

# Hardware Developments for the AMIGA Enhancement at the Pierre Auger Observatory

P. Buchholz\* for the Pierre Auger Collaboration<sup>†</sup>.

\**Fachbereich Physik, Universität Siegen, Walter-Flex-Str. 3, D57068 Siegen, Germany*

<sup>†</sup> *Observatorio Pierre Auger, Av. San Martín Norte 304 (5613) Malargüe, Prov. Mendoza, Argentina*

**Abstract.** To extend the energy threshold of the Auger Observatory to lower energies and to measure the number of muons in extensive air showers, the AMIGA (Auger Muons and Infill for the Ground Array) enhancement is being developed. The complete muon detector system, including the scintillation detectors, the analogue front-end, trigger and the digital readout electronics, as well as the power supplies and slow-control electronics, have been designed. Prototypes of all components have been produced and tested separately in system tests. The performances of all components and the complete system will be discussed.

**Keywords:** Pierre Auger Observatory, AMIGA, muon detector, readout electronics

## I. INTRODUCTION

The Pierre Auger Observatory is the largest air shower detector in the world with a hybrid detection system consisting of a surface detector array (SD) and a fluorescence detector (FD). The SD of the Southern site near Mendoza, Argentina, consists of more than 1600 water-Cherenkov detectors arranged in a triangular grid with 1500 m spacing. It is overlooked by 24 fluorescence telescopes of the FD, arranged in four groups of six telescopes each [1], [2]. The Auger collaboration has been successfully taking data for several years measuring with full efficiency energies above  $3 \times 10^{18}$  eV using the SD and above about  $10^{18}$  eV including the FD. To reach full efficiency also for lower energies down to about  $10^{17}$  eV, from which the second knee and the ankle of the energy spectrum can be fully seen and where the transition from galactic to extra galactic cosmic rays is assumed to occur, the Auger Observatory will be upgraded with two additional detector setups, AMIGA (Auger Muons and Infill for the Ground Array) and HEAT (High Elevation Auger Telescopes). HEAT will be discussed in detail elsewhere [3]. The AMIGA enhancement consists of 85 water-Cherenkov surface detectors, each with a  $30 \text{ m}^2$  plastic scintillator buried about 2.5 m underground. The final depth will be decided taking the results of the BATATA detector setup into account [4]. Out of the 85 detector stations 61 are arranged in a 750 m triangular grid and 24 in a 433 m grid. They are overlooked by the FD and HEAT. The scintillators will be used to determine the muon content of the air shower, which is one of the relevant shower parameters

e.g. for composition analyses. Since the Infill part of AMIGA, i.e. the additional arrays of surface detectors, is described elsewhere [5], this contribution concentrates on the muon detector part, especially on tests performed with a prototype system. For a detailed description of the muon detector system see also [5].

## II. THE AMIGA MUON DETECTOR

The muon detector of an AMIGA detector station consists of three independent muon scintillation counters, each divided into 64 strips and read out by a 64 channel multi anode photomultiplier (PMT). To process the PMT output signals, a modular readout system of four different electronic boards has been developed and prototypes of all modules have been produced and successfully tested. These modules are the Mother Board (MB), the Daughter Board (DB), the Digital Board (DGB) and the Power Distributor Board (PDB). By the end of 2009 a muon counter prototype will be installed in the Auger array using a 4.8 m long scintillator module (Figure 2) and the complete electronics system consisting of the existing prototypes. Following a test run of about two months with this detector, another prototype detector, consisting of a 8.8 m long scintillator module, will be added. After another test run period the first final muon counter of the AMIGA array will be installed. To equip all 85 AMIGA detector stations almost 3000 individual boards are needed, which underlines the need for an automatized test system during mass production. Each of the 85 AMIGA muon counter electronics setups will be tested and fully characterised in Siegen before being installed in the AMIGA array without any further dismantling. In the following, short descriptions of all boards and the corresponding test results are given. Figure 1 shows an overview of the complete prototype system and Figure 3 a picture of the assembled system in the laboratory.

