30-ps time resolution with segmented scintillation counter for MEG II

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Abstract

A new timing detector has been developed to measure $\sim$ 50 MeV/c positrons with a time resolution of $\sigma_t \simeq 30$ ps in the MEG II experiment. The detector is segmented into 512 scintillation counters, each of which consists of $120 \times (40 \text{ or } 50) \times 5$ mm^3 size BC-422 and two arrays of six AdvanSiD silicon photomultipliers. The single-counter resolutions are measured to be 70–80 ps. The counter layout is optimized to get the maximum number of hit counters (on average 9 for signal positrons). This multiple-counters measurement leads to a significant improvement in the time resolution down to 30 ps. Using the first one-fourth (128) counters, a pilot run was carried out using the MEG II beam of 7×10^7 μ^+/s and the basic functionality was tested.

Keywords: Scintillation counter, Time resolution, Silicon photomultiplier (SiPM).

1. Introduction

Nowadays, timing detectors with $O(10$ ps) resolutions are widely awaited and under development for many physics experiments. In the MEG II experiment, it is required to measure $\sim$ 50 MeV/c positrons with a resolution $\sigma_t \simeq 30$ ps to search for the $\mu^+ \to e^+\gamma$ decay with the unprecedented branching-ratio sensitivity of 5×10^{-14}.

In the past decades, time of flight detectors based on scintillator bars with photomultiplier tube (PMT) readout have widely been used. The best achievements with this technique is $\sigma_t \simeq$ 50 ps[1] (e.g. [1, 2]) whereas resolutions were often more limited in practical applications for several reasons such as a large variation of the optical photon paths due to the position or angle dependence, degradation of PMT performance in magnetic fields or due to the aging effects, inter-bar time jitter originating from electronics synchronization as well as timing alignment among the bars, and quality control in mass production. Pursuing the ultimate time resolution of a single device would not be sufficient to robustly achieve a time resolution below 50 ps.

2. Highly segmented scintillation counter

We focus on a highly segmented scintillation counter with silicon photomultiplier (SiPM) readout to overcome such limitations. SiPM-based scintillation counters possess intrinsically high time resolution with a high light yield of scintillation and a relatively good single photon time resolution of SiPM. This approach is a contrast to that with Cherenkov counters which rely on the small but prompt signal detected with excellent time-response photo-detectors such as microchannel plate photomultipliers. A resolution of $\sigma E^{0.5} = 18$ ps MeV$^{0.5}$, where E is the energy deposited in the scintillator, was achieved in [3] with a $3 \times 3 \times 2$ mm^3 counter. A better resolution of 15 ps MeV$^{0.5}$ is indicated to be achievable in [4] by scaling the sensor coverage effect.

More important, SiPM-based scintillation counters allow flexible detector layouts owing to SiPM properties such as compactness, low cost, and immunity to magnetic fields. As a consequence, multiple measurement of a single particle timing become possible. The total time resolution is expected to improve with the number of hit counters N_{hit} as

$$\sigma_{\text{total}}(N_{\text{hit}}) = \frac{\sigma_{\text{total}}^{\text{single}}}{\sqrt{N_{\text{hit}}}} = \sqrt{\frac{\sigma_{\text{counter}}^2 + \sigma_{\text{inter-counter}}^2 + \sigma_{\text{elec}}^2}{N_{\text{hit}}}}, \quad (1)$$

where $\sigma_{\text{total}}^{\text{single}}$ is the total time resolution with a single-counter measurement which includes the counter intrinsic resolution $\sigma_{\text{counter}}^2$, the error in time alignment over the counters $\sigma_{\text{inter-counter}}^2$, and the resolution of the electronics σ_{elec}^2. Therefore, it is an easy and robust way to improve the total time resolution of the system. This improvement was demonstrated via a series of beam tests. The detailed analysis is found in [5], where $\sigma_{\text{total}}(N_{\text{hit}} = 8) = 24 \pm 1$ ps was obtained with the MEG II prototype counters.

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[1] for a minimum ionizing particle

3. Design of the MEG II Timing Counter

Single counter design. The limitation on time resolution of SiPM-based scintillation counters comes predominantly from the photon statistics. Hence it is important to use high-light yield fast response scintillators such as BC-422 and high photon-detection efficiency (PDE) SiPMs. It is also important to increase the sensor coverage to make counters larger than SiPM dimensions, which are typically $O(10\ \mathrm{mm}^2)$. Then, other factors, signal pulse shape and dark noise of SiPMs, become severe issues. The design of readout electronics as well as SiPM characteristics plays an important role for those.

