Preprint typeset in JINST style - HYPER VERSION

Digitization and Real-Time Analysis of Detector Signals with GANDALF

Stefan Bartknecht, Horst Fischer, Florian Herrmann, Kay Königsmann, Louis Lauser[*], **Christian Schill, Sebastian Schopferer and Heiner Wollny**

Universität Freiburg, Physikalisches Institut
79104 Freiburg, Germany
E-mail: `louis.lauser@cern.ch`

ABSTRACT: For the measurement of Generalized Parton Distributions, the COMPASS-spectrometer will be upgraded with a Recoil-Proton-Detector (RPD). This detector consists of two layers of scintillating slats that are assembled ringlike around the target and read out by photomultiplier tubes. By measuring the time-of-flight as well as the energy-loss of charged particles in the detector, recoil protons can be identified. Due to short risetimes of the signals and a wide range of amplitudes, a precise Analog-to-Digital Conversion is mandatory for a measurement of energy loss. Furthermore, the generation of a proton trigger demands for real-time analysis and high-speed transmission of data. The GANDALF Module was designed as front-end module of the RPD: It is built as 6U VME64x/VXS module, and all calculations are performed by DSP-algorithms in a Virtex-5 FPGA. For a versatile use of the GANDALF Module, the analog inputs as well as the 12 bit/500 MHz ADCs are located on exchangeable mezzanine cards allowing the readout of up to 16 channels. An effective sampling rate of 1 GS/s for up to 8 channels is achieved in the time-interleaved mode, in which each input channel is guided onto two ADCs and the corresponding sampling clocks are phase-shifted by 180°. Measurements have been performed showing a highly effective sampling resolution along full input bandwidth, small clock jitter and a time resolution, which is in agreement with simulations. GANDALF equipped with digital mezzanine cards can be used as 128 channel TDC-, scaler- or logic module.

KEYWORDS: Front-end electronics for detector readout; Digital signal processing (DSP); Trigger concepts and systems (hardware and software).

---

[*] Corresponding author.

1. GPD Programme at COMPASS

In nuclear spin physics, Generalized Parton Distributions (GPD) are a known approach to study the contribution of the orbital angular momentum of quarks and gluons to the total spin of the nucleon [1]. They can be accessed through measurements of hard-exclusive processes like Deep-Virtual Compton-Scattering (DVCS) which are proposed at the COMPASS-II Experiment [2]. The exclusivity of the measurement is ensured by a Recoil-Proton-Detector (RPD), that will be installed around the target.

For low momentum proton detection down to 260 MeV/c, scintillating slats, which are 2.75 m long and 4 mm thick, surround directly the target. For a full coverage of proton kinematics, slats with a length of 3.6 m and a thickness of 5 cm are assembled at a distance of 2.2 m from the target. A drawing of the RPD is shown in figure 1. The detection of protons is accomplished by time-of-flight measurements in combination with the determination of the energy loss of the particle in the detector. Simulations have shown that a time resolution of 200 ps is required to separate protons from electrons and pions, which occur from various background scattering processes. Time and amplitude measurements will be accomplished by the GANDALF Module in real-time allowing the generation of a first-level proton trigger.

