

# The laser-based time calibration system for the MEG II pixelated Timing Counter

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## Abstract

We have developed a new laser-based time calibration system for highly segmented scintillator counters like the MEG II pixelated Timing Counter (pTC), consisting of 512-centimeter scale scintillator counters read out by silicon photomultipliers (SiPMs). It is difficult to apply previous laser-based calibration methods for conventional meter-scale Time-Of-Flight detectors to the MEG II pTC from the implementation and the accuracy points of view. This paper presents a new laser-based time calibration system which can overcome such difficulties. A laser pulse is split into each scintillator counter via several optical components so that we can directly measure the time offset of each counter relative to the laser-emitted time. We carefully tested all the components and procedures prior to the actual operation. The laser system was installed into the pTC and thoroughly tested under the real experimental condition. The system showed good stability and being sensitive to any change of timing larger than  $\sim 10$  ps. Moreover, it showed an uncertainty of 48 ps in the determination of the time offsets, which meets our requirements. The new method provides an example of the implementation of a precise timing alignment for the new type of detectors enabled by the advance of SiPM technology.

**Keywords:** SiPMs, scintillator counter, time calibration, pulse laser

## 1. Introduction

Recently, timing measurements in experimental particle physics have improved in terms of two characteristics: flexibility of the detector design and the timing resolution. Both aspects cannot be discussed separately and are related to the development of silicon photomultipliers (SiPMs). The new improved timing detectors require dedicated methods for time calibration. The challenges are the implementation in the complicated and multi-channel detectors and the accuracy of the calibration being sufficiently good compared to the improved detector intrinsic resolutions.

The MEG II pixelated Timing Counter (pTC)[1] is such a new timing detector. The MEG II experiment at Paul Scherrer Institut (PSI) in Switzerland will search for the lepton-flavour-violating muon decay,  $\mu^+ \rightarrow e^+\gamma$ , with a branching fraction sensitivity of  $6 \times 10^{-14}$ [2]. The pTC is the subdetector dedicated to the measurement of the positron emission time. It consists of two sectors (one placed upstream the target and the other downstream), each of which is composed of 256 scintillator counters read out by SiPMs as shown in Fig. 1. It achieves a time resolution of 38 ps for the signal positrons by measuring the transit

times with multiple counters. In this paper, we present a new laser-based time calibration system developed for the MEG II pTC.

In the past decades, laser-based calibration methods were developed to calibrate and monitor timing detectors [3, 4, 5, 6, 7, 8, 9]. However, it is difficult to apply similar methods to the MEG II pTC from the implementation and the accuracy points of view. First, our detector is finely segmented in a complex geometrical configuration in limited space compared with conventional meter-scale Time-Of-Flight (TOF) detectors. Scalability up to  $\sim 500$  channels and simplicity are required in the new approach. We adopt the combination of an optical switch and optical splitters to divide the laser light instead of the conventional method using a diffuser. This approach has higher scalability regardless of the original laser power and is more robust in distributing the light to each channel because a delicate optical system is not required. We also developed a simple but robust method for the laser light injection to the counter, mechanically fitting the small counters. Most of the optical components are commercially available and the system can easily be reproduced in other experiments.

Secondly, the precision and accuracy of the calibration are required to be good enough not to ruin the good detector resolution. In the previous study[10], the dispersion of laser pulse in optical components is considered to be the main source of

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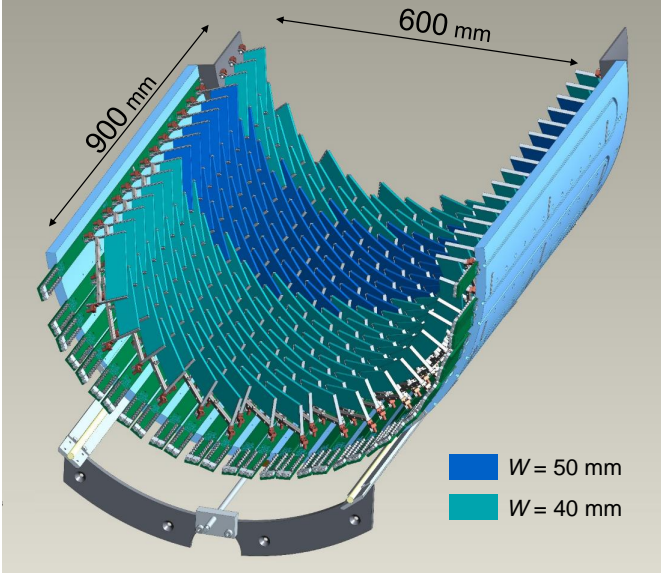


Figure 1: Schematic view of the downstream pTC sector; the upstream sector is mirror symmetric (from [1]).

uncertainty. In this paper, however, we discuss more on systematic uncertainties induced during the implementation of the system, which are found to be more important in actual operations. We carefully tested all the components and procedures and measured the quantities necessary for the calibration, including the dispersion effect, prior to the actual operation of the system to suppress the uncertainty.

In the following sections, first, we overview the proposed calibration system and summarise each component in Sect. 2. Then we report our R&D work to complete the system design in Sect. 3. In Sect. 4, the installation and operation of the system in the actual experimental environment are described and the performance is evaluated. Finally we summarise our work in Sect. 5.

## 2. System overview

### 2.1. MEG II pixelated Timing Counter

In the MEG I experiment, we achieved a positron time resolution of  $\sim 70$  ps whereas its intrinsic time resolution was 40 ps[2]. This degradation was because of a large variation of the optical photon paths due to the large scintillator size ( $80 \times 4 \times 4$  cm<sup>3</sup>), the worse PMT performance under the magnetic environment, and an incomplete time calibration. To overcome such limitations, we upgraded the timing counter for the MEG II experiment. We adopted a highly segmented design with 512 scintillator counters divided into two mirror symmetric sectors. The design was determined to maximise the experimental sensitivity under a limited number of electronics readout channels by a Monte-Carlo study. Multiple measurements with the smaller scintillator counters enable us to reach  $\sim 38$  ps time resolution. In addition, this multiple hit scheme makes the timing measurement less sensitive to the error of timing alignment and the electronics time jitter.

