第 30 卷 第 12 期
2006 年 12 月
高 能 物 理 与 核 物 理
HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS
Vol. 30, No. 12
Dec., 2006

Performance of the ALICE PHOS Front-End Electronics*

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Abstract The physics requirements and the main characteristics of the current design of the front-end electronics (FEE) of ALICE photon spectrometer (PHOS) are discussed. A dedicated test facility has been established in Wuhan to evaluate the physics performance of PHOS FEE. The test results show that the current FEE prototype has met the physics requirements of the PHOS detector.

Key words ALICE PHOS, front-end electronics, physics performance

1 Introduction

The collision of lead ions at the LHC at $\sqrt{s_{\rm NN}}=$ 5.5TeV, a factor of about 30 higher than that available at RHIC, will take heavy-ion physics into a new high energy regime with much higher energy density. Particle production at LHC is expected to be determined by the high density or saturated parton distributions and hard processes[1]. In particular, very hard strong interacting probes, whose attenuation can be used to study the hot and dense nuclear matter formed in the collision, will be produced at sufficiently high rates for detailed measurements. Weak interacting hard electromagnetic probes such as direct photons, which will provide information about nuclear parton distributions at very high Q^2, become also accessible.

The PHOS detector[2] in ALICE experiment[3] is dedicated to measuring photons, π^0 and η in a broad $p_{\rm T}$ range at mid-rapidity. Its primary goal is detection of a direct photon signal, which is considered to be the best means to determine the temperature of the initial phase of the collision. In addition, to provide information on both final- and initial-state effects on particle production, the $p_{\rm T}$ spectra of π^0 and η's need to be measured from about a hundred MeV/c up to 100GeV/c. Detection of high $p_{\rm T}$ photons allows to trigger on hard scattering in which a jet has been produced (i.e. γ-tagged jet). The emitted photon, which escapes the medium unaffectedly, will provide a kinematic tag for the recoiling quark or gluon which will suffer large energy loss[4] in the evolution of ultra-relativistic heavy-ion collisions. Thus, by triggering on a high $p_{\rm T}$ photon in PHOS and searching for and reconstructing a jet by using TPC and EMCal detectors, one can study in detail the nuclear modification of the parton fragmentation function and extract information on the property of the de-confined nuclear medium.

PHOS, consisting of 17920 detection channels of lead-tungsten crystals, $PbWO_4$ (PWO), of 2.2cm×2.2cm×18cm dimensions, is a high resolution electromagnetic calorimeter. To limit the punch-through effect on the energy resolution[5], crystals will be coupled to 5mm×5mm avalanche photo-diodes (APDs) which signal will be processed by low-noise

Received 22 February 2006

* Supported by National Natural Science Foundation of China (10547118, 10575044), China Ministry of Education for the Grand Science & Technology Research Project ([2006]55) and Scientific Research Foundation for the Returned Overseas Chinese Scholars, China Ministry of Education

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charge-sensitive preamplifiers (CSPs). The output of the pre-amplifiers will then be processed by a front-end electronics (FEE) to derive energy and timing information of the detected particles. In this paper, we will describe firstly in brief the physics requirements and the current design of the PHOS FEE in the section 2, then the setup of the test facility in section 3, and finally the results from the test in section 4.

2 The physics requirements and the current design of the PHOS FEE

The main physics requirements for the front-end electronics can be summarized as the followings:

1) The energy resolution of a calorimeter is commonly parameterized as

$$\frac{\sigma_E}{E}=\sqrt{\frac{a^2}{E^2}+\frac{b^2}{E}+c^2}, \tag{1}$$

where a represents the electronic readout noise, b stands for the stochastic fluctuations in the involved physical processes, and c indicates inhomogeneities in the detector and readout in addition to the energy detection loss and calibration errors. These parameters are required in the ALICE technical proposal[3] and PHOS technical design report[6] to be less than 0.03GeV, 0.03GeV$^{1/2}$ and 0.01 when E is in units of GeV. This requires that FEE has an electronic noise per channel of 5MeV or less, and also high inter-calibration precision of APD gain and uniformity across all channels.

