>
<td>Pitch 200‡</td>
<td>21 or 50</td>
<td>0.3keV</td>
<td>1·10^4 (22.1 keV)††</td>
<td>*</td>
<td>*</td>
<td>32/15%</td>
</tr>
<tr>
<td>LPD †</td>
<td>500×500</td>
<td>~1000</td>
<td>18keV</td>
<td>10^5</td>
<td>512</td>
<td>4/16%</td>
<td>65/20%</td>
</tr>
<tr>
<td>AGIPD †</td>
<td>200×200</td>
<td>~265</td>
<td>4.5keV</td>
<td>~10^4</td>
<td>352</td>
<td>~24</td>
<td>65/20%</td>
</tr>
<tr>
<td>JUNGFRAU</td>
<td>75×75</td>
<td>50 (HG0)</td>
<td>1.25keV</td>
<td>1.1·10^4</td>
<td>16</td>
<td>~2.4</td>
<td>535/7%</td>
</tr>
<tr>
<td>PERCIVAL</td>
<td>27x27</td>
<td>~15</td>
<td>0.25keV</td>
<td>5·10^4 (@ 0.25keV)††</td>
<td>1</td>
<td>0.12</td>
<td>2000/0%*</td>
</tr>
</tbody>
</table>

**Lower noise**

For low photon energies

---

* This might be unnecessary if EU-XFEL goes to CW
** For LCLS-II
Acknowledgments

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The AGIPD collaboration

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²DESY, HASYLAB Group, Hamburg, Germany
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(Pixelated Energy Resolving CMOS Imager, Versatile And Large)
Backup
> Front-side illuminated (FSI) sensor
> Photons have to traverse oxides and metals
> Limited and non-uniform sensitivity to soft X-rays

> Back-side illuminated (BSI) sensor bonded to carrier wafer
> High and uniform soft X-ray sensitivity possible
> Percival prototypes are BSI-processed at JPL (delta-doping)
The full PERCIVAL system

- **Pixel area**
- **Sampling**
- **ADC (12+1)**
- **Dig. out (120 fps)**

**P2M**
- 2 Mpixels
- ~4×4cm² area
- 2-side buttable
- 27um pixel pitch
- Available ~2017

P13M only
Some electronic design parameters:

- preamp: 1.2V 8uA
- CDS+comp: 1.4V 14uA
- settling time pre. ~100ns
- Tot. power 30uW/ch, max. 2A/chip

- 1st gain switch at 25 ph., 2nd at 600 (12keV)
- Linear up to >1000 12keV ph.
- Linearity err. <1%
- pix. to pix. X-talk <<1%
From modules to systems

- 500k (one module), 1M (2 modules), 4M and 16M (ESA-ESB main instruments) systems are foreseen
- same geometry as the EIGER systems (gaps, etc..)
- Horizontal gaps VERY small
- compact (20-25 cm) in the Z direction
- 16Mpix @ 100 Hz will generate ~3 GB/s

Example of 16M camera no holes

Horizontal gap 0.6 mm (8 px)

Vertical gap 2.7 mm (36 px)
• Average noise of 65 electrons r.m.s.
• Noise map quite uniform
• Some tails in the noise distribution:
  • 1% pixels above 85e-
  • 0.1% pixels above 100e-
• for every pixel a Gaussian + charge sharing model function is fit to the P.H. data
• Gain is extracted as Gaussian peak position
• gain variation ~3.5% r.m.s.
• gain depends (slightly) on power distribution and on readout (ADC+buffers mismatch)
Sensor and Focal Plane Architecture

- Non Linear DEPFET
  - Intrinsic low noise
  - Intrinsic signal compression

- Mini SDD array
  - Linear response
  - Simplified technology

  - Readout concept
    - Full parallel readout
    - Analog shaping
    - **8-9 bit digitization in pixel**
    - In-pixel SRAM (800 frames/bunch)

- Power cycling
  - 10.7 kW peak power
  - 240 W average power

- Focal Plane composition
  - 1024x1024 pixels
  - **16 ladders (512 x 128)**
  - 32 monolithic sensors 128x256
  - 256 Readout ASICS 64 x64

- Mini-SDD camera by end 2017
- Two ladder cameras (Mini-SDD and DEPFET) by middle of 2016
- DEPFET camera to follow