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Development of a Front-End Electronics for YAC-III detectors of Tibet ASgamma experiment

M. Amenomori[1], X. J. Bi[2], D. Chen[3], T. L. Chen[4], W. Y. Chen[2], S. W. Cui[5], Danzengluobu[4], L. K. Ding[2], C. F. Feng[6], Zhaoyang Feng[2], Z. Y. Feng[7], Q. B. Gou[2], Y. Q. Guo[2], H. H. He[2], Z. T. He[5], K. Hibino[8], N. Hotta[9], Haibing Hu[4], H. B. Hu[2], J. Huang[2], H. Y. Jia[7], L. Jiang[2], F. Kajino[10], K. Kasahara[11], Y. Katayose[*12], C. Kato[13], K. Kawata[14], M. Kozai[13], Labaciren[4], G. M. Le[15], A. F. Li[16,6,2], H. J. Li[4], W. J. Li[2,7], C. Liu[2], J. S. Liu[2], M. Y. Liu[4], H. Lu[2], X. R. Meng[4], T. Miyazaki[13], K. Mizutani[11,17], K. Munakata[13], T. Nakajima[13], Y. Nakamura[13], H. Nanjo[1], M. Nishizawa[18], T. Niwa[13], M. Ohnishi[14], I. Ohta[19], S. Ozawa[11], X. L. Qian[6,2], X. B. Qu[20], T. Saito[21], T. Y. Saito[22], M. Sakata[10], T. K. Sako[14], J. Shao[2,6], M. Shibata[12], A. Shiomi[23], T. Shirai[8], H. Sugimoto[24], M. Takita[14], Y. H. Tan[2], N. Tateyama[8], S. Torii[11], H. Tsuchiya[25], S. Udo[8], H. Wang[2], H. R. Wu[2], L. Xue[6], Y. Yamamoto[10], K. Yamauchi[12], Z. Yang[2], S. Yasue[26], A. F. Yuan[4], T. Yuda[14], L. M. Zhai[2], H. M. Zhang[2], J. L. Zhang[2], X. Y. Zhang[6], Y. Zhang[2], Yi Zhang[2], Ying Zhang[2], Zhaxisangzhu[4], X. X. Zhou[7]

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(The Tibet ASγ Collaboration)

[1]*Department of Physics, Hirosaki University, Hirosaki 036-8561, Japan*
[2]*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[3]*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*
[4]*Department of Mathematics and Physics, Tibet University, Lhasa 850000, China*
[5]*Department of Physics, Hebei Normal University, Shijiazhuang 050016, China*
[6]*Department of Physics, Shandong University, Jinan 250100, China*
[7]*Institute of Modern Physics, SouthWest Jiaotong University, Chengdu 610031, China*
[8]*Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan*
[9]*Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan*
[10]*Department of Physics, Konan University, Kobe 658-8501, Japan*
[11]*Research Institute for Science and Engineering, Waseda University, Tokyo 169-8555, Japan*
[12]*Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan*
[13]*Department of Physics, Shinshu University, Matsumoto 390-8621, Japan*
[14]*Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan*
[15]*National Center for Space Weather, China Meteorological Administration, Beijing 100081, China*
[16]*School of Information Science and Engineering, Shandong Agriculture University, Taian 271018, China*
[17]*Saitama University, Saitama 338-8570, Japan*
[18]*National Institute of Informatics, Tokyo 101-8430, Japan*
[19]*Sakushin Gakuin University, Utsunomiya 321-3295, Japan*
[20]*College of Science, China University of Petroleum, Qingdao, 266555, China*
[21]*Tokyo Metropolitan College of Industrial Technology, Tokyo 116-8523, Japan*
[22]*Max-Planck-Institut für Physik, München D-80805, Deutschland*
[23]*College of Industrial Technology, Nihon University, Narashino 275-8576, Japan*
[24]*Shonan Institute of Technology, Fujisawa 251-8511, Japan*
[25]*Japan Atomic Energy Agency, Tokai-mura 319-1195, Japan*
[26]*School of General Education, Shinshu University, Matsumoto 390-8621, Japan*

To measure heavy component of cosmic ray composition around the knee energy region, Yangbajing Air shower Core (YAC-III) experiment is planned in Tibet, China. We developed a new front-end electronics to read out charge signal from YAC detectors. The readout system consists of a charge-to-time converter circuit and a time-to-digital converter circuit. The system has a linearity of more than three orders, i.e., from less than 1 pC to more than 1000 pC. Two photomultiplier tubes of different sensitivity are used to achieve a wide readout range of six orders to measure the high energy particles at the air shower core by converting them into the electromagnetic cascades of up to 10^6 size through the lead plates of the YAC detector.