### A. Mother Board

The MB provides a socket for the multi-channel PMT, its power supply and monitoring of the high voltage applied. Signals are distributed to 8 DBs, plugged into the MB. In all tests concerning the steering and monitoring of the high voltage of the PMT, the MB prototype performed as specified.

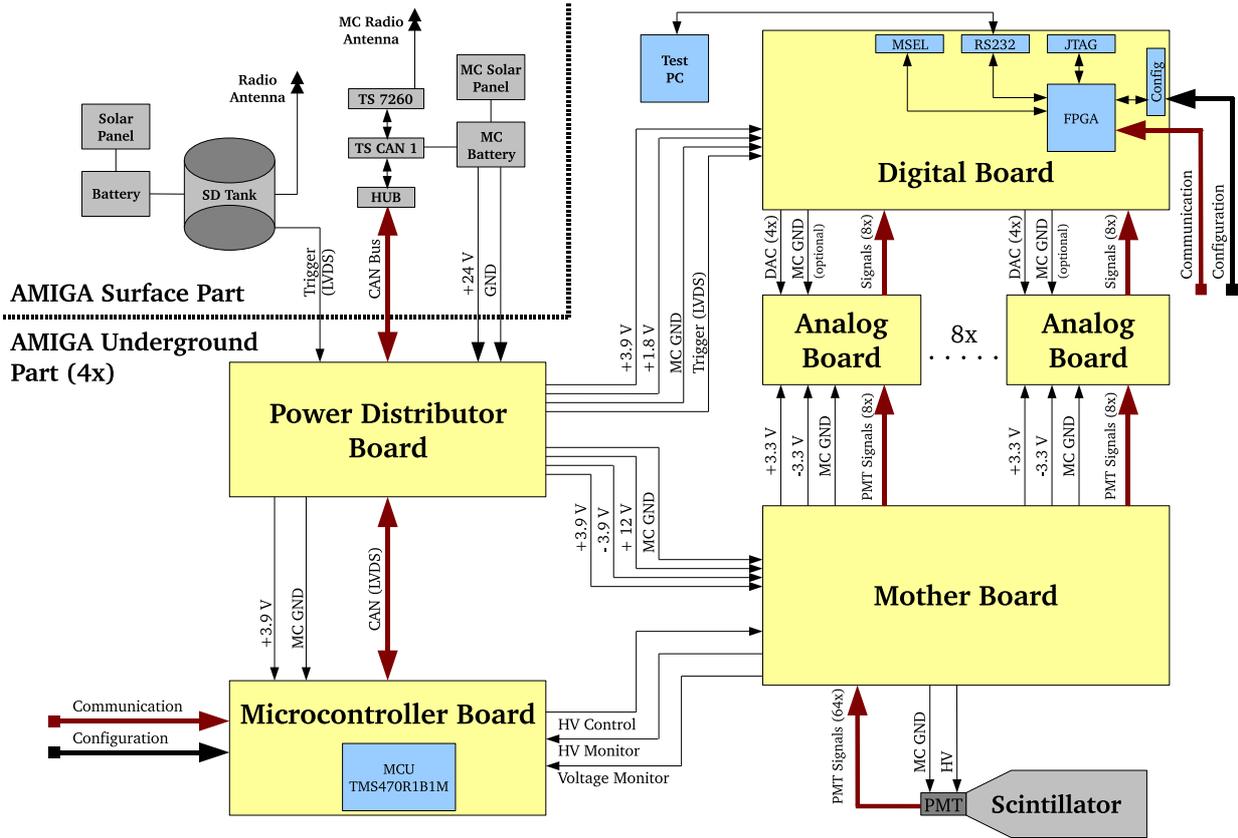


Fig. 1: Schematic overview of the AMIGA muon counter prototype system.

