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Readout ASICs and Electronics for the 144-channel HAPDs for the Aerogel RICH at Belle II

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Abstract

The particle identification (PID) device in the endcap of the Belle detector will be upgraded to a ring imaging Cherenkov counter (RICH) using aerogel as a radiator at the Belle II experiment. We develop the electronics to read out the 70,000 channels of hit information from the 144-channel hybrid avalanche photodetectors (HAPD), of the aerogel RICH detector. A readout ASIC is developed to digitize the HAPD signals, and was used in a beam test with the prototype detector. The performance and plan of the ASIC is reported in this study. We have also designed the readout electronics for the aerogel RICH, which consist of front-end boards with the ASICs merger boards to collect data from the front-end boards. A front-end board that fits in the actual available space for the aerogel RICH electronics was produced.

Keywords:

1. Introduction

The Belle experiment [1] is an experiment at KEK, Japan, for the study of flavor physics using large number of B mesons produced at the KEKB asymmetric-energy e^+e^- (3.5 GeV on 8 GeV) collider [2], which achieved the world's highest luminosity of $2.1 \times 10^{-34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The discovery of CP violation in the neutral B system and precise measurements of the Cabibbo-Kobayashi-Maskawa matrix in Belle proved the correctness of Kobayashi-Maskawa theory. The operation of the Belle experiment began in 1999 and concluded in 2010; it is planned to be resumed in 2014 as an upgraded Belle II experiment [3]. With the SuperKEKB collider which will provide 40 times higher luminosity than KEKB, the Belle II experiment aims to collect 50 ab^{-1} of data in order to study the New Physics through B mesons, charm, and τ.

The Belle detector is a general purpose detector with a drift chamber, vertex detector, calorimeter and particle identification (PID) devices. For Belle II, the detector will be upgraded for higher performance and

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a larger tolerance for accelerator backgrounds. For the PID at the endcap region, the threshold-type aerogel Cherenkov counter (ACC) will be replaced by an aerogel RICH, a ring imaging Cherenkov counter (RICH) utilizing aerogel as a radiator [4]. The aerogel RICH is expected to achieve π/K separation of more than 5σ for a momentum range up to 4 GeV, wider than the endcap ACC at Belle, which provided separation only below 2 GeV.

In the aerogel RICH, we measure the Cherenkov angle of photons from aerogel radiators with photo-detectors. A photo-detector must detect single photons, have position sensitivity with a pixel size of $\sim 5 \times 5$ mm^2, and provide a large effective area of coverage in the forward region of the Belle II detector (~ 4 m^2). It must also be immune to a 1.5 T magnetic field perpendicular to the photon detection plane. One such candidate photo-detector is a 144-channel multi-anode hybrid avalanche photodetector (HAPD) (Fig. 1a) developed in collaboration with Hamamatsu Photonics K. K. (HPK).

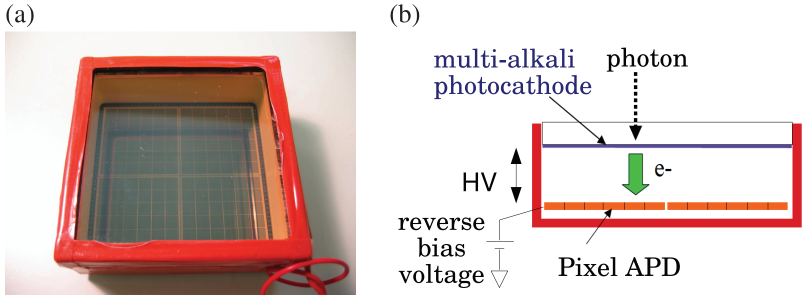

Fig. 1. (a) 144-channel multi-anode HAPD. (b) Structure of a multi-anode HAPD.

Figure 1b shows the structure of a multi-anode HAPD. Photoelectrons are accelerated by the high electric field produced by a high voltage inside the vacuum tube, after which they enter the pixelated avalanche photo diode (APD), creating $\sim 10^3$ electron-hole pairs per photoelectron. Amplification by the avalanche process inside the APD, provides an additional gain of around 10. As a result, the total gain of the HAPD is around $10^4 - 10^5$. In the counter under development, four APD chips are placed in a 2×2 array (Fig. 1a). Each chip is divided into 36 channels with a 4.9×4.9 mm^2 pixel size. The typical high voltage applied to the photo-cathode is -8 kV, and the APD is biased with 300 V.

