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High-speed readout of high-Z pixel detectors with the LAMBDA detector

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ABSTRACT: High-frame-rate X-ray pixel detectors make it possible to perform time-resolved experiments at synchrotron beamlines, and to make better use of these sources by shortening experiment times. LAMBDA is a photon-counting hybrid pixel detector based on the Medipix3 chip, designed to combine a small pixel size of 55 μm, a large tileable module design, high speed, and compatibility with "high-Z" sensors for hard X-ray detection. This technical paper focuses on LAMBDA's high-speed-readout functionality, which allows a frame rate of 2000 frames per second with no deadtime between successive images. This takes advantage of the Medipix3 chip's "continuous read-write" function and highly parallelised readout. The readout electronics serialise this data and send it back to a server PC over two 10 Gigabit Ethernet links. The server PC controls the detector and receives, processes and stores the data using software designed for the Tango control system. As a demonstration of high-speed readout of a high-Z sensor, a GaAs LAMBDA detector was used to make a high-speed X-ray video of a computer fan.

KEYWORDS: X-ray detectors; Materials for solid-state detectors; Hybrid detectors; Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases)

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Contents

1 The LAMBDA detector

X-ray scattering and imaging experiments at synchrotrons make it possible to study the structure of matter on an atomic scale, for example to study biological molecules or new materials. Due to the high brightness of third-generation synchrotron sources, high-frame-rate pixel detectors with high sensitivity would make it possible to perform experiments to study rapid changes in samples, such as chemical reactions, or to gain a higher throughput of experiments. LAMBDA (Large Area Medipix3 Based Detector Array) is a pixelated X-ray detector that was designed to provide a high frame rate (2000 frames/second), high sensitivity, large area and high spatial resolution [1]. This technical paper focuses on the development of high-frame-rate operation of LAMBDA.

The LAMBDA detector is a photon-counting hybrid pixel detector, based on the Medipix3 chip [2]. Photon-counting operation means that the chip has effectively noise-free operation at photon energies of 5 keV and above, which is important to achieving good imaging performance at high frame rates, since the number of photon hits per frame may be low. The hybrid pixel structure and chip design mean that the Medipix3 readout chip can be connected not only to silicon sensors, but also to "high-Z" (high atomic number) sensors such as GaAs, CdTe and Ge, to give greater detection efficiency at higher X-ray energies.

The Medipix3 chip was designed at CERN on behalf of a collaboration of 20 institutes, and was intended to be highly configurable. Each 55 µm pixel contains a two-stage amplifier, two sets of thresholding circuitry, two 12-bit counters and various forms of interpixel communication, which can then be configured for different applications. For high-frame-rate operation, the chip can operate in continuous-read-write mode, where it alternately counts photons with one counter while reading out the other one. Using this feature, it is possible to read the chip out at 2000 frames per second with 12-bit counter depth and no dead time between images.

A single Medipix3 chip has an array of 256 by 256 pixels. To provide a larger pixel array, a single LAMBDA module is designed to read out up to 12 Medipix3 chips in a 6-by-2 layout, giving a 1536-by-512 pixel array. The chips can be connected to a single large silicon sensor, as shown in figure 1, a smaller sensor, or multiple smaller sensors. For example, GaAs and CdTe modules have been produced with a 3-by-2 chip layout, since these materials are currently only available in 3-inch wafers. These modules can then be tiled to build a larger-area system, with each module being read out by a separate set of readout boards.