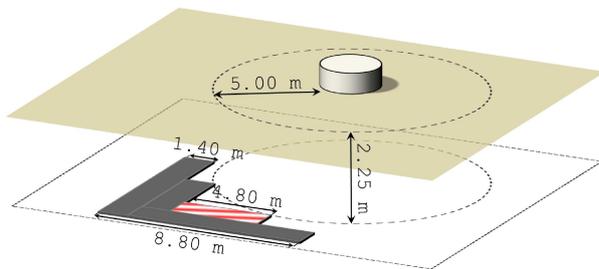


Fig. 2: Schematic view of one possible arrangement of the AMIGA detector pair consisting of one SD station and four buried muon scintillation counters. The hatched module with a length of 4.8 m will be used for the first prototype.

### B. Daughter Board

The DB is the signal forming module of the muon counter electronics chain. Each DB consists of eight channels, in which the analogue photomultiplier signals distributed by the MB are inverted and amplified by operational amplifiers by a factor of about 3.1. In a second step, the outputs of the operational amplifiers are compared to a given threshold. In case the amplitude of the signal in one channel exceeds the threshold voltage, the digital output signal of this channel is set to zero.



Fig. 3: Picture of the prototype system as assembled in the laboratory.

To compensate variations of the PMT gains as well as variations of the gains of the operational amplifiers, the threshold voltage can be set individually for each channel using an eight channel DAC (digital-to-analog converter) on each DB. Figure 4 shows measured single electron input pulses and the corresponding output of the DB. The bandwidth of the DB has been measured as  $(134 \pm 5)$  MHz, which is more than sufficient. The typical behaviour of a single channel is shown in Figure 5.

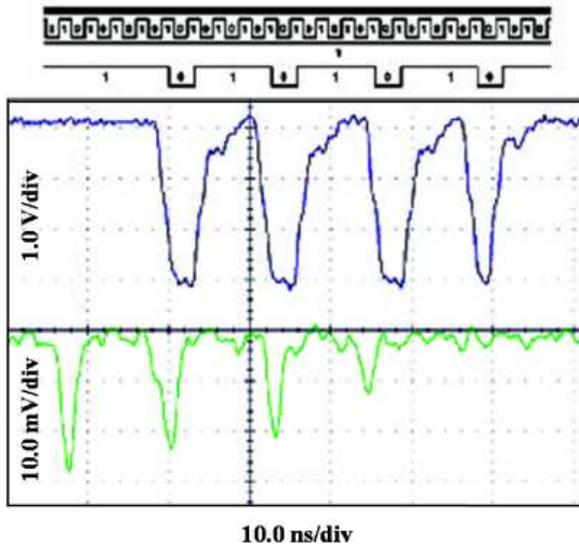


Fig. 4: Example of measured input and output pulses of the DB. The lower graph shows the amplitude of the input pulses, the middle graph the comparator output and the two upper graphs the clock and the resulting digital data in the FPGA.

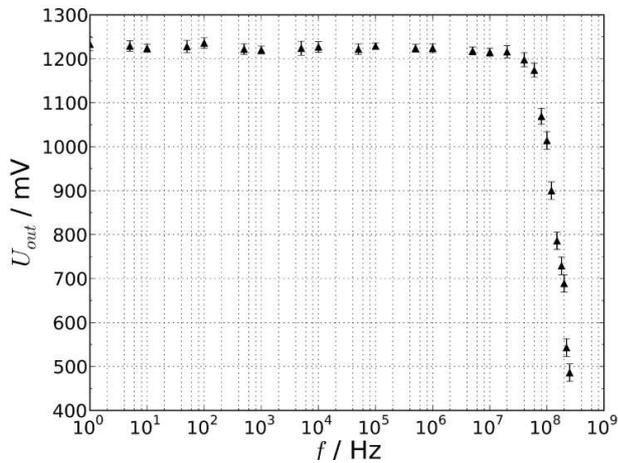


Fig. 5: Bandwidth measurement of a typical DB channel.