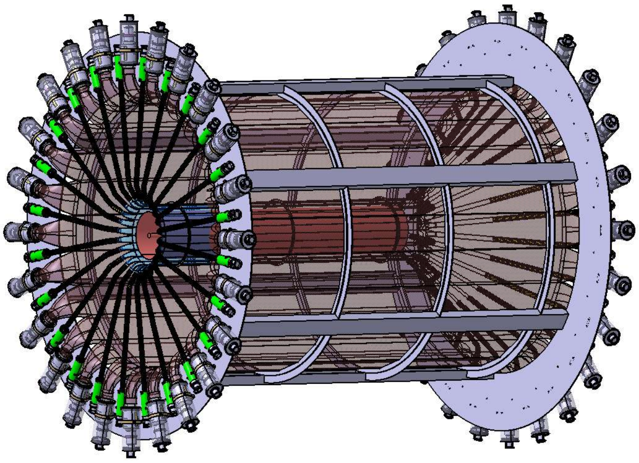


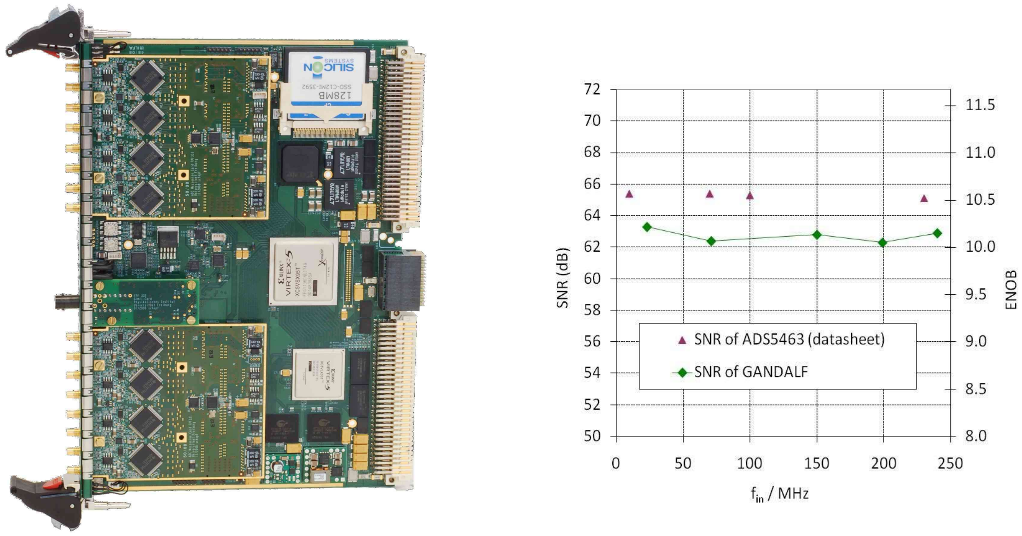
Figure 1. The Recoil-Proton-Detector at the COMPASS-Experiment. The 2.5 m long liquid hydrogen target is located in the center of the detector.

2. The GANDALF Module

As a General Advanced Numerical Device for Analytic and Logic Functions, GANDALF may provide the readout and processing of signals of many different sources. It is built as 6U VME64x/VXS Module to comply with the need for high-speed data transmission in conjunction with the requirement of remote configuration and monitoring of the module. Up to two plug-in positions for various kinds of mezzanine cards allow a wide range of applications. The heart of the carrier board is the Virtex5-SXT FPGA, which collects data from the mezzanine cards and processes data in real-time. In addition to the internal memory of the FPGA, external memory is provided by 144 MBit QDRII+ RAM and 4 GBit DDR2 RAM, which is controlled by a Virtex5-LXT FPGA. This FPGA also manages the 160 MB/s S-Link interface [3] to the COMPASS readout buffers. Bidirectional data flow between GANDALF and the VME single-board computer is possible via the VME64x interface in block transfers [4], whereas the USB2.0 interface provides full I/O-functionality in a stand-alone environment. A connection to the Trigger Control System (TCS) is located on the Gimli Card, which is mounted between the two I/O Mezzanine Cards. It allows to switch between a copper connection and an optical link.