2) The FEE should cover large energy dynamics range with the least count energy of 5MeV. To obtain an optimum energy resolution for the low energy region up to 10GeV together with less stringent resolution requirement for high energy region, it is desired that each signal from the pre-amplifier is processed by two shapers with “high” and “low” amplification and digitized by separate ADCs.

3) In order to select rare interesting high p_{T} events, PHOS is required to provide level 0 (L0) and level 1 (L1) trigger information to ALICE central trigger processor within limited time.

4) Simulation study shows that the time-of-flight resolution should be smaller than 2ns in order to discriminate against 1—2GeV/c anti-neutrons and limit the contamination of photons by anti-neutrons to a level below 2%[7].

5) The APD gain is strongly dependent on the reversal bias voltage. A large spread of the APD gain would result in either overflow in the high gain channels or resolution degradation in low gain channels and a significant degradation of the accuracy in the L0/L1 trigger information. Thus an individual bias voltage is required for each APD.

To fulfil the above requirements, an extensive research and development program on PHOS FEE prototype has been carried out jointly by CERN and Wuhan group in the past two years. The current prototype is described in detail in reference[8]. Here only the main characteristics and functionalities are summarized as the followings:

1) To cover a large dynamic range with optimal energy resolution, 64 second-order (CR-RC2) signal shapers are implemented on a 10-layer board with a gain ratio of ~ 16 for two shaper sections digitized separately with 10 bit ADCs contained in 4 ALTRO-16 chips[9]. An energy range from 5MeV to 5.12GeV is covered by the high gain channels, while a range of 80MeV to 81.92GeV is covered by the low gain channels.

2) With the second order implementation of the shaper, the output shape in time domain can be well described by a Γ-2 function[10],

$$V_{\mathrm{o}}=Ped+Amp*x^2*\exp(-2x+2), \tag{2}$$

where $x=(t-T_{\max}+Tau)/Tau$. $T_{\max}$ is the time when the signal reaches its maximum, Tau is the peaking time of the shaper, which is twice of the shaping time. Amp is the amplitude of the signal, and Ped is the pedestal level added to it.

3) The ALTRO-16 chip contains multiple buffers of up to 512 samples for each ADC, which can be sampled at a frequency up to 10MHz. The digitized pulse-shapes can be readout from the buffers via a custom GTL bus and used in off-line analysis to reconstruct the pulse shape so as to extract the energy and time-of-flight information of particles.

4) The gain for each individual APD is controlled

via 32 bias voltage control registers of 10 bit.

5) For trigger purpose, “fast-OR” output with 12 bit dynamic range are available.

3 The setup of the test facility in Wuhan

To evaluate the performance of the FEE card, it is desired that a test-bench includes the full readout chain under the same conditions as in experiment. Thus, as sketched in Fig. 1, a test facility has been set up in Wuhan with APDs, pre-amplifiers, T-card, Intermediate PCB (IPCB), FEE, GTL backplane, Readout Control Unit (RCU) card[11], Detector Control System (DCS) card[12], Source Interface Unit (SIU), Digital Data Link (DDL), Destination Interface Unit (DIU) and Data Read-Out Receiver Card (DRORC)[12]. A test-box, which is kept inside a refrigerator at a temperature of −25°C, contains an array of 8 APDs and pre-amplifiers connected with a T-card. A flat cable connects the T-card to the IPCB, which is inserted in an FEE input connector. A photon source with similar wavelength and timing characteristics of the scintillating light, produced by electromagnetic showers in PWO crystals, is generated by an avalanche LED pulser[13] and distributed via optical fiber to the 8 APDs. A pulse generator is used to trigger the avalanche LED pulser, which contains a LED with 470nm peak spectra emission. All APDs has been set via bias voltage registers to the nominal gain value of 50 so as to generate signals with equal amplitude. Upon reception of a trigger output from the pulse generator, the RCU sends via the GTL backplane a strobe signal to all ALTRO chips in the FEE, to store the following sequence of ADC samples of all channels in readout buffers. Data in these buffers are transmitted via the RCU through DDL to a DAQ computer, in which a 64 bit PCI card—DRORC is located. DCS and SIU are two mezzanine cards of the RCU. One can access the embedded system in the DCS via ethernet to configure and control the FEE and RCU.