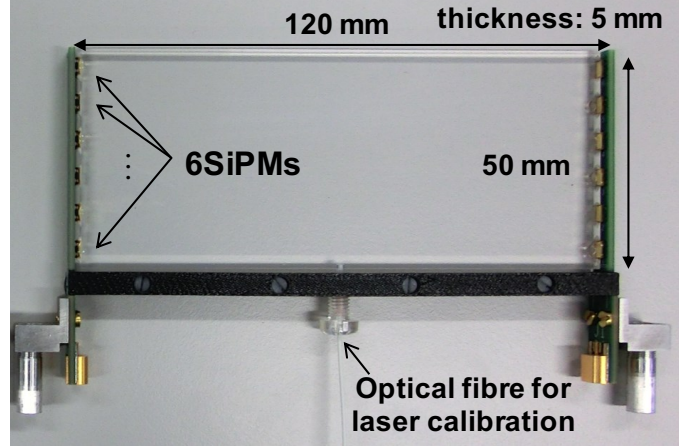


Figure 2: A single scintillator counter with height 50 mm.

The single scintillator counter is made of a fast plastic scintillator, BC422 with dimensions of  $40$  or  $50 \times 120 \times 5$  mm<sup>3</sup> read out by six series-connected SiPMs at both ends as shown in Fig. 2. The peak wavelength of the scintillator is 370 nm[11]. The rise time and decay time of the scintillator are 0.35 ns<sup>1</sup> and 1.6 ns, respectively[11]. The scintillator is wrapped in 32  $\mu$ m thick ESR2 film, which has a reflectivity higher than 98%[13]. The SiPMs, ASD-NUV3S-P High-Gain, are produced by AdvanSiD. The active area and pixel pitch are  $3 \times 3$  mm<sup>2</sup> and  $50 \times 50$   $\mu$ m<sup>2</sup>, respectively. The peak wavelength is 420 nm. The breakdown voltage is  $\sim 24$  V and the operational voltage for a six series-connected chain is  $\sim 164$  V. The optical fibre for the laser-based time calibration is inserted from the bottom. The counters are individually wrapped in a 25  $\mu$ m-thick black sheet (Tedlar) for light shielding. At each side,  $\sim 50$  photoelectrons are detected for a traverse of a minimum ionising particle such as a 50 MeV positron. The typical waveforms for the scintillation signal and the laser signal are shown in Fig. 3. The laser signal has a shaper shape than the scintillation signal: the rise times of laser and scintillation are measured to be  $1.10 \pm 0.04$  ns and  $1.41 \pm 0.01$  ns, respectively, and the widths are  $1.84 \pm 0.12$  ns and  $2.75 \pm 0.65$  ns, respectively. These differences should be taken into account in calculating the time offsets in Sect. 4.

The positron hit time at each counter is calculated as follows:

$$t_{\text{hit}} = \frac{t_1 + t_2}{2} - \frac{l}{2v_{\text{eff}}} - t_{\text{elec}}, \quad (1)$$

where  $t_1$  and  $t_2$  are the measured signal time on channel 1 and channel 2, respectively;  $l = 120$  mm is the longitudinal length of the counter;  $v_{\text{eff}} \approx 12.4$  cm/ns is an effective velocity of the light in the scintillator; and  $t_{\text{elec}}$  is a signal transmission time in electrical components such as cables and DAQ line. The sum of the last two components is defined as the time offset ( $t_{\text{offset}}$ ) of the counter to be calibrated:

$$t_{\text{offset}} = \frac{l}{2v_{\text{eff}}} + t_{\text{elec}}. \quad (2)$$

<sup>1</sup>This value is dominated by the measurement setup and the intrinsic one is much faster[12].

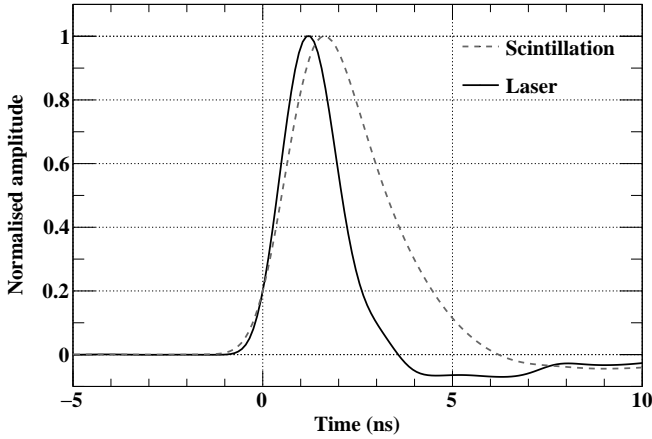


Figure 3: Averaged waveforms of the laser signal (solid line) and the scintillation signal (broken line) read out by the six series-connected SiPMs after shaping with pole-zero cancellation. The amplitudes are scaled to 1. The constant fraction of 20% is used for timing calculation and thus (Time, Normalised amplitude) = (0, 0.2) is fixed for comparison.

Table 1: Comparison between two time calibration methods

Item	Laser	Track
Position dependence	No	Yes
DAQ time	short (~ 30 min.)	long (~2 days)
Beam	not necessary	necessary
Coverage	84%	100%
Uncertainty	27 ps	13 ps (MC)

The relative value of the time offset among the scintillator counters matters in the time calibration proposed in this paper.

## 2.2. Time calibration

To determine the time offset in Eq. (2), we have developed two complementary time calibration methods: the track-based method and the laser-based method. Positron tracks from the Michel decays ( $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ ) are used in the track-based one and laser signals are used in the laser-based one. These methods are combined to determine the time offsets. The comparison between the two methods is summarised in Table 1. The laser-based method has advantages over the track-based method in terms of position dependence, DAQ time, and the beam requirement. On the other hand, it does not have 100% coverage because counters placed on the very inner part of the detector do not have enough space to insert any other items including laser fibres. In the development of the laser-based method, it is important to minimise its uncertainty retaining the advantages over the other method.

## 2.3. The laser calibration system

### 2.3.1. Optical components

The laser calibration system is shown in Fig. 4. The laser light is split along a ladder of optical components into  $> 400$  channels and distributed to the counters via optical fibres. The optical components were selected based on the detailed study presented in [10] and are summarised in Table 2.

We use a picosecond pulsed diode laser as the light source. It emits a short light pulse, typical duration of 60 ps (FWHM), at a wavelength of 401 nm. The peak power is 200 mW, equivalent to  $\sim 10^7$  photons per pulse (measured). The “laser controller” controls the ON/OFF switching, the repetition rate (up to 100 MHz), and the power. The laser power is monitored by the photodiode connected to one of the outputs of the first stage  $1 \times 2$  splitter.

The laser controller also provides a pulse signal<sup>2</sup> synchronised with the laser emission, with an adjustable delay. We call this signal the “SYNC signal” and use it for the trigger and the timing reference. The jitter between the SYNC signal and the optical output is less than 10 ps according to the specification and is negligibly small for the usages. By using this reliable time reference, it is possible to divide the counters to be illuminated at a time into several subsets.

