Time resolution measurements of scintillating counters for a new NA62 trigger charged hodoscope

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ABSTRACT: The results of time resolution measurements on cosmic muons with MWPC chambers as a tracking system are presented. Two options of dual SiPM readout considered: direct light collection from opposite cut corners of the scintillator and light collection using two oppositely directed bundles of WLS fibers. Two types of SiPMs are used: S10985-050C and MicroFB-60035. The best result achieved using mean-time between two SiPMs. For the direct readout from $134 \times 107 \times 20 \text{ mm}^3$ scintillator time resolution $\sigma = 300 \pm 10 \text{ ps}$ and maximum signal arrival time spread $\Delta T = 1.6 \pm 0.2 \text{ ns}$. Using WLS fiber readout option with $265 \times 107 \times 30 \text{ mm}^3$ scintillator tile signal arrival time spread $\Delta T = 150 \pm 50 \text{ ps}$ and time resolution $\sigma = 370 \pm 10 \text{ ps}$.

KEYWORDS: Timing detectors; Trigger detectors

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doi:10.1088/1748-0221/9/09/C09002
1 Introduction

The main goal of NA62 [1] experiment is to study extremely rare kaon decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with 10% precision. This decay is strongly suppressed in Standard Model (SM) and could be calculated with high precision $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 7.81 \cdot 10^{-11}$ which makes it sensitive to New Physics beyond the Standard Model. Current experimental value of branching fraction $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$ [2] was obtained by the E787 and E949 experiments and has limited accuracy.

NA62 experiment is designed to work with high intensity hadron beam (750 MHz) with 75 GeV/c momentum and $\approx 10$ MHz expected rate of decayed kaons. To study so rare decays it is important to have good particle identification system and strong background suppression. One of the important detectors of NA62 trigger system is Charged-particle Hodoscope (CHOD) — system of scintillation counters with pad structure covering area of $\odot 2140$ mm around the beam pipe. CHOD is designed to define the aperture for charged particles for the level-0 trigger and to veto possible interactions in the RICH mirror plane ($\approx 20\%$ of radiation length). According to Monte-Carlo simulation the total rate of hodoscope expected to be $\approx 32$–$35$ MHz with maximum 400–500 kHz rate per tile (see figure 1 left) in the beam pipe region. The acceptance of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay per tile is presented on figure 1 right. It is important to note specific region marked with red line that could be excluded from trigger to significantly reduce the total rate with less than 1% signal loss.

2 New CHOD prototypes

New CHOD is scintillating hodoscope with a pad structure and total number of 148 counters. Each pad designed to have dual SiPM readout. Thus 296 electronic channels are required. The New CHOD consists of pads with size $268 \times 108$ mm$^2$ on periphery and $134 \times 108$ mm$^2$ at the center region. Pads with different size are used to keep balance between minimum total number of channels
**Figure 1.** MC simulation of the total rate in hodoscope and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal acceptance: left — total rate of New Charged Hodoscope per small tile $132.5 \times 107 \text{ mm}^2$; right — acceptance of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay in per mil per tile.

and rate per channel less than 500 kHz. The sensitive area of hodoscope covers $\varnothing 2140 \text{ mm}$ except the region close to the beam pipe ($\varnothing 280 \text{ mm}$). Polymerized scintillators made in IHEP (Protvino) with similar to BC-408 properties are used. Two different options of light collection considered: direct light collection from opposite cut corners and light collection using WLS fibers.

**Direct readout.** For the direct readout the counter prototype consist of $133.5 \times 107 \times 20 \text{ mm}^3$ scintillator (wrapped by Tyvek) and two SensL MicroFB-60035 SiPMs with $6 \times 6 \text{ mm}^2$ sensitive area as a photodetectors. The SiPMs were glued with optical contact to opposite cut corners of scintillator (refer to figure 2 left).

**Fiber readout.** The prototype with WLS fiber readout consist of $268 \times 108 \times 30 \text{ mm}^3$ scintillator (wrapped by Tyvek) with 18 grooves: 16 on the top face plus one on each of two side faces. The grooves are oriented perpendicular to the long (268 mm) side of the tile to minimize the effect of geometry on time resolution (refer to figure 2 right). BCF-92 WLS Fibers with $\varnothing 1 \text{ mm}$ and 40 cm long are glued and grouped into two oppositely directed bundles with 9 fibers each. Distance between fibers in one bundle is $\approx 30 \text{ mm}$ and each SiPM is connected to 8 fibers on the top face plus one from the side face. WLS fibers are polished on both ends and mirrored by aluminium foil tape on the side opposite to SiPM. As photodetectors Hamamatsu S10931-05P SiPMs with $3 \times 3 \text{ mm}^2$ sensitive area are used.

