

AGIPD – The Adaptive Gain Integrating Pixel Detector for the European XFEL.

Development and Status

J. Becker, P. Göttlicher, H. Graafsma, H. Hirsemann, S. Jack, A. Klyuev, S. Lange A. Marras, B. Nilsson, F. Tian*, U. Trunk (DESY, Hamburg, Germany)
 R. Klanner, J. Schwandt, J. Zhang (University of Hamburg, Germany)
 R. Dinapoli, D. Greiffenberg, B. Henrich, A. Mozzanica, B. Schmitt, X. Shi (PSI, Villigen, Switzerland)
 M. Gronewald, M. Karagounis, H. Krüger (University of Bonn, Germany)

Abstract—The European XFEL [1] will provide fully coherent, 100 fs X-ray pulses, with up to 10^{12} photons at 12 keV. The high intensity per pulse will allow recording diffraction patterns of single particles or small crystals in a single shot. Consequently 2D-detectors have to cope with a large dynamic range: detection from single photon to $> 10^4$ photons/pixel in the same image. An additional challenge is the European XFEL machine: an Electron bunch train with 10 Hz repetition rate, consisting of up to 2,700 bunches with a 220 ns spacing. Recorded images have to be stored inside the pixel during the bunch trains and readout in between. To meet these requirements, the European XFEL has launched 3 detector development projects.

The AGIPD project is a collaboration between DESY, PSI and the Universities of Bonn and Hamburg. The goal is a 1024×1024 pixel detector, with 200 μm pixel size and a central hole for the primary beam. The ASIC operates in charge integration mode: the output of each pixels preamplifier is proportional to the charge from the sensor generated by the X-rays. The input stage of the pixel cells uses dynamically adjustable gains. The output signal is stored in an analogue memory, which has to be a compromise between noise performance and the number of images. This is operated in random access mode, providing means to overwrite bad frames for optimal use of the 352 memory cells per pixel, which have to be readout and digitized in the 99.4 ms bunch gap. The detector will be built of 8×2 fully depleted monolithic silicon sensors with a 8×2 array of CMOS readout chips bump-bonded to these. Several prototypes of the readout ASIC have been produced. The results presented originate from the 16×16 pixel matrices AGIPD 0.2, which was bump-bonded to a pixel sensor, and AGIPD 0.3, which includes the intended control algorithm and a fast differential interface to the off-chip world.

Index Terms—XFEL, 2D detector, Hybrid Pixel Detector.

I. THE EUROPEAN XFEL

THE European X-Ray Free Electron Laser (XFEL) under construction in Hamburg will provide fully coherent, < 100 fs long X-ray pulses, with up to 10^{12} photons at 12 keV. The high intensity per pulse will allow recording diffraction patterns of single macromolecules or small crystals in a single shot. As a consequence the 2D detectors have to cope with

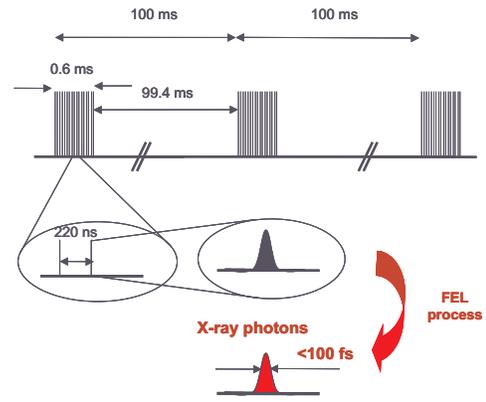


Fig. 1. Time structure of the European XFEL

a large dynamic range in the images, ranging from a single photon to $> 10^4$ photons/pixel. An additional challenge is the European XFEL time structure (c.f. fig. 1): an electron bunch train with 10 Hz repetition rate, consisting of up to 2,700 bunches with a 220 ns spacing. Thus the recorded images have to be stored for every pixel during the bunch trains and read out between bunch trains. AGIPD is one of 3 detector development projects supported by the European XFEL to cope with these requirements.

