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Detector developments at DESY

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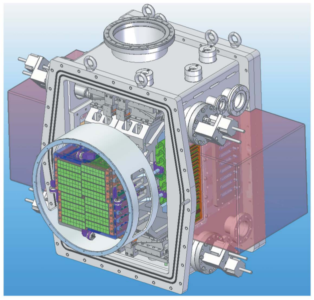
With the increased brilliance of state-of-the-art synchrotron radiation sources and the advent of free-electron lasers (FELs) enabling revolutionary science with EUV to X-ray photons comes an urgent need for suitable photon imaging detectors. Requirements include high frame rates, very large dynamic range, single-photon sensitivity with low probability of false positives and (multi)-megapixels. At DESY, one ongoing development project – in collaboration with RAL/STFC, Elettra Sincrotrone Trieste, Diamond, and Pohang Accelerator Laboratory – is the CMOS-based soft X-ray imager PERCIVAL. PERCIVAL is a monolithic active-pixel sensor back-thinned to access its primary energy range of 250 eV to 1 keV with target efficiencies above 90%. According to preliminary specifications, the roughly 10 cm × 10 cm, 3.5k × 3.7k monolithic sensor will operate at frame rates up to 120 Hz (commensurate with most FELs) and use multiple gains within 27 µm pixels to measure 1 to ~100000 (500 eV) simultaneously arriving photons. DESY is also leading the development of the AGIPD, a high-speed detector based on hybrid pixel technology intended for use at the European XFEL. This system is being developed in collaboration with PSI, University of Hamburg, and University of Bonn. The AGIPD allows single-pulse imaging at 4.5 MHz frame rate into a 352-frame buffer, with a dynamic range allowing single-photon detection and detection of more than 10000 photons at 12.4 keV in the same image. Modules of 65k pixels each are configured to make up (multi)megapixel cameras. This review describes the AGIPD and the PERCIVAL concepts and systems, including some recent results and a summary of their current status. It also gives a short overview over other FEL-relevant developments where the Photon Science Detector Group at DESY is involved.



1. Adaptive gain integrating pixel detector (AGIPD)

The AGIPD is one of three dedicated large-area imager developments for the European XFEL (Eu-XFEL) (Becker, Bianco *et al.*, 2013). The AGIPD is being developed by a collaboration led by DESY that includes PSI, University of Hamburg, and University of Bonn. Its cornerstone requirements are the capability to take X-ray images of at least 1000 × 1000 pixels at the frequency of Eu-XFEL pulses within a bunch train (2700 pulses at 4.5 MHz, followed by a 99.4 ms pause before the next bunch train), high dynamic range (single-photon sensitive to 10^4 photons per pixel and per frame at 12 keV) and sufficient radiation hardness (up to 1 GGy expected onto the most exposed pixels of the sensor within three years (Graafsma, 2009).

1.1. Concept

The AGIPD is based on hybrid pixel technology, *i.e.* a suitable pixellated Si sensor bump-bonded to the ASIC to enable separate optimization of sensor and in-pixel circuitry.

In order to enable measurements over a dynamic range spanning of the order of five decades from noise floor to maximum signal with a reasonable number of bits converted in the ADC, some form of switchable gain is unavoidable. As the intensity of illumination at any given pixel for many of the foreseen experiments cannot be anticipated, it is necessary for the system to automatically – per pixel and per frame – determine the suitable gain level to be used and record the illumination level accordingly.

For AGIPD, this automatically adjusting gain is implemented by means of switches and additional capacitors put in parallel to the capacitor of the charge-sensitive preamplifier (CSA) (see Fig. 1). A discriminator monitors the CSA output, and if a preset level is exceeded the control logic adds another (larger) capacitor to the CSA, reducing its gain. The settings of the switches controlling the addition of capacitors C2 and C3 are analogue-encoded in the pixel together with the CSA output voltage.

