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The data acquisition system of *pheno*PET

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Abstract: The PET scanner *pheno*PET is a system dedicated for plant research developed and used for phenotyping studies at the Research Center in Jülich. The detectors consist of LYSO scintillators and Philips digital silicon photomultipliers. A central processing board collects their data and transfers them through a USB-3 connection to the data acquisition server. The USB-3 restricts the maximum output rate to 380 MB/s, which requires controlled data dropping on the board in order to allow measurements with activities that would exceed this limit. Presently we are developing a new readout system that will eliminate this bottleneck. We will replace the USB-3 by a fiber optics link with a maximum data rate of 2 GB/s. In addition, the new central board will provide an embedded operation system (PetaLinux) that has direct access to the hardware interfaces for configuration and monitoring of the detector modules. This will allow the control software to run directly on the board.

Keywords: Data acquisition circuits; Data acquisition concepts; Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA)

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Contents

1 Introduction

Since decades Positron Emission Tomography (PET) is widely used in medical imaging. Besides clinical scanners for human diagnosis there also exist preclinical systems, in general with a smaller field of view, which are dedicated for medical research on animals, mainly mice and rats. A rather small field is the development of dedicated PET scanners for the application in plant research [1–5]. The scanner *pheno*PET is a system that has been developed in Jülich following the requirements of our institute for plant science (IBG-2) with the aim of investigating the transport of photo-assimilates within the plant [6]. This is realized by labeling carbon dioxide with the positron emitter ^{11}C and applying it to the leaves of the plant where it will be assimilated. Hereafter the ^{11}C decay allows *pheno*PET to follow the transport of the carbon compounds through the plant, especially into the root system [7].

2 Setup

As with most PET scanners, the detectors in *pheno*PET form a cylindrical ring around the object of interest. For a clinical scanner, which is supposed to examine the patient in a lying position, the ring will be oriented vertically. In contrast, a living plant needs to be scanned in an upright position and therefore *pheno*PET requires a horizontal ring orientation. The detector ring of *pheno*PET has an inner diameter of 255 mm and a height of 202 mm and is made up of 36 detector modules arranged in three parallel rings of 12 modules each (see figure 1). One module is equipped with 32×32 LYSO crystals of $1.85 \times 1.85 \times 10\,\text{mm}^3$ (*Crystal Photonics*) and four so-called detector *tiles* (DPC3200-22-44 by *Philips Digital Photon Counting*) [8]. One *tile* holds 4×4 digital SiPM chips (*dies*) which each is a fully digital photo detector providing 2×2 photo pixels with 3200 SPADs each. The *die* has only digital interfaces for configuration and read-out. No electronics for analog processing are required. Each *die* triggers independently whenever there is a signal on the pixels and the trigger condition is met. In this case it generates a data package containing the number of triggered SPADs on each of the four pixels together with a timestamp. The ratios of the pixel signals will be used to identify which of the 16 crystals that sit on the four pixels of one *die* scintillated and caused the triggering [9].

Each three detector modules of one sector of the ring sit on a so-called Sector Board which connects them via an HDMI cable to a central processing board (Concentrator Board) containing a Kintex-7 FPGA (*Xilinx*) (figure 2). HDMI cables from consumer electronics are very well suited for this task because they provide an I^2C connection and four differential lines which we use for the

