Development of a beam timing detector for the charmed baryon spectroscopy

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We plan the charmed baryon spectroscopy experiment (J-PARC E50[1]) at the high-momentum beamline of the J-PARC hadron experimental facility. In the experiment, the excited states of charmed baryons are produced via the $p(\pi^-, D^{*-})Y_c^{*+}$ reaction using π^- beam of 20 GeV/c. We measure the production rates and decay branching ratios of the excited states in a wide mass region by the missing mass method. The diquark correlation which is expected to appear in the properties of the excited state of charmed baryon can be clarified. In the experiment, a high-intensity secondary beam of 6.0×10^7/spill (30 MHz for the 2 sec. extraction) is used to obtain sufficient yields of charmed baryons. Beam timing detector must be operated under a high-counting rate environment. The requirement of time resolution of the beam timing detector is $60 - 80$ ps (rms) to identify scattering particles after reacting at the target by using the time-of-flight methods. Beam timing detector needs to be operated in the leakage magnetic field because it is installed at the entrance of the spectrometer magnet.

By considering requirements of the beam timing detector, we used a detector with a combination of a Cherenkov radiator(acrylic: PMMA) having a cross-section and a length of 3 mm square and 150 mm, respectively, and Multi-Pixel Photon Counter (MPPC). A Cherenkov detector which has a tilted radiator to the direction of the emission angle of Cherenkov light is used, called Bar-type. For the other Cherenkov detector, we devised a cross-shape radiator which is cut out an X-type acrylic from an acrylic plate, called X-type (Figure.1).

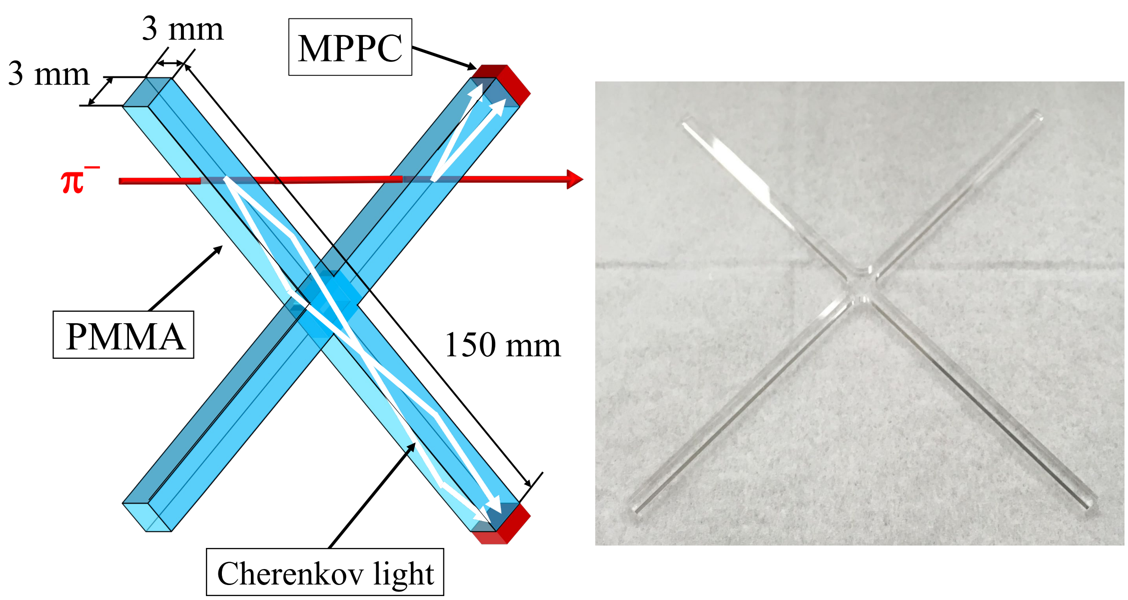

Figure 1: X-type Cherenkov detector. A cross-shape radiator which is cut out an X-type acrylic from an acrylic plate.

As a reference, a plastic scintillation counter having a cross-section and a length of 3 mm square and 150 mm, respectively, is also used with MPPC. Prototypes of the beam timing detectors of Bar-type and X-type Cherenkov detectors and plastic scintillator are tested. In particular, the characteristics of the X-type Cherenkov detector which is a new type one by applying the method of both edge readout timing detector for the Cherenkov light detection is investigated in detail.

