AGIPD: A multi Megapixel, multi Megahertz X-Ray Camera for the European XFEL

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ABSTRACT

AGIPD is a hybrid pixel detector developed by DESY, PSI, and the Universities of Bonn and Hamburg. It is targeted for use at the European XFEL, a source with unique properties: a train of up to 2700 pulses is repeated at 10 Hz rate. The pulses inside a train are $\leq$ 100 fs long and separated by 220 ns, containing up to 10^{12} photons of 12.4 keV each. The readout ASICs with 64×64 pixels each have to cope with these properties: Single photon sensitivity and a dynamic range up to $> 10^4$ photons/pixel in the same image as well as storage for as many as possible images of a pulse train for delayed readout, prior to the next train. The high impinging photon flux also requires a very radiation hard design of sensor and ASIC, which uses 130 nm CMOS technology and radiation tolerant techniques. The signal path inside a pixel of the ASIC consists of a charge sensitive preamplifier with 3 individual gains, adaptively selected by a subsequent discriminator. The preamp also feeds to a correlated double sampling stage, which writes to an analogue memory to record 352 frames. It is random-access, so it can be used most efficiently by overwriting bad or empty images. Encoded gain information is stored to a similar memory. Readout of these memories is via a common charge sensitive amplifier in each pixel, and multiplexers on four differential ports. Operation of the ASIC is controlled via a command interface, using 3 LVDS lines. It also serves to configure the chip's operational parameters and timings.

Keywords: AGIPD; Hybrid Pixel Detector; Photon Science; Free Electron Laser

1. INTRODUCTION

With the increased brilliance of state-of-the-art synchrotron radiation sources (fig. 1a) and the advent of Free Electron Lasers (FELs) enabling revolutionary science with X-ray photons, comes an urgent need for suitable photon imaging detectors. Requirements include high frame rates, very large dynamic range, single-photon resolution capability with a low probability of false positives, and (multi)-megapixels of spatial resolution.

Here we present AGIPD[a], a state-of-the-art detector system, tailored to the characteristics of the European XFEL,[b(2,3)] which features a quite complicated time structure: Trains of 2700 pulses spaced by 220 ns repeat at a rate of 10 Hz (fig. 1b). Each of these pulses can contain up to 10^{12} photons of 12.4 keV within a width of $\leq$ 100 fs. To exploit the scientific potential of this source, the detector has to provide a dynamic range of up to 10^4 photons/pixel while still being sensitive to single photons - in the same image.

2. AGIPD - ADAPTIVE GAIN INTEGRATING PIXEL DETECTOR

AGIPD[(1)] is a hybrid pixel detector, developed by DESY, the Paul-Scherrer-Institute and the Universities of Bonn and Hamburg to meet the requirements for the use at the European XFEL. It consists of 500 µm thick sensors to provide a high efficiency up to 12.4 keV photon energy. Each sensor features 512×128 pixels, which are 200 µm $\times$ 200 µm in size. 8×2 AGIPD ASICs are bump-bonded to each sensor for the readout. Larger detector systems of 1- or 4-megapixels are composed by tiling these sensors. The high photon flux together with single photon sensitivity require the detector to operate in vacuum, in order to prevent the intense beam from interacting with ambient air or exit windows, which would cause a huge background. In turn a vacuum vessel is an integral part of the AGIPD 1-megapixel detectors, housing four movable quadrants of four sensors each. These can be arranged to form a hole for the direct beam to prevent it from hitting

ulrich.trunk@desy.de [a] Adaptive Gain Integrating Pixel Detector [b] European X-Ray Free Electron laser - EuXFEL

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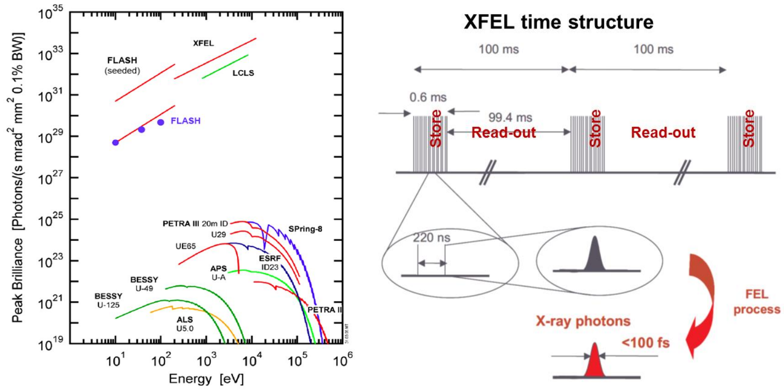

