The electronics, online trigger system and data acquisition system of the J-PARC E16 experiment

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Abstract. The J-PARC E16 experiment was proposed to investigate the restoration of chiral symmetry at the normal nuclear density. E16 will systematically measure in-medium mass of vector mesons at J-PARC Hadron Experimental Facility using a 30-GeV proton beam with an intensity of $2 \times 10^{10}$ protons per pulse. The E16 spectrometer was designed to detect $e^+e^-$ from slowly moving vector meson, particularly the $\phi$ meson. The detector system consists of GEM tracker, Gas Čerenkov detector based on GEM and electromagnetic calorimeter made of lead-glass, whose number of channels reaches about 100,000 in total. The readout electronics, trigger system and data acquisition system for the detectors have been developed, for which level-1 trigger rate of 1–2 kHz is required under several 10 MHz interaction rate. The preparation is underway for the first beam time in 2017.

1. Introduction
1.1. Physics motivation

The spontaneous breaking of chiral symmetry is considered to be the origin of the mass of protons, neutrons and other light hadrons, which make up more than 99% of the mass of the visible universe. The chiral symmetry is predicted to be restored in hot and/or dense matter and its partial restoration is expected even at the normal nuclear density. In order to reveal the quantitative relation between the chiral symmetry breaking and hadron mass, the J-PARC E16 experiment has been proposed. One of the promising experimental methods is the systematic study of the dilepton decay of vector mesons which are produced in a uncle target. Figure 1 illustrates the basic idea of the experimental method for $\phi$ meson case as an example. A proton beam is induced to a nucleus target and a $\phi$ meson is produced. The invariant mass of $e^+e^-$ from the $\phi$ depends on whether $\phi$ meson decays inside or outside nuclei. When the decay occurred outside nuclei, the spectrum is the same as that of the decay in vacuum, whereas the modified spectrum is obtained for the decay inside nuclei due to the finite density. The expected spectrum by the experiment is the sum of the spectra of the two cases. The systematic measurement,
Figure 1. The basic scheme of the experiment. A proton beam is induced to nuclei and a $\phi$ meson is produced. The mass of $\phi$ meson is measured by reconstructing the invariant mass of $e^+e^-$ pair. The invariant mass spectrum is supposed to be the sum of the spectra of which $\phi$ decays in vacuum and in medium.

where the size of target nuclei and $\phi$ momenta are properly selected, controls the staying time of $\phi$ in nuclei and hence the mixture ratio of the two spectra. Such study provides the dispersion relation of the QCD vacuum.

1.2. J-PARC Hadron Experimental Facility and high momentum beam line
The E16 experiment will be conducted at the high momentum beam line of J-PARC Hadron Experimental Facility. Figure 2 shows the plan view of the switch yard and the Hadron Experimental Facility. A 30-GeV primary proton beam with the intensity of more than $10^{13}$ proton per pulse (ppp) is slowly extracted to the Hadron Experimental Facility, where the slow extraction means 2-second beam pulse per 6 second cycle. Most of the beam go to LINE-A and bombarded on the T1 target to produce high intensity secondary hadron beams such as pions and kaons. A small fraction of the primary beam ($2 \times 10^{10}$ ppp) is delivered to the high momentum beam line, which is shown as LINE-B, using a Lambertson-type magnet. The beam line construction will be completed in 2016. The E16 spectrometer will be built at the end of the high momentum beam line.

