Integration of Hyper-Kamiokande Electronics and Test in Super-Kamiokande

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I. INTRODUCTION

Hyper-Kamiokande (HK) is a next generation neutrino experiment starts in 2027 [1]. The detector will be the largest ever water Cherenkov detector with 260kton water tank and more than 20k photomultiplier tubes (PMTs) on the wall. The detector's large scale and high performance require various challenges on the electronics and DAQ as follows.

1) digitizer to extract charge and time information from high performance HK Box&Line PMT (improved by a factor 2 compare to SK's).

2) DAQ with high throughput and large buffer to record nearby supernova burst (~200M events in ~10s).

3) timing synchronization (<100ps) for the electronics in the detector and also J-PARC beam line 300km far from Kamioka.

4) frontend electronics under water inside tank (~0.8MPa). It requires water tightness, handling of heat, low failure rate, etc.

HK electronics is designed to meet these requirements. Fig.1 shows the design of water tight case and frontend electronics. The designs of the components such as digitizer, data process board, LV/HV have been mostly finalized, and final prototypes were delivered in 2023. The intrinsic performance of the final prototype is shown in Fig. 2. It was confirmed to meet HK requirements.

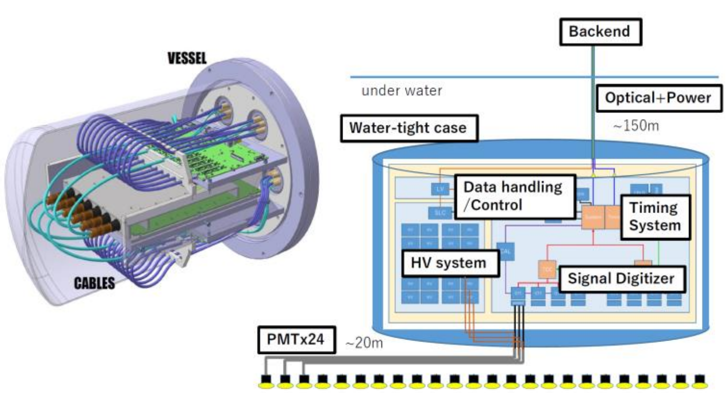

Fig. 1 Conceptual design of frontend electronics and water tight case.

Integration of the components and system tests went as follows. At first, prototypes of the components were connected in laboratory, and the functionality and performance were confirmed. That required firmware development of FPGA and Zynq. On the other hand, the frontend electronics was installed into water tight case and put under water where water tightness, heat control, long term stability were tested.

After a vertical slice setup of HK electronics established in laboratory, 12 HK PMTs were connected to the digitizer inputs in one of quality check (QC) facilities of PMT mass production. Then the performance was comprehensively measured by using LD source. Furthermore, the setup was also installed in Super-Kamiokande, and various data was taken with SK PMT and HK PMT installed in SK tank. It was the first time for HK electronics to take water Cherenkov data, and one of milestones for us. The details are described in the latter sections.

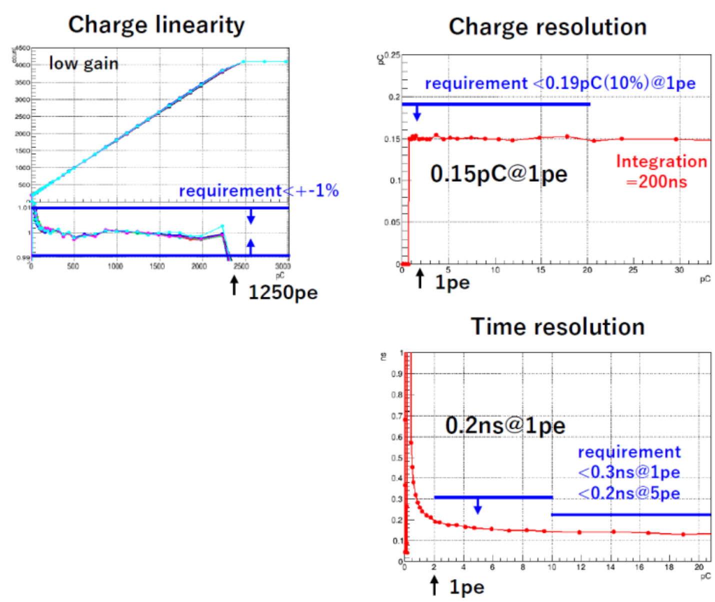

Fig. 2 Intrinsic performance of HK electronics

II. INTEGRATION OF ELECTRONICS

Final prototypes of the components were delivered in 2023, and integration of the components started. Fig.3 shows integrated components of frontend electronics, two digitizer boards which digitize waveform from PMT and get timing and charge information, a data process board which processes data from digitizer and transmit it to DAQ outside tank via optical fiber, and LV/HV modules that generate ~2kV HV supply for PMTs. The timing system that delivers clock and counter, and slow control system are also established in the system.