II. THE AGIPD DETECTOR

AGIPD [2] [3] [6] is a flat $1\text{k} \times 1\text{k}$ hybrid pixel detector featuring a pitch of 200 μm , composed of 2×8 sensor modules of $512 \times 128 = 65536$ pixels. The surface of each sensor is $102.6 \times 25.8 \text{ mm}^2$ and does not have any gaps or other dead area. The sensors are bump-bonded to 2×8 readout ASICs to form a module. Four of these modules are mounted to a cooling plate to form a quadrant. The four quadrants are attached to a vacuum flange and are shifted with respect to each other to form a hole for the very intense direct beam to pass (c.f. fig. 2). A beam stop in front of the detector or a gas-filled flight tube would cause a background exceeding the actual signal by several orders of magnitude.

* now at Infineon technologies, Munich, Germany

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U. Trunk is with Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany. e-mail: ulrich.trunk@desy.de.

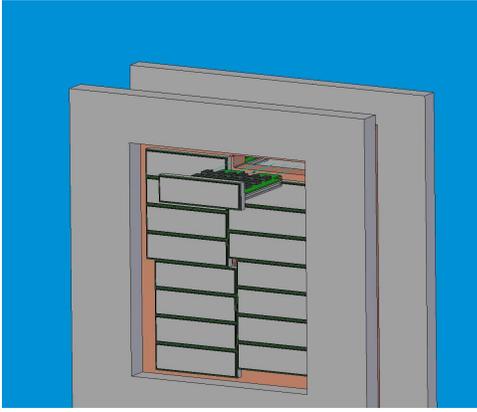


Fig. 2. Sketch of the mechanical layout of the AGIPD detector.

III. XFEL DETECTOR DESIGN CHALLENGES

Time structure of the photon signals calls for a pipelined architecture: recording 2,700 frames of a bunch train at a rate of 4.5 Mhz and the delayed readout of this data from a detector within the 99.4 ms bunch gap in an ideal case. However, the integration density of current CMOS technologies, the required sensitivity to single photons and the expected radiation dose, together with the chosen pixel size of $200\mu\text{m} \times 200\mu\text{m}$ limit the storage depth of an analogue memory to 352 images, i.e. 352 samples per pixel. To optimise the use of this limited storage depth, the memory is operated in random access mode. This way empty or bad images (i.e. when the X-ray pulse did not hit the target in case of single molecule imaging) can be overwritten with meaningful data, when this information becomes available from diagnostic detectors (e.g. registering fluorescent light) microseconds later.

Also the large dynamic range of the expected signals is very demanding: while single photons of 12 keV have to be detected with sufficient noise margin, the highest expected signals are up to 2×10^4 photons per pixel in the same image. To provide this dynamic range with a sufficient S/N ratio, the sensitivity of the preamplifier is dynamically adapted to the incoming signal.

Such high signals also provide a challenge for the sensor itself, since 10^5 photons in $10\mu\text{m} \times 10\mu\text{m}$ will create $10^5 \times 12 \cdot 10^3 / 3.6 = 3 \times 10^8$ electron-hole pairs at 12 keV. The high charge carrier density will effectively shield the field inside the sensor. The charge cloud has to spread in space (and time) allow the depletion field to become dominant again for charge collection. Results of the extensive studies on this subject for the development of AGIPD are published in [8].

These high intensities will also result in a substantial accumulated dose: over three years the example above would result in 1 GGy impinging the sensor, while the ASIC underneath would still accumulate about 100 MGy. Thus investigations on radiation damage on sensors [9] and on the radiation hardness of the electronics are performed. Despite the use of radiation hard layout techniques, many circuit components, especially the capacitors and switches (FETs) of the analogue memory, are deemed critical.