Because of the relatively low gain compared to conventional photo-multipliers, high-gain and low-noise electronics are required to readout the HAPD signal. The readout needs to provide only a single bit of on/off hit information for each channel. The total number of channels for the aerogel RICH is around 70000.

2. Readout ASICs for the HAPDs

We have developed an ASIC to digitize the HAPD signal. The standard input charge from the HAPD is $\sim 60000\ e^-$. The capacitance of the HAPD is ~ 80 pF, and the noise level at 80 pF must be a few thousand electrons to maintain the signal-to-noise ratio of 10. For the design of the ASIC, we set the target to 1200 e^-, because the gain of the HAPD was lower during early stages of the development. The target number of channels per chip is 36. The outputs of the ASIC are raw digitized signal for all the channels, which are supposed to be processed by an external field programmable gate array (FPGA). The production of the ASIC was done using the TSMC CMOS 0.35 μm process and the X-FAB 0.35 μm process as a second candidate for mass production.

Figure 2 shows a schematic of the ASIC we developed. This ASIC, the SA series, has a charge-sensitive preamplifier, shaper, and comparator to provide 1-bit on/off information for each channel. SA01, the first version of the SA series, has only 12 channels per chip; the next version, SA02, has 36 channels. The threshold voltage for the comparator is common to all channels, but the offset voltage can be adjusted for each channel in the range of ±300 mV with a 3 mV step using two 4-bit DACs. This offset can be used to adjust small differences in the baseline voltage among channels, and it can be used to vary the effective threshold voltage of each individual channel. The amplification factor of the preamplifier and the shaping time of the shaper are variable in four steps. In SA01, the amplification factor can be varied between 12.5 V/pC and 50 V/pC, while the shaping time is variable between 250 ns and 1 μs. These parameters are kept in the shift registers in the ASIC, which can be controlled with a simple protocol.

Figure 3 shows the measured noise level of SA01 as a function of the detector capacitance. We found that the target noise level of 1200 e^- at 80 pF is accomplished.

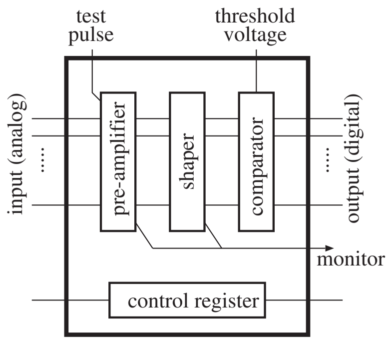

Fig. 2. Schematic of the ASIC (SA series).

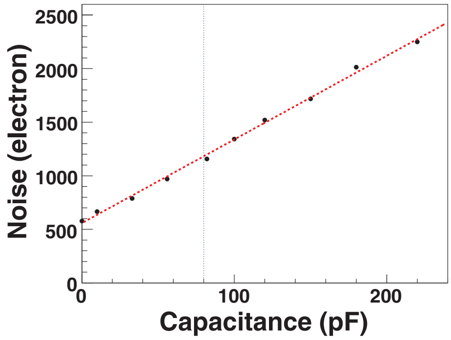

Fig. 3. Measured noise level of SA01 as a function of detector capacitance.

Figure 4a shows the signal pulse height measured before the comparator as a function of the input charge under four different gain settings for SA01. We observe good linearity when the input charge is small, but we observe saturation when the input charge exceeds 60000 electrons, which corresponds to one photoelectron signal from the HAPD, even when working at the lowest gain. To solve this problem, the gain of SA02 was reduced to one-fourth of that of SA01. As seen in Fig. 4b, SA02 has linearity up to input charge that corresponds to a few photoelectron signals.