1.3. E16 spectrometer
The E16 spectrometer was designed to measure the invariant mass of dielectrons from slowly moving $\phi$ meson decay with high resolution and high statistics. The schematic view of the E16 spectrometer is shown in Figure 3. All of the detectors are installed in a wide gap dipole magnet, whose maximum field is 1.7 T at the center. Various target nuclei, such as C, CH$_2$, Cu and Pb, are placed at the center point for the systematic study of the target size dependence of the mass modification. Typical target thickness is 0.1% interaction length and 0.5% radiation length to suppress the electron background caused by $\gamma$-conversion in the target. The target systems are surrounded by 26 detector modules, which form a barrel shape (9, 8, and 9 modules in the top, middle and bottom barrel, respectively). Each detector module comprises of a GEM tracker.
(GTR), a hadron blind detector (HBD) and a lead-glass electromagnetic calorimeter (LG). One GTR module has three tracking planes whose sizes are 100 × 100, 200 × 200 and 300 × 300 mm$^2$, respectively. The GTR is required to cope with the high rate of 5 kHz/mm$^2$ and to keep the good position resolution of 100 µm in the bending plane in order to resolve the modified mass component in the reconstructed $\phi$, which corresponds to the mass resolution of 5 MeV/$c^2$. HBD is a mirror-less and windowless gas Čerenkov detector filled with pure CF$_4$ as a radiator. HBD also uses GEM with a CsI photo-cathode to detect Čerenkov photons. LG is equipped with 3-inch fine mesh photomultiplier tube to keep a high gain under a magnetic field of 0.8 T. HBD and LG is used for an electron identification, whose hadron rejection power is expected to be $1 \times 10^{-2}$ and $4 \times 10^{-2}$, respectively. Details of GTR and HBD are described in [2], [3] and [7].

The spectrometer is getting ready for the first beam in the beginning of 2017. At first, physics run will start with 8 detector modules. After that, the number of detector modules will
be progressively upgraded towards the full installation.

2. Readout system

2.1. Overview

The numbers of readout channels of GTR, HBD and LG are 56,160, 35,880 and 988, respectively. Waveforms from all the detectors are recorded using analog memory ASICs (APV25[4] for GTR and HBD, and DRS4[5] for LG) for the offline analysis.

To trigger $e^+e^-$ pairs, three fold coincidence of GTR, HBD and LG is used. Since the APV25 does not have fast output signals for trigger primitives, cathode GEM foils of the most outer GTR and HBD are divided and used as trigger segments. An analog signal from a trigger segment is discriminated by its pulse height and the binary output signal is merged to make a trigger decision. The numbers of trigger segments of GTR, HBD and LG are 624, 936 and 988, respectively.

Front-end digitizer modules (FEM) are synchronized with the global clock. Data collection and slow control are performed via the Ethernet. E16 data acquisition (DAQ) system is required to cope with the level-1 trigger of 2k events and data rate of 660 MB per spill. The development of DAQ software based on the DAQ-Middleware framework is in progress. The DAQ software is detailed in [6].

2.2. GTR and HBD readout

The FEM for GTR and HBD is based on the Scalable Readout System (SRS)[7], which is developed by the CERN-RD51 collaboration. Signals from strips of GTR and pads of HBD are fed into the preamp hybrid card using the APV25s1 ASIC. One APV25 chip contains 128 channels of low-noise preamplifiers followed by a shaper stage. Each channel has an analog memory whose depth is 4 $\mu$s with the sampling frequency of 40 MHz. The pulse shapes of ~500 ns for GTR (150 ns for HBD) stored in the analog buffer are read out in a single channel through a built-in analog multiplexer. The waveforms are digitized and zero-suppressed on the SRS-ADC module. The data after zero-suppression are transfer ed to PCs by UDP. The APV25 hybrid card of SRS, on which one APV25 chip is mounted per card, is utilized for the HBD pad signal. As for the GTR readout, a more compact card with two APV25 chips, named TRK-APV, was developed in order to save installation space and to make a more flexible connection between the hybrid card and the GTR using microminiature coaxial cables, which is shown in Figure 4(a).

Test experiment of GTR using the prototype TRK-APV card was performed at J-PARC K1.1BR beam line in December 2012. In order to achieve the position resolution of 100 $\mu$m even for the track incident angle of 30°, hit timing information was extracted from the waveform and the position in the drift gap was calculated. Figure 4(b) displays the obtained position resolution. The position resolution and the detection efficiency satisfied our requirement.