We choose multi-mode fibres with a graded index (GI) for the light transmission because they have less insertion loss than single mode fibres thanks to their larger core diameter (50  $\mu\text{m}$ ). However, optical paths in multi-mode fibres differ depending on the optical modes. The graded refractive index mitigates the effect on the dispersion of propagation time. The mode scrambler is used to stabilise the optical mode propagation in the multi-mode fibres by removing high-order modes within a wound fibre.

The optical switch actively switches from one output channel to another using a micro-mechanical technology. It has 12 output channels and 8 of them are used for the calibration while the others are kept as spares. The components up to the switch (shown in Fig. 4b) are placed in a laser hut next to the detector hut.

The optical splitters passively split the input signal into the output channels using the Fuse Biconical Taper (FBT) technology [23]. Two cascaded stages of  $1 \times 8$  splitters are used to simultaneously deliver the laser pulse to up to 64 counters. The combinations were selected to optimise the output uniformity. About 40 splitters connected to each (upstream or downstream) sector of the pTC are housed in a box placed close to the detector.

The final component to inject the laser pulse into the counter is the 2.5 m fibre. The far end of the fibre is covered with a ceramic (zirconia) ferrule, without any magnetic metal sleeve, to allow operation in a high magnetic environment.

FC/PC connectors are used at all the connections between the components.

In total, the light power is attenuated to  $\sim 10^{-4}$  of the original, resulting in thousands of photons are delivered to each counter; and finally,  $\sim 50$  photoelectrons are detected by the six SiPMs at each end.

### 2.3.2. Monitoring and controlling

Slow control tasks such as monitoring temperatures and controlling the laser, and the optical switch are performed remotely based on the Maximum Integrated Data Acquisition System

<sup>2</sup>either NIM or TTL signal

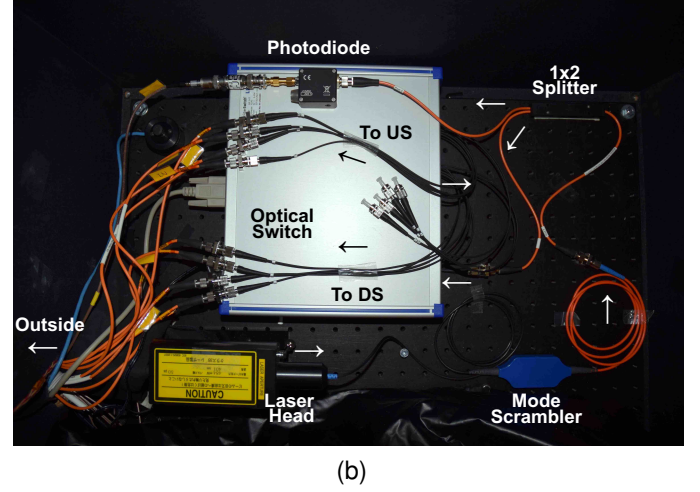
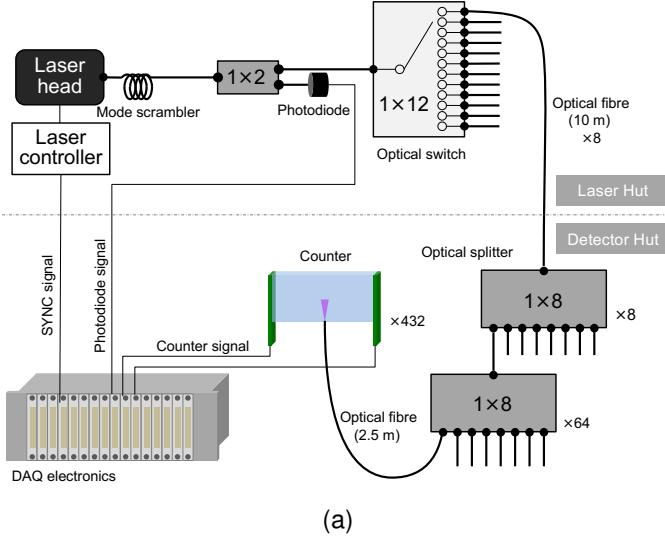


Figure 4: (a)Schematic and (b)picture (from [14]) of the laser-based time calibration system for the MEG II pTC. The individual components are described in the text.

Table 2: Optical components used in the laser calibration system

Item	Model (Manufacturer)	Specifications	Pieces (spares)	Ref.
laser	Picosecond Light Pulser PLP-10 (HAMAMATSU PHOTONICS K.K.)	Wavelength 401 nm, pulse width 60 ps, peak power 200 mW	1	[15]
optical fibre (2.5 m)	QMMJ-31-IRVIS-50/125-1HYWT-2.5-SP (OZ OPTICS)	High power GI multimode, core/clad 50/125 $\mu\text{m}$ , NA 0.2, 400–2000 nm, 1 mm jacket	432 (+129)	[16]
optical fibre (10 m)	MMJ-33-IRVIS-50/125-3-10 (OZ OPTICS)	GI multimode, core/clad 50/125 $\mu\text{m}$ , NA 0.2, 400–2000 nm	8 (+6)	[17]
mode scrambler	ModCon Mode Controller (Arden PHOTONICS)	Insertion loss < 3 dB at 850 nm	1	[18]
1x2 splitter	FUSED-12-IRVIS-50/125-50/50-3S3S3S-3-0.25 (OZ OPTICS)	FBT multi-mode coupler, 400–1600 nm, excess loss < 1.0 dB for 480–700 nm	1	[19]
1x8 splitter	MMC-18-A-EVEN-1-A-30CM-R-1 (Lightel Technologies Inc.)	FBT multi-mode coupler, insertion loss $\leq$ 11.5 dB	70 (+11)	[20]
photodiode	DET02AFC (THORLABS)	400–1100 nm, bandwidth 1 GHz, rise time 1 ns	1	[21]
optical switch	fibre Optical Switch mol 1x12-50 $\mu\text{m}$ (LEONI)	Insertion loss < 2.0 dB for 5–16 output channels	1	[22]

(MIDAS)<sup>3</sup> [25] developed at PSI and TRIUMF. Temperature sensors, the laser controller, and the optical switch are monitored and controlled by the system remotely.