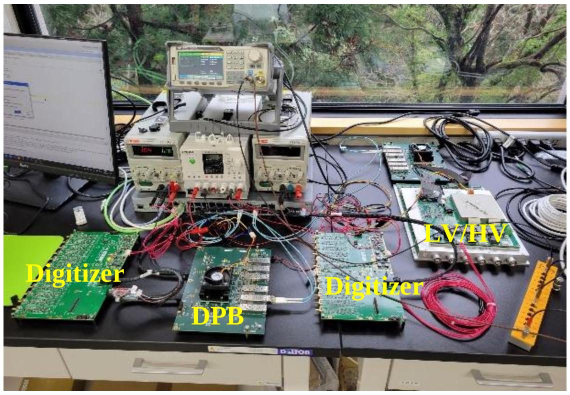

Fig. 3 Integrated frontend components

The other components are water tight equipments such as water tight case, feed-through, composite cable with optical fiber and metal (LV). Fig.4 shows assembled water tight case. The heat guide stand inside the case is also one of critical components since temperature inside case affects lifetime of the electronics. The mechanical and electrical interferences inside case were also tested.

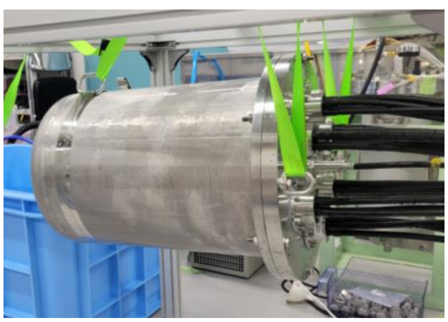

Fig. 4 Water tight case

III. TEST WITH HK PMT

Mass production of HK Box&Line PMT is on-going. About 40% of 20k HK PMTs have been produced. Fig.5 shows one of the facilities to check quality of the PMTs. After integration tests in laboratory, the vertical slice setup of HK electronics was installed in the facility. Then the performance of the system was comprehensively measured with real PMT inputs not just for charge and timing but also for noise level, cross talk, high rate tolerance, and the other properties. As a result, HK electronics was confirmed to work with HK PMTs as expected.

Fig. 5 Facility to check quality of mass production HK PMT. There are 100 PMTs in a room.

IV. TEST IN SUPER-KAMIOKANDE

After intensive tests in laboratory and QC facility, the vertical slice setup of HK electronics was installed in electronics hut in SK. Fig.6 shows the HK setup (bottom) together with SK electronics (middle). HK electronics was synchronized with SK clock (60MHz) that was delivered from SK master clock (top). One out of 12 PMT inputs was HK PMT which was installed in SK tank in the past (2019). The others were SK PMTs used for SK experiment in usual.

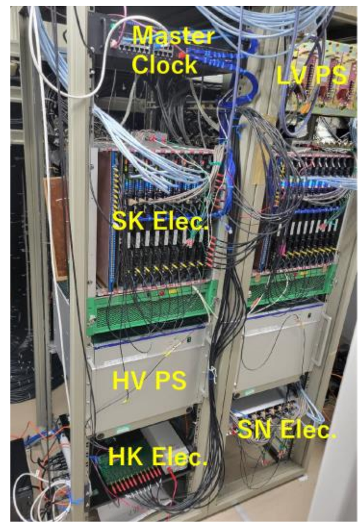

Fig. 6 HK electronics (bottom) and SK electronics (middle) in SK electronics hut.

Fig.7 shows noise hit rates of 12 channels of the HK electronics. The noise level is much lower than the nominal threshold 1mV (1/6 p.e.) required in HK even with the longer cable (~60m) in SK than that in HK (~20m).

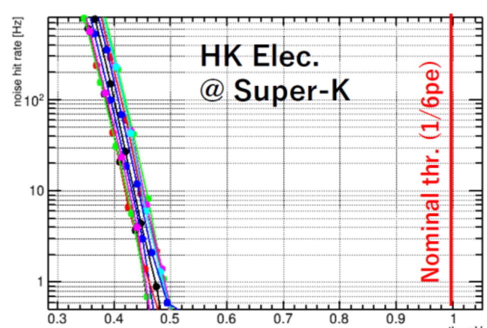

Fig. 7 Noise hit rate of HK electronics in SK environment. The noise level (~0.5mV) is about half of the requirement.

Fig.8 shows charge and timing distribution taken by a combination of HK electronics and HK PMT. The charge and timing resolution are 32% (at 1pe) and 1.3ns (at 1~5pe) respectively, these are almost half of SK PMT’s. The intrinsic resolutions of HK electronics are much smaller 8% for charge and 0.2ns for timing, so we can fully take advantage of high performance of HK Box&Line PMT.