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*Speaker.

1. Introduction

The mechanisms of cosmic ray acceleration and distributions of acceleration sources are reflected in an observed spectrum of the cosmic ray nuclei, and precise measurements of these are considered key in solving the mystery of the origin of cosmic rays. To study the origin of galactic cosmic rays, we measure the intensities of cosmic nuclei with energies around $10^{14} \sim 10^{16}$ eV called ”knee region”. We have been performing air shower observations using both an air shower array (Tibet-III) and air shower core detectors at Yangbajing highlands, Tibet, China, which is at an elevation of about 4300 m. In this method, we measure the energy of primary cosmic ray particle at the altitude around which the size of an air shower is near maximum and we are able to discriminate primary nuclides by measuring the lateral density distribution of high-energy particles in a shower core. This method enables nuclide discrimination that minimizes “differences due to an assumption about the composition of primary cosmic rays” and “dependence on air shower interaction models”, both of which are major causes of systematic errors in indirect measurements of cosmic rays.

To measure the spectra of primary protons and helium nuclei, we performed Phase I experiments from 1996 to 1998 by using air shower core detectors composed of both emulsion chambers and scintillators located below the emulsion chambers. In addition, we performed Phase II experiments to confirm the validity of the observation results. As a result, we revealed that the ratio of light atomic nuclei to the all particles gradually decreases for energies greater than 100 TeV and heavy particles become dominant in the knee region [1][2][3]. In addition, the sharpness of the bend in the all-particle spectrum measured by Tibet-III cannot be explained by a simple superposition of spectra from each atomic nuclei predicted by Fermi acceleration in supernova remnants, and it was suggested that there exists a possible component that has a specific spectrum around the knee [4][5]. On the other hand, the position of the bend in a proton spectrum and a helium spectrum, and the proportions of atomic nuclei heavier than helium are not well known with satisfactory accuracy. To clarify how the intensity of compositions varies with much higher accuracy, we developed a new core detector (YAC ; Yangbajing Air shower Core detector) to measure high-energy particles in an air shower core. We have also been developing a method to discriminate nuclides by differences of the lateral distribution of shower core particles using Monte Carlo simulations [6][7]. In 2009, for a test measurement, we installed the YAC-I array ($\sim 10\text{m}^2$), in which 16 YAC detectors were placed in grids with dense spacing in the center of the Tibet-III array, and performed observation experiments [8]. The energy range of the measurement is around 100 TeV, where a high-accuracy composition was obtained by direct observation. Hence, we could investigate an interaction model combined with calculation by simulations. In addition, to observe the spectra of protons and helium nuclei with energies from 50$\sim$10000 TeV, we built the YAC-II array (Figure 1) in which the number of detectors was increased to 124 ($\sim 500\text{m}^2$). We have been performing continuous observations using the YAC-II array together with the Tibet-III array and muon detectors (MDs) since 2014 [9]. It is expected that an accurate result in the shape of a knee in a proton spectrum and helium spectrum will be clarified by our observations.

It is reported by many observations that as energy increases, the average mass number of cosmic ray compositions tends to increase. However, there is no clear result, since there are large systematic errors due to observation methods, dependence on interaction models used for analyses, etc. We plan to perform YAC-III experiment in the future, in which the number of detectors will be increased to 400 to measure the composition of heavy cosmic ray nuclei such as iron. For this purpose, we have been developing a new data acquisition system, and we report its development status in this study.