#### 2.4. Readout electronics and data acquisition

The counters are mounted on 1-m long PCBs, which have a 50  $\Omega$  characteristic impedance. The signals are transmitted on RG-178 coaxial cables ( $\sim$ 35 ns), which connect to custom DAQ boards. A multi-functional DAQ board called WaveDREAM2 [26, 27] has been developed at PSI for the MEG II detectors, including pTC. It has the following functionalities: SiPM biasing, amplification, shaping with pole-zero cancellation, waveform digitisation at GPS using Domino Ring Sampler (DRS4) chip[28], and the first level trigger. The SYNC

and the photodiode signals, as well as the counter signals, are fed into the boards and digitised. The SYNC signal is used to trigger the laser data.

### 3. Research and development

#### 3.1. Experimental setup

The setups used in the laboratory measurements are shown in Fig. 5. We used three different setups depending on the purpose:

- Setup (1) To measure the power of laser light at each point and the insertion loss of the component under test, a power meter<sup>4</sup> is used.

<sup>3</sup>MIDAS provides several tools and a general program framework to assist experiments. An example of the usage can be found in [24].

<sup>4</sup>Model 840-C HandHeld Optical Power Meter by Newport

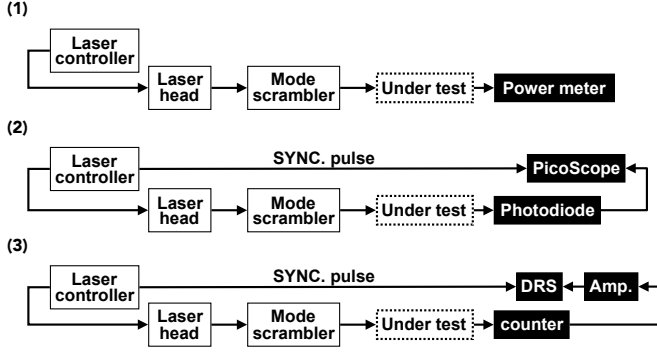


Figure 5: Experimental setups used in the research and development phase.

Setup (2) To measure the optical length of the component under test, a PC-connected oscilloscope<sup>5</sup> is used. The lengths are measured as the delay time with respect to the SYNC signal.

Setup (3) To acquire the waveform signal from the scintillator counters, a waveform digitiser<sup>6</sup> and a SiPM amplifier are used. The SYNC signal is used for the trigger and the time reference.

### 3.2. Light injection and fibre fixing method

In the past, several approaches were used to couple an end fibre to a scintillator: simply attaching the fibre to the scintillator face beside a photo sensor [4, 8] or using a prism [3, 5, 6, 7, 9]. We have developed a novel approach to fix a fibre in order to reduce materials and cost and to achieve good properties described in this section.

Fig. 6 illustrates our method for inserting a fibre into the scintillator counter. The laser light is vertically incident on the centre of the bottom face of the scintillator. The fibre tip is fixed in two ways: the top is fixed by a hole on the scintillator, and the bottom is fixed by a specially machined screw (polycarbonate) supported by a bar (ABS resin) across the two PCBs.

Since this is the most delicate part of the system, we performed several measurements to examine the functionality of this method.

*Effect of the hole on the scintillator.* The size of the hole was minimised (2.5 mm diameter, 1 mm depth) to avoid any negative effect on the counter performance. To study the effect on the scintillation light collection efficiency, we first made a Geant4-based Monte-Carlo simulation. The result did not show a significant decrease in the light collection efficiency and thus in the time resolution. Then, we measured the time resolution of a few test counters before and after drilling the holes and confirmed that the hole does not affect the time resolution.

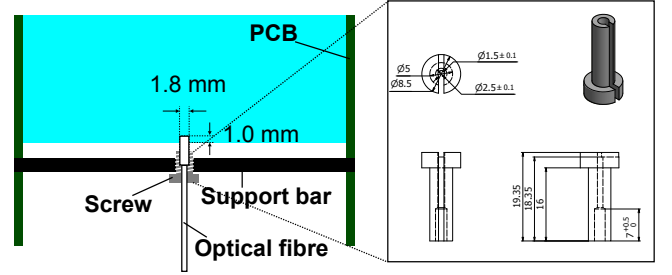


Figure 6: A cross-sectional view of fibre fixing method (left) and the design of the screw. The screw has a slit to insert the fibre and dedicated hole to fix the fibre (right).

*Coupling method.* We tested the coupling between the fibre and the scintillator under the following two cases: in air and with optical grease. The measured time turned out to be dependent on the amount of the grease put in the hole. The amount of the laser light observed at the photosensor can be changed by 4 times at the maximum and the measured time changed by 300 ps depending on the amount of the grease although we tried to put the same amount at every measurement. Since it is difficult to control the amount of grease with sufficient precision during the assembly, we decided not to use optical grease.

*Asymmetry between two channels.* We also checked the splitting ratio of laser light between channel 1 and channel 2. The ratio  $R_{ch1}$  defined as

$$R_{ch1} = \frac{A_1}{\epsilon_1} \left/ \left( \frac{A_1}{\epsilon_1} + \frac{A_2}{\epsilon_2} \right) \right. \quad (3)$$

is measured to be  $(50 \pm 4)\%$  where  $A_i$  denotes the signal amplitude and  $\epsilon_i$  is the product of the gain and the photon detection efficiency (PDE) of the SiPMs. PDE was relatively calculated from the scintillation signal data obtained by irradiating the centre of counters with electrons from a  $^{90}\text{Sr}$  source. The injection method showed good splitting ratio and needs no correction.

*Reproducibility.* One of the important points is the reproducibility of the light injection; the measured time should be stable after reinserting the fibre. To test it, we repeated the timing measurement 10 times by extracting and inserting the fibre every time. The standard deviations of the measured time for 4 cm counter and 5 cm counter were 11 ps and 3.0 ps, respectively. The lower variation for 5 cm counter stems from the fact that the distance between fibre support and the hole on the scintillator is shorter than that of 4 cm by 1 cm and thus the tip of the fibre is fixed more accurately. Note that these measured values are well below our requirement.

*Stability.* The stability was first checked using a test bench for 70 hours and the standard deviation of the measured time was 9.2 ps, which is sufficient for our use. Then it was confirmed in the commissioning phase after installation of the system (Sect. 4).

<sup>5</sup>PicoScope9210 by Pico Technology

<sup>6</sup>DRS Evaluation board V. 4 developed at Paul Scherrer Institut

### 3.3. Timing accuracy, precision, and dispersion

The timing property is determined by the number of detected photoelectrons and the arrival time distribution. As shown in Fig. 3, the arrival time distribution of laser light is narrower than that of scintillation light, resulting in a good timing accuracy.