2.1 Analog Mezzanine Card

As front-end module of the RPD, GANDALF is equipped with two Analog mezzanine cards (AMC) (see figure 2). The digitization of analog signals from 8 channels with a sampling rate of 500 MS/s is located on one Analog Mezzanine Card (AMC). Each of the single-ended SMC inputs accepts a signal range of 4 V_{pp} and is connected via a preamplifier circuit to a 12 bit ADC (ADS5463). The baseline of the DC-coupled analog input can be adjusted from 0V to 2 V individually by a 16 bit DAC. To achieve an effective sampling rate of 1 GHz, the signals of a given analog channel are split to two adjacent ADCs, which are clocked with a 180° phase-shift between the corresponding sampling clocks. The switch to this time-interleaved mode, in which the number of channels is reduced by a factor of two, only requires the removal and integration of a few passive components [5]. As a design constraint, the effective number of bits (ENOB) shall fulfill ENOB$\geq$ 10, which is achieved by the ADS5463 alone, but had to be validated along the full signal path. In experimental tests with an Arbitrary Function Generator (AFG3252) in combination with narrow bandpass filters and a sampling rate of 1 GS/s measurements yielded ENOB$=$ 10.1 for an input bandwidth up to 250 MHz (see figure 2). The sampling clocks for the ADCs are generated by an Si5326 clock multiplier from the 155 MHz TCS-Clock. The required effective resolution of the ADC-system can only be fulfilled with a jitter of the sampling clock that is below 1 ps and therefore the clock network had to be designed very carefully. As a result, the measured jitter of 900 fs RMS complies with this condition.



(a)

(b)

Figure 2. a) The GANDALF Module equipped with Analog Mezzanine Cards; b) The measured signal-to-noise ratio as a function of input bandwidth and the corresponding values of the ADC data sheet.

2.2 Time extraction

As simulations have shown [6], the best time resolution can be achieved by using the digital Constant Fraction Discrimination (dCFD) algorithm. Figure 3 illustrates the calculation of the time of a signal. Each sample of the pulse is inverted and delayed before a constant fraction factor is applied on it. The resulting value is then added to the corresponding inital sample. Carried out for every sample of a signal, this procedure results in a characteristic constant-fraction signal shape, which shows one zero-crossing. Finally, its time can be determined by two-point interpolation.

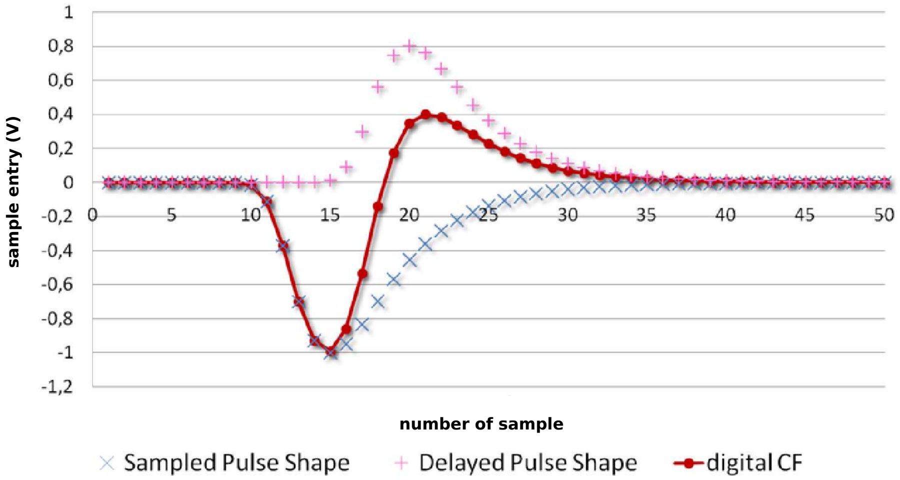


Figure 3. Signal processing by digital Constant Fraction Discrimination (dCFD). The zero-crossing of the resulting pulse shape defines the time of the signal.

3. Performance of the GANDALF Module

Detailed measurements were performed to determine the time resolution of GANDALF. At first, a given signal was digitized by two independent ADCs and the difference in time was measured as a function of amplitude. This could be done by passively splitting the pulses that were provided by an arbitrary waveform generator. Further measurements include a laser and photomultiplier setup.

3.1 Measurements with lab-generated pulses

To determine the time resolution of GANDALF, pulses which were generated by the AFG3252 were guided onto the analog inputs. With the use of a passive splitter each pulse could be sampled by two independent ADCs, followed by the calculation of the corresponding times by the dCFD-algorithm in the FPGA. Then, after having read-out data via the S-Link interface, the differences in time could be calculated and histogramed. Finally, the time resolution could be taken from a gaussian fit.