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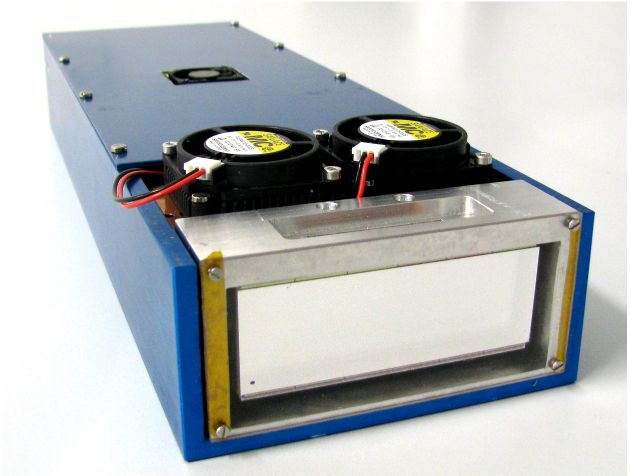

Figure 1. A single LAMDBA module with silicon sensor. The sensor has 1536 by 512 pixels of 55 µm, giving an area of 83 mm by 28 mm, and a thickness of 300 µm. The sensor layer is bump bonded to 12 Medipix3 readout chips.

To allow high-frame-rate operation, the LAMBDA readout system includes a high-speed readout mezzanine card [3]. This card contains a Virtex-5 FPGA to allow control and high-speed readout of the Medipix3 chips, and up to four 10-Gigabit Ethernet links for data transfer to a server PC. This card is intended for common use in different systems, and is currently being used in two other detector systems at DESY: AGIPD and PERCIVAL. This mezzanine card is connected to the detector head via a "signal distribution" board, which is detector-specific and also provides power to the detector head.

2 High speed readout process

The key steps in the high-speed readout process are as follows. Firstly, the FPGA on the high-speed readout card receives instructions from a server PC via a 1 Gigabit Ethernet link using TCP, then issues the appropriate commands and control signals to the chips. Slow control processes (e.g. interpreting commands from the PC) are performed by a PowerPC core on the FPGA, whereas high-speed control is done more directly in firmware using a state machine — for example, controlling the "shutter" signal that tells the chips when to acquire data. The image data output from each chip consists of 8 differential signal pairs, with a data rate of 200 MHz for each pair. This means the full 12-chip detector head has 96 signal pairs, plus additional clock output signals to allow accurate sampling of the data, and a total data rate of 19.2 Gbit/s. The signal pairs are connected to the FPGA on the high speed readout board. After receiving the data from these lines, the FPGA serialises this data into a single stream. The data stream is then split across two 10 Gigabit Ethernet links. The links use the UDP protocol, which simply does one-way transmission with no resending of data. Each packet contains a continuous section of the data stream.

The two 10 GbE links from the detector are connected to the server PC. This is a multi-core machine with a large amount of RAM, with 4 cores being dedicated to receiving the data from the links at a sufficiently high rate and buffering the data in RAM. The raw data stream from the

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detector needs to be processed to produce each image. For example, in standard image formats the value of each pixel is represented by a whole number of bytes, and the pixel values are sequentially ordered row-by-row. In contrast, the raw detector data consists of 12 bits (1.5 bytes) of data per pixel, interleaved in a more complicated way. So, the data stream needs to be re-ordered, and the pixel values must be converted from 12-bit to 16-bit values by adding leading zeroes. (In the longer term, more of this processing could be done in the FPGA to reduce the load on the server.) After processing, the images can be saved to disk.

The control software for the detector uses a library of LAMBDA control functions, which is then built into a Tango device server. Tango is a control system used at DESY and other synchrotron labs, which makes it possible to control and monitor the detector and a range of other systems at an X-ray beamline in a standardised and convenient way [4]. The Tango server code is also responsible for writing output files using the HDF5 format. This is a standard format that allows a large series of images to be saved to a single file with extensive metadata. The format includes optional data compression, using an approach where metadata and images can be extracted from the file without needing to decompress the entire file.

3 Experimental tests with high-Z materials

As a test of the high-speed readout process, an experiment was set up where a LAMBDA detector was used to take X-ray images of a moving computer fan. For the measurement, a LAMBDA module with a Gallium Arsenide sensor was used [5], since this material provides better detection efficiency than silicon across the broad photon energy range produced by an X-ray tube. This detector has a 768 by 512 pixel layout (6 readout chips) and 500 µm sensor thickness, and was operated in electron collection mode with a bias of −300 V applied to the back contact. To provide something interesting to image, lead foil letters were taped to the computer fan blades. The fan was then placed directly in front of the detector (2 cm distance) and illuminated with X-rays from a Molybdenum-target X-ray tube at a distance of 1.5 m. The X-ray tube used 60 kV tube voltage and 40 mA anode current. A series of 10000 images were then taken with the detector, using a 1000 Hz frame rate in continuous read-write mode, i.e. a 1 ms shutter time per image.