Figure 1: a) Brilliance of FELs and Synchrotron sources. (left)
b) Time structure of the European XFEL source. (right)

detector components and inflicting damage to the system. The intense beam and the experiments envisioned also require a huge dynamic range, which can reach 10^4 photons/pixel/image at 12.4 keV. To cope with this, AGIPD adaptively lowers the sensitivity of the preamplifiers, independently for each pixel in two steps. Furthermore the system has to comply with the rather inconvenient time structure of the European XFEL. Since it is not possible to read out an image within 220 ns, the detector has to record as many images as possible during a pulse train and read these out during the 99.4 ms gap in-between the trains.

3. THE AGIPD ASIC

The AGIPD 1.0 ASIC[4,5] incorporates 64×64 pixels together with the necessary readout and control circuitry and is manufactured in 130 nm CMOS technology, using radiation hardened layout techniques in most parts of the circuit. Figure 2 shows a schematic diagram of the ASIC, while fig. 3a shows the layout.

The input of each pixel is formed by a resettable charge sensitive preamplifier, built around an inverter core. Its output feeds a discriminator and a correlated double-sampling (CDS) stage. The latter is used to remove reset switches' noise from the signal and to suppress low frequency noise components.[6] The discriminator is used to add additional feedback capacitors to the preamplifier, if its output exceeds a defined amplitude. This way the sensitivity of the preamplifier is adaptively decreased and the dynamic range is extended in two steps.[7]

The output of the CDS and a voltage encoding the gain are simultaneously written to a capacitor (200 fF for the amplitude and 30 fF for the gain setting) matrix at ≥ 4.5 MHz, serving as an image memory.[8] The memory occupies about 80% of the pixel area (fig. 3b) and can store up to 352 images, which was chosen as a compromise between pixel size, analogue performance and memory depth. It can be randomly accessed, providing the option for overwriting images or a frame selective readout. At the EuXFEL it is used to implement a veto system.

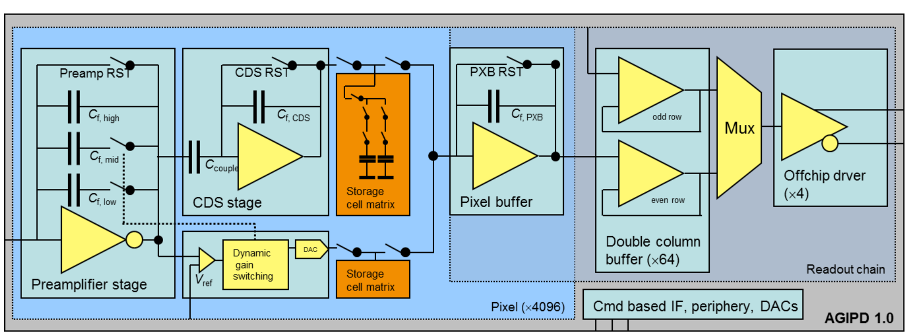

Figure 2: Circuit schematic of the AGIPD 1.0 ASIC.

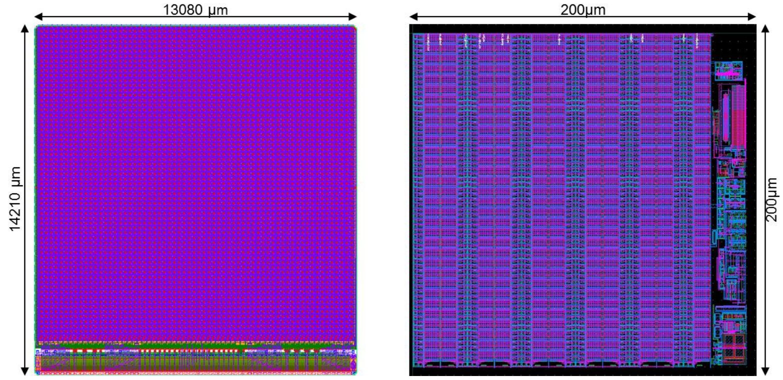

Figure 3: a) Layout of the AGIPD 1.0 ASIC. The size is 13.08mm × 14.21mm. (left)
b) Pixel layout of the AGIPD 1.0 ASIC. About 80% of the area is occupied by the frame memory, the active circuitry is contained only in the vertical 'stripe' on the right hand side. (right)

A second charge sensitive amplifier in each pixel is used to readout the memory – operated in parallel for each row of pixels. The further readout path is via interleaved dual column buses and four multiplexers. In an interleaved schema[(9)] data of one memory address is read for one pixel row, while that of the previous row is serialised within the same command cycle. The outputs of the four multiplexers are hooked up to an instrumentation amplifier type off-chip drivers each, providing four differential analogue outputs per chip. The gain information is read out via the same path as a second set of images.