2. YAC detector

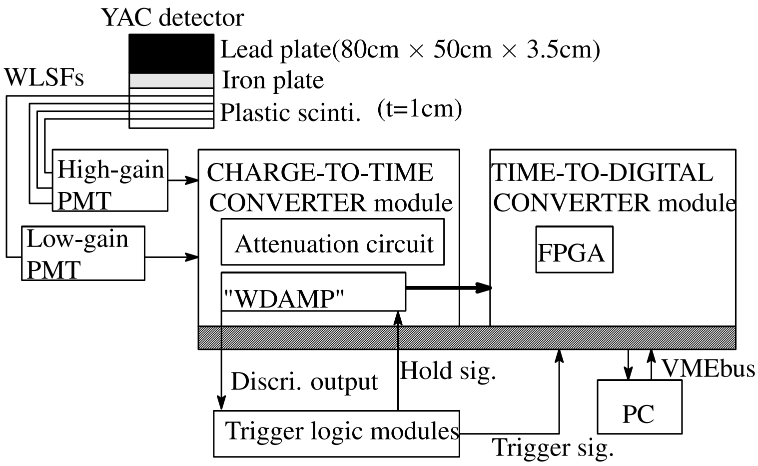

Figure 1: Design of YAC detector and block diagram of data acquisition system

As shown in Figure 1, each YAC detector is composed of a lead plate with an area of 50 cm×80 cm and a thickness of 3.5 cm, plastic scintillators of 1cm thickness placed under the lead plate, wavelength shifting fibers (WLSFs) along the scintillator, and two photomultiplier tubes (PMTs), each with a different gain. To measure high-energy particles of an air shower core, the thickness of the lead plate was designed to be 6.3 radiation lengths. Scintillation counter measures the number of secondary electromagnetic particles generated in the lead plate. The number of measured secondary particles increases with the energy of the primary cosmic ray, reaching 10^6 particles for 10^{16} eV. In addition, the minimum ionization particles (MIPs) resulting from muons need to be measured for calibration of the number of particles for the instrument. For such a reason, each YAC detector has two read-out systems with different gains. One part (high-gain part) uses a higher gain PMT in which twenty WLSFs are bundled to obtain a high gain, while the other part (low-gain part) uses a lower gain PMT in which ten WLSFs are bundled to obtain a low gain. This enables the high- and low-gain parts to be used for measurements for $1 \sim 10^4$MIPs and $10^3 \sim 10^6$ MIPs, respectively. Therefore, signal read-out electronics are also required to have a broad measuring range of more than three order of magnitude.

3. Read-out system

As shown in Figure 1, the data acquisition system is composed of a charge-to-time converter (QTC) circuit to integrate charge pulses from PMTs and convert the charge pulses to a logic signal that has a time width proportional to the electric charge, and a time-to-digital converter (TDC)

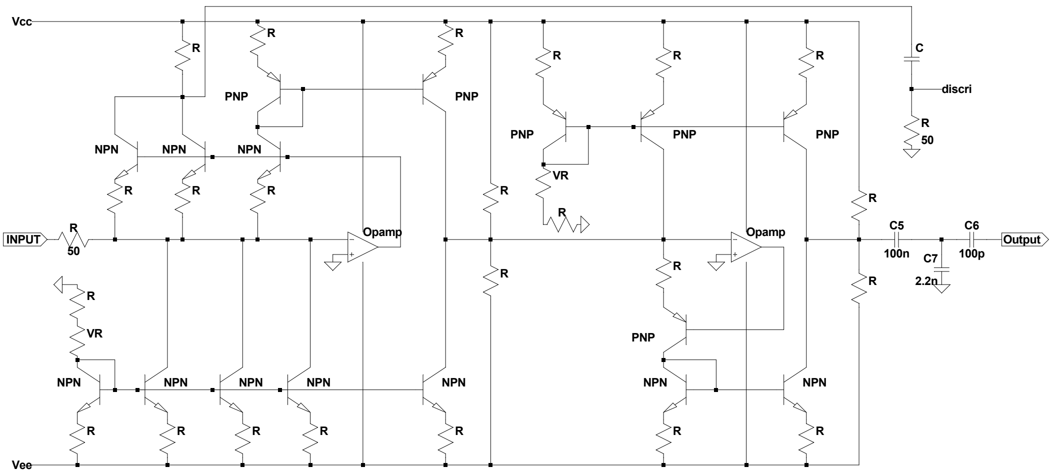

Figure 2: Circuit diagram of attenuation circuit.

circuit to digitize the time width. In the YAC-III experiment, 400 YAC detectors are used to measure an air shower core, which expands owing to heavy cosmic ray nuclides. Therefore, 800 channels in read-out circuits for two PMT signals from each detector are required.

3.1 Charge sensitive amplifier

For a QTC, we use a “Wide Dynamic range Amplifier (WDAMP)” [10], which is an ASIC developed to read out signals from a semiconductor photo-sensor like a photodiode. The WDAMP ASIC consists of a charge sensitive preamplifier, four wave-shaping circuits with different amplification factors and Wilkinson-type analog-to-digital converter (ADC). The output of a preamplifier is shared by the four wave-shaping circuits with four amplification factors 1:4:16:64 to adapt the input range of ADC. Hence, a WDAMP can measure charges in a very large range with more than four orders of magnitude, from less than 1 fC to more than 20 pC. On the other hand, the range of charge signals from PMTs in a YAC detector is about 1 pC to 1000 pC; therefore, we developed a circuit that damps PMT charge pulses to 1/50 $\sim$1/100. As shown in Figure 2, the attenuation circuit is composed mainly of a current mirror type attenuation circuit, a capacitive T-type attenuation circuit, an inverting circuit, and a current bias circuit. The input part is connected to the current mirror circuit that comprises three PNP transistors, and charges are damped to one third of the original. In addition, the base current of a transistor is controlled by an operational amplifier that has a virtual ground to reduce input impedance. We installed 2200- and 100-pF capacitors in the capacitive T-type circuit in the subsequent part. In a simulation calculation using SPICE code, a charge pulse is damped to 1/3.3 by the current mirror type circuit , and the damping rate after the pulse passes through the capacitive T-type circuit is $\sim$1/73. The inverting circuit is used to adjust the polarity of PMT signals to the input polarity of the WDAMP.

