Waveform digitization for high resolution timing detectors with silicon photomultipliers.

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Abstract.

The results of time resolution studies with silicon photomultipliers (SiPMs) read out with high bandwidth constant fraction discrimination electronics were presented earlier [1- 3]. Here we describe the application of fast waveform digitization readout based on the DRS4 chip [4], a switched capacitor array (SCA) produced by the Paul Scherrer Institute, to further our goal of developing high time resolution detectors based on SiPMs. The influence of the SiPM signal shape on the time resolution was investigated. Different algorithms to obtain the best time resolution are described, and test beam results are presented.

Keywords

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1. Introduction

In our previous studies of high resolution timing detectors based on silicon photomultipliers, SiPMs, we used Ortec front end electronics, including the 9327 constant fraction discriminator (CFD) and a combination of a 566 Time to Amplitude Convertor (TAC) and the 114 14-bit ADC. In that setup we needed to shorten the SiPM signal in time, especially in view of the requirements of the 9327 CFD [5]. With the DRS4 [4], a 5 Gs/sec waveform digitizer, this is not a limitation. It provides a sampling of the SiPM output every 200 ps, allowing us to study the dependence of the time resolution on the signal shape, and to develop algorithms for optimizing the resolution. It enables us to investigate the dependence of the rise time (leading edge) and fall time (long signal tail) on signal clipping. We have compared new results with the DRS4 with our earlier Ortec-based measurements. We used the PiLas laser [6] as a light source that could be attenuated to provide single photoelectrons at a well defined time. Bench tests were done in the Fermilab Silicon Detector facility (SiDet), and beam tests in the Fermilab Test Beam Facility (FTBF).

2. SiDet setup and measurements

The time resolution depends mainly on two parameters: the signal rise time and the signal to noise ratio, S:N, both of which should be high to give good time resolution. Thus the shape of the SiPM signal plays an important role. With the Ortec 9327 constant fraction discriminator (CFD) we needed to use a clipping capacitance to shorten the SiPM response (see Fig. 1) due to the requirements on its input signal. This capacitive coupling (C = 10 pF) reduced the signal by a factor of 30 (see Fig. 2 a, b). With the DRS4 readout we did not expect to see a significant difference in the time resolution with or without signal clipping, because the rise time of the output signal should be similar for both options, and the time information is extracted from the leading edge in both cases. Some measurements were performed which confirmed this. The SiPMs mounted inside shielded Pomona boxes are shown in Fig. 3.

We used a version of the DRS4 with 4 input channels. The DRS4 evaluation board allows a digitization of the signal with a maximum sampling rate of 5 GS/s, with a depth of 1024 per channel. For some studies we used Ortec VT120 amplifiers on the SiPM signals to match the dynamic range of the DRS4.

We first measured the DRS4 intrinsic "electrical" time resolution. We used a BNC model 8010 pulse generator into an LRS model 621 BL quad discriminator. One NIM output signal of the discriminator was split passively into two by a high frequency Mini-Circuits ZFRSC-42-S+ splitter (4.2 GHz BW), and the two outputs were sent to channels 1 and 2 of the DRS4. At this stage we derived time measurements t_i by simply fitting the leading edge of the signals to a straight line, and finding its intercept with the base line. The time difference $\Delta t = t_1 - t_2$ was measured; the distribution was approximated by a Gaussian distribution, and its width $\sigma(\Delta t)$

derived. The dependence of the intrinsic time resolution (σ) on the time interval between these two signals is shown in (Fig. 4). The time interval was changed by introducing calibrated cables into one channel.