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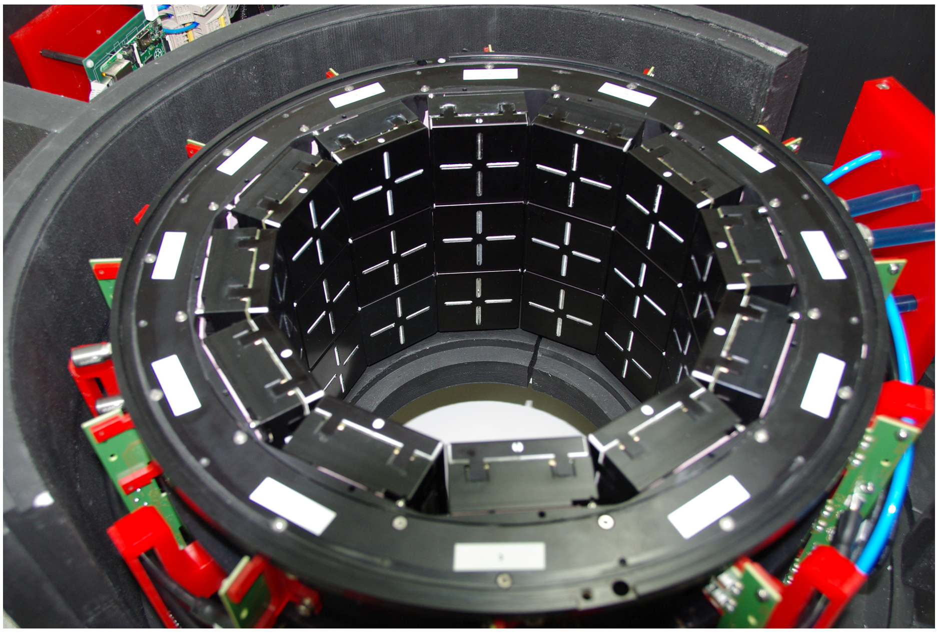

Figure 1. The detector ring.

common clock and the three data signals of the three modules. The Concentrator Board on the one hand collects and preprocesses the fast output data from the modules and handles the transfer to the data storage and processing system via a USB-3 connection. On the other hand, it enables the communication between the modules and the controlling computer that configures the detectors and controls the measurements via the I^2C interfaces. Furthermore, the Concentrator Board distributes the 200 MHz system clock synchronously to all modules.

3 Processing

Every SiPM chip contains a 16-bit counter which is clocked by the 200 MHz system clock. All these counters start at the same time and therefore count synchronously throughout the entire system. Together with an 8-bit TDC they serve as base for the generation of the 24-bit timestamp which is attached to each registered event and later on used to identify coincident events. The TDC provides a resolution of $1/200\,\text{MHz}/2^8 \approx 19.5\,\text{ps}$ while the max. timestamp is restricted by the counter to $2^{16}/200\,\text{MHz} \approx 328\,\mu\text{s}$. For this reason the data transfer from the modules is organized in time frames of 328 µs and the Concentrator Board receives numbered frame packets containing the event data. One task of the processing on the Concentrator Board is the coordinated transfer of the incoming packets from the 36 modules to the output data stream via USB-3. While the modules are able to cope with data rates of up to 50 MB/s each, the USB transfer is limited to a max. rate of 380 MB/s. So for higher activities the input rate can easily exceed the possible output rate and data have to be discarded in a controlled way, i. e. all data packets that belong to a certain time frame are dropped. This allows the remaining frames to stay complete and contain data from all modules, which enables a coincidence sorting. Of course, the Concentrator Board keeps track of the numbers of received and dropped frames which is necessary for dead time correction and quantification [6].