3.2 Time to digital converter

The output charge for 1 MIPs of the high-gain PMT is adjusted to about 500 fC $\sim$ 1 pC. These charges are measured by the Gain 64 channel in the WDAMP ASIC. The output pulse width for 100 fC is approximately 100 ns, and a TDC with a resolution of several nanoseconds is required to

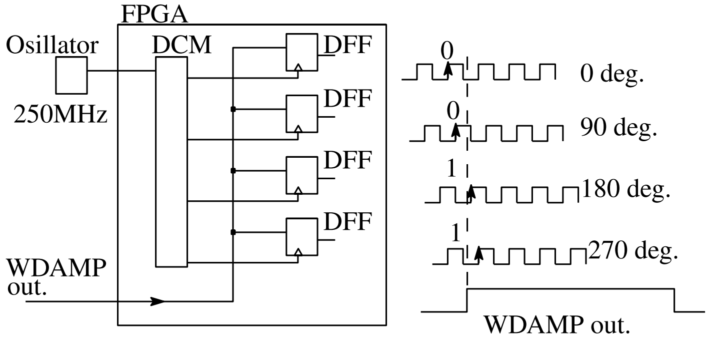

Figure 3: Conception diagram of TDC circuit

digitize the output within the accuracy of several percent. We fabricated a TDC circuit with a field programmable gate array (FPGA) using a hardware description language, and we implemented it in a general-purpose FPGA produced by Xilinx. The simplest way to measure pulse width is to measure the time width of a state with the logical value of the input pulse being " 1 " using an external clock. However, there is a limit for external clock frequencies. For instance, the time resolution obtained using a crystal oscillator with 250 MHz is ± 4 ns. Furthermore, in order to improve the time resolution, we made a circuit with four clocks, each of which has a phase difference of 90°. In the right part of figure 3, an input pulse and the four clocks, each with a phase difference of 90°, are shown. The state of an input pulse is latched by these four clocks by using a D flip-flop. The FPGA produced by Xilinx (Spartan3A), which was used in this study, can generate four clocks, each with a phase difference of 90°, by using an external clock. In the example in the figure, the state latched by the clock with a phase of 270°, which has the most delayed timing, is " 1 ". Similarly, the ones by the clocks with phases of 0°, 90°, and 180° are "0", "0", and "1", respectively. In principle, we obtain the time information with an accuracy of 1 ns from the pattern of "0011". By implementing TDC circuits for 16 channels in the Spartan3A and investigating the time accuracy of each TDC, we found that the standard deviation of the distribution of measuring times within a range of the input pulse width up to 30μs was less than ± 1.5 ns. There was a systematic deviation in each channel, but it can be removed by calibration.

4. Performance of read-out system

To evaluate the performance of the read-out system, we made a test VME board composed of four channels that was incorporated with the attenuation circuit and the WDAMP. The attenuation circuit was implemented in a mezzanine card, and it was installed on the VME board. The power sources of the attenuation circuit, and those of the analog processing part and the digital control part of the WDAMP were made using the same power sources of the VME with $+5$ V and ± 12 V. A logic signal from the WDAMP was converted to an LVDS signal, and the time width was digitized by using a TDC implemented in an commercial FPGA evaluation board and transferred to a PC.