We next measured the time resolution for SiPMs from STM (Catania) as a function of the number of photoelectrons (PE) detected. The PiLas light signal was 33 ps full width at half maximum (FWHM), the wavelength was $\lambda = 405$ nm, and most of the data were taken at a rate of 100 Hz. We changed the light intensity by the "TUNE" laser option, as well as by applying optical filters between the laser and the SiPMs. The pulse height (PH) distribution was obtained by integrating the charge collected over all the time bins (~200 ps) in each DRS4 sample. Many samples were taken before the signal appearance to measure the baseline of the signal. The number of PE was obtained by measuring the PH distribution and fitting it with a Gaussian, the width of the Gaussian fit being given by the statistical spread in the number of PE. The time resolution was measured by applying linear fits to the rising edge of the signals. The dependence of the time resolution on the number of photoelectrons is presented in Fig. 5. This simple initial approach showed that the result we obtained for the laser data with the DRS4 is consistent with that using ORTEC electronics [1]. The time resolution was obtained without a clipping capacitance, using the leading edge approximation. The time resolution with a clipping capacitance was approximately the same. These preliminary results showed that the best time resolution is obtained with 60 – 400 mV peak signals, corresponding to the mid-range of the DRS4 digitizer. When we increased the light intensity, we kept the signal in that range by using an attenuator, or by using a VT120 Ortec amplifier with a clipping capacitance. We also found that the time resolution for these data depends on the algorithm used, we discuss that in more detail below.

3. Algorithms

The simple first method was to fit the leading edge of the signals to a straight line, and to find the intercept at t_i with the base line, as described above. This method was applied both to data obtained with and without a clipping capacitance. Another approach was introduced using a functional form to fit the SiPM signal. The chosen function describes different conditions, e.g. SiPM signals with and without the clipping capacitance. A simple model of a SiPM as a charging/discharging capacitance was taken as a first approximation to the function. The analytical expression for this function is:

$$p(t) = ((1-\exp(-t/\tau1))*\exp(-t/\tau2),$$

where $\tau1$ and $\tau2$ are the charging and discharging time constants. To take into account experimental conditions (jitter, etc.) we convoluted that pulse function with a Gaussian resolution function with one parameter σ, which represents the experimental resolution. We used three steps to obtain timing data. First, we fit the pulse function to the whole signal to find the position of the leading edge. Second, we fixed the discharge time parameter τ_2 and fitted only the leading edge region. On the third step we draw a tangent to the point on the half of the maximum. We defined the time stamp t_i as an intersection of the tangent with the base line. Another algorithm used was an analog of a constant fraction discriminator (CFD). The time t_i was taken to be the point on the signal leading edge corresponding to a fixed percentage of the maximum amplitude. We found that the best time resolution was obtained with about 7% of the peak amplitude. No big different result was obtained with the time stamp jitter extracted from a leading edge approximation by straight line. We found also not big difference in time resolution by using a functional form approach. The time resolution difference was less of 10% for all algorithms presented. Anyway we present results which obtained by fitting signals by the pulse function as described above. We also have to highlight that we present data when the SiPms were illuminated by very fast Cherenkov or Pilas laser light (light pulse duration in a range of few tens ps).

4. Test beam results

In our beam tests we used the Fermilab Test Beam Facility with 120 GeV/c protons from the Main Injector. All the detectors were placed close to each other in a dark box lined with copper sheet for RF shielding. The trigger counter was a single 2x2 mm^2 scintillation counter, 16 mm thick, viewed by two PMTs in coincidence. An octagonal scintillation counter 10 cm across with a central 7 mm diameter hole was used as a veto counter to reject events with additional particles, mostly from upstream interactions. It was viewed by two photomultipliers, with the signals put in ‘‘OR’’. The detectors under study were located between trigger and veto counters. A Photek 240 microchannel plate photomultiplier tube (MCP-PMT) was placed in the beam behind the detectors under test, to serve as a high resolution reference counter. Its 9 mm thick quartz window generated enough Cherenkov light; each proton gave about 90 photoelectrons (~ 10 PE/mm). Previous beam measurements gave σ_{240} ~ 7 ps for the Photek 240, which can therefore be neglected in the SiPM measurements. SiPMs #5 and #6 were Hamamatsu MPPC's type S10362-33-050C, area 3x3 mm^2, 50 μm pixel size, with 3600 pixels. These were mounted at the back end of 30 mm long quartz (fused silica) Cherenkov radiator bars, in line with the beam, and in front of the Photek 240.