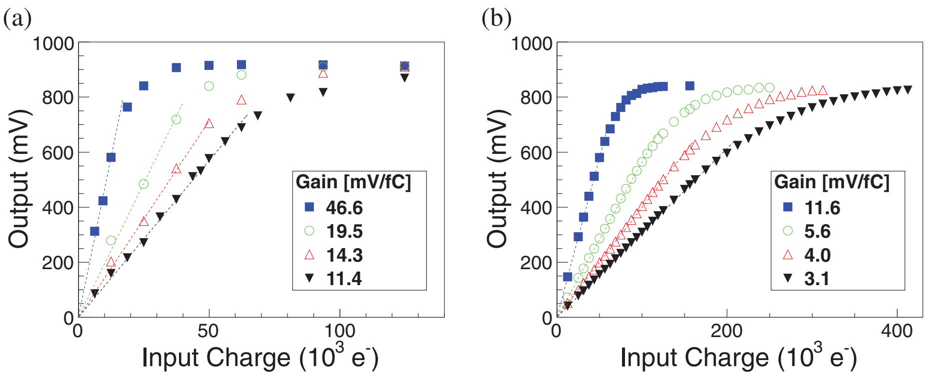

Fig. 4. Measured linearity of (a) SA01 and (b) SA02. The horizontal axis shows the input charge from the test pulse, while the vertical axis shows the pulse height before the comparator. An input charge of 60×10^3 corresponds to one photoelectron, and (b) has linearity up to larger input charge values. Measurements for four different gain settings are shown, where the numbers are measured values.

Because the space available for electronics is limited, the package of the ASICs must be small. Hence, we produced a package using low-temperature cofiered ceramic (LTCC) technology. With LTCC, we produced a 144-pin BGA package for SA02 with a size of 13 mm $\times$ 13 mm, in which additional resistors and capacitors were placed, as shown in Fig. 5.

To test the ability of the developed ASIC to read out the HAPDs, we performed a beam test on prototype aerogel RICH using a 2 GeV electron beam at the Fuji test beam line at KEK. The experimental setup of the beam test is shown in Fig. 6a and Fig. 7. The detector is composed of an aerogel radiator and a 2×3 array

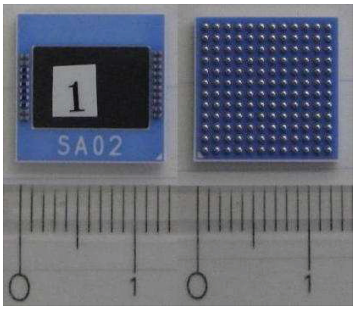

Fig. 5. Front view (left) and back view (right) of the LTCC package for SA02. The scale is in mm.

of HAPDs, the photo-detection plane of which is parallel to the radiator face and at a distance of 20 cm. The electron tracks are measured by two multiwire proportional chambers (MWPC) . Signals from each HAPD are read out by a board with three SA01 chips and a FPGA as seen in Fig. 7b. The offset for each channel of the ASICs is adjusted so that the noise is below the threshold. The hit distribution at the photo-detection plane is shown in Fig. 6b, where a clear Cherenkov ring is observed. Single-track resolution is calculated to be 3.9 mrad, which corresponds to 5.0σ π/K separation at 4 GeV. This result confirms that our ASICs can be used for the readout of a HAPD.

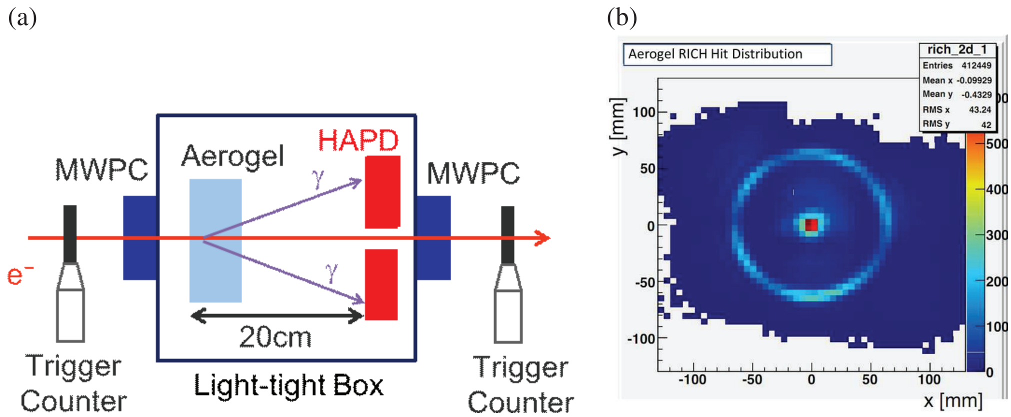

Fig. 6. (a) The experimental setup of the beam test for the prototype aerogel RICH. (b) Hit distribution at the photo-detection plane. For each hit, the difference between the beam position and the HAPD hit position is plotted.

