

AN ULTRAFAST LINEAR ARRAY DETECTOR FOR SINGLE-SHOT ELECTRO-OPTICAL BUNCH PROFILE MEASUREMENTS

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Abstract

A new spectrometer system has been developed at ANKA for near-field single-shot Electro-Optical (EO) bunch profile measurements with a frame rate of 5 Mfps. The frame rate of commercial line detectors is limited to several tens of kHz, unsuitable for measuring fast dynamic changes of the bunch conditions. The new system aims to realize continuous data acquisition and over long observation periods without dead time. InGaAs or Si linear array pixel sensors are used to detect the near IR and visible spectrum radiation. The detector signals are fed via wire-bonding connections to the GOTTHARD ASIC, a charge-sensitive amplifier with analog outputs. The front-end board is also equipped with an array of fast ADCs. The digital samples are then acquired by an FPGA-based readout card and transmitted to an external DAQ system via a high-speed PCI-Express data link. The DAQ system uses high-end Graphics Processors Units (GPUs) to perform a real-time analysis of the beam conditions. In this paper we present the concept, the first prototype and the low-noise layout techniques used for fast linear detectors.

INTRODUCTION

During the low- α_c -operation at the ANKA storage ring at the Karlsruhe Institute of Technology, the momentum compaction factor α_c is reduced to compress the bunches longitudinally and thus generate Coherent Synchrotron Radiation (CSR) in the THz range [1]. The emitted CSR exhibits a bursting behavior [2–4], which is caused by dynamic changes of the longitudinal bunch shape (e. g., microbunching). To study these dynamic changes, single-shot measurements with a sub-ps resolution are required.

The method of Electro-Optical Spectral Decoding (EOSD) offers the possibility to measure the longitudinal bunch profile and its arrival time relative to the revolution clock with a sub-ps time resolution without averaging. For EOSD, the field induced Pockels effect inside an electro-optical crystal is used to modulate the temporal profile of the electron bunch onto a laser pulse. Subsequently this laser pulse is detected with a commercial InGaAs line array inside an optical spectrometer and from the spectral modulation the bunch profile can be extracted.

First single-shot measurements with the EOSD setup at ANKA have indicated the formation of substructures on the compressed bunches [5, 6]. In principle, EOSD, offers the possibility to measure the longitudinal bunch profile on a turn-by-turn basis ($f_{\text{REV}} = 2.7$ MHz at ANKA) because the laser can easily be adjusted to the ANKA revolution frequency. The laser system at ANKA operates at 1050 nm, so

an InGaAs based line array is required. The acquisition rate of the commercial InGaAs line arrays, however, is limited to the low kHz range [7] thus it is not possible to monitor fast dynamic changes of the longitudinal bunch profile. For this reason a fast spectrometer is being developed at KIT and the target frame rate has been set to 5×10^6 frames per second (Mfps) to make it also applicable to other facilities such as XFEL and ELBE for which the repetition rates are higher. The final system must also be able to perform some on-line analysis of the bunch conditions in order to be used as a real-time and non-destructive diagnostic tool.

DESIGN CONCEPT

The architecture of the new spectrometer system is shown in Fig.1. The system consists of a mezzanine card where the detector (a), the front-end electronics (b) and the ADCs (c) are mounted, an FPGA-based high-throughput readout board (d) and an external DAQ system (e).

Two different detectors technologies can be used to detect the modulated spectral response over different frequency ranges: an InGaAs linear array for the near IR and an uncoated Si linear array for visible light. The final version of the system will be based on a 1D detector with 512 pixels and a pitch of 50 μm .

The detector's output signals are fed via high density fine-pitch wire-bonding connections to the front-end electronics. A low temperature fine pitch wire-bonding technology is required. Therefore, an ultrasonic wedge-to-wedge aluminium wire with a diameter of 25 μm has been chosen.