IV. AGIPD ASIC ARCHITECTURE

Each readout chip contains a square matrix of 64×64 pixels, read out on four ports. Each pixel contains

- a charge sensitive preamplifier
- a discriminator
- the switch control circuit and a DAC to encode the switch settings
- a CDS¹ buffer
- analogue memory of 2×352 cells
- a charge sensitive readout buffer,

as fig. 3 shows.

The output of the charge sensitive preamplifier not only connects to the CDS buffer, but also to a discriminator. If an input signal triggers this discriminator, additional feedback capacitors are added to the preamplifier feedback, thus lowering sensitivity and increasing the dynamic range in two steps. The output of the CDS buffer and an analogue encoding of the selected gain are written to the analogue memory, which can store 352 samples.

The signals for the operation of the pixel and the addressing of the memory are generated by a command based serial interface.

V. AGIPD ASIC DEVELOPMENT

For the development of the AGIPD readout ASIC, several prototypes and test chips have been produced. In addition to the readout chips listed in tab. I, two chips, HPAD 0.1 and HPAD 0.2, have been manufactured to evaluate the radiation hardness of the chosen 130 nm CMOS technology and its components.

VI. COMMAND-BASED INTERFACE

The command based interface uses three lines: clock, data and *start of bunch*. The latter triggers the interpretation of a command, i.e. its execution. Thus it also provides the synchronisation with the European XFEL's 4.5 MHz bunch timing. Since the command length is 13 bits, the clock signal has to be at least 94.1 MHz to accomplish the readout of $352 \times 2 \times 16 \times 64$ samples within 99.4 ms. This signal also serves as an internal timing reference, i.e. determines the granularity of all internal signals, since these are derived from it by means of a programmable sequencer, as shown in fig. 4. The implementation of the interface on AGIPD 0.3 implements 6 commands:

- Capture frame (argument: memory address)
- Set memory address (argument: memory address), it can also serve as a NOP command
- Program a status register (arguments: register number, register bits)
- Program internal timings (arguments: function, time in clock cycles)
- Program on-chip DACs (arguments: DAC register, value)
- Read pixel (arguments: memory increment bit, pixel address)

¹correlated double sampling – Samples are only correlated for the highest sensitivity. The correlation is broken if gain switching occurs.

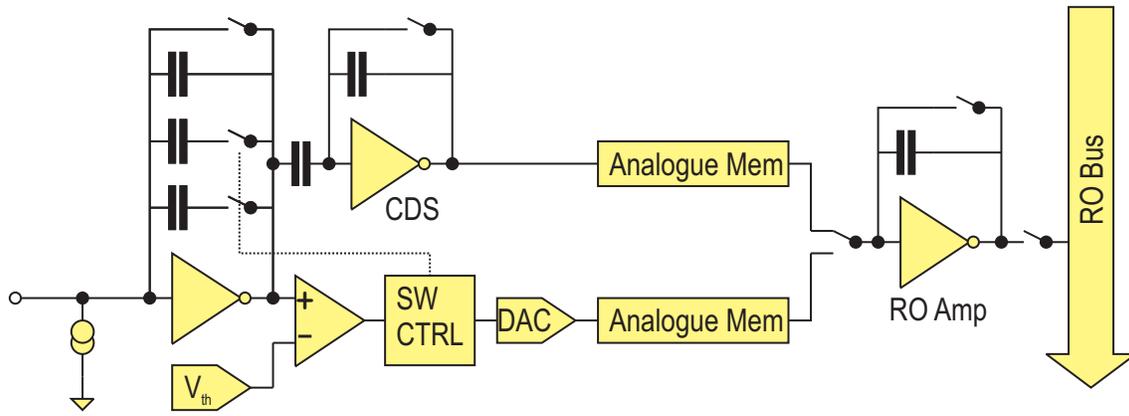
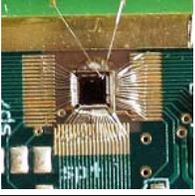
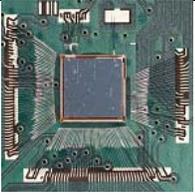
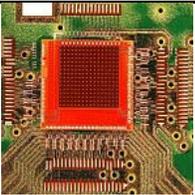
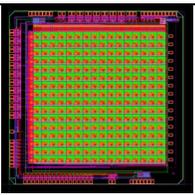
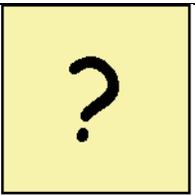