2.3. LG readout

The FEM for LG uses DRS4, which is a GHz sampling ASIC, and a fast comparator to generate a trigger primitive signal. Analog pulse of LG is stored for 2 $\mu$s in the DRS4 for the sampling speed at 1 GHz. When the Level-1 trigger is received by the FEM, the waveform for ~200 ns duration is digitized by 33 MSPS ADC. The data are zero-suppressed on the FEM and sent to DAQ PCs through Ethernet using TCP.

The prototype DRS4 ADC board with 16 channel inputs has been developed. A picture of the board is given in Figure 5(a). The main amplifier and the discriminator part is schematically illustrated in Figure 5(b). The negative input pulse is inverted with the opamp THS4513 and split to two lines, one is fed into the comparator LMH7322 to generate a binary output used for trigger primitives, and the other goes into the DRS4. Preliminary results of the performance
Figure 4. (a): Pictures of TRK-APV. The card has 256 input channels, which are connected with the chamber strips by microminiature coaxial cables. The slow control signals of the APV25 chips and the waveform data are transferred via a micro-HDMI cable. The card dimension is $50.8 \times 65.0 \text{ mm}^2$. (b): Position resolution obtained by the beam test. A timing method, which calculates the drift length, is useful to achieve a good position resolution for the incident angle of up to $30^\circ$.

Figure 5. A prototype of LG-FEM. The board form factor is KEKVME-6U, a localized VME standard for KEK and J-PARC experiments [8].
test using a function generator are as follows. The timing jitter of the discriminator part was better than \( \sigma = 200 \) ps (50 ps) for input signals with an amplitude of 50 mV (larger than 500 mV). The charge measurement integrating the waveform without a gain correction of DRS4 was found to be around 0.9\%. These properties are satisfactory for LG-FEM.

2.4. Trigger

E16 uses very high intensity beam of \( 10^{10} \) Hz in order to obtain a considerable yield with very thin targets whose thickness of 0.1–0.2\% interaction length in total. The main background is charged pions, which can be suppressed by requiring a coincidence of a HBD segment and a LG block. In addition, a GTR segment is also joined into the coincidence to identify the track candidate originating in the target region. After the pion suppression, there are still \( e^+e^- \) background processes. Two main sources of the background \( e^+e^- \) are \( \pi^0 \) Dalitz decays and the \( \gamma \) conversion in the target material, where the contribution of the two sources is expected to be almost same number though the branching ratio of the former is \( Br \sim 1\% \) and that of the latter is \( Br \sim 99\% \). The electrons from these sources can be reduced by requiring the two electron candidates which have an opening angle of larger than 60\(^\circ\) at the HBD pad, because the dielectron from slowly moving \( \phi \) is produced back-to-back while the low mass pair from \( \gamma \) conversion and \( \pi^0 \) Dalitz decay have a small opening angle.

The trigger electronics is detailed in [9]. The trigger logic implementation is under way.

2.5. Synchronization of the electronics

The FEMs for GTR, HBD and LG and the trigger merger must be synchronized using a global clock. The Belle-II FTSW (Front-end Timing Switch)[10] is used as the global clock distributor module as well as the trigger distributor. 8b10b encoded trigger information, which contains a trigger type and its time stamp, and the global clock are broadcast via a category-7 LAN cable. The global clock frequency is \( \sim 125 \) MHz and the trigger data is transmitted and captured in the double data rate of the global clock frequency. Implementation of the encoding/decoding trigger data and test on the electronics synchronization is ongoing.

3. Summary

The J-PARC E16 experiment aims to investigate the mass modification of vector mesons in nuclei through the systematic measurement of the invariant mass of \( e^+e^- \) with high resolution and high statistics. The electronics, online trigger system and data acquisition system have been developed for the J-PARC E16 experiment. Waveforms of detector signals from about 100,000 readout channels of GTR, HBD and LG in total are recorded using analog memory ASIC after zero suppression. The trigger is composed of the three-fold coincidence of the trigger segments of about 2600 channels in total. Data acquisition system is built on the DAQ-Middleware framework. The development of the readout module has been practically completed. The R&D of the trigger system is ongoing. The physics data taking will start with 1/3 of the detectors in 2017.

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