### 3 Test setup

The test setup is schematically presented on figure 3 and consist of four ordinary scintillation counters $S_1$–$S_4$ with EMI 9813B PMT, four planes of MWPC with $120 \times 120 \text{ mm}^2$ sensitive area — two pairs of X and Y planes, time setting counter $C_{\text{Fast}}$ and light tight box with a prototype.
The coincidence of four counters $S_1$–$S_4$ generates a triggering signal for cosmic muon. Two counters are above ($S_1$ and $S_2$ with $100 \times 160\text{ mm}^2$ sensitive area) and two below ($S_3$–$S_4$ with $95 \times 90\text{ mm}^2$ sensitive area) the prototype. MWPC with delay line readout and $4\text{ mm}$ step between wires generates two signals for each event. The time difference between two signals from one plane defines the coordinate of cosmic muon. To reconstruct the coordinates specific calibration events are generated with $1\text{ Hz}$ rate, firing three specific wires.

Time setting Cherenkov counter $C_{\text{Fast}}$ is a $\odot 40\text{ mm} \times 45\text{ mm}$ cylinder made of Plexiglas viewed by XP2020 PMT. Time resolution of $C_{\text{Fast}}$ counter is $175 \pm 10\text{ ps}$. The prototype is placed in the light tight box located between two blocks of X and Y planes of MWPC.
Electronics. The signal from each of four scintillating counters \(S_1\)–\(S_4\) comes to passive splitter. One part goes to ADC module through delay cable. The second part of signal goes to Constant Fraction Discriminator (CFD ORTEC 934 QUAD) with two output NIM signals: one output signal used by coincidence module and the second signal goes to TDC. The coincidence of signals from four scintillating counters \(S_1\)–\(S_4\) generates a triggering signal to start ADC and TDC modules and DAQ readout process. Signals from Fast Cherenkov counter \(C_{\text{Fast}}\) and both SiPMs installed on CHOD prototype go to ADC and TDC modules through CFD (CAEN N253). Multi-hit TDC CAEN Mod.V1290N allows to select different combinations of time setting counters during offline analysis.

4 Results

For the time analysis intervals between signal from \(C_{\text{Fast}}\) and signals from SiPMs measured by TDC were fitted with Gaussian. Fit parameters MEAN and SIGMA were used for further analysis as signal arrival time and time resolution respectively. Amplitude spectrum was fitted with Landau function and fit parameter MPV (peak value) in ADC channels was recalculated to the approximate number of photoelectrons using a calibration with LED. Linear track parametrization was used to retrieve the coordinate of cosmic muon on the prototype.

To compare results of measurements with WLS fibers and direct readout options the minimum GATE width parameter is introduced: \(\text{GATE} = \Delta T + 5 \times \sigma\), where \(\Delta T\) is a maximum signal arrival time spread while the cosmic muon hit point is moved over the prototype area, \(\sigma\) is intrinsic local time resolution. Within such a gate \(\approx 98\%\) of signals are contained. Different algorithm options of time measurements are considered: mean-time of the signals from SiPMs, first and last signals.

4.1 Fiber readout

For the WLS Fiber readout cartesian coordinates with two axis are used: along and across fibers.

Across fibers: on figures 4, 5 (left) the amplitude in number of detected photoelectrons and signal arrival time vs coordinate across fibers are presented. Both dependencies have oscillating character with a period \(\approx 30\) mm — the distance between fibers in one bundle. Amplitude dynamic range defined as \(A_{\text{max}}/A_{\text{min}}\) is about 1.10.

Along fibers: signal arrival time vs coordinate along the fibers is presented on figure 5 (right). The amplitudes vs coordinates along fibers for one SiPM presented on figure 4 (right). Signal arrival time depends on muon coordinate along fiber as \(4.0 \pm 1.5\) ns/m and is close to the expected light speed in plastic with refractive index of \(n = 1.58\). Maximum signal arrival time spread estimated as as \(400 \pm 150\) ps. Amplitude of SiPM is decreasing with increasing distance to SiPM as \(\approx 0.03\) p.e./mm.

The final results for WLS Fiber readout are presented on the table 1. The best time resolution with dual SiPM readout achieved using mean-time signal and is \(\sigma = 370 \pm 10\) ps.