Fig. 3. Schematic of a pixel in the AGIPD readout ASIC

TABLE I
LIST OF AGIPD (PROTOTYPE) ASIC SUBMISSIONS. THE RIGHTHAND COLUMN LISTS THE FEATURES OF THAT CHIP AND THE SUBCIRCUITS UNDER TEST.

AGIPD 0.1	Jan. 2009
	<ul style="list-style-type: none"> No pixels 3 readout blocks consisting of: <ul style="list-style-type: none"> Readout chain (Preamp + CDS stage) 3 different kinds of leakage current compensation
	<ul style="list-style-type: none"> May 2009 16 × 16 pixels 100 storage cells No leakage current compensation Different combinations of preamps and storage cell architectures
	<ul style="list-style-type: none"> Nov. 2010 16 × 16 pixels 200 storage cells Radiation hard storage cell design High speed command based control interface Improved discriminator and CDS buffer
	<ul style="list-style-type: none"> Nov. 2011 16 × 16 pixels 352 storage cells Double-column readout New multiplexer New off-chip buffer No command based control circuit
	<ul style="list-style-type: none"> Q2 2012 Full-scale chip: <ul style="list-style-type: none"> 64 × 64 pixels 352 storage cells Double-column readout High speed command based control interface

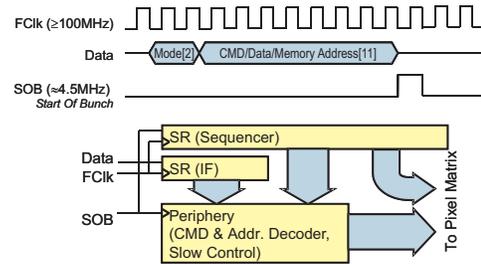


Fig. 4. Signals and schematics of the readout ASICs control interface

VII. ADAPTIVE GAIN PREAMPLIFIER

The preamplifier uses a simple inverter as a core cell. Feedback is provided by means of a 100 fF MiMCap². For lower sensitivities, additional dual-MiMCaps of 3 pF and 10 pF respectively are connected in parallel to the initial feedback. Including parasitic effects, like the finite open loop gain of the core cell and fringe capacitances, gain ratios of $1 : \frac{1}{23} : \frac{1}{100.5}$ were found, as fig. 5 shows.

VIII. ANALOGUE MEMORY & RADIATION HARDNESS

The analogue memory consists of two types of storage cells: for amplitude values and for the encoded gain settings.

The requirements on amplitude values are demanding an accuracy of better than 0.1 photon to ensure the single photon sensitivity of the detector, which translates to 0.1% of the preamplifier-CDS frontend output range. Thus leakage currents in the storage capacitors and switches were considered the most critical issue in the ASIC design and investigated with the very first chips submitted (HPAD 0.1 and HPAD 0.2, c.f. sect. V). These storage cells are also considered the part of the circuit most seriously affected by radiation damage, which was also investigated with these chips. As a result storage cells use a DGNCAP³ as storage element and two thin-oxide p-FETs as switches (c.f. fig. 6). The two transistors in series serve two purposes:

²Metal-inter-metal capacitor, formed by a thin dielectric and an additional metal layer in the BEOL.