Eight GOTTHARD ASICs [8] developed by PSI are used as charge-sensitive pre-amplifiers. Although the GOTTHARD has been developed for a Si microstrip detector, it can also be used with different detectors thanks to its automatic and adaptive gain selection stage. The current version of the GOTTHARD (v1.4) has 128 inputs and 4 outputs. A group of 32 inputs is connected to one output through a distributed multiplexer, clocked at 32 MHz. Therefore, a maximum frame rate of 1 Mfps can be achieved. A new GOTTHARD version (v1.6) with 8 analog outputs and an operating maximum frequency of 50 MHz is currently being submitted to the foundry. The new version allows to achieve a maximum frame rate of 3.1 Mfps. In order to meet the requirement of 5 Mfps with a linear array of 512 pixels, a special routing is required: each GOTTHARD chip will be connected to the detector in interleaving mode, and only 64 inputs of each chip will be used. In this way each output serves 8 pixels. With a reset after 8 clock cycles, a frame rate of up to 6.25 Mfps can be realized.

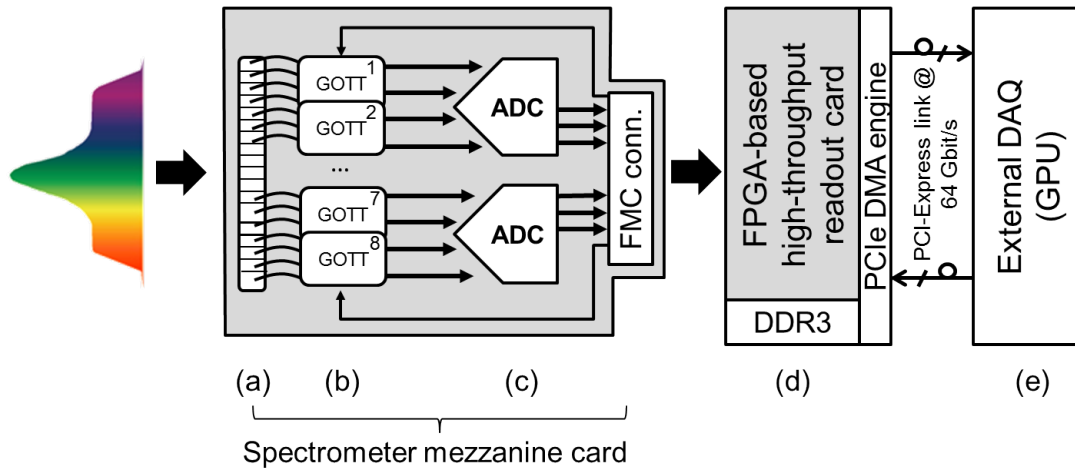


Figure 1: Architecture of the novel spectrometer.

The front-end card is completed by an array of fast ADCs and an high-density Samtec FMC connector.

The FPGA-based back-end card acquires the digital samples from the mezzanine card and performs a preliminary data analysis. A dedicated input stage is used to control and synchronize the GOTTHARD chips and the ADCs. The FPGA firmware includes several IP cores developed at KIT which are already employed in different experimental setups [9] and [10]. In particular, the system will use a DDR3 memory interface for temporary data storage and a PCI-Express Direct Memory Access (DMA) architecture [11] to transfer data to an external DAQ system with a throughput of up to 64 Gbit/s.

The setup is completed by a real-time data processing stage based on high-end Graphics Processors Units (GPUs) for an on-line monitoring of the beam conditions. The final system aims to realize continuous data acquisition without any dead time and will be controlled by a dedicated software.

FIRST PROTOTYPE OF THE SPECTROMETER MEZZANINE CARD

A first prototype of the spectrometer mezzanine card with a target frame rate of 1 Mfps is being developed to study the most critical aspects of the system.

The bias voltage of the detector can be supplied by an external source. In this way the voltage can be carefully adjusted to achieve the best performance in both the detector and the GOTTHARD input stage. Also, the electrical properties the wire-bonding connection between each pixel and the analog front-end must be carefully characterized and optimized with a dedicated layout. The working parameters of the GOTTHARD must then be calibrated to minimize the Equivalent Noise Charge (ENC) of the system.

The first prototype will also be used to further develop the FPGA firmware, the GOTTHARD's control logic, the

algorithms for the on-line data analysis and the software interface.