Nevertheless, a finite width of the distribution would cause a systematic error on the detected timing of the laser signal. In [10], the dispersion of laser pulse in optical components is considered to be the main source of the error. To evaluate the impact on the output signal, we compare the signals when we inject the laser pulse via only an adjustable optical attenuator and when we do via the attenuator and the full sequence of the optical components. The rise times are  $975 \pm 66$  ps and  $965 \pm 77$  ps, respectively; no significant difference was observed, validating our choice of the optical components with a multi-mode network.

An optical simulation indicates that the photon timing distribution is predominantly determined by the dispersion inside the scintillator. The fast rise time is given by direct or a few times reflected photons while the width is given from photons reflected many times. The counter-by-counter variation of the distribution causes a systematic error if we do not know the impact. Therefore, we measure the effective optical length of the full sequence of the optical components, including the scintillator, for all the counters in the mass test described in Sect. 3.5. The effective optical length includes the effect of the dispersion and thus the systematic error is eliminated by subtracting the effective optical length from the measured time.

The time resolution for the laser signal is 50 ps (standard deviation of a fitted Gaussian), better than that for the scintillation signal. The time offset is determined from the mean of the Gaussian and thus the precision can be improved with the statistics. For example, 1 ps precision is achievable with 3000 events.

### 3.4. Temperature dependence

A temperature variation may change the optical and electrical length of the system components. Therefore, we measured their temperature coefficients. The results are summarised in Table 3. In these measurements, only the item under test was put in a thermal chamber<sup>7</sup> and the others were kept in the room temperature.

Originally, we used an RG174/U cable for the SYNC signal transmission, but it turned out to be the dominant source of the temperature dependence of the system. Therefore, we replaced it with a less-temperature-sensitive cable, FSJ1-50A (COMMSCOPE)[29]. It is designed to have a linear expansion of the conductor part canceling out the temperature dependence of the dielectric constant of the insulator part. As a result, it has a small temperature coefficient of  $-0.08$  ps/K, two orders of magnitude smaller than that of RG 174/U ( $-8.8$  ps/K).

We measured the temperature coefficient of the whole system to be  $-1.3 \pm 0.2$  ps/K. The temperature in the detector hut is expected to be stabilised within 1 K by an air conditioner. Thus, the temperature effect on the measured time is negligible.

Table 3: Summary of temperature dependence. The last column reports the sign of the effect on the time offset.

Item	Coefficients (ps/K)	Effect
Fibre (2.5 m)	$+0.45 \pm 0.02$	+
Fibre (10 m)	$+1.00 \pm 0.04$	+
Optical splitter	$+0.24 \pm 0.11$	+
Scintillator counter	$+1.24 \pm 0.04$	+
Counter signal cable	$-4.1 \pm 0.1$	-
SYNC signal cable	$-0.08 \pm 0.02$	+
Total	$-1.3 \pm 0.2$	-

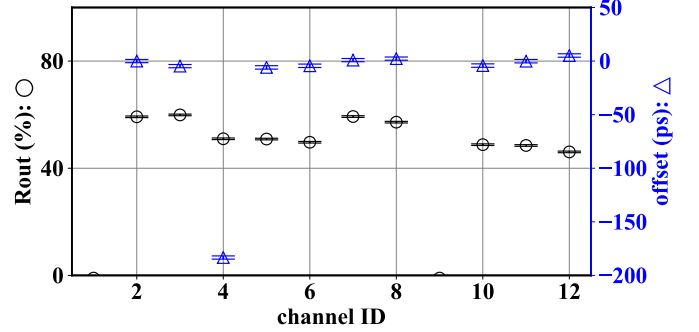


Figure 7:  $R_{out}$  (circle) and optical length difference (triangle) of the optical switch. The optical length differences are given with respect to channel 2. Channel 1 and 9 are broken.

### 3.5. Mass test

We thoroughly tested all the optical components in terms of optical length and the ratio of output to input power ( $R_{out}$ )<sup>8</sup>. Since the optical lengths of all the optical components are not controlled with the required precision, we need to measure them beforehand as a pre-calibration and then subtract them when we determine the time offsets. The overall lengths measured with the final combinations of the components are used for this purpose, while the lengths of individual components can be used when we replace some parts in the future. The results of  $R_{out}$  measurement are used in making the combination of these items to make the outputs uniform.

*1 × 2 splitter.* The difference of optical length between channel 1 and channel 2 is measured to be  $17.0 \pm 0.6$  ps (channel 2 is longer) while the absolute optical length is  $\sim 3.1$  ns. The  $R_{out}$ 's are measured to be  $26.6 \pm 0.3\%$  (channel 1) and  $31.6 \pm 0.3\%$  (channel 2).

*Optical switch.* Fig. 7 shows the results for the optical switch. The  $R_{out}$ 's are measured to be 50–60%. The differences of the optical lengths are less than 6 ps but for channel 4. This channel has a larger difference ( $\sim 200$  ps) because it was originally broken after its shipment and repaired by the manufacturer. Channel 1 and 9 have no data because they were broken.

*Long fibres.* Fig. 8 shows the results for the long fibres. The  $R_{out}$ 's are measured to be 70–80%. The optical length is  $\sim 52$  ns on average.

<sup>7</sup>Bench-Top Type Temperature and Humidity Chamber SU-241 by ESPEC

<sup>8</sup>The insertion loss is given by  $-10 \log_{10} R_{out}$ .

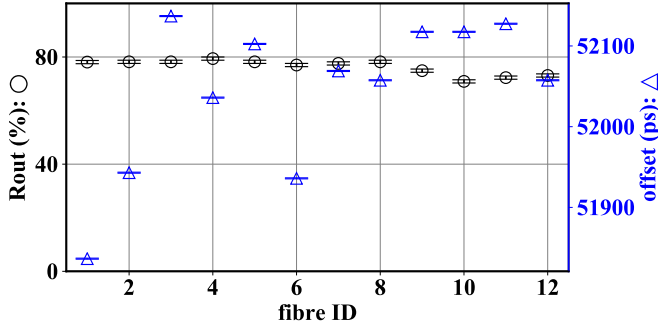


Figure 8:  $R_{\text{out}}$  (circle) and optical length difference (triangle) of the long fibres.

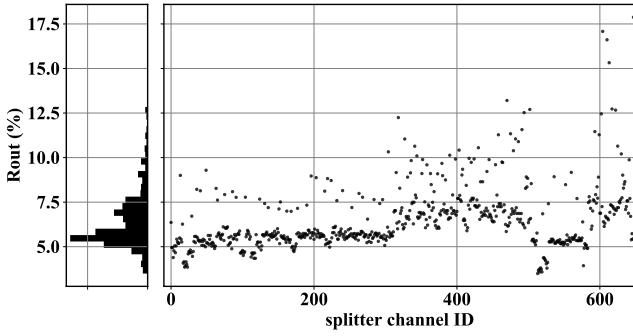


Figure 9: Distribution of  $R_{\text{out}}$  of the  $1 \times 8$  splitter channels.