³Thick oxide n-FET in an n-well

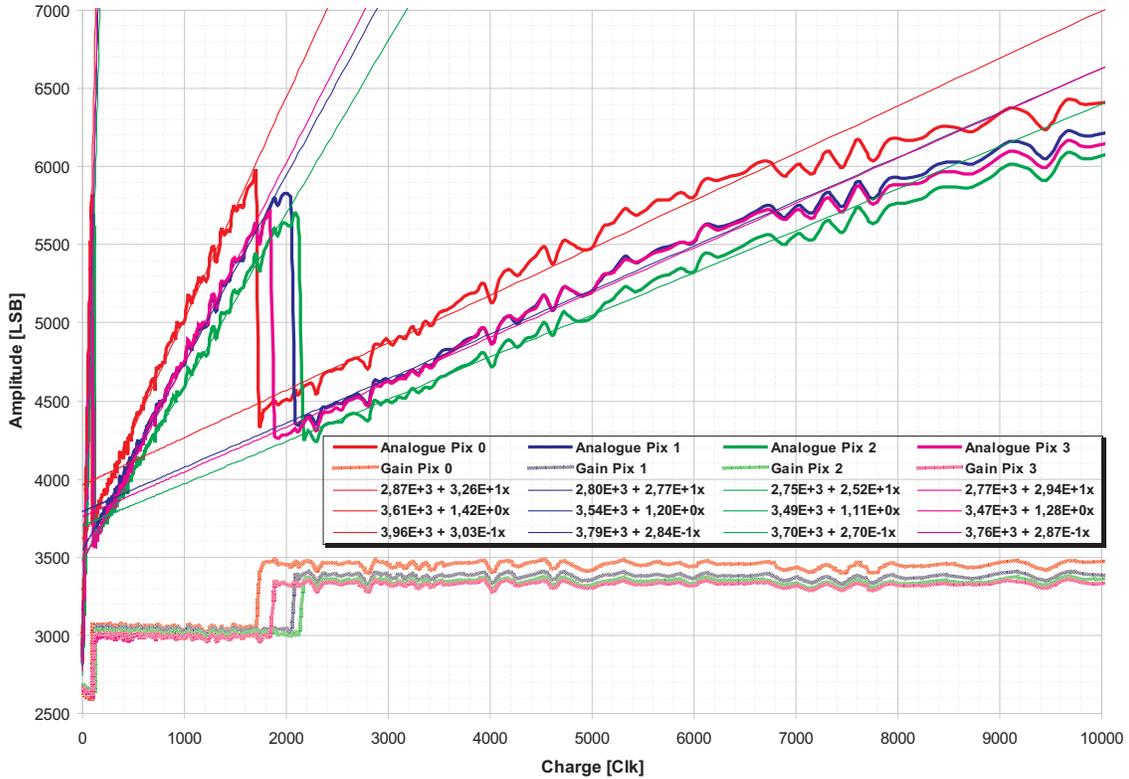


Fig. 5. Output of the AGIPD 0.3 chip. The input signal is generated by in-pixel current sources and varying the integration time. The spread of the curves is attributed to the mismatch of these current sources.

- A logic AND of the row and column lines of the Memory are formed.
- The voltage drop across the lower FET and thus the leakage current is minimised.

On AGIPD 0.3 several implementations of these storage cells, differing in transistor type and the potential of n-wells and guard rings were realised. Fig. 7 shows the droop of these storage cells for different doses. The results show, that for the correct potentials of guard rings and n-wells radiation damage saturates, and that in general the LP⁴-FETs, which due to the higher V_{th} show a lower initial leakage current, degrade more with dose than their RVT⁵-counterparts.

