Soft X-ray detectors at European XFEL

Andreas Koch
European XFEL, WP-75, Detector Development
26.1.2012
Outline

- Status of detector activities for low energy applications
- Overview on potential suppliers, collaborations for developments
- Most promising suppliers, labs examples
Requirements for low energy 2D detection at XFEL

**General**

- **Carbon K-edge:** 284 eV
- **Nitrogen K-edge:** 410 eV
- **Oxygen K-edge:** 543 eV
- **SASE 3**
  - 0.45 → 2 keV
  - 0.73 → >3 keV
- **SASE 1/2**
  - 6.4 → >25 keV
  - 4.1 → >20 keV

**Specific RIXS requirements (dispersive imaging):**

- **Dispersive axis:** pixel size down to 10 μm, even smaller.
- **Axis for angular coverage of incoming radiation:** more pixels or larger pixel size, i.e. rectangular pixel (aspect ratio x2 ... x10).

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**Table:**

<table>
<thead>
<tr>
<th>Pixel size</th>
<th>10 ... 100s μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector size</td>
<td>1kx1k or rectangular</td>
</tr>
<tr>
<td>Tiling</td>
<td>central hole</td>
</tr>
<tr>
<td>Quantum eff./ sensor thichn.</td>
<td>&gt; 80%</td>
</tr>
<tr>
<td>Energy range</td>
<td>0.25 – 3 keV</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$10^3$ ... $10^4$...</td>
</tr>
<tr>
<td>Noise / noise equ. signal</td>
<td>Single photon sensitivity</td>
</tr>
<tr>
<td>Frame rate</td>
<td>4.5 MHz, 2700 im., 10 bursts</td>
</tr>
</tbody>
</table>
Baseline detector at XFEL
for low energy applications is the DSSC detector (DEPFET Sensor with Signal compression)
Full scale, full commissioned version is delayed to 2017.

Day-1 detector
in 2015 for SPS, SQS is needed.
Small pixel size down to 50 µm is an additional requirement.
Possible solutions and options are presented.

A phase 2 detector
with enhanced performance is under discussion.
Detectors for RIXS

Low energy detector alternatives

18 companies and laboratories contacted.
5 contacts are closer investigated.

**Companies:**
- e2v
- Hamamatsu
- Bruker
- Photonic Science
- Dalsa
- Dexela
- Pyxalis (ex – e2v)

**Labs:**
- Cornell Univ.
- BNL
- LCLS
- SACLA (with e2v)
- ESRF
- SLAC
- LBNL
- CEA
- Desy
- RAL
- MPI

**Promising replies:**
- LBNL (with Dalsa)
- XCAM / SACLA (with e2v)
- Photonic Science
- Desy
- MPI
## Detectors for RIXS

