PROCEEDINGS OF SCIENCE

R&D status of HAPD

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We are reporting the R&D status of a large-aperture Hybrid Avalanche Photo-Detector (HAPD). We have developed a 13-inch aperture HAPD. The HAPD is a photo detector expected to replace the photomultiplier tube (PMT) in next-generation imaging water Cherenkov detectors such as Hyper Kamiokande. We will present the excellent performance of the HAPD (~200 ps time resolution and single photon sensitivity). We will also describe the readout and high-voltage power supply designed for the HAPD.

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1.Introduction

We have successfully developed a large-aperture (13-inch) Hybrid Avalanche Photo-Detector (HAPD) and its readout system for next-generation imaging water Cherenkov detectors. We previously reported on the performance of prototypes [1][2][3][4]. Since then, we have made significant improvements in the HAPD developments. The readout system involves a fast sampling device; the HAPD needs two high-voltage (HV) power supplies to apply HV and bias voltage to the photo sensor in HAPD. We are presenting an improved fast sampling device and new compact high-voltage power supplies. We also present a new 8-inch aperture HAPD. This paper reviews the HAPD performance and its new developments. First we will discuss the HAPD structure, its operation principle, and its advantages over a photomultiplier tube (PMT). Then we will explain its readout system and the improvements made in the fast sampling device. Finally, we will report on new compact HV power supply and the newly developed 8-inch aperture HAPD.

2.HAPD

Fig. 1 illustrates the structure of the HAPD. The HAPD accelerates photo-electrons by applying a high voltage of 10 to 20 kV to bombard them into an avalanche diode (AD). Since the photo-cathode of the HAPD is grounded, the AD requires two positive high voltages (HV and HV-bias voltage) to function. Each photo-electron generates numbers of secondary electrons (5000 at 20 kV) and each newly produced electron then yields another few dozen electrons in the subsequent avalanche multiplication. The total gain of the HAPD is the product of the two. Due to the operation principle, HAPD has superiority to PMT in the following two ways: 1) larger gain at the first electron multiplicity stage; and 2) no dynode in electron multiplier. The pulse height resolution of a photo-detector depends on the gain at the first stage of electron multiplicity. The HAPD has significantly larger gain at the first stage (>1000) than that of a PMT (~10). HAPD was expected to have better pulse height resolution than PMT. The dynode leads variation in transit time distribution of secondary electrons. The variation results in deterioration of time resolution. There is no dynode in HAPD and HAPD is free from the problem. A more detailed discussion of the HAPD can be found in other literature [1][2][3].

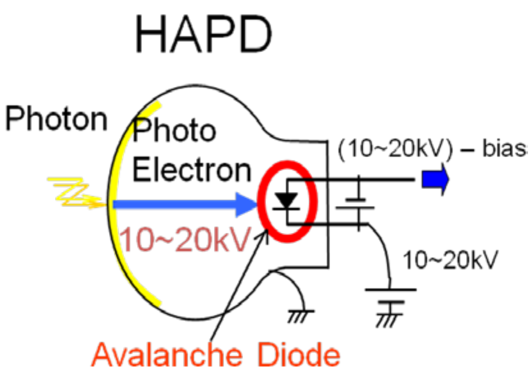

Fig. 1 Overview of the HAPD structure

Table 1 summarizes the characteristics of the HAPD as compared with those of PMTs. The HAPD performs better in time and pulse-height resolutions, but requires a dedicated readout system due to its smaller gain of ~10^5.

Table 1 Summary of performance comparison between the HAPD and PMTs

Parameters	13-inch HAPD	13-inch PMT	20-inch PMT
Time resolution (1P.E.)	190 ps (σ)	1400 ps (σ)	2300 ps (σ)
Pulse height resolution (1P.E.)	24%	70%	150%
Quantum efficiency	20%	20%	20%
Collection efficiency	97%	70%	70%
Power consumption	<<700mW	700mW	700mW
Order of gain	10^5	10^7	10^7

3.Readout system and its improvements

A more detailed description of the readout system can be found in [4]. We employed waveform sampling and digital signal processing (DSP). The system involves an analog memory cell (AMC) as a fast waveform sampler. The AMC resembles a Switched Capacitor Array [5] but does not require an external clock pulse to switch the analog-switches of the hold capacitors. Fig. 2 shows the simplified equivalent circuit and the operation principles of the AMC. Each cell of the AMC consists of an analog-switch, a hold capacitor, and a delay buffer. ASIC was selected for the fabrication of the AMC. We had previously obtained a time resolution of 200 ps for one photo-electron (PE) signal and clear pulse height separation for up to six PEs for the prototype AMC with a sampling depth of 64 [4].