IX. HORUS A DETECTOR SIMULATION PACKAGE

The HORUS⁶ [4] [5] has been written in order to predict the impact of physics and electronics processes in AGIPD (and other pixel detectors) on measurement results. The program is coded in IDL and its modular structure follows the signal processing chain in AGIPD. The implemented models of processes are purposely kept simple, to achieve fast processing and easy modification. The current version is 3.0, which implements the following steps:

- The **incoming photon distribution** has to be provided by the user and can be oversampled with respect to pixel

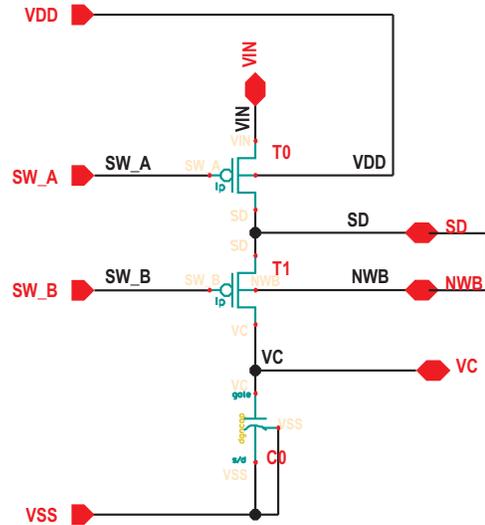


Fig. 6. Schematics of the analogue storage cells on AGIPD 0.3. The difference between the various implementations are the potential of the upper n-well and of the guard rings, as well as the threshold voltage V_{th} of the transistors used.

size or quantised if necessary.

- The **photon interaction in the sensor volume** takes the thickness of the entry window, the mean free path of photons, and parallax into account. It also implements Compton/Thomson scattering and fluorescence.