An extensive R&D to optimize the single counter design was carried out in [4]. In the study, the characterization of several models of SiPM, comparison of scintillator material, and the dependence of time resolution on the counter size and the sensor coverage were studied. Based on these studies, the MEG II counter design was determined by optimizing trade-offs between the single-counter resolution (smaller is better) and the hit multiplicity and the detection efficiency (larger is better) and between different characteristics of SiPMs and the cost.

Fig. 1 shows the final design of a counter. A counter consists of a plate of BC-422 with dimensions of $L \times W \times T = 120 \times (40 \text{ or } 50) \times 5\mathrm{mm}^3$ and 12 SiPMs, 6 at each ($W \times T$)-plane, directly coupled to the scintillator with optical cement (BC-600). The different W size counters are used at different location in the detector to optimize the acceptance. The six SiPMs are mounted on a custom PCB, in which the SiPMs are connected in series. We employ series connection because the total capacitance of the sensor becomes one sixth of that of a single SiPM and the resultant pulse shape becomes sharper. The merits are discussed in [4] and a direct comparison with parallel connection in time measurement is found in [6], in which series connection gives better time resolution than parallel connection at the same over-voltages.

A SiPM from AdvanSiD, ASD-NUV3S-P-50-High-Gain, is adopted. The main characteristics were measured with the dark signal at 30°C. Fig. 2 shows the single-cell-fired signal. The long tail is due to the SiPM recharge current via the quench resistor (measured by the forward current to be $1100 \pm 50\ \mathrm{k\Omega}$) and has a time constant of 124 ns. The dark count rate is $258\ \mathrm{kHz/mm^2}$. The transit time spread is measured using a pulsed laser (PLP-10) to be $\sigma_{\mathrm{TTS}} = 71 \pm 8$ ps with a subtraction of contributions from the electronics and noise.

The scintillator is wrapped in 32-μm thick ESR2 film and equipped with an optical fiber for the laser calibration (described later). To fix the optical fiber and to stably insert the laser light a small hole (2.5 mm diameter, 1 mm depth) is made on the bottom face. Finally, each counter is wrapped in black sheet (Tedlar®) for light shielding.

Detector design. The MEG II Timing Counter (TC) consists of two super-modules, mirror symmetric each other placed upstream and downstream in the spectrometer. Fig. 3 shows one of the super-modules composed of 256 counter modules fitting to the space limitation between a cylindrical drift chamber and the solenoid magnet. Sixteen counters align and 16 lines are cylindrically arranged and alternately staggered by a half counter. The counters are tilted at 45° to maximize the acceptance. This counter configuration was determined via a Monte-Carlo (MC) study to maximize the experimental sensitivity (given by the detection efficiency and the total time resolution) with a limited number of electronics readout channels (1024). The average number of hits is 9 for the signal positrons.

The counters are mounted on 1-m long PCBs (back-plane) which transmit the signal out the spectrometer. They have coaxial-like signal lines with a 50 Ω characteristic impedance and independent ground lines to avoid a possible ground loop. Signals are then transmitted on RG-178 coaxial cables to the readout electronics.

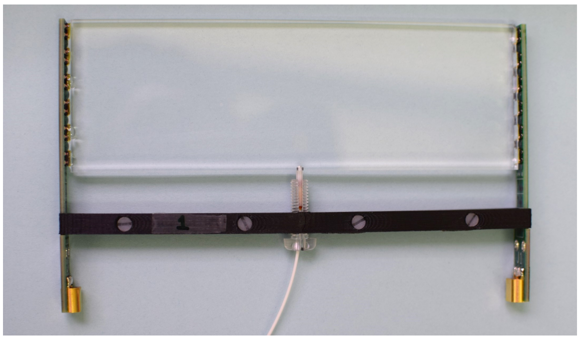

Figure 1: Picture of a counter (W = 40 mm). The scintillator will be wrapped in the reflector and then in the black sheet.

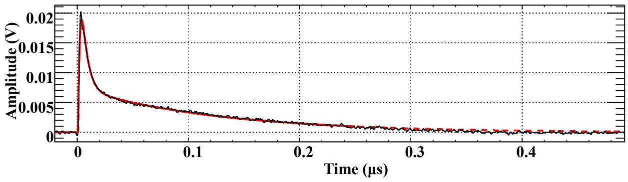

Figure 2: Pulse shape of single-cell-fired signal from an ASD-NUV3S-P-50-High-Gain. The black line shows the averaged pulse shape over 100 events and the red curve is the best fit function. This signal was measured with the PSI amplifier (see the text) with gain 60 and without the pole-zero cancellation shaping.

