Development of a Cherenkov timing detector for measuring high-intensity secondary beams

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  • Time resolution evaluation of proto-type detectors

• To do

• Summary
Introduction
Investigation of effective degree of freedoms

- To understand role of effective degree of freedoms for hadrons
  - Diquark correlation, molecule states
- Systematic studies: Charmed baryon (q-q + Q) ↔ Ξ⁺ (q + QQ) and Ω⁺ (QQQ) systems
  - Heavy (heavier) quarks are key.
Experimental situations of $\Xi^*$ and $\Omega^*$ baryons

- Poor experimental data of $\Xi^*$ and $\Omega^*$
  - Systematics studies are essential.

- Narrow decay width expected
  ⇒ Chance to find and separate states
  - $\Gamma \sim$ a few 10 MeV of $\Xi^* <$ a few 100 MeV of $\Lambda^*/\Sigma^*$
  - $\Omega^*$ expects to have also narrow width.
  ⇒ Systematics measurements
  - Production and decay

*$K^-$ beam is effective tool to produce multi-strangeness baryons.
  - High-momentum beam: 5–10 GeV/c
  - Large yield: $\sigma = \sim 1$ µb order and high-rate beam
  ⇒ Systematic studies by E50 spectrometer
  - Beam measurement is essential for missing mass and decay measurement
High-momentum beam line for 2\textsuperscript{nd}ary beam

- High-intensity beam: \(> 1.0 \times 10^7 \text{ Hz} \, \pi \, (< 20 \text{ GeV/c})\)
  - Unseparated beam: \(\pi/K/p_{\text{bar}}\) : MHz K beam ⇔ 100 MHz \(\pi\) beam

- Beam timing measurement: Start timing
  ⇒ “Bottleneck” to increase beam intensity

\[
\text{Design Intensity [Hz] in spill (2.0 sec)}
\]

\[
\text{K/\pi \& p_{\text{bar}}/\pi \text{ ratio}}
\]

\@ 15 kW loss
High-momentum beam line for 2\textsuperscript{nd}ary beam

- High-intensity beam: \( > 1.0 \times 10^7 \) Hz \( \pi \) (< 20 GeV/c)
  - Unseparated beam: \( \pi/K/p_{\text{bar}} \): MHz K beam \( \Leftrightarrow \) 100 MHz \( \pi \) beam
- Beam timing measurement: Start timing \( \Rightarrow \) “Bottleneck” to increase beam intensity

- High-rate capability
- Good time resolution
High-rate Cherenkov timing detector: R&D status

Fine segment test
Signal processing method test
T0 detector

- Segment by Acrylic (PMMA)
  ⇒ Cross shape: X-type
    - Cherenkov angle direction
      - Suppress time spread
    - Both edge readout
      - ×2 light yield

- 3-mm width segment + MPPC
  - MPPC amplifier: ~10 ns width

⇒ Time resolution: $\Delta T \sim 50 \text{ ps(rms)}$
  - 3 MHz/segment ⇒ Achieved
  - No position dependence
  * Akaishi master thesis

* Limit: ~3 MHz/3-mm segment

⇒ < 1-mm width fine segment
  - Handle 100 MHz beam
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Simulation: Radiator width dependence

- Fine segment simulation
  - Geant4: Optical photon
    - Realistic parameters: PMMA, MPPC and so on

- Normalization of # of p.e.
  - 3-mm radiator light yield data
    ⇒ Reflection probability of PMMA: 99.5%

- Light yield is decreased by fine segments.
  - ~16 p.e. @ 0.5 mm

- Smaller loss of fast components
  - Small number of reflections
    - Resolution is expected to be kept.

* Production by company
  - Cut from one PMMA board

⇒ Actual fine segment test
Fine segments of Cherenkov radiator

- Radiators can be fixed by Silicone sheet with glue and some wires.
Test experiment @ LEPS

• Purposes
  • **Fine segment test**
    • 1.0 mm and 0.5 mm segments
  • **New amplifier test**
  • **Signal processing test**
    • Schottky Barrier Diode filter circuit
    • Integration circuit for TOT

• **Time resolution evaluation by MIP**
  • $e^\pm$ from $\gamma$-ray conversion
  • RF timing reference: $\Delta T \sim 14$ ps
  • Time walk correction by pulse height
    • Data taking: DRS4 and HUL HR-TDC

• **MPPC (s13360-3050PE) conditions:** $V_{ov} = +7V$
  • One p.e. pulse height: $\sim 70$ mV (amp gain: $\times 18.8$)
Number of photoelectrons

- Average: ~20 p.e.
- Light yield tendency of both edge is consistent.

T. Akaishi, Master thesis
Number of photoelectrons

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- Light yield tendency of both edge is consistent.