3. Readout Electronics for Belle II Aerogel RICH

In the aerogel RICH detector, signals from 456 HAPDs are digitized by the ASICs in the front-end electronics, and these signals are sent to the central data acquisition (DAQ) system through optical links using the Belle II common protocol called “Belle2Link.” One constraint for readout electronics is space; only 5 cm space is available for the electronics behind HAPDs.

An overview of the readout electronics of the aerogel RICH is shown in Fig. 8. Each front-end board is attached to a HAPD, and signals from one HAPD are digitized by four ASICs and are processed by an FPGA on the front-end board. To reduce the number of optical links to the central DAQ system, the output of the front-end board is first sent to a “merger” board located just behind the front-end board, which collects data from several HAPDs. The merger needs to work as a level-1(L1) buffer, which keeps the hit data whenever a global trigger is issued until the data are transferred through Belle2Link. The depth of the L1 buffer is

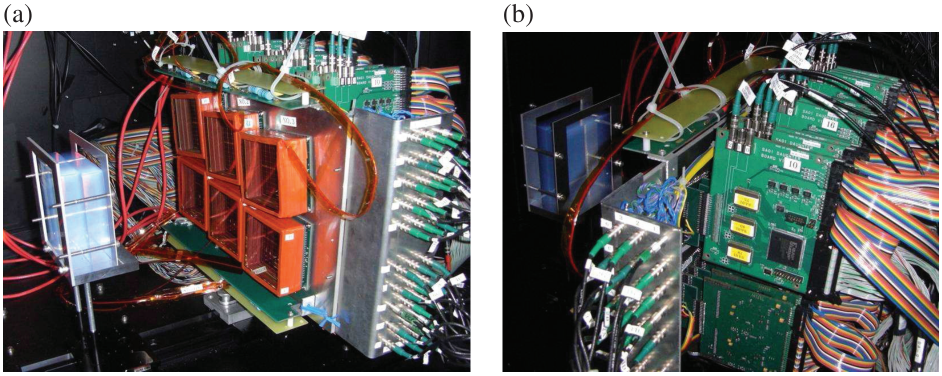

Fig. 7. Pictures of the beam test with a prototype aerogel RICH.

required to be five or more. We have developed a large prototype merger board to test the basic function as shown in Fig. 9. The board has an FPGA (Xilinx Virtex5), connectors for cables from the front-end boards, an optical connector for Belle2Link and a few RJ-45 connectors for the trigger input and for the download of the FPGA configuration using JTAG protocol (IEEE 1149.1 Standard Test Access Port and Boundary-Scan Architecture). The L1 buffer is implement in the FPGA.

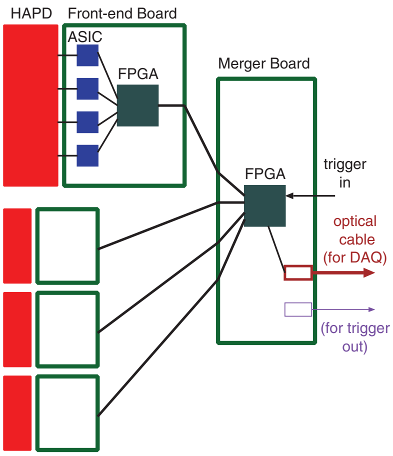

Fig. 8. Overview of the readout electronics of the aerogel RICH.