To test the functionalities of all channels of the FEE, a step pulse with a rise-time of about 15ns, similar to the output signal of CSP, is generated by a pulse generator and used as input of all shaper channels via two slightly modified IPCBs. With this simple setup, one can study uniformities of the FEE characteristics over all channels.

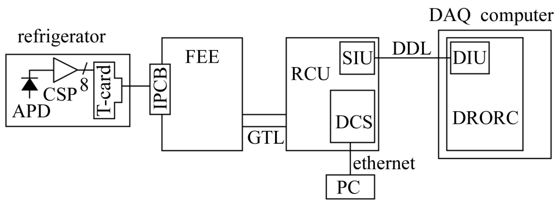

Fig. 1. Sketch of the PHOS readout chain.

4 Performance of the FEE prototype

An analysis package based on ROOT[14] framework is developed to decode the raw data collected by the DAQ system and to sort all ADC data into histograms. Fig. 2 shows a histogram filled with ADC samples from a high gain channel together with a fitting function of Γ-2 (see Eq. 2). Since the ADC sampling frequency is set to be 10MHz, the bin width of the histogram corresponds to 100ns. From the fit one can extract the pedestal level, the amplitude of the input signal, the shaper peaking time and $T_{\max}$ value. Since the pedestal level and peaking time are of the physics characteristics of the FEE, they should be fixed to extract accurately the amplitude and timing information. As a first step, the measurements of the pedestal and RMS noise are taken from the pre-samples before real signal starts. Fig. 3 shows the pedestal and RMS noise in high gain channels measured with 8 APDs in dark at the nominal gain of 50 connected to FEE channels 24 to 31. Due to component tolerances, there is a variation of pedestal levels in different channels. The RMS noise in the APD connected channels shows a clear enhancement over the unconnected ones and reaches 0.262 times of ADC counts. Since 1 ADC count is set to 5MeV in the high gain channels, the RMS noise of 0.262 times of ADC counts corresponds to an energy of 1.31MeV, which is far below the requirement set in the technical proposal.

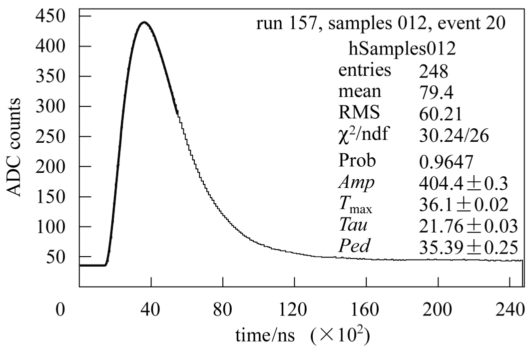

Fig. 2. Γ-2 fit to ALTRO samples from a high gain channel of a FEE card with LED pulse.

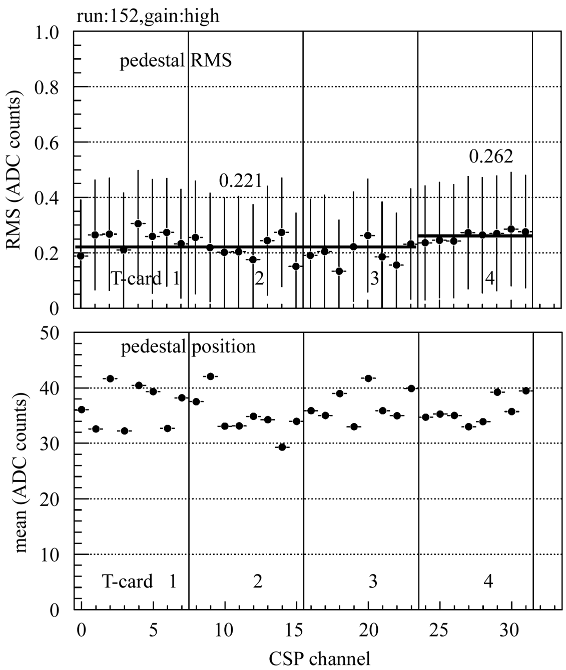

Fig. 3. Pedestal and RMS noise measurement with 8 APDs connected to FEE channels 24 to 31.