### Benchmarking

<table>
<thead>
<tr>
<th>Requirements low energy detector XFEL</th>
<th>DSSC</th>
<th>CS-PAD</th>
<th>pn CCD MPI</th>
<th>Commercial CCD, Cmos, &lt; 15 keV</th>
<th>Commercial CCD, Cmos, &gt; 15 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>For SCS, SQS</td>
<td>XFEL baseline</td>
<td>Operational at LCLS</td>
<td>Commercial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>DEPFET hybrid</td>
<td>hybrid</td>
<td>CCD</td>
<td>e.g. Roper CCD deep depleted PIXIS-XO</td>
<td>e.g. Dexela 2930MAM mammography</td>
</tr>
<tr>
<td>Pixel size</td>
<td>10 ... 100s μm</td>
<td>204x236 mm², hex.</td>
<td>110 μm</td>
<td>75μm</td>
<td>13 μm</td>
</tr>
<tr>
<td>Detector size</td>
<td>1kx1k or rectangular</td>
<td>1kx1k</td>
<td>1516x1516 or smaller</td>
<td>1kx1k central hole</td>
<td>29x30 cm²</td>
</tr>
<tr>
<td>Tiling</td>
<td>central hole</td>
<td>Yes, with central hole</td>
<td>Yes, multiple tiles</td>
<td>2 tiles</td>
<td>4 tiles</td>
</tr>
<tr>
<td>Quantum eff./sensor thickn.</td>
<td>&gt; 80%</td>
<td>&gt;80% @0.4-10 keV 60% at 0.25 eV</td>
<td>500 μm Si</td>
<td>&gt;80% @ 0.3-12 keV</td>
<td>100 μm Si</td>
</tr>
<tr>
<td>Energy range</td>
<td>0.25 – 3 keV</td>
<td>0.5 – 4 keV</td>
<td>&lt;1 –10 keV, opt. 8 keV nominal</td>
<td>0.05-24 keV</td>
<td>0.03-10 keV (Roper)</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$10^3$ ... $10^4$ ...</td>
<td>$10^4$</td>
<td>$10^3$-$10^4$</td>
<td>$10^3$</td>
<td>$10^3$-$10^4$</td>
</tr>
<tr>
<td>Noise / noise equ. signal</td>
<td>Single photon sensitivity</td>
<td>1 keV rms</td>
<td>1 keV rms</td>
<td>2 el. rms</td>
<td>2 el. rms</td>
</tr>
<tr>
<td>Frame rate</td>
<td>4.5 MHz, 2700 im., 10 bursts</td>
<td>4.5 MHz, 576 images dig. on-chip</td>
<td>120 Hz</td>
<td>200 Hz</td>
<td>2 Hz (Roper) 5 Hz (4x4)</td>
</tr>
<tr>
<td>Costs</td>
<td>≈ 60 keuros</td>
<td>≈ 45 keuros</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product full spec</td>
<td>2017</td>
<td>?</td>
<td>2015</td>
<td>commercial</td>
<td>commercial</td>
</tr>
<tr>
<td>Risks</td>
<td>Calibration, Delay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remarks</td>
<td>Specific needs for dispersive</td>
<td>ongoing</td>
<td>to be rebuilt option low energy</td>
<td>to be rebuilt</td>
<td>For vacuum operation</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th></th>
<th>LBNL FS-CCD</th>
<th>XCAM / SACLA</th>
<th>Desy / RAL</th>
<th>Photonic Science</th>
<th>Cornell / SLAC / ESRF</th>
<th>Phase 2 development ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Frame transfer CCD, back-illuminated</td>
<td>CCD open electrode, Riken design (MPCCD)</td>
<td>MAPS, Cmos</td>
<td>New Cmos design, back-illumin.</td>
<td>sCmos Fairchild (back-illum. in preparation)</td>
<td>3D Cmos, bump bonded sensor, 65 nm SOI</td>
</tr>
<tr>
<td>Pixel size</td>
<td>30 μm</td>
<td>40 μm</td>
<td>25-30 μm</td>
<td>15 μm</td>
<td>6.5 μm</td>
<td>50–100 μm</td>
</tr>
<tr>
<td>Detector size</td>
<td>1kx1k, monol., option hole</td>
<td>1kx1k, 4 tiles, central hole</td>
<td>20x20 cm², hole, 4 tiles</td>
<td>4kx4k, monolithic</td>
<td>2kx2k, monolithic</td>
<td>1kx1k or larger, tiles</td>
</tr>
<tr>
<td>Tiling</td>
<td>Several mm gaps if tiled</td>
<td>Yes</td>
<td>2 side buttable</td>
<td>Yes, with gaps</td>
<td>no</td>
<td>4 side buttable</td>
</tr>
<tr>
<td>Quantum eff. / sensor thickness</td>
<td>200 μm Si</td>
<td>20% @ 10 keV 40 μm Si</td>
<td>95% @ 1 keV 12 μm Si</td>
<td>15 μm Si</td>
<td>?</td>
<td>Si sensor tbd.</td>
</tr>
<tr>
<td>Energy range</td>
<td>0.25-8 keV</td>
<td>0.3-10 keV</td>
<td>0.25-1 keV</td>
<td>To be defined</td>
<td>?</td>
<td>0.2-20 keV</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>10³-10⁴</td>
<td>10³-10⁴</td>
<td>10⁶, 3 gains</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁶, 4 gains</td>
</tr>
<tr>
<td>Noise / noise equ. signal</td>
<td>30-40 el. rms</td>
<td>20 el.rms</td>
<td>15 el. rms 50 eV rms</td>
<td>4 el. rms</td>
<td>2.5 el. rms</td>
<td>200 eV rms</td>
</tr>
<tr>
<td>Frame rate</td>
<td>100 Hz</td>
<td>10 Hz</td>
<td>120 Hz</td>
<td>10 Hz</td>
<td>17 Hz (34 Hz for 1k)</td>
<td>4.5 MHz, 2700 images, digital</td>
</tr>
<tr>
<td>Costs</td>
<td>rel. low</td>
<td>rel. low</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product, full perf.</td>
<td>2014</td>
<td>2013</td>
<td>2014</td>
<td>1.5-2 years</td>
<td>?</td>
<td>4-5 years</td>
</tr>
<tr>
<td>Risks</td>
<td>Noise, delay</td>
<td>Consortium needed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remarks</td>
<td>Ongoing, ~15 cameras</td>
<td>Riken prototype, options possible</td>
<td>Ongoing project for Flash</td>
<td>Proposal</td>
<td>• Project idea • scintillator ?</td>
<td>Proposal - high-end</td>
</tr>
</tbody>
</table>

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Other specifications, open points

- Radiation hardness
- Medium term stability (temperature, voltages, charge effects)
- Local electron / hole plasma effects in the Si sensor
- Calibration
- Data acquisition
- a.o.
**Key Detector Parameters**

- **Goal:** Single photon sensitivity
  
  \[5 \sigma @ 1 \text{ keV and } 4.5 \text{ MHz}\]

- **Energy range**
  
  \[0.5 – 6 \text{ (25) keV}\]

- **Dynamic range**

  \[> 6000 \text{ photons/pixel/pulse @1 keV}\]

- **Single photon sensitivity**

  \[5 \sigma @ 1 \text{ keV (5 MHz)}\]

  \[5 \sigma @ 0.5 \text{ keV (} \leq 2.5 \text{ MHz)}\]