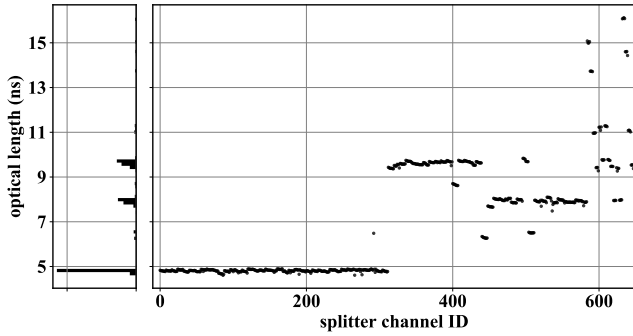


Figure 10: Distribution of the optical lengths of the  $1 \times 8$  splitter channels.

*1 × 8 splitter.* Figs. 9 and 10 show the  $R_{\text{out}}$ 's and the optical lengths, respectively, for all the 648 channels of the 81  $1 \times 8$  splitters. The mean  $R_{\text{out}}$  is  $\sim 6\%$ . We rejected the channels below  $R_{\text{out}} \sim 4\%$  from the final use to get enough power.

In each splitter, one of the outputs has a significantly larger output than the others, as observed in [10]. This is due to the primary fibre in the fusion processing having a larger output than the others. To make the splitting ratio more even increases the excess loss.

The channels whose IDs are in the range of  $\sim 320$ – $500$  have relatively larger outputs than the others. We also see three groups with different optical lengths in Fig. 10. These groups correspond to three different production lots. The channels whose IDs are larger than  $\sim 580$  are spare splitters which were purchased  $\sim 2$  years later compared with other splitters. A part of them has different optical length and power due to the differ-

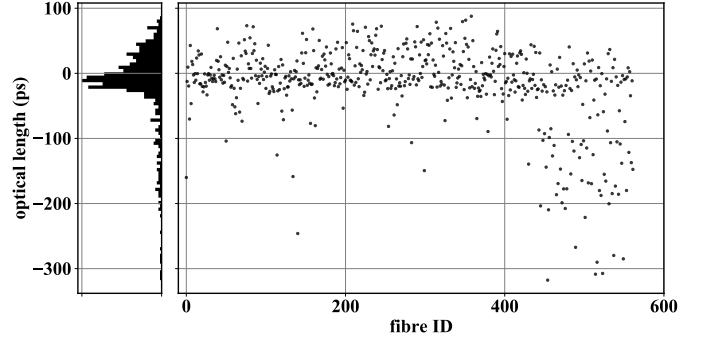


Figure 11: Distribution of the optical lengths of the short fibres.

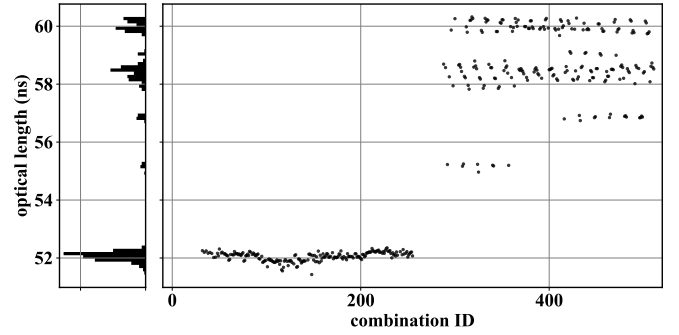


Figure 12: Distribution of the overall optical lengths including  $1 \times 8$  splitter, 2.5 m fibre, and counter.

ent production lot.

One remarkable result we obtained is a power enhancement in the staged combination: when we connect the first stage and the second stage splitters, one out of the  $8 \times 8$  channels have a larger output than expected from the product of the two individual  $R_{\text{out}}$ 's. The reason for the enhancement is not clear. The enhanced channels are not used to get the better uniformity of outputs.

*Short fibres.* The optical lengths of short fibres relative to a reference fibre are shown in Fig. 11. Most of the differences are in the 0–100 ps range. The fibres whose IDs are larger than 400 have larger (negative) differences due to a difference of the production lots.

*Overall optical length.* The overall optical lengths are measured with the following final combination: the first and the second splitters, the short fibre, and the counter. The results are shown in Fig. 12. The lengths are grouped around a few different values and this is mainly due to the optical lengths of the splitters. These values are used to calculate the time offsets in Sect. 4.2.

## 4. Commissioning and performance

### 4.1. Commissioning in 2017

In 2017<sup>9</sup>, we assembled the whole pTC detector, including the laser calibration system, and installed it into the  $\pi$ E5 beam-line of the PSI proton accelerator complex, where the MEG II experiment will be located, to perform a commissioning run (see Fig. 13)<sup>10</sup>. The DAQ system described in Sect. 2.4 was also installed, commissioned, and used to take pTC data. We operated the system for two months and collected data with Michel positrons ( $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ ) as well as laser data.

In this commissioning run, the optical switch was not used; instead, we manually switched the eight subsets. Laser runs with one of the eight subsets were regularly taken (at least once per day) over the period. In addition, the laser data were taken during the Michel positron run with a mixed trigger configuration. The full set of laser runs were taken more sparsely, roughly once per a few days, depending on other activities.

The laser signal was not detected on a small number (2 in upstream and 9 in the downstream sector) of counters. The short fibres turned out to be broken during the installation work. After the commissioning run, we replaced the broken fibres with spares and the time offsets were corrected accordingly towards the next run. This experience shows that the proposed method copes with replacement work in the future. The installation procedure was reviewed to protect the fibres.

The laser system was used also to determine the bias voltage of the SiPMs. We scanned the bias voltage, counter by counter, to minimise the time resolution for a fixed power laser signal. The laser system enabled us to dynamically determine the bias voltage depending on the experimental situation, such as the detector operating temperature and the radiation damage on the SiPMs, in situ.

### 4.2. Determination of the time offsets

The time offset of a counter is calculated from the mean value of  $\frac{t_1+t_2}{2} - t_{\text{SYNC}}$  of 3000 laser events in a run minus the overall optical length measured in the mass test (Sect. 3.5). The statistical uncertainty is 1 ps. In addition, we applied two corrections to the time offset: SiPM bias voltage correction and time-walk correction.