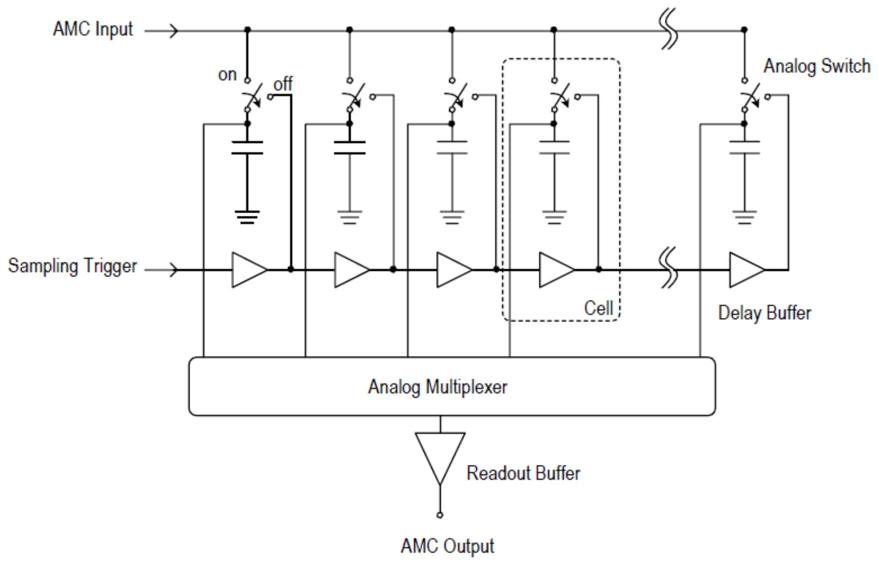

Fig. 2 Conceptual structure and operation principles of the AMC

Here, we will report on the further improvements made to the AMC. The improvements are as follows.

1. The number of sampling depth was increased to 256.
2. A new function was implemented to correct systematic AC gain variation depending on sampling time.
3. The input analog bandwidth was improved.

So far, we developed the AMC with a sampling depth of 64 to optimize its performances such as pulse height resolution, pedestal variation between samples, and input dynamic range, separating the problems caused by a large sampling depth. The performances of the AMC with a sampling depth of 64 satisfied our requirements as discussed above. On the other hand, it is required that the AMC should measure the waveform length for 1μs, to use the AMC in imaging water Cherenkov detectors. It was not obvious to produce the AMC with sampling depth more than 100 by repeating the present electric circuit pattern, since the electric circuit layout modification with ASIC production might affect the AMC performances such as sampling intervals and pedestal variations. With a new prototype having a sampling depth of 256, we have achieved a sampling interval of 870±48 ps, equivalent to a sampling frequency of 1 GHz. We found negligible variations in the sampling intervals and no sampling time dependence in propagation time delay (Fig. 3). We also found that pedestal variations between samplings are smaller than 2 mV. All findings suggest that the current circuit design is viable up to a depth of 256.

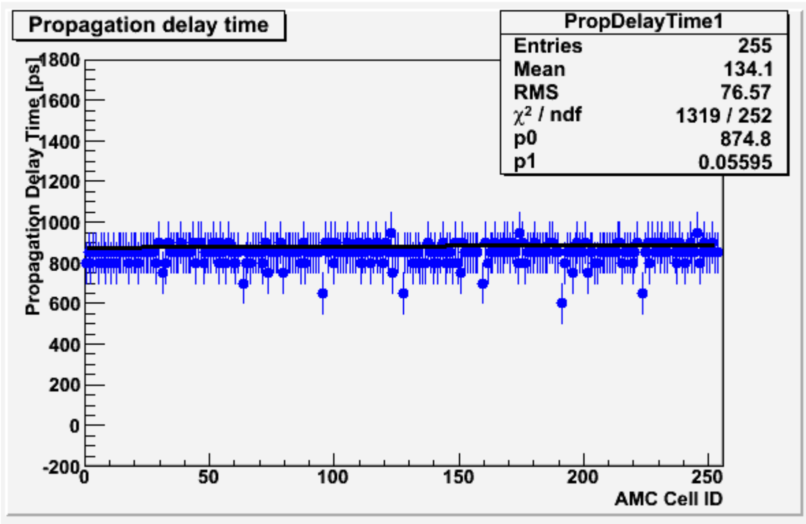

Fig. 3 Propagation time delay between samplings [ps] vs. sampling number

The previous AMC prototype showed variations in AC gain as a function of sampling time. For example, when feeding sine curve signals to the AMC, the amplitude of the signal output increased for later sampling time. The output amplitude at the last sampling was twice as large as that at the start of sampling when 120-MHz sine curve signals were input. The variation happened since the capacitance seen from the input side of the AMC changed with sampling time; the capacitance became small as sampling time became late (the number of hold capacitors connected to the AMC input line become smaller). The circuit pattern of the AMC resembled a low pass filter (see Fig. 2). The small capacitance passed fast analog signals. We have implemented a new function to reduce these variations. The current prototype AMC has shown that the difference in amplitudes between the first and last samplings is less than 5% when using 120-MHz sine curve input signals.