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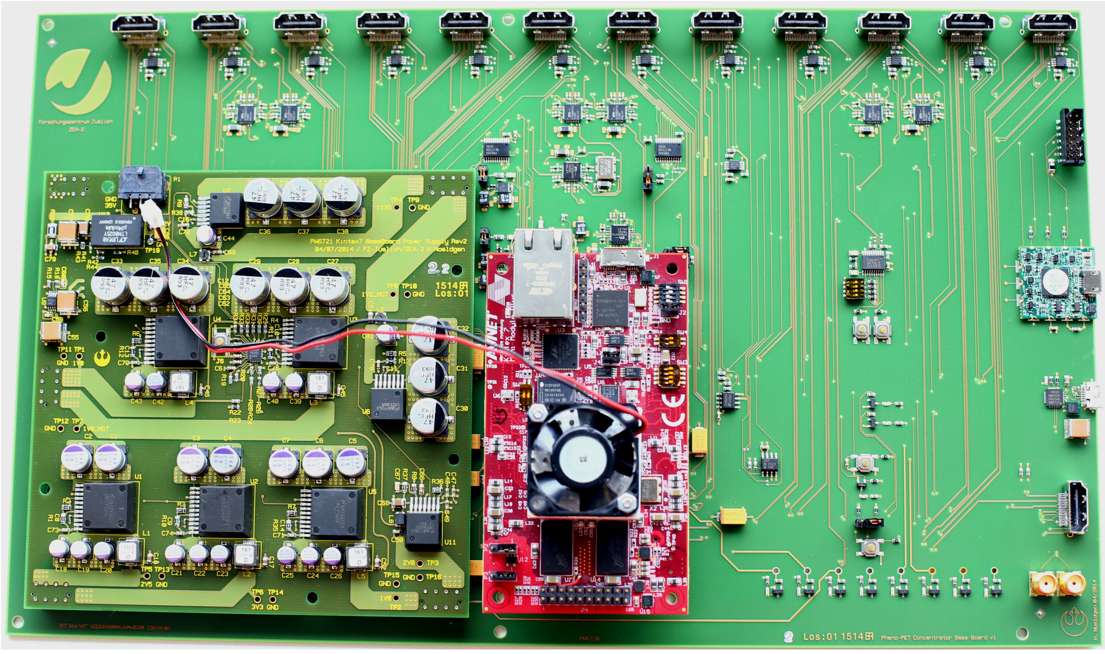

Figure 2. The Concentrator Board with the red mini module (*Avnet*) bearing the Kintex-7 FPGA and the USB-3 interface. The 12 HDMI sockets (on top of image) provide the connection to the Sector Boards.

4 Improvements

Even with data dropping the number of transmitted events is still high and will generate images with sufficient statistics. However, it also leads to a reduction in the dynamic range of the recorded activity distribution. In some studies, for example, it is desirable to measure an entire plant with leaves, stem and roots in one scan. While there will be a high activity in the *hot* leaf much fewer counts will be recorded from the rather *cold* root system. Here the high count rate from the *hot* region will cause the data dropping but with the consequence that the already limited image quality in the *cold* region is further reduced.

In order to overcome this restriction we decided to upgrade the data transfer electronics for higher throughput. With a bandwidth of 1.8 GB/s we could store all data from the 36 modules even if they all send on their full rate of 50 MB/s. To this end we replace the USB-3 connection by two SFP+ interfaces which provide 2×10 Gbit/s data rate. For the SFP+ modules we chose optical links which guarantee longer transfer distances without any problems. The *pheno*PET system itself is located within a climate chamber that provides defined conditions (temperature, humidity, illumination) for the observed plant. But the computer system and the data server need a dry and stable environment outside the chamber. By employing optical links the server might even be placed in a dedicated server room somewhere else in the building.

This new interface implies a redesign of the Concentrator Board. Figure 3 shows the prototype of the new board. The board carries a piggyback module (UltraSOM+, *trenz electronic*) with a System-on-a-Chip (Zynq UltraScale+, *Xilinx*) that provides an FPGA together with an ARM core. The processor allows the implementation of a full operating system (*PetaLinux*) which will be used as the platform for the controlling software [10]. Thus, in contrary to the previous setup, no additional computer is required and the software has direct access to the I^2C interfaces on the chip in order to

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configure and monitor the modules which again are connected via the 12 HDMI cables. External communication to the platform is realized by a Secure Shell connection (*ssh*). The processor only controls the modules, while the processing of the module data is carried out by the FPGA firmware. Each module sends its data as a one bit LVDS signal, which is clocked at double data rate (DDR) by the 200 MHz clock. The firmware de-serializes it and writes it into a buffer, one for each module. From there a 36-to-2 multiplexer builds the output stream for the two SFP+ ports. For this purpose beginning and length of the time frames are recognized and the output stream only contains data packets representing complete frames. In this setup no frame dropping is required as the system is capable of processing all incoming data. All data will be sent out by the two optical links running at 10 GHz and guarantee the max. transfer rate of 2 GB/s.