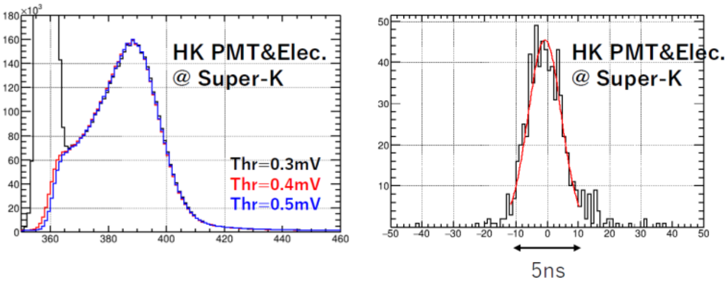

Fig. 8 Charge distribution by HK PMT and HK electronics. The resolution of 1p.e. peak (~30%) is almost half of SK PMT's.

Fig. 9 shows the first observation of neutrino events taken by HK electronics. The charge and timing distributions are as expected. That is one of milestone to detect real signal in water Cherenkov detector.

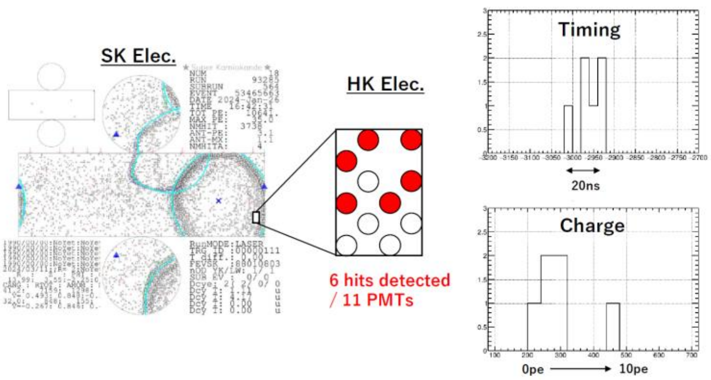

Fig. 9 Observation of neutrino event by HK electronics.

It is important to detect consecutive hits in short time period for some type of events such as muon decay, neutron capture supernova burst, etc. Fig.10 shows delayed signal of muon decay events taken by HK electronics. The 0.5 μs gap after prompt comes from deadtime of HK electronics, that is improved from 1.0 μs of SK electronics.

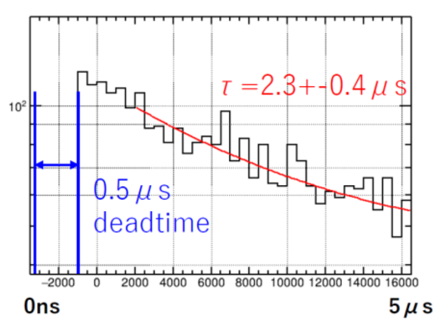

Fig. 10 Observation of muon decay event by HK electronics.

Fig. 11 shows supernova burst test which make use of LD source in SK tank. The light source emulates time profile of supernova burst and the intensity can be adjusted up to 60M events that is much higher than nearby supernova like Betelgeuse. The HK electronics process high hit rate up to 700kHz/channel without any error and total number of recorded hit for a burst is up to 1.6M/channel.

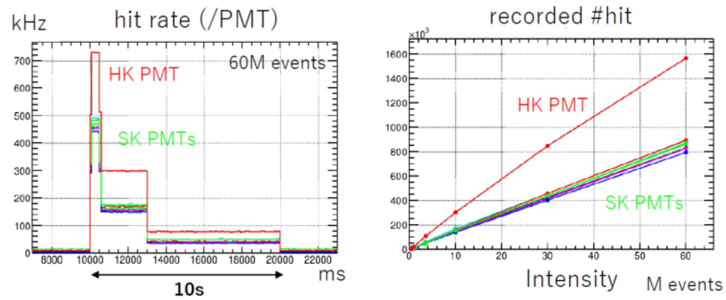

Fig. 11 Supernova burst test of HK electronics with SK detector.

V. CONCLUSION

Physics programs of HK experiment require harsh requirements on HK PMT and electronics. The design of HK electronics has been mostly finalized, and final prototypes were delivered in 2023. After integration of the components in laboratory, the vertical slice setup was connected to HK Box&Line PMTs in QC facility for mass production PMTs. And the requirements of HK electronics were confirmed to be met. Furthermore, the setup was installed in SK and connected to SK PMTs and HK PMTs that were installed in the SK tank. That was the first time for HK electronics to take data from water Cherenkov detector. HK PMT and HK electronics were confirmed to work together as a water Cherenkov detector and shows excellent performance as expected. It's one of milestones for HK collaboration.

REFERENCES

[1] "Hyper-Kamiokande Design Report", KEK Preprint 2016-21 ICRR-Report-701-2016-1, Feb. 2016