One of the challenges posed for detectors by the XFEL pulse structure is the necessity to retain images generated by as many of the up to 2700 pulses within a train as possible, whereas the 99 ms between pulse trains is the obvious time for reading out stored information. The AGIPD retains gain and CSA output value information in analogue memory within each pixel (see Fig. 2) and is capable of storing 352 frames. Fig. 3 shows the layout of one 200 µm × 200 µm AGIPD pixel. The majority of space within each pixel is taken up by the storage cells for 352 frames. The chip can accept external veto signals and overwrite information from vetoed images in specific memory cells with later, presumably good, images – enabling it to make use of up to the full pulse train of 2700 shots in situations where only a fraction of the X-ray pulses for example hits a target particle as determined by some fast auxilliary detection system.

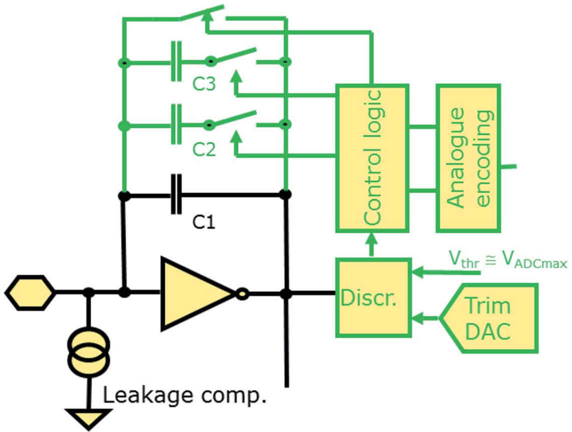


Figure 1
AGIPD dynamic gain implementation. Elements of a regular charge-sensitive amplifier are shown in black, the additions made to achieve dynamic gain switching over three gains are shown in green (for more details see Henrich *et al.*, 2011).

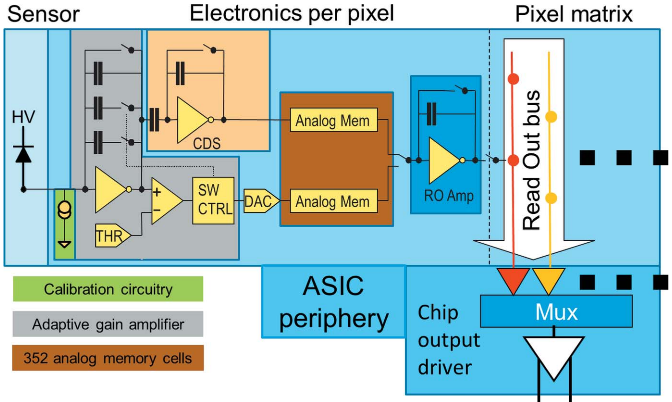


Figure 2
AGIPD readout schematic, showing the automatically gain-switching preamplifier, analogue storage cells for pixel value and gain, and readout scheme with multiplexers and off-chip ADCs (for more details see Becker *et al.*, 2012).

The AGIPD system to be delivered to the Eu-XFEL is a 1 Megapixel camera with moveable quadrants to give a central hole of variable size for passage of the direct FEL beam. Fig. 4 shows a CAD view of this camera. It consists of 16 modules (four per quadrant), each of which is made up of a single 500 µm-thick sensor bump-bonded to 2 × 8 ASICS of 64 × 64 pixels each – so one module has 128 × 512 pixels.

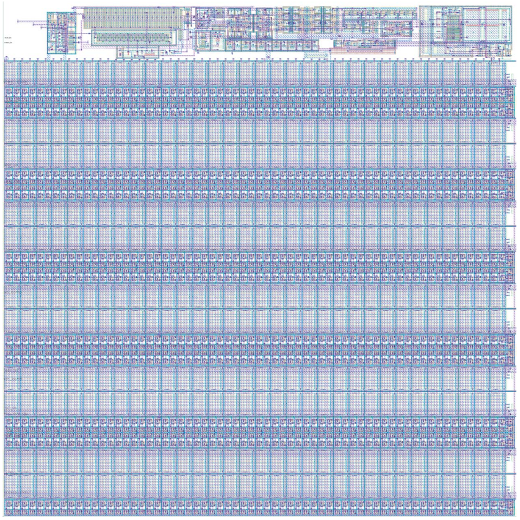


Figure 3
AGIPD1.0 pixel layout. Note that the bulk of the area is taken up by the 352-frame storage cells.