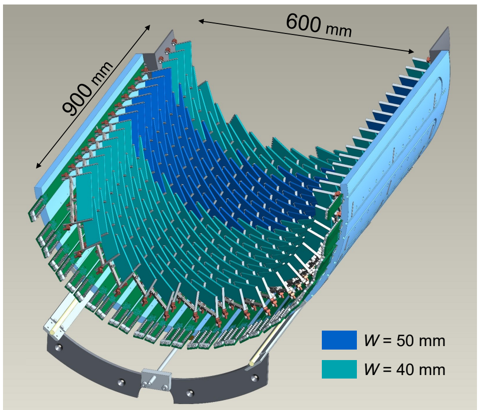

Figure 3: Design of downstream TC super-module.

Readout electronics. The basic idea of readout scheme is to send the raw SiPM-output signals to readout boards where the signals are amplified, shaped, and digitized. The SiPMs and amplifiers are separated by long cables without any pre-amplification to match the environmental limitations (e.g. space and power consumption) of MEG II. The time constant (both rise and fall) of SiPM output signal is shaped by the high capacitance of SiPMs and the input impedance of subsequent readout electronics. The reduction of capacitance by the series connection allows the 50 Ω transmission and use of voltage amplifiers.

In the R&D stage, an amplifier developed at the Paul Scherrer Institute (PSI) has been used (PSI amplifier). It is based on a two-stage voltage amplifier (MAR-6SM) and a pole-zero cancellation circuit (see [4] for the schematic). The shaping works to eliminate the SiPM specific long tail and to quickly restore stable baseline. It is particularly important at the high dark count rate summed over the six SiPMs.

In the MEG II experiment, a custom multi-functional readout board WaveDREAM [7] will be used. This board includes functions of amplifier, shaper, waveform digitizer, bias voltage supply, and first-level trigger. The analog part is designed based on the experience with the PSI amplifier. Two DRS4 chips are mounted on each board to digitize 16 channels. SiPM bias voltages are supplied from an on-board Cockcroft–Walton circuit regulated by a DAC for each channel and applied to SiPMs through the signal line; only one cable is used for each channel.

Calibration methods. The time alignment among counters is important for high granularity detectors. In order not to degrade the high precision measurement by the counters, RMS $\lesssim$ 30 ps is required as the accuracy of time offset calibration for each counter. Note that this contribution is also diluted by the multiple measurement as seen from Eq. (1). Two kinds of methods are considered: one is a track-based time alignment using the abundant high-momentum Michel positrons and the others is a laser-based calibration. They are complementary. Generally, the track-based method provides very precise results (O(ps) is achieved in a MC study) but is subject to some systematic position-dependent biases caused by small systematic errors in the time-of-flight estimation. Such biases would be detected and corrected by using the second method. For this purpose, we have developed a laser system distributing the synchronous light signal to every counter. For the detailed design of the optical system see [8]. It is found that RMS $\simeq$ 20 ps is achievable in this method by the R&D study.

4. Construction and pilot run in 2015

All the materials were procured in 2015 and the mass test and counter production have been underway. About 7 000 SiPMs were individually tested for the I-V characteristics before grouped into the arrays [9]. After soldered onto the PCBs, the first one-fourth SiPM-arrays were tested for the relative PDEs using a reference scintillator plate; about a 30% variation was observed. The scintillator was produced in four batches. A variation of the quality (mainly the light yield) was found

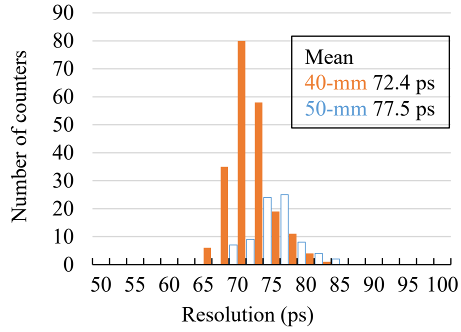

Figure 4: Distribution of the time resolution for the assembled counters.

Figure 5: One-fourth system of the MEG II TC (half of the downstream super-module).

and good quality plates were selected; the production yield was $\sim$ 40%. After each element is tested, counters are assembled by hand. Up to this moment, about 330 counters (64% of total) have been assembled and tested. Fig. 4 shows the time resolution distribution measured in the laboratory using a ^{90}Sr source. The mean resolutions are 72 and 78 ps for W = 40 and 50 mm counters, respectively. These are about 10% worse than those obtained with the prototypes.

The MEG II collaboration carried out a pilot run in the fourth quarter of 2015. The purposes are to test the modified design of the MEG II spectrometer, to study and tune the beam at the target intensity 7×10^7 μ^+/s, and to test the TC in the beam. It is also important to figure out some potential problems prior to the MEG II full run. We built a one-fourth system of the TC with 128 counters and installed it into the spectrometer (see Fig. 5). The TC system was thoroughly tested from the hardware point of view. The laser system was partially implemented and the data were collected during the run. It is also the first time to test the final configuration of the electronics and the data acquisition system [10] with the TC signal.