We performed a test experiment under the low-counting rate environment at the J-PARC K1.8BR beamline to understand characteristics of the prototype detectors. In the experiment, we measured detector responses by changing the operating voltage of MPPC, the threshold of a discriminator, and the beam position. We used an FPGA based high time resolution TDC (time resolution: 20 ps). Dependences of the time resolution of prototype detectors were investigated. Furthermore, we investigated whether the sufficient number of photoelectron by Cherenkov detectors could be obtained by using a 3-mm thick PMMA radiator which was tilted to the emission angle (48°) of the Cherenkov light from the beam direction. Figure.2 is shown the position dependence of the photoelectron(a) and time resolution(b). The number of photoelectron for each position was measured, and the detection efficiency evaluated by assuming the Poisson distribution. In the case of the Cherenkov detectors, the average number of the photoelectron of 25 p.e. and 43 p.e. for Bar-type and X-type were obtained, respectively. It is a sufficient amount of photoelectron for the threshold (3.5 p.e.) to achieve the best time resolution. We found that both scintillation and Cherenkov detectors achieved the goal of time resolution of better than 80 ps (rms) without no position dependence. In particular, X-type Cherenkov detector showed time resolutions of (35.6 $\pm$ 0.9) ps at the central position and of (42.0 $\pm$ 1.8) ps at +40 mm from the central position by measurement conditions of the overvoltage of +7 V and the threshold of 3.5 p.e. By the test experiment, we found the optimum operation conditions were the overvoltage of +7 V and the threshold of 3.5 p.e. by taking into account the number of photoelectrons and the threshold dependence.

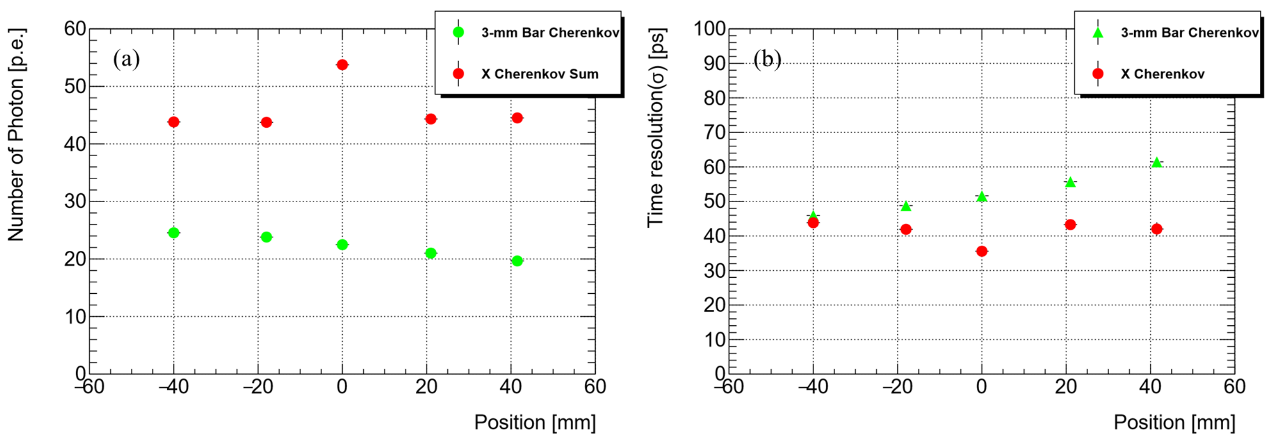

Figure 2: The position dependence of the photoelectron(a) and time resolution(b).

We performed a test experiment under the high-counting rate environment at the Research Center for Electron Photon Science in Tohoku University (ELPH). Time resolutions were evaluated at the counting rate of 2–3 MHz which is assumed beam rate per segment in the J-PARC E50 experiment. While we gradually increased the counting rate from the low-counting rate, the performance of the prototype at beam rate up to 5 MHz was evaluated. We measured the timing information using DRS4 and HUL modules having the FPGA based high-resolution TDC. By increasing the counting rate, the time resolution of all detectors became worse. However, all detector achieved time resolution of better than 80 ps (rms) at the counting rate of 2-3 MHz by the HUL module measurement. The X-type Cerenkov detector achieved the best time resolution (Figure.3). The time resolutions of (66.4 $\pm$ 0.9) ps and (54.0 $\pm$ 0.80) ps by the DRS4 and the HUL modules, respectively.