A command based control circuit provides all the signals for memory access, read and write operation to the pixels. It uses a 3-line serial interface and also provides slow control tasks, like the programming of internal timings, and on-chip DAC[c] generated biases, as well as pixel-selective test signals. These provide access to all 3 gains and are fed to the preamplifier inputs via a pulsed capacitor or a current source in each pixel.

4. READOUT PATH

The 64 analogue signals from one sensor module are brought outside the detectors vacuum vessel via the *vacuum board*, a PCB[d] with a flexible section to compensate for the motion of the quadrants, and a vacuum flange formed by another PCB. Outside the vacuum vessel PCBs with receiver amplifiers and ADCs provide digitisation of the data with 14 bit quantisation. This data is then collected by an FPGA[e] and sent on via an 10 GB ethernet link per module to the so-called *train builder*, which combines the data of individual modules to full frames and passes them on to storage.

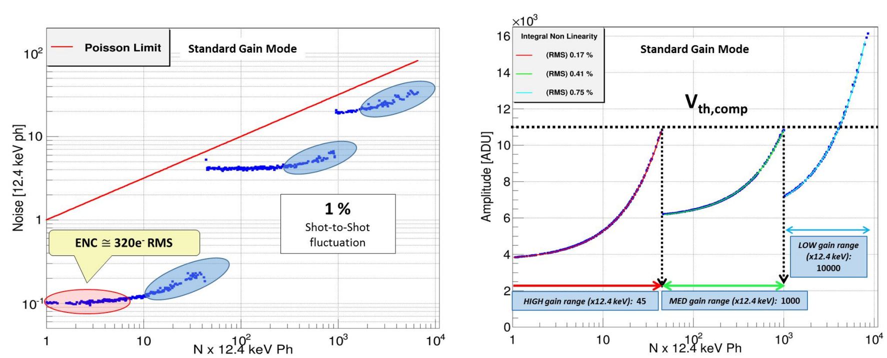

Figure 4: a) Noise performance of AGIPD 1.0. An IR laser was used to access the different gains. Fluctuations of this stimulus add an amplitude-dependent contribution to the measured ENC. (left)
b) Transfer characteristics of AGIPD 1.0. (right)

[c] Digital to Analogue Converter [d] Printed Circuit Board [e] Field-Programmable Gate Array

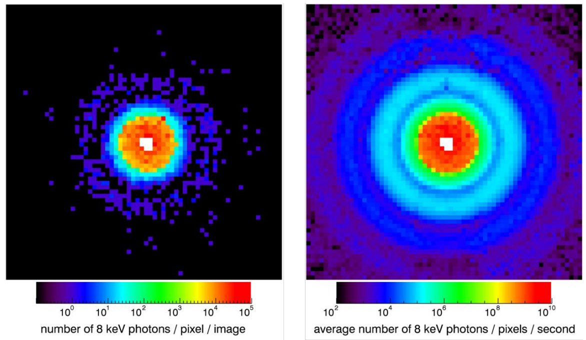

Figure 5: a) Single shot image from a colloidal sample at PETRA P11. It covers a dynamic range from single photons (blue) to $> 10^5$ photons in the direct beam. (left)
b) Sum of 1000 images from a colloidal sample at PETRA P11. Diffraction rings are clearly visible and the low Q-range not accessible with other detectors is resolved. (right)
The logarithmic scale should be taken into account when comparing these graphs to other results.

5. DYNAMIC RANGE AND NOISE PERFORMANCE

The AGIPD 1.0 ASIC has been thoroughly characterised electrically and with a sensor. Since the medium and low gain settings are not accessible with lab X-Ray sources, an IR laser has been used for characterisation. This way an ENC[f] of $\approx 320\mathrm{e}^-$ was achieved[g], as fig. 4a shows. This value corresponds to a signal to noise ratio of 12σ for a single 12.4 keV photon in the high gain. Fig. 4a furthermore shows, that the noise in the lower gains is always less than the limit imposed by the Poisson statistics of the impinging photons.
The dynamic range was measured up to $344 \times 10^6\mathrm{e}^-$ or 10^4 photons of 12.4 keV, as fig. 4b shows. The linear fits in fig. 4b also confirm a nonlinearity of better than 0.44% up to 5×10^3 photons of 12.4 keV.