- **Number of storage cells** 576

- **Smallest detector unit “ladder”**

  \[128 \times 512 \text{ pixels}\]

- **4 ladders built on quadrant**

- **4 quadrants = 1k x 1k detector**
**Pixel Cell**
- DEPFET combined with Silicon drift detector
- → scalable pixel size
- Low noise
- → Good energy response down to 500 eV

**Pixel Geometry**
- 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

Porro et al. NIM A (2010) vol. 624 pp. 509
Fast X-ray Pixel Detectors for Synchrotron Radiation Light Sources

Devis Contarato

on behalf of the EG/ALS Detector Engineering Group:

P. Denes (P.I.), N. Andresen, D. Doering, C. Grace, J. Joseph, P. McVittie, J.P. Walder, C. Tindall, B. Zheng ...

... and many more contributors
Readout architecture options

<table>
<thead>
<tr>
<th>Conventional CCD</th>
<th>Fast CCD</th>
<th>Very Fast CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to few-port</td>
<td>(almost) Column Parallel</td>
<td>Column Parallel</td>
</tr>
<tr>
<td>Commercial readout</td>
<td>fCRIC (custom 0.25 (\mu)m CMOS readout IC)</td>
<td>HIPPO (custom 65 nm CMOS readout IC)</td>
</tr>
<tr>
<td>(10^0) fps</td>
<td>(10^2) fps</td>
<td>(&gt; 10^{3\ldots5}) fps</td>
</tr>
</tbody>
</table>

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Fast X-ray Pixel Detectors for Light Sources

IWORID 2011
Zurich, July 7, 2011
Prototype Fast CCD

- 1st generation direct soft X-ray detector developed by LBNL in collaboration with ANL:
  - multi-port
  - 200 μm thick, fully depleted
  - back-illuminated
- 480×480 pixels, 30 μm pitch
- 96 analog outs, quasi-Column Parallel readout (10 column MUX)
- 200 fps readout rate

- Performance:
  - 900000 e-/pixel full well
  - 250 eV single photon resolution
  - PSF < 1 pixel

[P. Denes et al., Rev. Sci. Instruments 80, 083302 (2009)]
**1k Frame-Store CCD**

- 1920x960 pixels, 30 μm pitch, sensor based on Fast CCD design and cFCCD detector head
  - 960x960 pixels X-ray sensitive area in frame transfer mode (200 fps)
  - 1920x960 pixels X-ray sensitive area in full imaging mode (100 fps)
- 192 analog outputs (quasi-CP readout), 12 custom readout ASICs, raw data bandwidth 400 MB/s
- Full detector systems being developed under Recovery Act funding, to be delivered in 2011 (8 systems @ ALS, 2 systems @ APS, interest from SSRL/LCLS and NSLS-II)

Devis Contarato

*Fast X-ray Pixel Detectors for Light Sources*

**IWORID 2011**

Zurich, July 7, 2011
## Detectors for RIXS

### Fairchild sCMOS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>sCMOS</th>
<th>Interline CCD</th>
<th>EMCCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Format</td>
<td>5.5 megapixel</td>
<td>1.3 to 4 megapixel</td>
<td>0.25 to 1 megapixel</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>6.5 µm</td>
<td>6.45 to 7.4 µm</td>
<td>8 to 16 µm</td>
</tr>
<tr>
<td>Read Noise</td>
<td>&lt; 2 e⁻ @ 30 frames/s</td>
<td>4 -10 e⁻</td>
<td>&lt; 1 e⁻ (with EM gain)</td>
</tr>
<tr>
<td>Full Frame Rate</td>
<td>100 frames/s @ full resolution</td>
<td>3 to 16 frames/s</td>
<td>~30 frames/s</td>
</tr>
<tr>
<td>Quantum Efficiency (QE)</td>
<td>60%</td>
<td>65%</td>
<td>90% ‘back-illuminated’ 65% ‘virtual phase’</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>&gt; 16,000:1</td>
<td>~ 3,000:1</td>
<td>8500:1</td>
</tr>
<tr>
<td></td>
<td>(30 frames/s)</td>
<td>(11 frames/s)</td>
<td>(30 frames/s with low EM gain)</td>
</tr>
<tr>
<td>Multiplicative Noise</td>
<td>None</td>
<td>None</td>
<td>1.41x with EM gain (effectively halves the QE)</td>
</tr>
</tbody>
</table>
Detectors for RIXS

Next steps, opportunities

- LBNL
  - Prototype testing at ALS in March.

- MPI
  - 1 Mpx sensor available at HLL Munich.

- SLAC / Cornell / ESRF
  - New project ideas will be followed up:
    - Modified CS-PAD.
    - Fairchild sCMOS, back-illuminated or with scintillator.

- …. and look to future trends, a phase 2 project?
  - Contacts and discussions foreseen.
  - Carefully understand: detector technology evolution & scientific requirements.
  - Identify partners, interests, costs.

Through Silicon Vias, TSVs, to link DRAM chips, by IBM