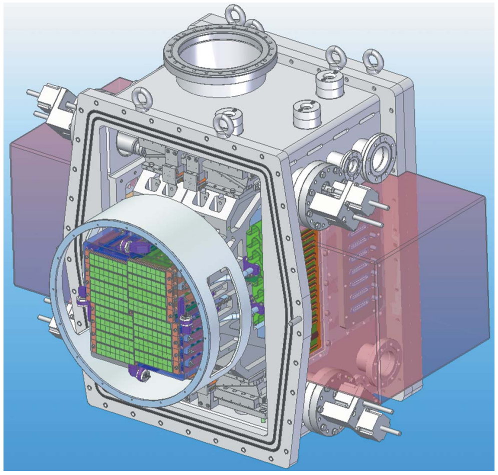


Figure 4
CAD view of the AGIPD megapixel camera for the Eu-XFEL.

1.2. Status and results

The AGIPD has gone through several prototype stages, most with 16 × 16 pixels of 200 μm pitch, before a first full-size chip (AGIPD1.0) with its 64 × 64 pixels of 200 μm pitch was taped out in 2013. Currently, single-module units based on the AGIPD1.0 chips (see Fig. 5) are undergoing tests including demonstrator experiments with X-rays both from a laboratory X-ray generator and from synchrotron beamlines.

The AGIPD1.0 achieves an equivalent noise charge level of less than 265 e$^-$ RMS at highest gain, with noise over the full dynamic range of the system remaining well below the Poisson limit for 12.4 keV photons. The linearity achieved in all three gains is better than 1.0% up to 5000 photons. From 5000 to 10000 photons the linearity is slightly worse than 1%. Depending on applied reference voltages, gain switching occurs at around 50–80 and around 1200 photons at 12.4 keV (Allahgholi *et al.*, 2015*a*).

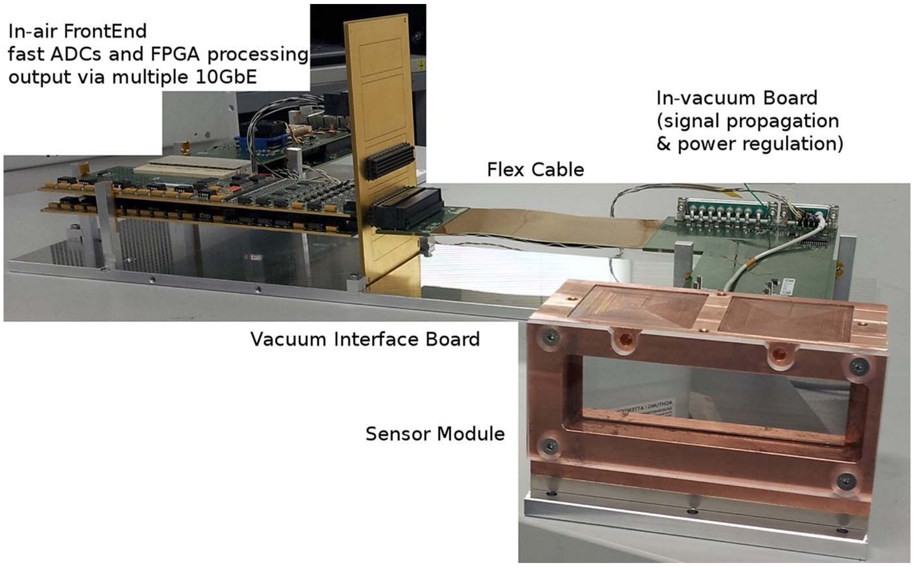


Figure 5
Photograph of the single-module AGIPD system currently undergoing testing including first beamline measurements. See Allahgholi *et al.* (2015*b*) for more details.

An earlier test performed with smaller prototypes already demonstrated the dynamic range, automatic gain switching and simultaneous single-photon sensitivity of the system at 7.05 keV: at the P10 beamline at Petra III, AGIPD imaged the direct unattenuated beam (see Fig. 6) while, only a few pixels to the side, simultaneously recording single-photon spectra (see Fig. 7) (Becker, Marras *et al.*, 2013).