C. Digital Board

The DGB continuously stores the digitised data received from the DBs into a ring buffer. Receiving a trigger signal (T1) from its corresponding SD station digitised muon data of 1.6  $\mu$ s before and 3.2  $\mu$ s after the trigger signal are stored in a memory. Only the muon data confirmed by a higher trigger level signal (T3) is sent via radio to the central data acquisition.

This readout is realized by using an FPGA, an external RAM, a microcontroller unit (MCU) and a single board

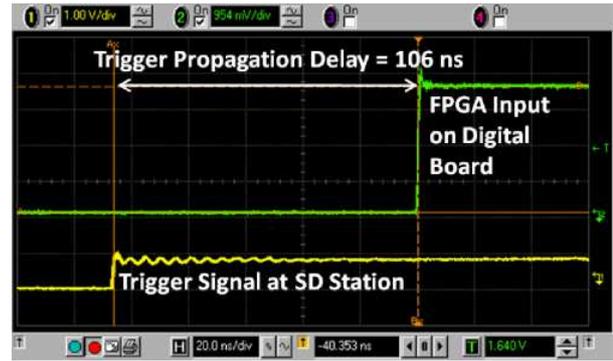


Fig. 6: Measured trigger propagation delay.

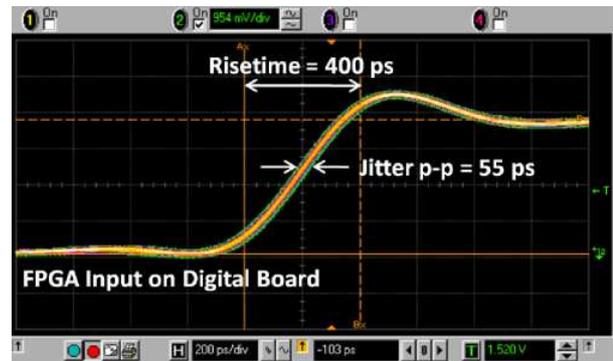


Fig. 7: Measured signal jitter.

computer (SBC) and is described in detail in [6]. The tests discussed here were performed using a prototype system consisting of two separate boards, one for the FPGA and one for the MCU. These will be merged into one DGB in the next iteration.

To synchronise data from the muon detectors with events recorded by the SD, a dedicated line for the T1 trigger is used. The signal delay of this line has been measured using the prototype system. It stems from the cable length of about 15 m, the galvanic isolation in the underground electronics and the latencies of the transmitter and receiver module. The latter also adds jitter to the signal.

As can be seen in Figures 6 and 7 a delay of 106 ns and a jitter of about 55 ps have been measured. Since the digital input pulses from the DBs are sampled with a rate of 320 MHz by the FPGA, which corresponds to sampling intervals of 3.125 ns, this jitter is negligible.

D. Power Distributor Board

The PDB derives all supply voltages needed by the electronics modules from the battery voltage of + 24 V. In addition, the ground levels of both detectors, the SD station and the muon detector, are electrically isolated from each other to reduce noise generated by ground

loops. For the same reason, also the ground levels of the communication lines (trigger and CAN) are isolated by the PDB. The PDB performed in all tests within its specifications.

### III. SYSTEM TESTS

The full readout chain has been set up using the prototype modules described above, i.e. the performance of the complete system can be studied. As an example Figure 8 shows the efficiency of one channel of the readout system as a function of the input signal amplitude for a given comparator threshold.

Instead of connecting a scintillator and a PMT to the electronics, a pulse generator is used. The output of the pulse generator can be fanned out with a 64-channel multiplexer to each of the 64 input channels, using a specially developed interconnection card. Square-pulses at 200 Hz, with a width of 100 ns and variable amplitudes, are used. For each amplitude, 1000 pulses are sent to the electronics.