With an intentional variation of the time difference between two signals to be compared, systematic behavior can be minimized. This could be achieved by applying a phase-modulated time shift between the two signals. In sweep mode, the AFG3252 generates identical pulses at each of the two outputs whose difference in time varies according to the phase of a modulating waveform. Each pair of pulses is again digitized and analysed by the GANDALF Module. Now, the histogram of the time differences is expected to follow a sine density distribution convoluted with a gaussian. The time resolution could be extracted by a deconvolution of the fit function. This measurement was repeated for different amplitudes yielding a resolution of smaller than 50 ps for amplitudes down to 3.8 % of relative dynamic range. The measured time resolution as a function of the signal amplitude is shown in figure 4.

3.2 Measurements with laser and photomultiplier setup

In this measurement setup, a light pulse from a 620 nm laser module is send through optical filters to a RT1450 photomultiplier tube (PMT). The GANDALF Module now receives both the signal from the photomultiplier tube and the trigger signal that is sent out by the laser module in correlation with the light

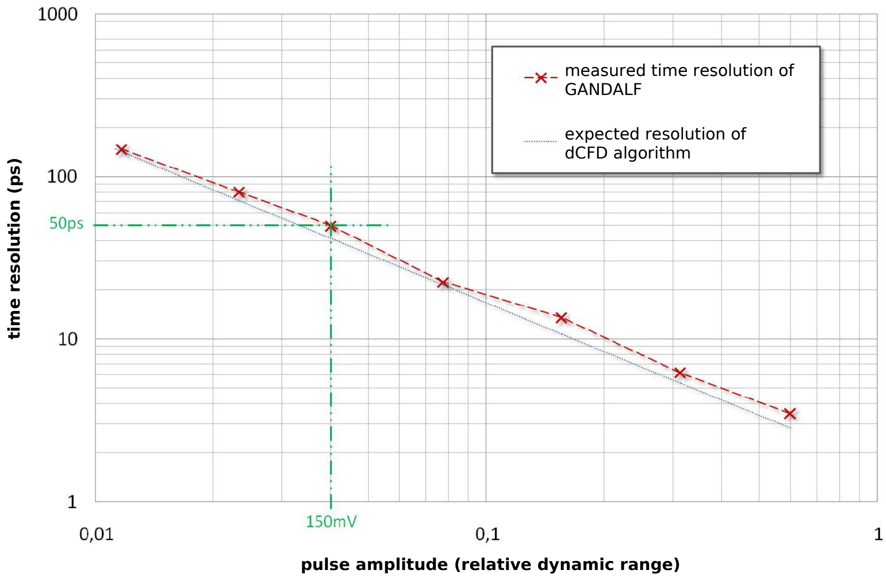


Figure 4. The time resolution of GANDALF as a function of amplitude in comparison with simulation results.

pulse. As it can be seen in figure 5, the measurements follow a characteristic shape, which is except for small signal amplitudes determined by the time resolution of the PMT- and laser system.