We have also improved the input bandwidth of the AMC. The input analog bandwidth of the AMC is restricted with its capacitance of the signal holding capacitor, switch size, and circuit composition. Since the input analog bandwidth of an AMC changes depending on an ASIC production process or an electric circuit layout, it was not easy to improve the bandwidth. By making not only optimization of parameters, such as the capacitance of the hold capacitor, but also the circuit correction to the AMC, a fast input analog signal can be inputted now. As a result, we expect that it can input now into the AMC to the analog signal of the half of the sample frequency of the AMC (500MHz). We confirmed that the AMC performance was improved when 100-MHz since curve signals were inputted.

4.New compact HV and bias voltage supplies

As mentioned in Section 2, the HAPD needs two HV supplies to operate. Since it would be convenient to equip the HV power supplies close to the HAPD, physically compact supplies are preferable. The existing HV and bias voltage power supplies each occupy a space of $500 \times 500 \times 100$ mm^3. From a viewpoint to optimize in the use of the HAPD as shown in Fig. 1, we examine the HV system and the small current capability (<1μA) in the operation of the HAPD. It was not easy to fabricate a compact HV supply, securing the electric strength of 20 kV. The operation high voltage of 20 kV was determined to have more than 97% photoelectron collection efficiency of HAPD as reported in Table 1. We have developed a new compact power supply to supply both high voltage and bias voltage, at a size reduced to $150 \times 92 \times 30$ mm^3 [6] (Fig. 4). We used the power supply to measure single photo-electron signals from the HAPD.

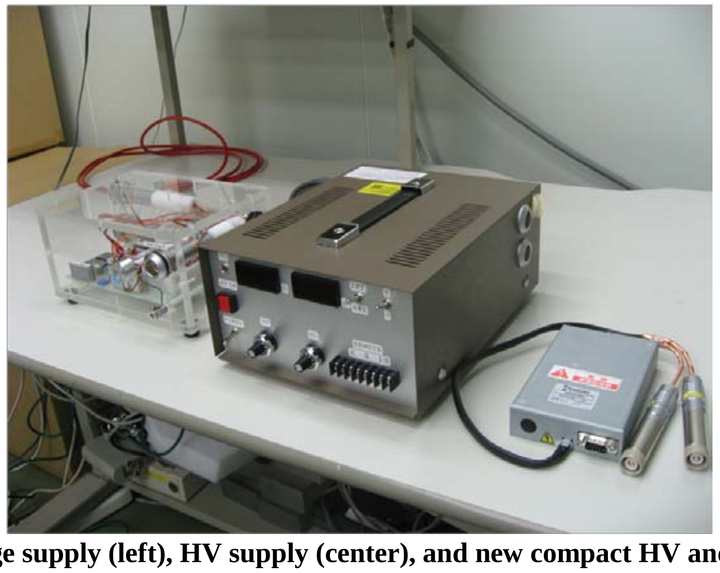

Fig. 4 Bias volatege supply (left), HV supply (center), and new compact HV and bias voltage supply (right)

5.8-inch aperture HAPD

We have initiated R&D of an 8-inch aperture HAPD (Fig. 4). This 8-inch aperture HAPD is expected to have the following characteristics:

1. Lower operation HV of 10 kV (versus 20 kV for the 13-inch HAPD).
2. A significantly smaller spread of transit time between the center of photocathode and 70 degree angle from the tube axis (210 ps) than that (500 ps) for the 13-inch HAPD.

The detailed studies of the performances of the 8-inch aperture HAPD should be reported soon.

Fig. 5 8-inch aperture HAPD (left) and 13-inch aperture HAPD (right)

6.Summary

We have developed a large-aperture (13-inch) HAPD and its readout system. This HAPD has demonstrated excellent performance. A fast waveform sampling device has also been developed. Prototypes of the new compact HV and bias voltage power supplies and the 8-inch aperture HAPD are now being produced.

References

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[2] Y. Kawai et al., *Large-aperture hybrid photo-detector*, Nucl. Instrum. Meth., A579 (2007) 42

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[5] S. A. Kleinfelder, *A 4096 Cell Swithced Capacitor Analog Waveform Integrated Circuit*, IEEE Transactions on Nuclear Science, Vol. 37, No. 3, June 1990

[6] The HV and bias voltage power supply was manufactured by the Spellman High Voltage Limited Company. Their technology enables to make such the compact power supply.