Michel positrons were measured with several configurations of the trigger at the MEG II beam intensity. Fig. 6 shows an example of the observed hit pattern by a Michel positron. The data quality was found to be not so good as designed; we found several problems in the electronics. For this reason, it is difficult to evaluate the full performance of the TC with these data. Nevertheless, they are useful to study the TC response in the beam

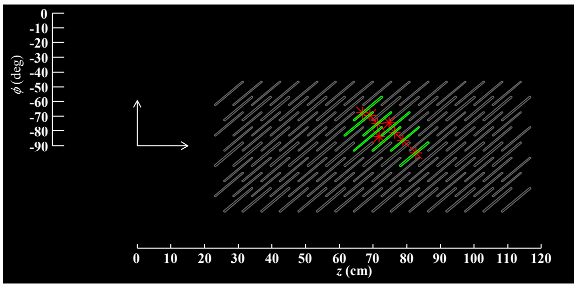

Figure 6: An example of the hit pattern by a Michel positron.

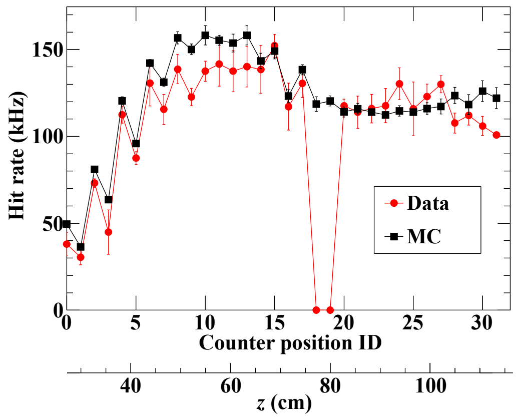

Figure 7: Counter hit rate versus counter position measured in the pilot run (red) and in the MC simulation (black). The points with zero hit rate are due to dead channels in the readout electronics.

and develop and optimize the analysis software. Fig. 7 shows a preliminary result of hit rate measurement. A fair agreement with the MC calculation is obtained. Fig. 8 shows the preliminary result on the time resolution measured with the time difference between a combination of two counters as a function of the fraction value of the constant-fraction method used in the time pickoff. The optimal fraction value in the run is shifted to higher value due to the higher noise in the readout electronics. A more detailed analysis is now underway.

The problems found in the electronics are now addressed and modifications are applied to the present system. To test it and to collect better quality data, we plan to carry out another Michel positron run in the first half of 2016. After the confirmation of the full functionality, the mass production of WaveDREAM boards will be ordered. In parallel, the construction of the rest three-fourths TC is continued and will be finished by summer 2016.

5. Conclusions

The SiPM-based scintillation counters have intrinsic resolution $\sigma(E)^{0.5} < 18$ ps MeV$^{0.5}$ and hence $\sigma_t \simeq 30$ ps is achievable with a single-counter measurement with counters whose cross section is not much larger than the SiPM dimensions. With the series connection of SiPMs, counter sizes can be enlarged, e.g., to $120 \times 40 \times 5$ mm^3 while keeping resolutions ~ 70 ps.

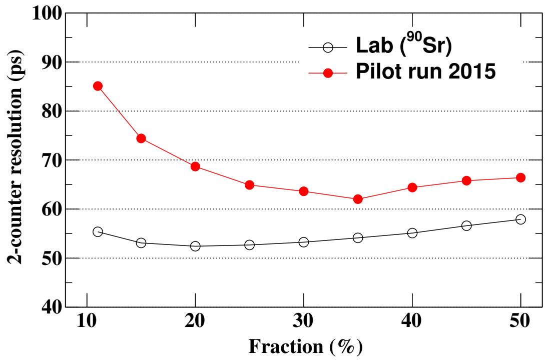

Figure 8: Two-counter time resolution measured in the laboratory (black) and the pilot run (red) as a function of the fraction value of the constant-fraction time pickoff method.

More important, they allow flexible designs of detectors leading to the multiple measurement of each particle timing. We employ this technique in the MEG II TC to achieve $\sigma_t \simeq 30$ ps for the measurement of ~ 50 MeV/c positrons. All the detector technologies such as the counter configuration, mechanics, signal transmission and readout, and calibration methods are established by extensive R&D in the last three years. The full system will be ready and installed into the spectrometer in 2016 to start physics data taking with the full MEG II detectors in 2017. The MEG II TC is an example of application and we consider this technique to be applicable to many other experiments.

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