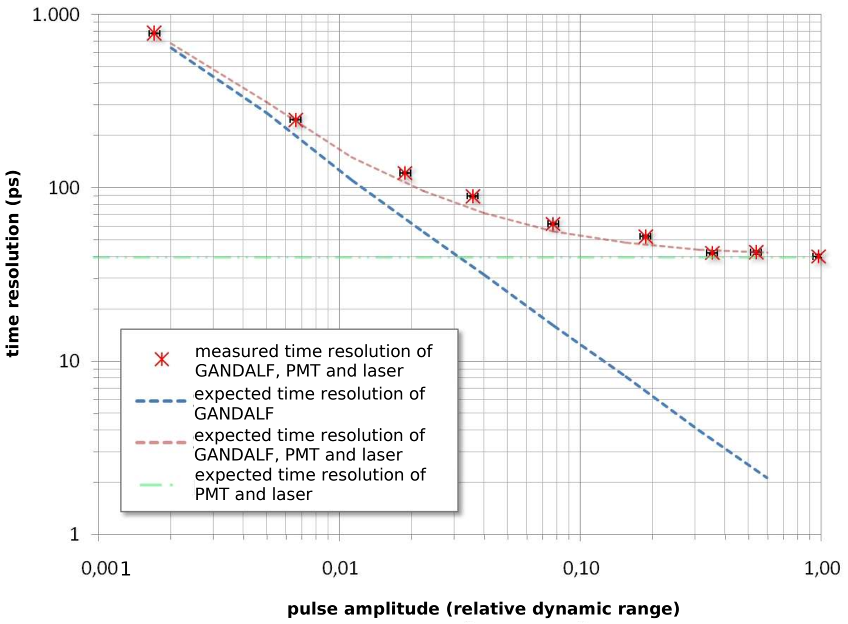


Figure 5. The time resolution measured by GANDALF using a PMT-Laser system for pulse generation. The digitization was carried out with a sampling rate of 1 GS/s.

4. The TIGER Module

A global trigger decision will be realized with the TIGER Module which is located in the center of the crate (see figure 6). This Trigger Implementation of GANDALF Electronic Readout is based on high-speed transmission of data and latest FPGA-technology. From each GANDALF Module, time and signal amplitude is transmitted through 16 differential pairs via the VXS backplane to the TIGER Module. Considering a full crate hosting 18 GANDALF Modules and a maximum clock rate of 500 MHz its data acceptance sums up to $18 \times 500\,\text{MHz} \times 2\,\text{byte} = 18\,\text{GB/s}$. The generation of a global proton trigger is then accomplished by applying user-defined physical cuts onto time and energy of corresonding slats.

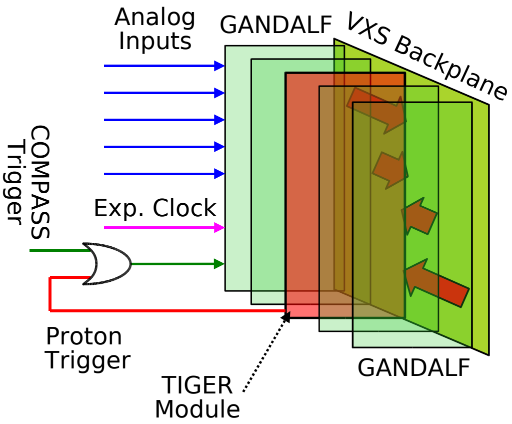


Figure 6. The generation of a proton trigger by the TIGER Module in a VXS-System.

5. Further applications of the GANDALF Module

The layout of GANDALF allows the use of different input mezzanine cards for versatile applications. For instance, a Digital Mezzanine Card (DMC) was developped. Equipped with two DMCs and all logic elements integrated into the Virtex-5 FPGA, GANDALF serves as 64 channel mean-timer, 128 channel TDC- or 128 channel scaler module. A resolution of 150 ps per TDC-channel could already be achieved.

Acknowledgments

This research project is supported by the Bundesministerium für Bildung und Forschung (BMBF) of Germany and by HadronPhysics2, a FP7 Integrating Activities and Infrastructure Program of the European Commission under Grant 227431.

References

[1] X. Ji, *Gauge-Invariant Decomposition of Nucleon Spin*, *Phys. Rev. Lett.* **78** (1997) 610-613

[2] The COMPASS-Collaboration, *The COMPASS-II Proposal*, *CERN-SPSC-2010-014; SPSC-P-340* (2010)

[3] H. C. van der Bij et al. *S-LINK*, *IEEE Trans. Nucl. Sci.* **44** (1997) 398-402

[4] L. Lauser, *Diploma Thesis, Universität Freiburg* (2009)

[5] S. Schopferer, *Diploma Thesis, Universität Freiburg* (2009)

[6] S. Bartknecht, *Research Thesis, Universität Freiburg* (2009)