Since then tests of the full AGIPD1.0-based module are ongoing with laboratory and synchrotron radiation sources. Fig. 8 shows the flat field- and dark field-corrected sum of 30000 X-ray images obtained at an integration time of 50 μs with an Mo $K\alpha$ source. Note that among the details of the pen drive electronics both its housing and the tape used for mounting the pen drive are visible. Recently, results of a measurement campaign at APS proving the capability of the AGIPD to perform single-bunch imaging at 6.5 MHz with single-photon sensitivity were presented at the iWoRID 2015 meeting (Allahgholi *et al.*, 2015*b*).

The first AGIPD megapixel camera will soon be assembled: delivery of first AGIPD 1 Megapixel system to beamline SPB at the Eu-XFEL is scheduled for the beginning of 2016. A second AGIPD 1 Megapixel system will follow and will be delivered to the MID beamline of Eu-XFEL in the summer of 2017.

2. PERCIVAL

The pixellated energy-resolving CMOS imager, versatile and large (PERCIVAL) is a DESY-led development project in collaboration with RAL/STFC, Elettra Sincrotrone Trieste, Diamond and Pohang Accelerator Laboratory (Wunderer *et al.*, 2014*b*). PERCIVAL was conceived to answer the need for FEL-suitable soft X-ray imagers, in particular to provide simultaneously a good efficiency and single-photon counting in the soft X-ray regime above $\sim$250 eV, high dynamic range (up to $\sim 10^5$ photons per pixel per frame), fast readout (120 Hz frame rate, commensurate with most FELs), in a multi-megapixel imager with small pixels (27 μm pitch) and minimal dead areas.

2.1. Concept

PERCIVAL is based on a monolithic active-pixel sensor (MAPS). This technology naturally enables small pixels with low capacitance and the inherent downside of the comparatively thin epilayers available in CMOS wafers is not as relevant at soft X-ray energies.

The PERCIVAL sensor will come in two sizes – a ‘2M’ version with 1408 × 1484 pixels on an $\sim$4 cm × 4 cm piece of

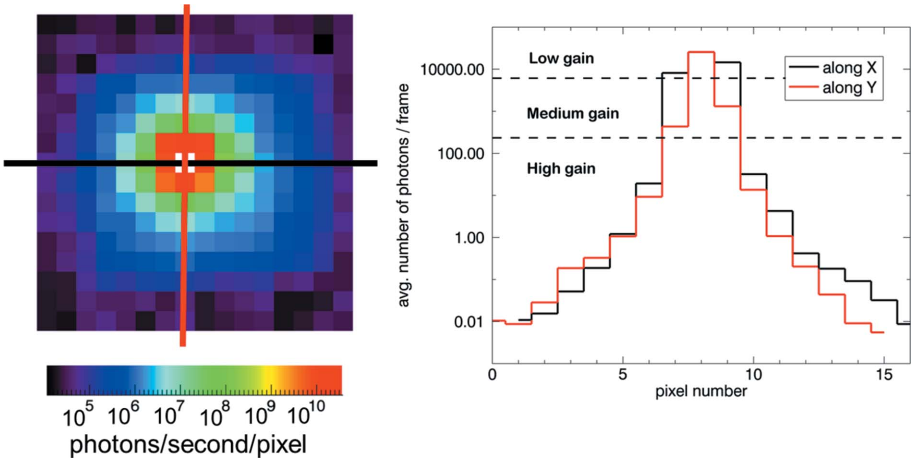


Figure 6
Image of the unattenuated direct beam of the P10 beamline (Petra III), recorded by an AGIPD prototype. [From Becker, Marras *et al.* (2013). Reproduced by permission of IOP Publishing. All rights reserved.]