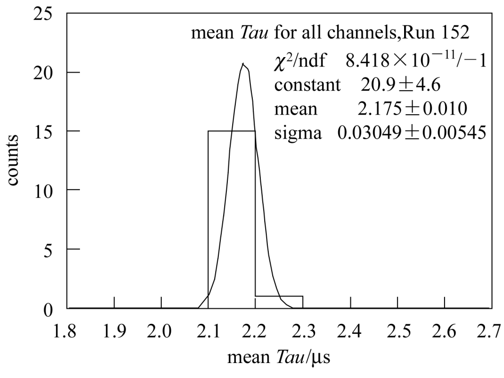

Fig. 4. Peaking time measurement of a FEE shape with 1μs shaping time.

To fix the peaking time, Tau values resulted from a Γ-2 fit on event-by-event basis are filled to one-dimensional histograms for each shaper channels, the mean values of the histograms are then taken as the peaking times. Fig. 4 shows the peaking time distribution of 16 shaper channels with 8 APDs pulsed with a LED pulse. The measured value is (2.175±0.01)μs, which is comparable to the designed value of 2μs for a second order shaper with a shaping time of 1μs.

With the pedestal and peaking time fixed, the ADC samples are fitted again with Γ-2 function to determine the amplitude and $T_{\max}$ values. One can then study the linearity and gain of the shaper, and derive the timing resolution of each channel. Fig. 5 shows a measurement on the relation between the amplitude of signal resulted from the Γ-2 fit and the input voltage of step pulse. The lower line represents the linearity of the low gain range, while the upper line shows that of the high gain range. A linearity better than 99.0% is achievable in both high and low gain channels. From the slope values, i.e. the p_1 parameters, one can derive the gain of the two shapers after converting ADC counts into input voltage to ADC according to 1 ADC bit = 1V/1024 = 0.9765mV. With

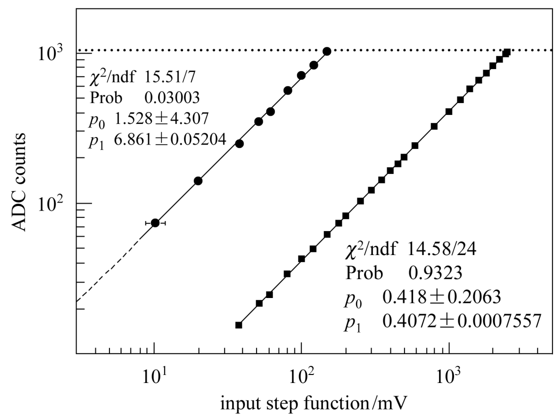

Fig. 5. Linearity measurement over dynamic range.

this, the gains are 6.69 and 0.3976 for high and low gain shapers, which are in good agreement with the designed values of 6.69 and 0.418, respectively. The ratio of the two slope parameters gives the gain factor between high and low gain shapers of 16.85, which is comparable to the designed value of 16. In addition, by taking the ratio of the Amp values resulted from the fits to the pulse shapes in both high and low gain channels, we derive a mean value of 16.83±0.02 for the gain ratios between high and low gain shapers over all CSP channels. An excellent uniformity across all channels is demonstrated by the peaking time and the gain ratio measurements.

In order to discriminate efficiently against 1—2GeV/c anti-neutron from photon signal by applying a sharp time-of-flight cut, great efforts were put to achieve an timing resolution below 2ns at an energy of 2GeV/c. The timing resolution with particles and APD diodes can be evaluated by taking the difference of the $T_{\max}$'s between two high gain channels, measured in good approximation by placing the APDs with the same gain factor, temperature and connectivity environment as in experiment. With a LED pulse of amplitude equivalent to $\sim$ 2GeV photons distributed to the two CSP channels, the timing resolution for individual channels is the σ from the Gaussian fit as depicted in Fig. 6 divided by $\sqrt{2}$. Thus, a timing resolution of 1.5ns is achievable with the current prototype of FEE. Taking the timing information of low gain channels into account, one can in principle improve a little bit the timing resolution.