⁴Low-power (high) V_{th}

⁵Regular V_{th}

⁶HPAD Output Response fUnction Simulator

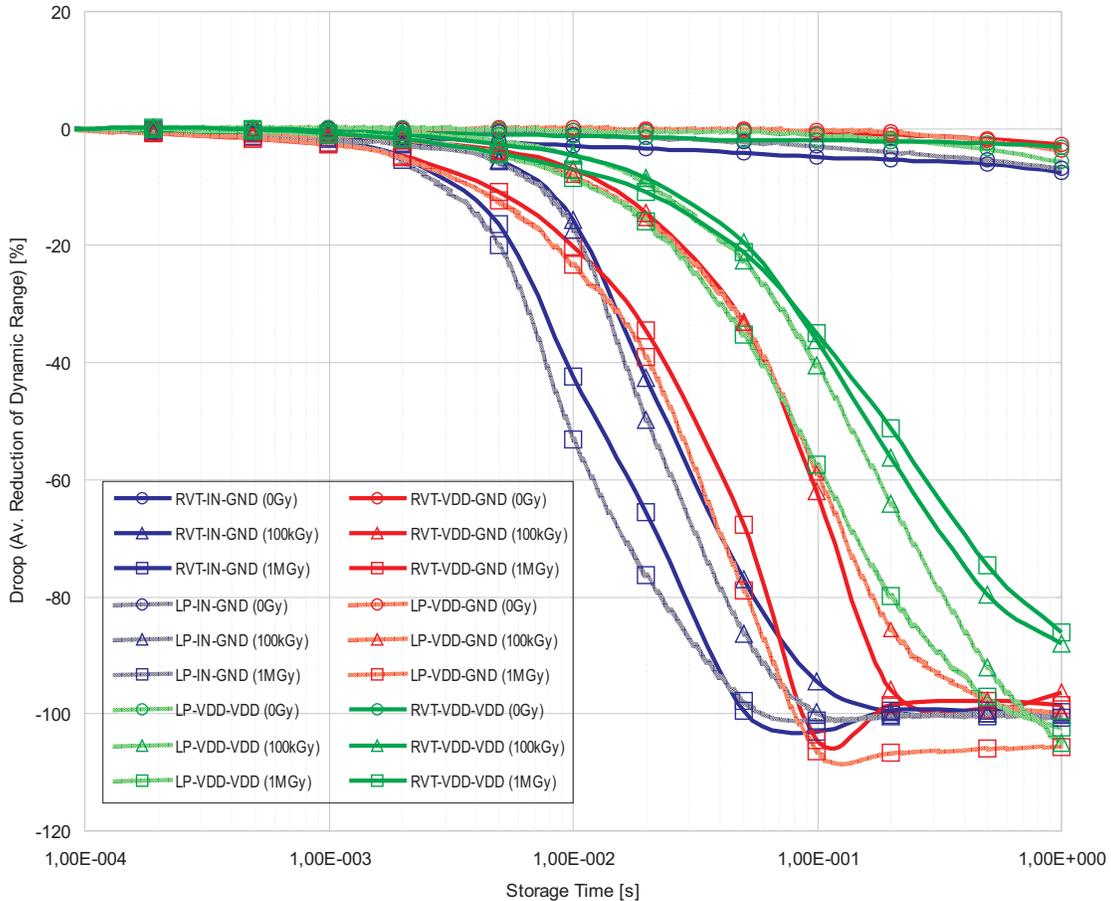


Fig. 7. Droop of different implementations of the storage cells on AGIPD 0.3 for different doses. The curves are labelled according to: type of p-FET used as switch – potential of the n-well – potential of guard rings

- The **charge transport in the sensor volume** implements phenomena like charge sharing between pixels, plasma effects due to extreme charge carrier densities, and arbitrary charge collection efficiencies.
- In the **ASIC and FE electronics** the effects of amplifier noise, the dynamic gain switching, imperfections of storage cells and the AD conversion are considered.
- Finally the **requantised number of detected photons** is calculated for a given threshold.

X. CONCLUSIONS

AGIPD is a hybrid pixel detector for the European XFEL with 1024×1024 Si-pixels of $(200\mu\text{m})^2$ size. It provides single photon sensitivity and a 2×10^4 photons dynamic range at 12 keV by means of adaptive gain switching. It provides random access to an analogue storage for 352 images, thus providing veto and trigger capabilities. These images are recorded 4.5 MHz frame rate at the European XFEL. Goal is also a radiation hard design (for up to 1GGy incident dose, i.e. $\gg 10\text{MGy}$ on the ASIC). In the framework of this development also HORUS, a simulation tool for AGIPD (and other detectors) has been written.

Currently a fully functional 16×16 pixel prototype readout chip, AGIPD 0.3, is available, while a full sized (64×64 pixel) readout chip is planned for 2012. The complete detector system is expected to be available before 2014.

REFERENCES

- [1] The European XFEL, <http://www.xfel.eu/en/index.php>
- [2] The AGIPD detector, http://hasylab.desy.de/science/developments/detectors/agipd/index_eng.html
- [3] G. Potdevin et al., *Performance simulation of a detector for 4th generation photon sources: The AGIPD*, Nucl. Instrum. Meth. A 607 (2009) 51
- [4] G. Potdevin et al., *HORUS, an HPAD X-ray detector simulation program*, 2009 JINST 4 P09010
- [5] J. Becker et al., *Simulation study of the impact of AGIPD design choices on X-ray Photon Correlation Spectroscopy utilizing the intensity autocorrelation technique*, J. Inst. 6 2011 P11005
- [6] B. Henrich et al., *The Adaptive Gain Integrating Pixel Detector AGIPD: A Detector for the European XFEL*, Proceedings of the 11th iWoRiD Conference, June 28 - July 2, 2009, Prague, Czech Republic, Nucl. Instrum. Meth. A 633 (2011) 1114
- [7] X. Shi et al., *Challenges in chip design for the AGIPD detector*, Nucl. Instrum. Meth. A 624 (2010) 387391
- [8] J. Becker et al. *Impact of plasma effects on the performance of silicon sensors at an X-ray FEL*, Nucl. Instrum. Meth. A 615 (2010) 230236
- [9] J. Zhang et al. *Study of X-ray Radiation Damage in Silicon Sensors*, Proceedings of the 13th iWoRiD Conference, July 3-7 2011, Zurich, Switzerland, arXiv:1111.1180v1