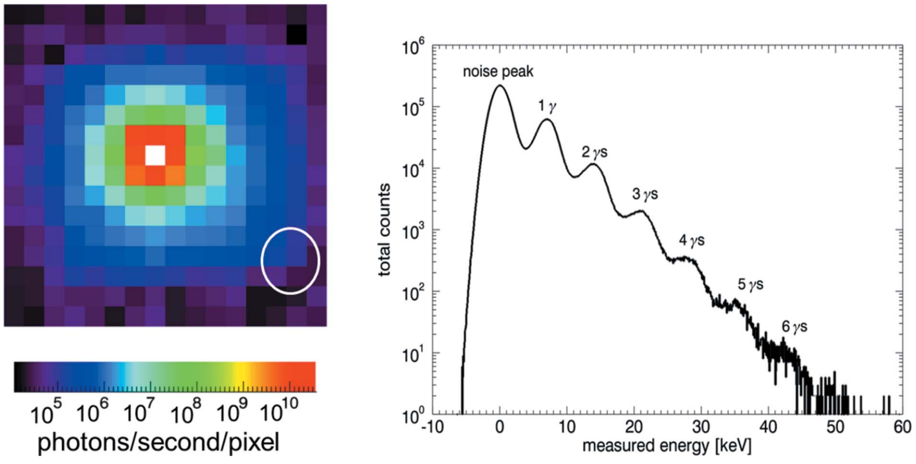


Figure 7
At the edge of the image of the unattenuated direct beam of the P10 beamline (Petra III) already shown in Fig. 6, only a handful of pixels from the central beam, summing data from only slightly illuminated pixels from a series of images reveals clear and distinct photon-counting peaks. [From Becker, Marras *et al.* (2013). Reproduced by permission of IOP Publishing. All rights reserved.]

Si, followed by a '13M' version with 3520 × 3710 pixels on a ~10 cm × 10 cm piece of Si.

Within each pixel, an annular partially pinned photodiode (PPPD; Lahav *et al.*, 2011) is connected to a series of three capacitances and switches. This architecture enables by-pixel on-demand gain switching by means of lateral overflow. The transistor gate is set at a moderate voltage (0.7 V). As the voltage on the diode (or higher-gain capacitor) approaches this value, the switch towards the larger capacitor (associated with the next-lower gain) opens. A fourth switch, set also for lateral overflow, acts as antiblooming protection. Fig. 9 shows the pixel schematic.

The signals from each pixel are converted by on-chip ADCs and sent out *via* 111 LVDS lines with ~480 MHz data rate (13M case). To achieve this, each column is viewed by seven ADCs (plus one spare) and groups of seven rows are read out simultaneously in a rolling shutter arrangement that is slightly modified to have all pixels ready to receive photons when the FEL pulse arrives. The signal from each pixel is converted to 12 ADC bits (plus one overrange bit) plus gain information (2 bits). In addition, the baseline reading for correlated double sampling (another 15 bits) is recorded before every new image. At the full operating speed of 120 Hz, the 13M sensor outputs ~50 Gbit s^{-1} data.

The PERCIVAL sensor was designed by RAL/STFC and fabricated in a commercial 180 nm CMOS process. In order to make high quantum efficiency and a uniform sensor response feasible at sub-keV energies, the sensor must be back-thinned and back-processed for back illumination. This BSI processing for PERCIVAL is

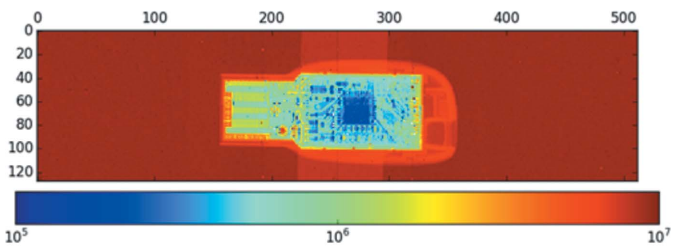


Figure 8
Flat field- and dark field-corrected sum of 30000 X-ray images of a memory stick obtained with the AGIPD1.0-based module at 50 µs integration time with an Mo *Kα* source. Note that among the details of the pen drive electronics both its housing and the tape used for mounting the pen drive are visible (for details see Allahgholi *et al.*, 2015*b*).