#### 4.2.1. Additional corrections

**Voltage correction.** Since we adjust the SiPM bias voltages depending on the environmental situation as described in Sect. 4.1, the applied voltage can be different from the mass test. This affects the time offset. Thus, we measured the difference in the measured times of laser signal at the two bias voltages and corrected the time offsets for the difference. Fig. 14 shows correction values of each counter and they are distributed from  $-10$  ps to  $20$  ps depending on its position. The first half corresponds to the downstream sector and the other half corresponds

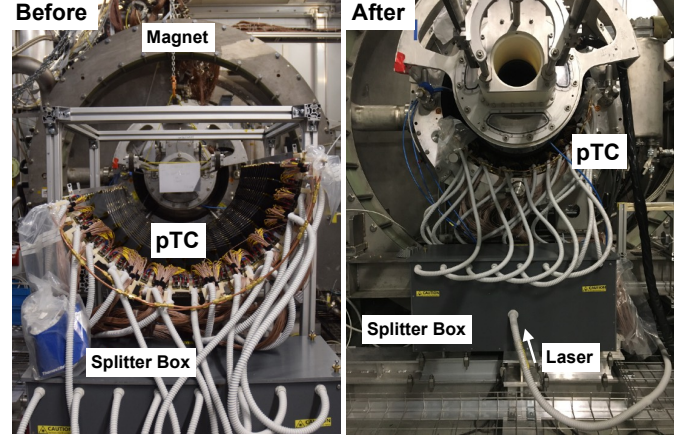


Figure 13: Before-and-after pictures of installation of the downstream pTC and the end part of the laser calibration system. Optical fibres are put inside the white tubes. The detector is slid into the magnet (pointing into the paper) together with the splitter box. The pTC is not visible after installation.

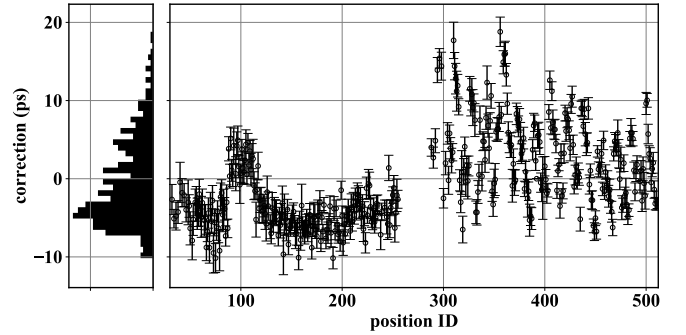


Figure 14: Voltage correction of the time offsets.

to the upstream one. The difference comes from the different radiation level because the SiPMs in the upstream were already suffered from the radiation damage in previous beam tests. The counters whose position IDs are around 100 have different tendency compared with the others. It is because the type of SiPMs is slightly different from the others. The uncertainty from this correction is estimated to be 1.5 ps.

**Time-walk correction.** We use a constant fraction method for the timing pickoff algorithm from the SiPM output signal to eliminate the time-walk effect. Nevertheless, the small dependence of the measured times on the signal amplitude remains due to non-linear effects of SiPMs and electronics. The signal amplitude of the laser data and that of the positron data can be different counter by counter, though we adjusted the laser power so that the signal amplitude is the same level as that of the positron data on average. To evaluate the amplitude dependence of the measured times, we took amplitude scanning data by using an optical attenuator.<sup>11</sup> The time-walk effect (measured time vs. signal amplitude) is measured to be

<sup>9</sup>In 2016 we installed one-fourth of the detector and a part of the calibration system to check its basic functionality [30].

<sup>10</sup>Performance evaluation of the pTC can be found in [31]

<sup>11</sup>Since the change of the laser power changes the output light pulse shape, we used the passive attenuator (OZ OPTICS, BB-100-11-400-50/125-M-35-3S3S-3-0.5).

Table 4: Summary of uncertainties.

Item	Uncertainty(ps)	Section
Reproducibility	11	Sect. 3.2
Measurement error in the mass test	5.4	Sect. 3.5
Statistics	1.0	Sect. 4
Stability	8.8	Sect. 4
Voltage correction	1.5	Sect. 4.2.1
Time-walk correction	4.2	Sect. 4.2.1
Waveform difference	4.3	Sect. 4.2.2
Variation of transit time inside the SiPMs	21	Sect. 4.2.2
Total	27	-

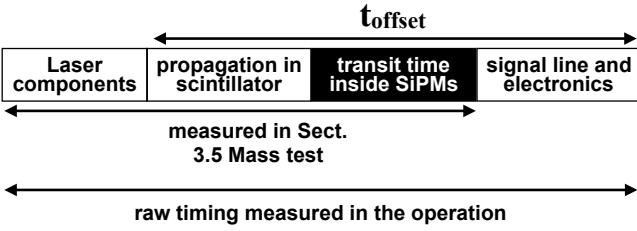


Figure 15: Schematic description of the uncertainty coming from variation of transit time inside SiPMs. See Sect. 4.2.2 in detail.

$-5.74 \pm 0.13$  ps/100 mV where signal amplitude is from 200 mV to 600 mV. We corrected the time offsets for the time difference between the positron data and at the laser data using its difference of the amplitude and the measured coefficient. The uncertainty from this correction is estimated to be 4.2 ps.

#### 4.2.2. Estimation of the uncertainties

The uncertainty related to the laser calibration is due to several components, summarised in Table 4. Parts of them are already discussed. The overall uncertainty is estimated to be 27 ps. In this section, we focus on the two other contributions: waveform difference and variation of transit time inside the SiPMs.

*Waveform difference.* The waveform difference between the scintillation light and the laser light can cause systematic error on the estimation. As shown in Fig. 3, the laser light has a smaller rise time than the scintillation light. If the difference is stable over all the channels, it does not affect the time offsets because only the relative time offsets between counters matter in the time calibration. The standard deviation of the difference over selected  $\sim 250$  channels was estimated to be 6.1 ps by using the  $^{90}\text{Sr}$  data. We did not apply any correction related to the waveform difference, but we set  $\frac{6.1}{\sqrt{2}} = 4.3$  ps<sup>12</sup> as a systematic uncertainty of the waveform difference summarised in Table 4.

*Variation of transit time inside SiPMs.* The goal of the time calibration is to determine the time offsets  $t_{\text{offset}}$  written in Eq. (2).

The laser data during the operation, however, includes not only  $t_{\text{offset}}$  but also optical lengths of laser components shown in Fig. 15.<sup>13</sup> This is why we need to measure laser components beforehand in Sect. 3.5. If we simply subtract it from all the components in Fig. 15, two components are doubly subtracted: propagation in scintillator and transit time inside SiPMs. The propagation time difference between the scintillation light and the laser light should also be included in the former and estimated in Sect. 4.2.2.