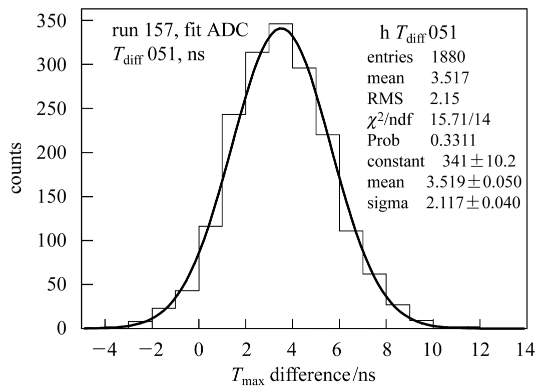

Fig. 6. Timing resolution of the FEE prototype with APD and CSP connected, measured with a LED pulse of equivalent energy of 2GeV.

According to Nyquist theorem, a signal can be reconstructed perfectly by sampling the signal with a frequency greater than twice of the maximum frequency of the signal component. As shown in Fig. 7, the timing resolution has been measured as a function of ADC sampling frequency in off-line analysis by taking every the second samples, the third, the fourth, and so on. The plot indicates that a sampling rate above 2MHz gives almost a constant timing resolution. It is worthwhile to mention that it is desired to have a smaller sampling frequency because this can reduce considerably the online data bandwidth and data storage space.

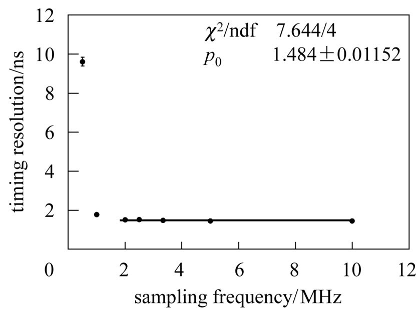

Fig. 7. Timing resolution versus the ADC sampling frequency.

To equalize APD gains, individually programmable reverse bias voltages are generated by the FEE for each APD via 10 bit DAC. Fig. 8 confirms that the high voltage bias controller can achieve 0.2V/bit as designed with good linearity and cover a range from around 210V to 415V. With an APD gain dependence $(1/M)*\mathrm{d}M/\mathrm{d}V\approx 3.3\%$ at the nominal gain of $M=50$, an inter-calibration precision of 0.66% can be achieved.

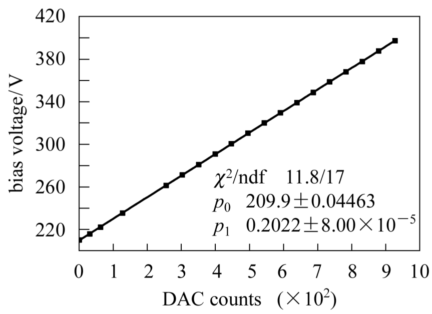

Fig. 8. Linearity measurement of bias voltage controller.

5 Summary

The performance of the current FEE prototype with a dynamic range of 14 bits for ALICE PHOS detector has been evaluated in a dedicated facility in Wuhan. The linearity over the dynamic ranges has been verified and found to be above 99% in both low and high gain shaper channels. With APD and CSP detector at −25℃, the noise level is 0.264 ADC counts, i.e. 1.32MeV per channel, which is far below the PHOS requirement on the electronic readout noise. Off-line data analysis shows that with an ALTRO sampling frequency above 2MHz, a timing resolution of 1.5ns at 2GeV can be achieved with full PHOS readout chain. This can limit the antineutron contamination of photons to a level bellow 2%. In addition, with high voltage bias controller for individual channels, an inter-calibration precision of 0.66% can be achieved at an APD gain of 50. It is worthwhile to mention that, although the capability to provide an L0/L1 trigger to ALICE can only be evaluated when a prototype of the trigger region unit (TRU) card[15] is ready, the logic for fast analog sum generation works fine. One can thus conclude from the test results that the performance of the current FEE prototype has met the physics requirements of the PHOS detector.

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ALICE光子谱仪前端电子学系统的性能研究*

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摘要 首先讨论了ALICE光子谱仪前端电子学的物理需求, 介绍了光子谱仪前端电子学测试系统. 采用该系统对光子谱仪前端电子学系统板(FEE)进行了检测, 检测表明现行设计的前端电子学系统板的物理性能已达到了ALICE实验的预期物理目标.

关键词 ALICE光子谱仪 前端电子学系统板 物理性能

2006 – 02 – 22 收稿

* 国家自然科学基金(10547118, 10575044), 教育部科学与技术研究重大项目基金([2006]55)和教育部留学回国人员科研启动基金资助

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