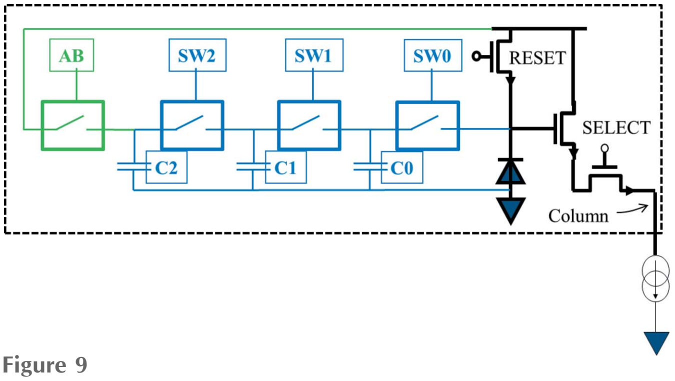


Figure 9
Schematic of the PERCIVAL CMOS sensor pixel. The basic 3T pixel elements are shown in black. Circuitry pertaining to the multiple-gain overflow is shown in blue and the antiblooming architecture is shown in green. See also Wunderer *et al.* (2014*a*) for a more detailed explanation.

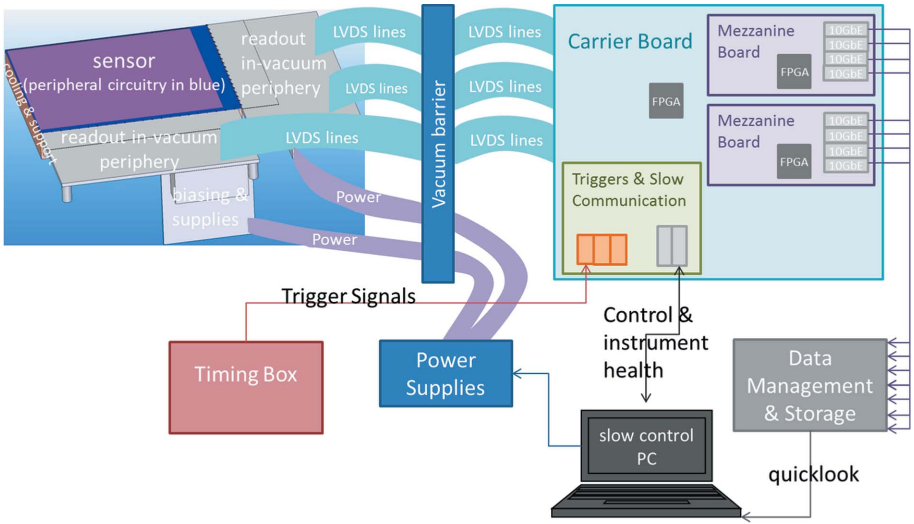


Figure 10
Block diagram of the PERCIVAL system [from Wunderer *et al.* (2014*b*)].

performed by the Jet Propulsion Laboratory using their delta-doping process (Jacquot *et al.*, 2012).

Turning this intricate monolithic piece of silicon into a working detection system requires a complex periphery – in terms of power supplies and biases, finite state machine (FSM) control, handling the large data volume (50 Gbit s^{-1} for one 13M sensor), and mechanical and thermal interfaces. For soft X-rays, in-vacuum operation is mandatory, adding to the challenges. Fig. 10 gives an overview of the PERCIVAL system.

The collaborating partners DESY, Elettra Sincrotrone Trieste, Diamond, and Pohang Accelerator Laboratory share this effort, with DESY leading the in-vacuum electronics development of the immediate sensor vicinity including power and bias provision, mechanics and thermal design, and providing data handling FPGA boards with 4 × 10 GbE stream-out capability that are shared between multiple DESY developments (Zimmer & Sheviakov, 2012), Elettra Sincrotrone Trieste taking the lead for the carrier board and FSM development including early control software, Diamond leading the effort on data receiving and handling and Pohang Accelerator Laboratory joining the control, calibration and testing efforts.

2.2. Status and results

Currently, small sensor prototypes (33600 pixels of 25 µm pitch, covering 5.25 mm × 4 mm active area on an overall 1.2 cm × 0.6 cm chip) are undergoing testing in the laboratory with optical photons and 5.9 keV radiation from ^{55}Fe, as well as at soft X-ray beamlines. Fig. 11 shows a test chip wire-bonded to its carrier PCB, and Fig. 12 shows the vacuum chamber used for testing these small prototypes.

First pixel prototypes were available with BSI processing in early 2014. They demonstrated a soft X-ray response to 350 eV in some of the pixel types investigated (Wunderer *et al.*, 2015).