The latter is estimated as follows. We measured the hit times of electrons from a  $^{90}\text{Sr}$  source impinging at the centre of the counter, triggered by a  $5 \times 5 \times 5$  mm<sup>3</sup> reference counter put below the counter under test. We repeated this measurement for  $\sim 100$  counters with the identical setup, and thus, the mean times of electron incidence with respect to the reference counter time are the same for all the measurements. The mean value of the measured times shows the response of the counter, including that of the SiPMs. The counter-by-counter variation includes the systematic errors from the setup reproducibility and the difference of scintillators, but we consider it the upper limit of the variation of transit time of SiPMs, being 21 ps.

### 4.3. Performance evaluation

#### 4.3.1. Uncertainty on the time offsets

In order to evaluate the uncertainty on the time offsets from the data, the results of the laser calibration were compared with those from the other time calibration method that uses positron tracks. Fig. 16 shows the difference of time offsets obtained with the two methods; they are in good agreement with a standard deviation of 48 ps averaged over the downstream and upstream counters.

This value includes the intrinsic uncertainty of the laser calibration estimated in Sect. 4.2.2, and that of the track-based calibration. It is hard to separate these effects. In the end, these two methods are to be combined to finally determine the time offsets. The larger value compared with the intrinsic uncertainty of the laser calibration implies a possibility of improvement of the time calibration methods. As a conservative estimation, we conclude that the uncertainty of the determination of the time offsets is less than 48 ps.

The effect of the time calibration on the time resolution of the pTC is estimated conservatively as follows: The time resolution of the pTC is 38 ps for positrons with nine hits on scintillator counters. The uncertainty of the time calibration is randomly distributed among the hit counters. Thus, it is smeared with the number of hit counters by averaging over all the hit counters. Therefore, the time resolution including the effect of time calibration is estimated to be 41 ps:

$$38 \text{ ps} \rightarrow 38 \text{ ps} \oplus \frac{48 \text{ ps}}{\sqrt{9}} = 41 \text{ ps}. \quad (4)$$

<sup>12</sup>by averaging over two channels

<sup>13</sup>see Sect. 4.2 for determination of the time offsets.

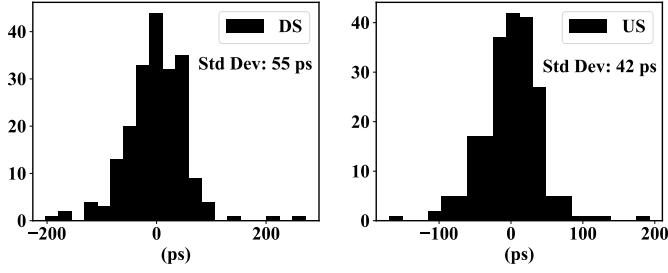


Figure 16: The difference of time offsets between the laser calibration and the track-based calibration method. DS (left) and US (right) denote downstream and upstream sector, respectively.

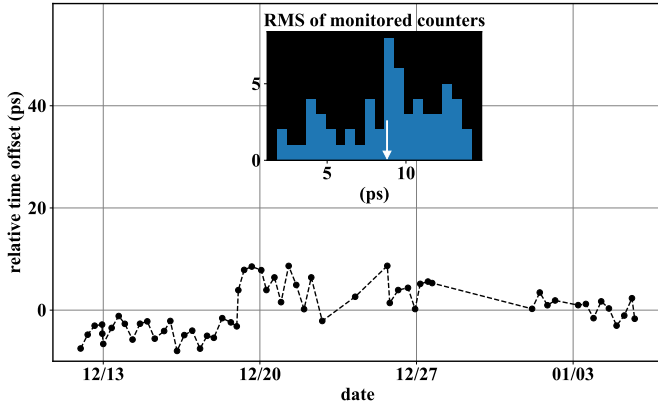


Figure 17: The history of time offsets for the one-month data taking period. One typical counter is picked up from the upper histogram. The RMS of this counter is 8.8 ps.

#### 4.3.2. Stability and timing monitoring

To evaluate the stability and the monitoring precision, we traced the evolution of the relative time offsets during a one-month period when the electronics and detector operation conditions were stabilised. The mean RMS spread for the one-month period for  $\sim 60$  monitored counters is 8.8 ps. The small histogram in Fig. 17 shows its distribution and one typical example is picked up (white arrow) and shown below, in which the average of time offset over time is set to zero.

This value includes the stability of the detector and that of the laser system. Thus, we conclude that the stability of the time offset calculated from the laser calibration system is 8.8 ps and the stability of the laser calibration system itself is less than 8.8 ps. For the timing monitoring purpose, we can detect anomalies more than  $\sim 10$  ps by using the laser calibration system.

#### 4.4. Prospects

Since the optical switch was not used in 2017, we installed and tested it in 2018. The functionalities, such as switching, the remote control, the reproducibility, and the insertion losses, were validated. However, we found gradual degradation of output power over time and we send it back to the company for a detailed investigation. It will be fixed or replaced towards the coming operation.

One possible upgrade on the current laser system is to introduce an asymmetric  $1 \times 2$  splitter instead of the current one with an equal splitting ratio. By using one with a splitting ratio 80:20, for example, we can deliver the larger laser power to the counters while delivering sufficient power to the photo-diode for the monitoring purpose.

We reported the time resolution of the laser signal being  $\sim 50$  ps. It is good enough for our usage, but there is a way to improve it. An MC study shows that the time resolution was dominated by how to deliver the laser light to the SiPMs inside the scintillator and the direct light from the insertion point is crucial. Therefore different fibre insertion methods which can more directly deliver laser light to the SiPMs with less reflection can improve the time resolution.

Another possible usage of the laser calibration system is monitoring of the performance of SiPMs. Radiation damage on SiPMs increases dark currents and worsens the time resolution. We can measure the time resolution of the counters any time in situ without having a beam time using the laser calibration system and estimate the effect of the radiation. In addition, we can also monitor the gain of the SiPMs using a fixed laser power.

## 5. Conclusion

A laser-based time calibration system for the MEG II pTC has been proposed and demonstrated. All the optical components in the system are commercially available and easily maintained. We have successfully developed and commissioned the system in the experimental environment. The system shows good stability with drift smaller than 8.8 ps and we can monitor and detect anomalies related to the detector and DAQ system larger than  $\sim 10$  ps. The uncertainty on the determination of time offsets is estimated to be 48 ps and it has a moderate effect on the pTC time resolution.

The proposed system provides a precise timing alignment method for SiPM-based timing detectors.

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