Handwriting curbs

T. Akaishi, Master thesis
Number of p.e.: @ +20 mm

\[ 38.7 \pm 0.4 \text{ p.e.} \quad (\sigma = 7.8 \text{ p.e.}) \]

\[ 38.6 \pm 0.7 \text{ p.e.} \quad (\sigma = 8.0 \text{ p.e.}) \]

\[ 40.4 \pm 0.5 \text{ p.e.} \quad (\sigma = 7.8 \text{ p.e.}) \]

• Sum of both edge and its distribution are same.
  \[ \Rightarrow \] Collection of Cherenkov lights w/o surface loss
Time resolution: @ V\text{th} = 3.5 \text{ p.e.}

• All data: Similar time resolution of \(~45\) ps(rms).
  • Time resolution is kept. = Same light yield

\*3.0 \text{ mm} \Rightarrow 0.5 \text{ mm}: \times 6 \text{ higher counting rate}
  • 3 MHz/3 mm @ 30 MHz \Rightarrow 3 MHz/0.5 mm @ 180 MHz

* RF ΔT \sim 14 \text{ ps(rms)} subtracted
1. Ringing suppression
   • Effects to time resolution by pile-up signal
     • Time resolution: 43 ps ⇒ 54 ps @ High-rate condition
   ⇒ Schottky Barrier Diode (SBD) was used as kind of filtering methods.

2. TOT measurement
   • Time-walk correction by Time-Over-Threshold (TOT) method
     • Width = (Leading edge – Trailing edge)
   • Only TDC measurement without ADC
     • Dead-time less digitalization for streaming DAQ
Schottky barrier diode: SBD

- Kind of rectifier diode
  - Quick responses
  - Smaller forward voltage: 100–200 mV level

*Revered pulses and smaller pulses are suppressed.
⇒ Ringing suppression

- BAT63: Series connection to amplifier
  - Signals width: Same
  - \( V_{\text{out}} = 0.62 \times (V_{\text{in}}) - 70.0 \) (Minimum input: ~120 mV)

![MPPC amp](image1)

![SBD circuit](image2)

![Series connection](image3)
• Similar time resolution of ~45 ps(rms).
  • W/SBD data showed little worse resolution.
  • Smaller pulse height affected by noise

• SBD can be used as filter circuit. ⇒ High-rate test
Time-Over-Threshold method

- Straight forward method cannot correct time-walk of leading edge.
  - Differential circuit for narrow signal width
    ⇒ Width is saturated in the higher pulse height region.

*Extract pulse height information from width*

⇒ Integration by slow shaping
  - SBD + slow shaping is essential.

- RC integration circuit
  - \( \tau = 2.4 \) ns
    - \( R = 51 \ \Omega, \ C = 47 \ \text{pF} \)
  - Signal width: \(~15\) ns
    - Original: \(~10\) ns
Time resolution: TOT method

- Width analysis showed similar resolution. @ Vth = 4.5 p.e.
  - Response is not completely understood by using amplifier w/ SBD and RC circuit.
  ⇒ Investigation of optimum time constant

⇒ Vth = 3.5 p.e. data
⇒ Correlation is almost same as of Vth = 4.5 p.e. data.
⇒ It is necessary to investigate.

* RF ΔT ~14 ps(rms) subtracted

By PH

By width

* Tail component
To do

* To finalize R&D and production of Cherenkov beam timing detector

- Tests in early 2020 are affected by COVID-19.
  - Segmented detector test by EMPHATIC @ Fermilab (Postponed by November)
    ⇒ Test at other facilities (LEPS, ELPH ?)
  - High-rate test @ ELPH ⇒ It will be performed in July(?) or October (?).
    + Test by mixed signal: Emulate pile-up events

- Investigate and optimization of filtering circuit
  - SBD and RC circuit

- Design of actual detector
  - Segment width size adjustment for beam profile
  - Simulation study for fixing radiators with good filling rate
  - MPPC array (TSV type) for assembling fine segments

- Publication plan
  - X-shape Cherenkov detector: 1st draft is under preparation.
  - High-rate measurement: Signal processing, TOT and so on
Summary

• Investigation of effective degree of freedom for hadrons
  • Systematic study: Charmed baryon \( \Leftrightarrow \Xi \) and \( \Omega \)

• \( K^- \) beam @ J-PARC High-\( p \) beam line
  • High-intensity \( K^- \) beam \( \Rightarrow \) Dominant \( \pi \) in unseparated beam
  • High-rate capability of beam timing detector: Fine segment beam detector

• R&D of Cherenkov timing detector
  • X-shape Acrylic radiator with thin width: 0.5 mm, 1.0 mm, 3.0 mm
  • Test experiment @ LEPS
    \( \Rightarrow \) Time resolutions of \( \sim 45 \) ps(rms) were kept by using fine segment radiators.
    • Availability of much higher counting rate beam: \( \times 6 \) higher rate
    • 3 MHz/3 mm @ 30 MHz \( \Rightarrow \) 3 MHz/0.5 mm @ 180 MHz
  • Filtering method test for suppressing ringing effects by SBD
    • High-rate test is necessary for finalizing R&D.
  • TOT method test: SBD + Integration circuit
    • It was found that measurement without ADC can be performed.

* To finalize R&D and production of Cherenkov beam timing detector
  • \( K^- \) beam intensity is as high intensity as possible at J-PARC high-momentum beam line.
    \( \Rightarrow \) To drive investigation of multi-strangeness baryons