The mezzanine card mounts a single InGaAs linear array detector provided by Xenics, with 256 pixels and 50 μm pitch. The detector has been according to the operational wavelength of the laser that is used in the experimental setup for EO bunch profile measurements at ANKA. The detector's bias voltage can be supplied from an accurate external source through an SMA connector mounted on the board.

Two GOTTHARD v1.4 chips are connected to the InGaAs detector. The analog samples are digitized by an AD9252 ADC with 8 channels and a 14-bit resolution, operating at 32 MS/s. A FMC connector is used to connect this card with the readout board.

The back-end board mounts a Xilinx Virtex6 device. The FPGA firmware architecture consists of a DDR3 memory interface for temporary data storage, an on-line data analysis stage and a PCI-Express DMA engine, capable of sustaining

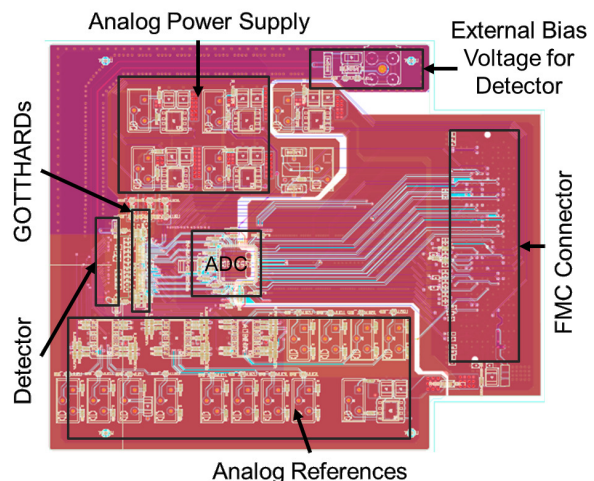


Figure 2: Layout of the spectrometer mezzanine card.

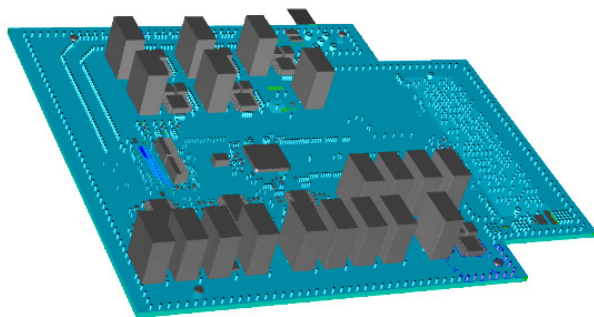


Figure 3: Rendering of the spectrometer mezzanine card.

the required throughput of 3.6 Gbit/s (14 bits \times 8 channels @ 32 MS/s).

Low-noise Layout Techniques

Several low-noise layout design practices have been employed in order to achieve the best noise performance and reduce electromagnetic interference (EMI). To isolate the digital circuitry from the analog part, two separate grounds are used (as can be seen in Fig. 2). An inductor located below the ADC connects the two grounds and provides the required common voltage reference. Multiple ground planes are used, and signal pairs are routed near their respective planes in order to reduce the signal's return current path. All the power planes and the critical traces (including the external detector bias voltage) have been filtered, routed between the corresponding ground planes and shielded with via guard fences (Fig. 3). Decoupling capacitors are placed near the components to filter the power supply and the analog references. These capacitors also act as a low-impedance source for dynamic currents, thus minimizing the switching noise.

The high-speed digital signals (maximum clock frequency = 330 MHz) have been routed using differential coplanar waveguide transmission lines with controlled impedance. To avoid signal reflections on these traces, series termination resistors have been placed near the outputs pins.

CONCLUSIONS AND FUTURE WORK

In this paper we have described the design concepts of a novel spectrometer based on an InGaAs detector and operating with a frame rate of up to 5 Mfps. A first prototype of the front-end board is currently being developed in order to study the critical parts of the front-end board. The system will be

tested at the ANKA synchrotron light source to characterize the InGaAs linear array detector and its compatibility with the GOTTHARD chip. The board will then be integrated in the novel EO setup currently under development at ANKA.

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