6. FIRST EXPERIMENTS WITH AGIPD

6.1 Beamline tests at PETRA III

Diffraction images of a colloidal sample were recorded at PETRA III beamline P11. Aim of this experiment was to show AGIPD's capability to provide images covering the full dynamic range. For that purpose single images were recorded synchronous to the source. Fig. 5a shows a single shot image. The absence of photons is encoded as black colour on the logarithmic scale. Each image contains pixels in all three gain stages simultaneously. Note that no beam stop was used and besides the scattering pattern the direct synchrotron beam was recorded. Imaging the direct beam provides access to

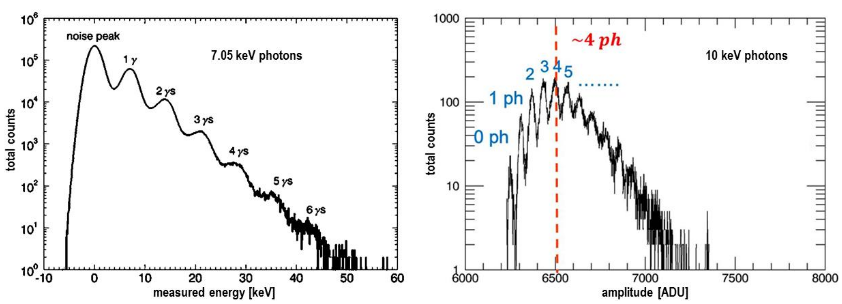

Figure 6: Amplitude spectra of a single AGIPD pixel:
a) at 7.05 keV. The imperfect separation of the photon peaks is due to charge sharing between pixels (left).
b) at 10 keV from the monochromatic beam at APS' 1-BM.

[f] Equivalent Noise Charge [g] Sacrificing dynamic range by selecting the high gain of the CDS, ENC $\approx 240\,\mathrm{e}^-$ can be reached.

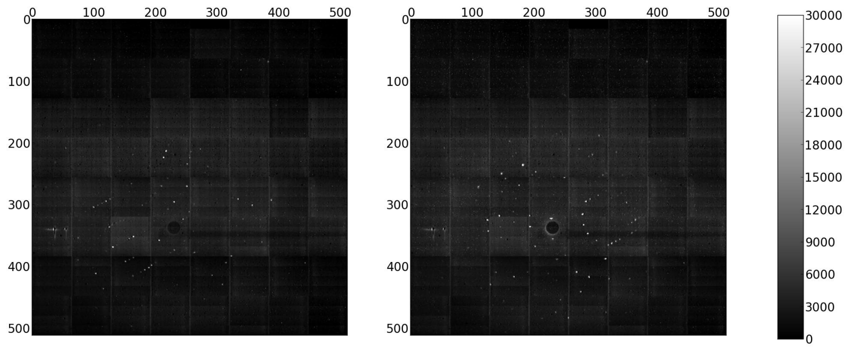

Figure 7: Diffraction patterns of a Lysozyme crystal at different orientations. Except for pedestal subtraction to remove fixed pattern noise, no further processing was applied to the data of a *'Quadrant'* (four module) system.

very small angles not accessible with conventional detectors. The experiment furthermore confirmed the radiation hard designs of sensor and readout ASIC. Fig. 5b shows the time average with a clear ring structure. It also contains the direct beam to explore the beam profile and the low-Q region not accessible with other detectors.
Fig. 6[(10)] shows the histogram of the data from a single pixel, recorded with the AGIPD 0.4 prototype at PETRA III beamline P10. The goal of this experiment was to demonstrate the single photon resolution capability of the detector. Single images were recorded synchronous to the source. The average intensity was 0.3 photons per 200 ns, corresponding to a count rate of 1.5 Mcps/pixel or 37.5 $\mathrm{Mcps/mm^2}$. The RMS noise of this pixel is 320 electrons at 5.2 MHz and the peaks of individual photons are clearly visible, but not perfectly separated due to charge sharing with neighbouring pixels.[(10)] Charge sharing is an intrinsic feature of all pixelated semiconductor detectors. On the contrary to photon counting detectors, this feature can be used in advantage in charge integrating detectors: The centre of gravity of the impinging photons can be calculated, resulting in a sub-pixel spatial resolution.