4.1 Linearity

To investigate the dynamic range of the system, we used test charge pulses generated by using

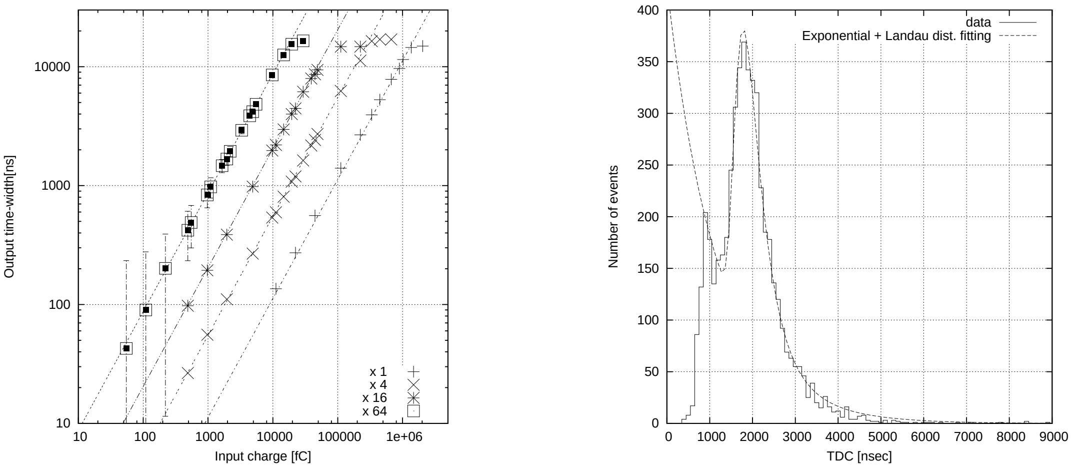

Figure 4: Left figure is lineaity curve of a typical channel for negative charge input. The upper data points shows high-gain output and the lower data shows low-gain output. Right figure is cosmic ray muon distribution measured by YAC detector with the read-out system.

rectangular voltage pulses and capacitors, and we input them into the attenuation circuit. In left figure of 4, the horizontal axis represents an input charge, and the vertical axis represents the pulse width measured by the TDC. The WDAMP has four outputs since an input is amplified in four shaping circuits with different gains. The slope of the line that fits the data of Gain-64 channel is 8.7×10^{-1} [ns/fC] approximately, and a linearity is observed up to about 20 pC. The error bars in the figure represent the standard deviation per event, which is about 188.7 ns; it is 216 fC when converted to an electric charge. The slopes of fitting plots for Gains -16, -4, and -1 channels were approximately 2.0×10^{-1} [ns/fC], 5.5×10^{-2} [ns/fC], and 1.1×10^{-2} [ns/fC], respectively. In the data of Gain-1 channel, the region that was more than 400 pC was fit with an error function, and we defined the linearity as the value of the input charge that results in 5% deviation of the curve from the linear line. Here, the linearity was up to 1300 pC approximately.

4.2 Measurement of 1MIP with cosmic ray muon

Using this read-out system and the YAC detector, we confirmed that 1 MIP resulting from secondary cosmic ray muons was observed without being buried under noise. Two trigger scintillators were placed above and below the YAC detector, and we obtained data by using the coincidence of signals in the two trigger scintillators. As shown in right figure of 4, the output from the high-gain part of the YAC detector measured by the Gain-64 channel in the WDAMP showed the Landau distribution overlaid on the tail of the exponential noise distribution. The peak was well separated from the noise part. The peak position was approximately 1865 ns when the data were fit with the sum of the Landau distribution and the exponential distribution, and it was approximately 1.0 pC when the pedestal was subtracted and converted to an electric charge.

5. Summary

We developed a data acquisition system that consists of a QTC module and a TDC module for YAC-III experiment. The QTC uses an attenuation circuit and a charge amplifier ASIC ("WDAMP") . The attenuation circuit was composed of a current conveyer circuit that uses transistors and a capacitance-type attenuation circuit. The damping rate was about 1/70, which enables uniform damping of charges ranging from 100 fC to more than 1000 pC to those ranging from several femtocoulombs to ten and several picocoulombs. The TDC was implemented in an FPGA, and could obtain measurements with an accuracy of 1.5 ns approximately. With examination using test charge pulses, we confirmed linearity up to 1300 pC, and the noise level at Gain channel 64, which has the maximum gain, was about 200 fC. In addition, from measurement results of cosmic ray muons, a measuring range up to 1300 MIPs was verified when 1 MIP was measured with 1.0 pC by the high-gain part. If the low-gain part is used for measurements from 1000 MIPs, we can measure the number of core particles with wide range from 1MIP to 10^6 MIPs using the two read-out systems. On the other hand, the noise level was around 200 fC. It is possible to reduce the noise by improving the capacity damping part in the attenuation circuit and reconsidering the ground of the analog circuit power source. In addition, for the TDC, it is possible to obtain highly accurate time measurements by using an FPGA with fast signal processing speed. In the future, we plan to integrate module substrates for charge-time conversion, and perform a verification experiment by using an actual instrument.

Acknowledgments

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