4.2 Direct readout

For the direct readout there is a preferred direction — the diagonal between opposite corners with SiPMs. In this case the polar coordinate system is used with parameters \(R\) — distance from cosmic muon coordinate in prototype to SiPM and \(\phi\) — angle to the diagonal between SiPMs.
Figure 4. Amplitude in photoelectrons vs coordinate across (left) and along (right) fibers. Arrows on the left figure represent coordinates of glued WLS fibers.

Figure 5. Δt vs coordinate across (left) and along (right) fibers, where Δt — SiPM signal arrival time with respect to Fast Cherenkov counter $C_{\text{Fast}}$. Bold blue line on the right figure — fit with linear function.

Table 1. Results of time resolution measurements for WLS readout option.

|                  | Single SiPM | Mean signal |
|------------------|-------------|-------------|
| Local time resolution $\sigma$, ns | 610 ± 10 ps | 370 ± 10 ps |
| Time spread $\Delta T$, ns | 400 ± 150 ps | 150 ± 50 ps |
| Effective GATE, ns | 3.5 ± 0.2 ns | 2.0 ± 0.2 ns |

For the direct readout the amplitude and signal arrival time strongly depend on the distance between cosmic muon hit point and SiPM. On figure 6 the amplitude vs coordinate position is presented using cartesian (left) and polar (right) coordinate systems. Amplitude reaches maximum close to the active SiPM (point $[0, 0]$) and has nearly the same minimum values at other corners of scintillator including the opposite corner with second SiPM [point $107,133$]. The dynamic range is estimated as $A_{\text{max}}/A_{\text{min}} \approx 3$. The signal arrival time versus position is presented on figure 7 for single SiPM readout and using mean-time of two SiPMs. The maximum signal arrival time spread for single SiPM is $2.7 \pm 0.2$ ns and is decreased to $1.6 \pm 0.2$ using mean-time of two SiPMs. Another possible option is to use the First or the Last signal. The final results are presented on table 2.
Figure 6. Amplitude vs distance to SiPM in cartesian (left) and polar (right) coordinates. The right figure with polar coordinates contains three regions: black rhombs — center region close to diagonal between SiPMs; blue squares — middle angle region; red circles — large angle region close to the edge of scintillator.

Figure 7. SiPM signal arrival time $\Delta t$ vs distance to SiPM for single SiPM (left) and mean time between SiPMs (right). Black rhombs — center region close to diagonal between SiPMs; blue squares — middle angle region; red circles — large angle region close to the edge of scintillator.

5 Conclusion

Two different options of light collection considered: direct light collection from cut corners of scintillator and light collection with WLS fibers.

*WLS fiber readout* provides $370 \pm 10$ ps local time resolution with good amplitude uniformity and signal arrival time spread $400 \pm 150$ ps. Required minimum trigger gate width is $2.0 \pm 0.2$ ns.

*Direct readout* provides good $300 \pm 10$ ps local time resolution using two SiPM mean-time signal but leads to significantly increased maximum signal arrival time spread $\Delta T = 1.6 \pm 0.2$ ns. Signal arrival time spread could be decreased using the “Last signal” method with the price of worse time resolution $\sigma = 450 \pm 10$ ps. Minimum trigger gate width for “Last signal” and “Mean-time” methods are $3.0 \pm 0.2$ ns and $3.1 \pm 0.2$ ns respectively.

As a result, WLS Fiber readout is selected as a main option for New NA62 Charged Particle Hodoscope.
Table 2. Results of time resolution measurements for direct readout with “Single SiPM”, “First signal”, “Last signal” and “Mean signal” options.

|                | Single SiPM | First signal | Last signal | Mean signal |
|----------------|-------------|--------------|-------------|-------------|
| ΔT, ns         | 2.7 ± 0.2 ns| 2.7 ± 0.2 ns | 0.8 ± 0.1 ns| 1.6 ± 0.2 ns|
| σ, ns          | 400 ± 10 ps | 370 ± 10 ps  | 450 ± 10 ps | 300 ± 10 ps |
| GATE, ns       | 4.7 ± 0.2 ns| 4.5 ± 0.2 ns | 3.0 ± 0.2 ns| 3.1 ± 0.2 ns|

Acknowledgments

The authors want to thank S. Balev† for MC simulation of total rate and $K^+ \to \pi^+ \nu \bar{\nu}$ acceptance, Y. Guz, P. Shatalov, V. Chernov, K. Kachnov, V. Rykalin, L. Di Lella and E. Gushchin for their assistance with organizing and operating the setup. The work is supported by the Russian Fund for Basic Research (grant No.12-02-91513-CERN-a).

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