6.2 Protein Crystallography at PETRA III P11

Diffraction patterns from rotating Trypsin and Lysozyme crystals were recorded at 12.4 keV photon energy. The experiment was performed at PETRA beamline P11 in collaboration with EMBL[h]. Data was recorded in burst mode, acquiring 352 images before readout to resemble the conditions at the European XFEL as close as possible. The images in fig. 7 show diffraction patterns from a Lysozyme crystal at two different angles. Different patterns of Bragg spots are clearly visible. The images are the sum of the 352 frames of a burst and unprocessed except for a pedestal subtraction to remove fixed pattern noise.

6.3 Single bunch imaging at 6.5 MHz repetition rate at beam line 1-BM at APS

At APS' beamline 1-BM a rotating disc with equidistant holes was imaged synchronous to the 6.5 MHz bunch clock of the source. This is an attempt to image changes within a burst of 352 images, i.e. on the time scale of ≈ 150 ns. Within the recorded bursts of 352 consecutive bunches a translation of the holes by ≈ 8 pixels was observed (fig. 8). From this result the speed of the disc was calculated to be $V_{\mathrm{disc}_{\mathrm{AGIPD}}} = \frac{n_{\mathrm{pixel}} \cdot x_{\mathrm{pixel}}}{n_{\mathrm{frames}}} \cdot f_{\mathrm{frame}} = \frac{8 \cdot 200\,\mu\mathrm{m}}{352} \cdot 6.5\,\mathrm{MHz} = 29.54\,\mathrm{m/s}$ This was in very good agreement with $V_{\mathrm{disc}_{\mathrm{laser}}} = 29.83\,\mathrm{m/s}$ the speed of the disc measured with a photoelectric barrier.

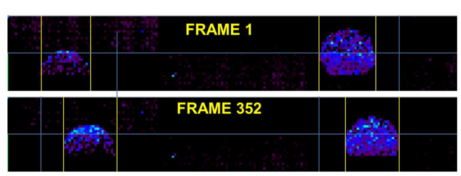

Figure 8: First and last image of a burst recorded at 6.5 MHz frame rate. The translation of the holes is about 8 pixels.

[h] European Molecular Biology Laboratory

6.4 Single photon sensitivity at 6.5 MHz repetition rate

Also at APS' beamline 1-BM single pixel spectra were recorded at 10 keV photon energy at 6.5 MHz rate. In fig. 6 peaks for integral photon counts are clearly visible. Due to the high average flux of $\approx 4\,\text{photons/frame/pixel}$, the 0 photon peak (baseline) had to be artificially increased by also recording dark images to provide a reference.

7. AGIPD 1.1

An improved version of the AGIPD readout ASIC has been received in March 2016 as a dedicated engineering run. It improves AGIPD in several aspects:

- *Faster readout speed* (33 MHz) due to reduced parasitics of the lines to the off-chip driver.
- *Less crosstalk inside the pixel* by a reduced coupling of the memory access lines to sensitive nodes, resulting in a more homogeneous memory map.
- *Removal of crosstalk between analogue outputs* by buffers for the reference voltage of each off-chip driver
- *Easier calibration* due to improved calibration circuits and less crosstalk
- *Minor other improvements*, e.g. gain encoding in fixed gain mode
- *Improved power distribution and additional filter caps* for the power supply networks

8. SUMMARY

The adaptive gain approach and burst mode imaging was tested and found working very nicely on single chips, 2×8 chip modules and multi-module systems. The high dynamic range of AGIPD allows for direct imaging of a synchrotron beam simultaneous with single photon sensitivity. The system shows good linearity in all the dynamic range and noise below the Poisson limit. The system can operate at frame rates even higher than those of the European XFEL, which was successfully tested during beamtimes at the PETRA III and APS synchrotron sources. Its performance and characteristics make AGIPD a useful imaging tool for the European XFEL, as many requests for scientific experiments already with prototypes indicate. The revised version of the ASIC, AGIPD 1.1, removed minor annoyances and greatly eases calibration requirements. The delivery of the first 1 Mpix system to the SPB[i] beamline at EuXFEL is scheduled for Dec. 2016. In addition the MID[j] and SFX[k] endstations at EuXFEL are to be equipped with 1 Mpix and 4 Mpix systems respectively in the subsequent years.

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[i] Single Particles, clusters, and Biomolecules [j] Materials Imaging and Dynamics [k] Serial Femtosecond Crystallography