For the FPGA, special system test software was developed. The comparator thresholds of the 64 readout channels are programmed. The FPGA is reading the comparator output information with 160 MHz. If a digital 0 is detected on at least one channel, a trigger flag is set and the information of all comparators at trigger time and the following 4 sample times is given to the microcontroller together with a timestamp. The system test software driving the microcontroller then submits these data to a PC via Serial Port.

Thus, depending on the amplitudes of the input pulses, the electronic noise of each channel can be extracted from the efficiency curves recorded as shown in Figure 8 for a single channel.

The threshold voltage of the comparator has been set to 14.7 mV including an offset value of 9.7 mV. This offset has been measured when programming the comparator to nominal 0 V. The output voltages of the comparator can be set with a precision of 1 mV.

The data points were fitted with the function  $f(u)$  given in Equation 1.

$$f(u) = 0.5 + 0.5 \cdot \frac{2}{\sqrt{\pi}} \int_0^u e^{-t^2} dt \quad (1)$$

In Equation 1,  $p_0$  in  $u = \frac{x-p_0}{p_1}$  describes the position and  $p_1$  the width of the s-curve. A  $\chi^2$ -fit has been performed and the threshold level has been reconstructed at  $(15.1 \pm 0.1)$  mV. The electronic noise is below a level of  $(0.33 \pm 0.04)$  mV, determined from the width of the fitted curve as  $U_{\text{noise}} = 1.812 \cdot \frac{p_1}{2}$ .

The system tests so far employ especially developed code. As soon as the original/final codes for the FPGA and the microcontroller are available, these will be used also in the system tests.

The data transferred has been checked for its correctness and no errors have been found at a CAN bus transmission rate of 1 Mbps. In future the test system

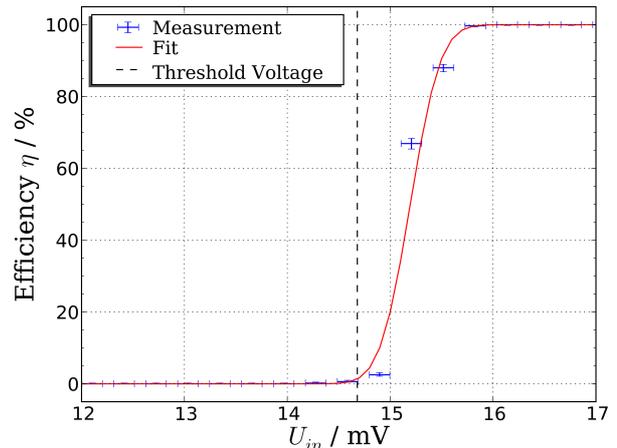


Fig. 8: Readout efficiency for a single channel using system test software. The adjusted threshold and the electronic noise level were reconstructed.

will be used for several additional tests, e.g. crosstalk measurements. In parallel, the test procedures for the mass production of the final system are being developed and checked.

### IV. SUMMARY

A muon detector system has been developed for the AMIGA enhancement of the Pierre Auger Observatory. This development includes a complete prototype system of the highly modular readout electronics, which has been successfully produced and tested. The performances of all components are well within their specifications. The bandwidth of the analogue front-end has been measured to be sufficiently large and the trigger propagation delay has been determined and shows negligible jitter. In addition, the readout efficiency of the complete system has been measured as a function of the input signal amplitude, which shows, that the system is fully efficient above threshold.

### REFERENCES

- [1] J. Abraham et al. [Pierre Auger Collaboration], NIM A 523 (2004) 50.
- [2] I. Allekotte et al. [Pierre Auger Collaboration], NIM A 586 (2008) 409-420.
- [3] M. Kleifges [Pierre Auger Collaboration], these proceedings # 410, 2009.
- [4] G. Medina-Tanco [Pierre Auger Collaboration], these proceedings # 137, 2009.
- [5] M. Platino [Pierre Auger Collaboration], these proceedings # 184, 2009.
- [6] Z. Szadkowski [Pierre Auger Collaboration], these proceedings # 371, 2009.