We considered the cause of the deterioration of the time resolution under the high-counting rate environment. The amplifier of MPPC has a ringing after the tail of the signal. The time resolution was deteriorated due to the signal pileup on this ringing. The waveform information was acquired by the DRS4 module. The effect of the pileup on ringing was investigated by removing the event with the preceding signal which came to before the trigger timing. As a result, we obtained time resolution of (59.9 $\pm$ 1.8) ps and (39.6 $\pm$ 1.9) ps by the DRS4 and the HUL modules, respectively. It was found that the ringing affected the time resolution while variations of the baseline and gain were sufficiently small. Optimization of the shaping circuit is essential to obtain a better time resolution.

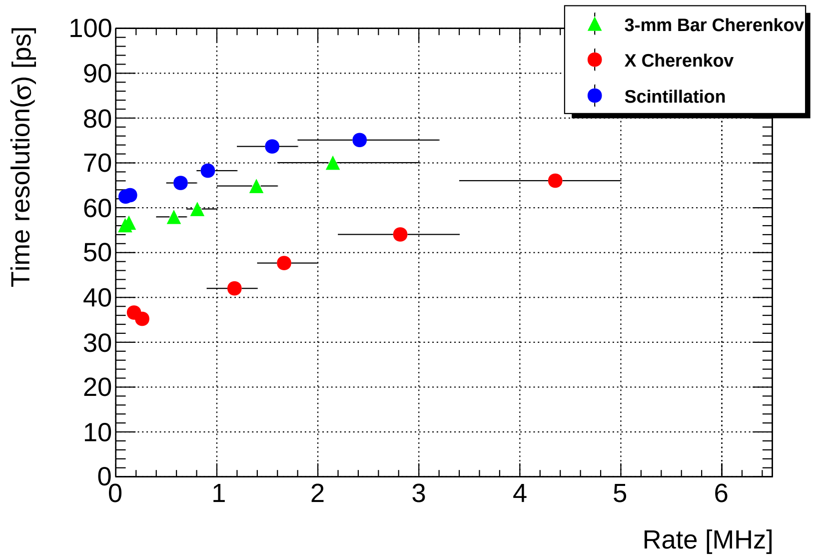

Figure 3: Counting rate dependences of time resolutions by the HUL module. All detector achieved time resolution of better than 80 ps (rms) at the counting rate of 2-3 MHz.

It is concluded that the X-type Cherenkov detector which has the best time resolution with no position dependence provides the best as the beam timing detector. Furthermore, the X-type Cherenkov detector which has a sufficient number of photoelectron, and the characteristic of the voltage dependence and the threshold dependence fully satisfies the operation as a beam timing detector. For the beam timing detector of the J-PARC E50 experiment, the development of the detector component which fulfills the required performance was achieved by using the X-type Cherenkov radiator and MPPC.

For the next step, we need to design the actual detector. X-type radiators should be arranged closely together in order to cover the beam region. In the present study, we performed a slewing correction with both TDC and ADC. In the charmed baryon spectroscopy experiment, we need to use a fast signal digitalization without ADC due to the high-counting rate beam so that we also consider the timing measurement by using only the TDC information. It is necessary for the signal shaping circuit for the slewing correction by the Time-over-Threshold method instead of that by ADC. Since the shaping circuit has only differentiates the rise of the signal, the width of the signal is saturated when the pulse height becomes high. It is not sufficient to correct the pulse height from the information of the signal width. Therefore, in addition to the output of the timing information as a shaping circuit, it is necessary to improve the output for shaping signals (integral or slow time constant) by keeping the relation between the pulse height and the signal width. In order to eliminate the effect of a ringing pileup in the high-counting rate environments, we need to improve to reduce the ringing of the amplifier. The ringing can be suppressed by finely adjusting circuit elements such as the time constant, multiplication factor, and the damping resistance. We will solve these problems and plan to produce the actual beam timing detector in the future.

References

[1] H. Noumi et al.: J-PARC E50 Proposal (2012).