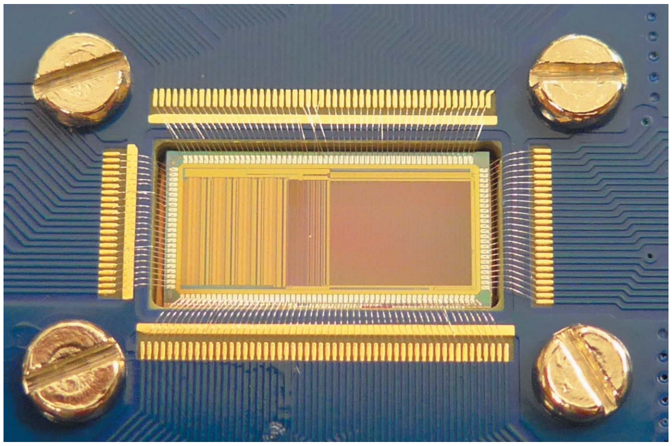
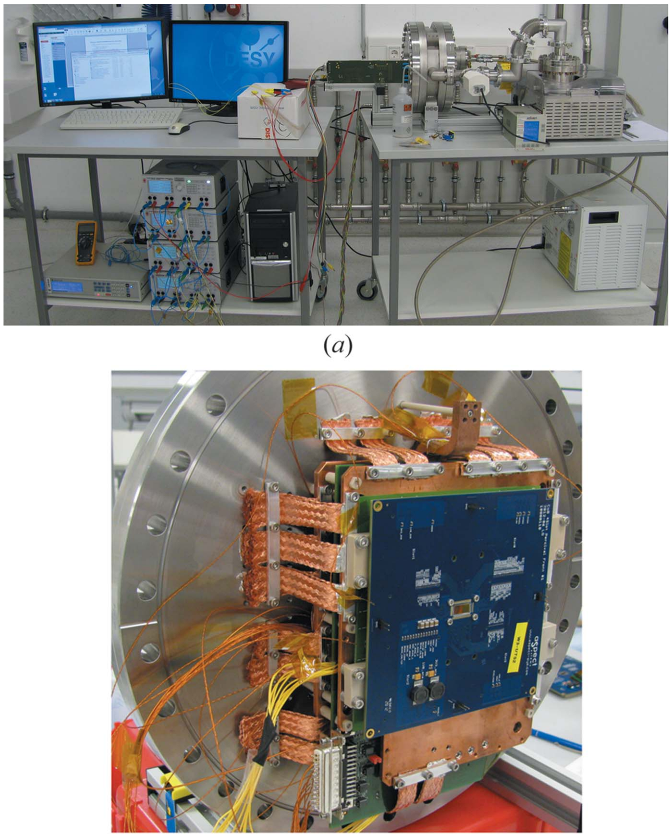


Figure 11
Photograph of a PERCIVAL prototype sensor, wire-bonded to its chip on board (CoB) PCB support. Usage of the CoBs with their standard connection interfaces enables easy switching between sensors, as well as easy exchange of sensors between different laboratories and test environments.


(*a*)

(*b*)

Figure 12
(*a*) The PERCIVAL test chamber on a tabletop, with associated control PC, voltage supplies, cooling and pump. (*b*) A view onto the chamber flange holding the power and bias periphery board and the sensor with cooling infrastructure in-vacuum inside the vessel.

However, efficiency and charge collection were lower than anticipated and in some pixel types predominantly higher-energy photons from harmonics were recorded. One possible explanation for this is an inadvertent introduction of contaminants during BSI processing of the wafer.

Since then, another wafer – from the same batch as the first BSI-processed wafer yielding the chip used in the 2014 beam time – has been BSI processed, and in the first soft X-ray tests performed at 400 eV on beamline I10 at Diamond a much higher efficiency and a significantly more uniform response was shown.

When a photon beam falls through a pinhole, diffraction patterns – circularly symmetric rings called Airy rings – are generated. The spatial frequency of these rings depends on the photon energy, the pinhole size and the distance from the pinhole. For a known pinhole size and pinhole–detector distance, the Airy pattern can be used as a measure of the photon energy.