After taking the images, a flat-field correction was applied to the images, using data previously taken using uniform illumination with no sample. This was necessary because GaAs sensors have significant pixel-to-pixel nonuniformity in response [6]. Two image frames separated by 6 ms (i.e. 6 images apart) are shown in figure 2. The image scale corresponds to the square root of the number of photons per pixel per image, since this provides a clearer distinction between different layers. Although the number of photons per pixel per image is low — around 70 in the lighter areas of the image, and only a few counts in the darker areas — the single-photon-counting capability means that a good image contrast is still achieved. *The supplemental materials include a video showing both the fan viewed with a video camera, and a high-speed X-ray video produced with these images.* The video runs at 25 frames per second, compared to the 1000 frames per second acquisition, giving a factor of 40 slowdown. The fan rotated at 10 Hz, so the motion of the blades can be easily seen in the X-ray video.

The LAMBDA detector has been used in high-speed experiments at synchrotrons to obtain time-resolved information about samples. To take an example, a silicon module was used in a series

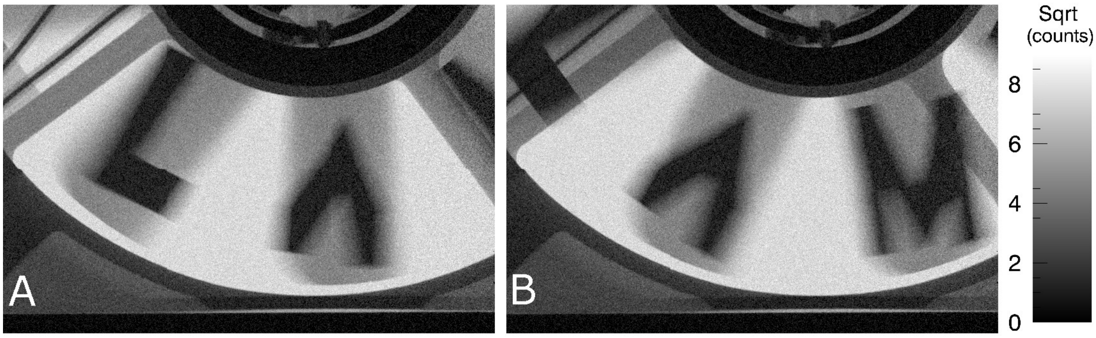

Figure 2. Two X-ray images of a computer fan with lead foil letters attached to the fan blades. The images were taken with the LAMBDA GaAs detector, running at 1000 images/second (1 ms shutter time), with the two images being separated by 6 ms (i.e. 6 images apart). The experiment used a molybdenum target X-ray tube at 60 keV, and 6 keV threshold on the detector. The supplemental materials to this paper show a video of this measurement.

of experiments looking at the dynamics of colloidal samples under shear forces. Proof-of-principle experiments have been done using the GaAs LAMBDA detector in hard X-ray experiments involving samples under extreme temperature and pressure. These showed that useful data can be obtained from a 1 ms diffraction image from a standard sample, showing that the detector could be used in future to study rapid changes in samples during changes in pressure or temperature [5].

4 Conclusions

The LAMBDA detector system has successfully demonstrated high-frame-rate readout of silicon and high-Z hybrid pixel detectors. This feature can now be used for high throughput and time-resolved experiments at synchrotrons. The next stage in the development of the system is to build multi-module systems to provide a larger detector area. To combine large multi-module systems with high readout speeds, it will be necessary to develop a control system that can operate and read out many modules in parallel.

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