The server on the receiver side contains a PCIe card (KCU105, *Xilinx*) with two SFP+ ports and a Kintex UltraScale FPGA. The data transfer uses the 8b/10b-code [11] and special characters marking beginning and end of a transfer packet. It is completely organized on the hardware layer and independent from the operating system (OS). The received data are written to memory via direct memory access (DMA) from where they will be accessed by the OS. Due to the high throughput data have to be written to a fast Solid State Disk (SSD).

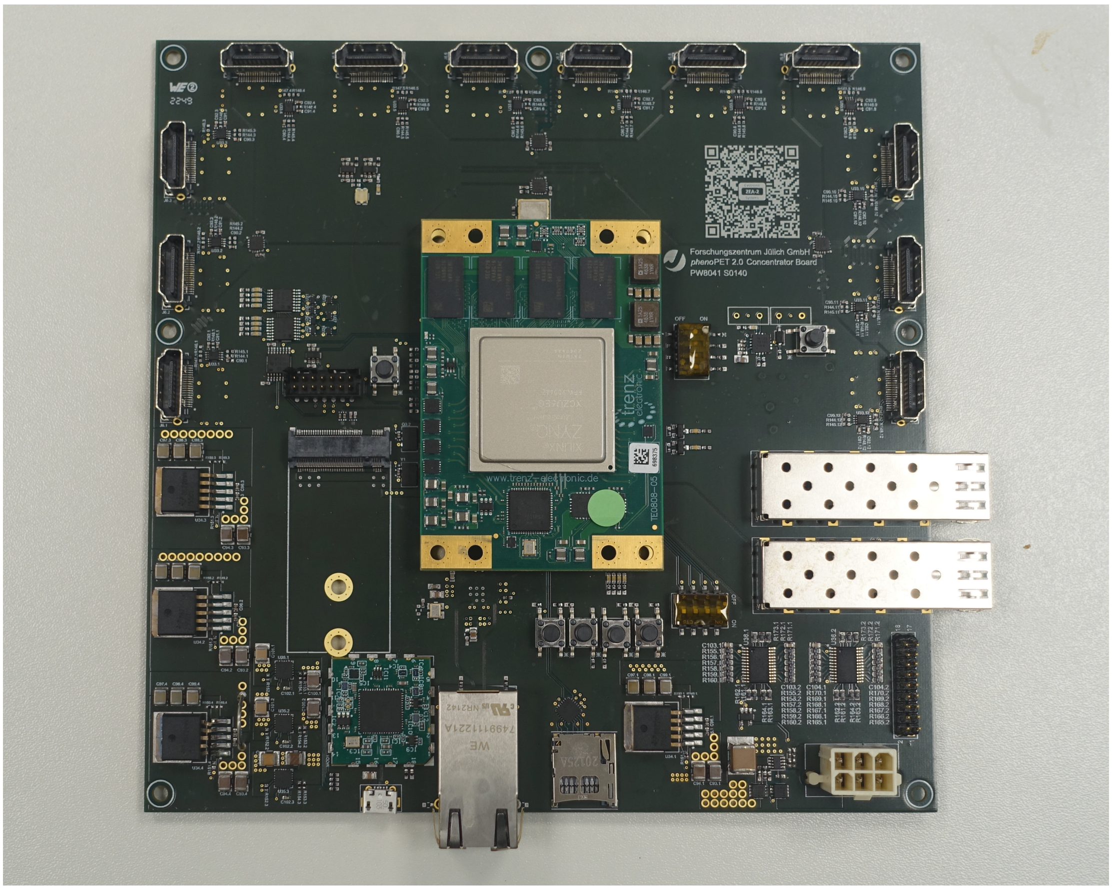

Figure 3. Prototype of the new Concentrator Board with the UltraSOM+ module in the center. The 12 HDMI sockets are visible in the upper half of the image at the edges of the board. Below on the right hand side are the two SFP+ cages for the optical links and on the bottom the RJ-45 socket for network connection to the PetaLinux system.

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