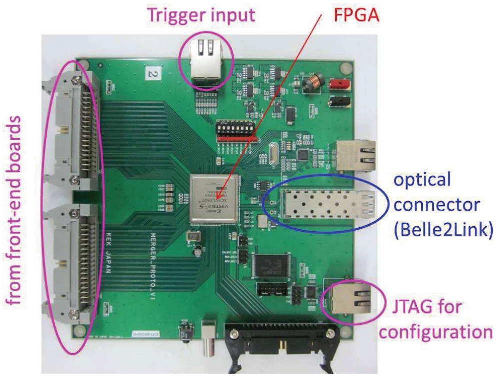

Fig. 9. Prototype merger board.

Figure 10 shows the prototype of the front-end board. The main board contains four SA02 chips with an LTCC package surrounded by a connector for the HAPD on the back side. An FPGA (Xilinx Spartan6) together with connectors to merger is assembled on the front side. The main board also has circuits for an on-board test pulse to SA02, a threshold setting, a temperature monitor, and an analog multiplexer for the analog monitor signal. The board is designed to fit in the actual available space. For a standalone operation, we can also use a piggyback board for SiTCP [5] communication. We tested the basic function of this front-end board, and we are designing the next version with minor modifications.

4. Development of SA03

One of the present concerns in the aerogel RICH detector is the radiation tolerance of the HAPDs, especially to neutrons. The expected dose of 1 MeV equivalent neutrons in Belle II is expected to be $10^{12}/\mathrm{cm}^{-2}$ for ten years of operation. We performed a neutron irradiation test of the HAPDs at Yayoi, the

(a) (b)

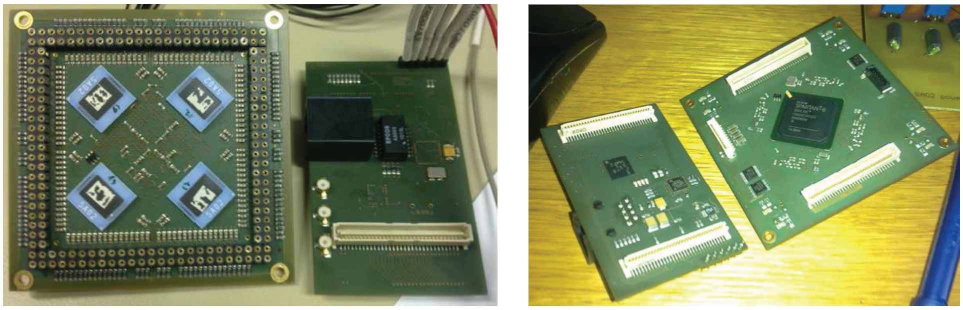

Fig. 10. Picture of the prototype o the front-end board. The smaller board is a piggyback board for a stand-alone operation. (a) The back side of the front-end board and the front side of the piggyback board; (b) the sides of the front-end and piggyback boards are reversed.

fast neutron source reactor of the University of Tokyo, in Tokai. After irradiation with $10^{12}/\mathrm{cm}^{-2}$ neutrons, we found that the leakage current, which is normally below 1 μA, increased to around 10 μA per APD; hence the ratio of the one photo-electron signal to the noise is decreases after neutron irradiation.

One solution is to shorten the shaping time of the readout ASIC. We confirmed that the signal-to-noise ratio for a neutron-irradiated HAPD is better when we set the shaping time of SA02 to be 250 ns rather than 1 μs. Therefore, we decided to develop another version of ASIC, namely SA03, where the minimum shaping time is further shortened to 100 ns. Although the radiation tolerance of the ASIC itself was tested by an irradiation test at Yayoi using SA02, we also implemented registers for SA03 using a dual interlocked cell (DICE) [6], which has redundant storage and restores the original register state when a single event upset (SEU) happens. SA03 can be the final version of our ASIC to be used in the readout system of the aerogel RICH detector.

5. Summary

We developed readout electronics of a 144-channel HAPD for use in the aerogel RICH at Belle II. The developed ASIC has enough gain and linearity to digitize a HAPD signal that corresponds to one or a few photoelectrons. With the ASIC, we successfully read out HAPD signals during a beam test of a prototype aerogel RICH. We are also developing the front-end electronics using these ASICs for the final aerogel RICH system of the Belle II detector.

Acknowledgments

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