The Airy patterns recorded with the first BSI prototype in 2014 clearly showed different spatial frequencies of the Airy pattern dominating in different areas of the test chip – corresponding to different pixel types. We concluded from this that some pixel types were predominantly responding to higher harmonics in the beam [see Wunderer *et al.* (2015) for images and a more detailed description of results].

Fig. 13 shows an Airy ring image recorded during March 2015 at I10 beamline (Diamond) with 400 eV photons. The pattern recorded is commensurate with the primary beam energy and fits to the recorded Airy pattern have not revealed any significant residuals. The pattern, shown in the image in units of measured electrons, is nicely continuous over pixel-type boundaries, indicating little or no difference in overall response between pixel types. Additional results from this beam time are discussed by Correa *et al.* (2015).

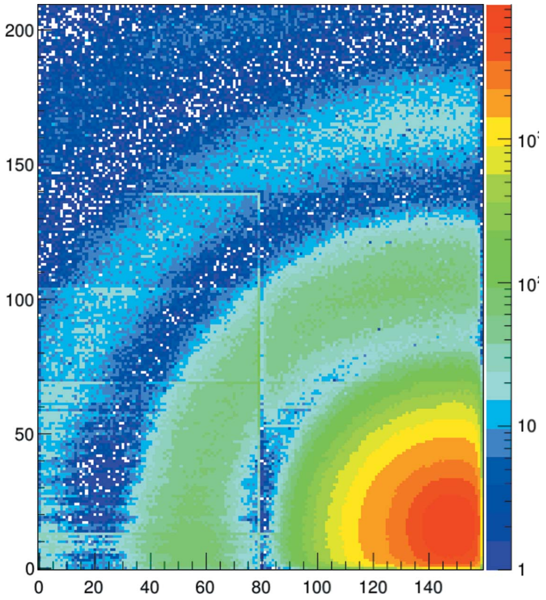


Figure 13
Airy ring pattern recorded with a PERCIVAL BSI prototype chip at the I10 beamline (Diamond) with 400 eV photons impinging on a 5 µm pinhole located ~2.7 m from the detector. The spatial frequency of the pattern is commensurate with the primary beam energy, and the response appears uniform across pixel types. See Correa *et al.*, (2015) for more details.

At the time of writing of this article, a new prototype chip TS1.2 with improved ADC design and additional gain stage for lower noise in the few-photon regime, implementation of a change in capacitor design following leakage currents observed at lower gains in the first generation of test chips, and variations on the PPPD ring sizing in combination with the multi-gain capacitor architecture just became available for testing. Assuming the results from this prototype in front-side illuminated configuration, together with yet-outstanding tests and analysis from the BSI-prototype (TS1.0) results, prove satisfactory, the design for a first incarnation of a larger (2M, ~4 cm × 4 cm) sensor could be submitted to the foundry as early as the end of 2015 – and a first BSI version suitable for soft X-ray evaluation of this sensor might be available towards the end of 2016.

3. Other FEL-relevant developments

This paper focuses on a summary of the development efforts for two-dimensional detection systems suitable for FELs that are spearheaded from within the group. A third two-dimensional imager development relevant to FELs in which the DESY Photon Science Detector Group is involved is the development of the DSSC detector for XFEL. This is a hybrid detector with hexagonal ~200 µm pixels optimized for photon energies of 0.5–6 keV consisting of a dedicated ASIC bump-bonded to either a mini-SDD or DEPFET sensor, capable of recording up to 800 frames per Eu-XFEL bunch. Similar to AGIPD, individual images can be vetoed and overwritten. Details are given by Porro *et al.* (2012).

4. Summary and outlook

The Photon Science Detector Group at DESY is spearheading developments for X-ray and soft X-ray FEL-suitable area detectors. AGIPD is geared for the Eu-XFEL. This project is well advanced, a first megapixel camera is to be delivered to SPB beamline at Eu-XFEL in early 2016. The soft X-ray project PERCIVAL is still in a prototype stage. Results from existing prototypes are mostly promising, and the new prototype TS1.2 sensors are ready for testing. Provided results from their tests are satisfactory, first larger PERCIVAL sensors of 2 Megapixels might be ready for soft X-ray testing towards the end of 2016. The larger 13M monolithic 10 cm × 10 cm PERCIVAL sensor could then be ready for first tests in 2017.

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