The distribution of the time difference $t_5 - t_6$ is presented in Fig 6. This distribution was obtained after a pulse height cut removing 10% of the events, and applying residual time slewing (t_i vs. PH) corrections to the raw data. These improved the measured resolution by about 10%. The time resolution was not significantly different with or without a clipping capacitance. When using the clipping capacitance we used an Ortec 120 C amplifier. No correction for the time resolution of the electronics was made.

We now present the results for the SiPMs 5 and 6 after replacing the Hamamatsu MPPCs with the STM SiPMs; these had area 3.5x3.5 mm^2, with 4900 48 μm pixels. The distribution of the time difference $\Delta t = t_5 - t_6$ is presented in Fig. 7. Again the time resolution is the same with or without a clipping capacitance.

5. Discussion

We found that the intrinsic time resolution of the DRS4 increases as the time interval Δt between the signals increases (Fig. 4). This effect can be explained by random small differences between the duration of the DRS4 time cells; as more cells are involved this results in an increasing uncertainty.

Previously we did not correct for the intrinsic time resolution of the electronics, but in this case it is significant. As can be seen from Fig. 4 the DRS4 time resolution depends on the delay between the signals. We now make a correction for this, by subtracting it in quadrature. At the test beam we could not keep the time interval between SiPM signals at DRS4 very close to zero. We therefore made a correction of the measured SiPM time resolution for this time interval Δt effect. We subtracted the DRS4 time jitter from the measured spectra (Figs.6, 7) and then divided the obtained results by $\sqrt{2}$ to get the time resolution for a single SiPM, assuming them to be the same. The corrected results obtained with the DRS4 readout are then consistent with those obtained with the data acquisition system (DAQ) based on the Ortec electronics [1, 2]. The best time resolution we obtained using the DRS4 is $\sigma(t) \sim 21$ ps (for one MPPC) with 30 mm of quartz radiator, and $\sigma(t) = 49$ ps with the STM SiPMs. The best time resolution we obtained with the Ortec readout was $\sigma(t) = 14.5$ ps for the MPPC and $\sigma(t) = 26$ ps for the STM SiPM under the same other conditions [1]. Some worsening of the time resolution with the DRS4 readout can result from the intrinsic time resolution of the DRS4, and also by possibly not using an optimum timing algorithm. In both cases the results obtained with MPPCs are better than with STMs.

STMicroelectronics is continually working to improve their production devices. All the STM measurements we described were done with N-type on P-type devices (N-type silicon facing the light). We already have new impressive results with P on N (P side faced to the light) STMs, to be presented in a future paper.

6. Conclusion

The goal of this work was to study the performance of the DRS4 waveform digitizer for fast time measurements with silicon photomultipliers. The time resolution obtained with the DRS4 readout is somewhat worse than earlier measurements obtained with Ortec readout [1], but the DRS4 readout is less expensive, and it does not require additional electronics for pulse height analysis. An algorithm which allows to define the signal's leading edge and to get a time measurement point as close as possible to the base line provides the best time resolution. With the DRS4 readout we did not find a significant difference in the time resolution with and without a clipping capacitance when the light pulse is very short (PiLas or Cherenkov light). We have to note the data obtained without any DRS4 time calibration what we plan to perform in future.

References

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Figures

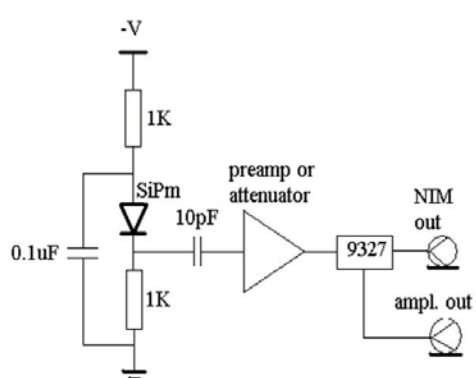

Fig. 1. Schematic of the biasing and readout circuit used for the SiPM timing measurements.

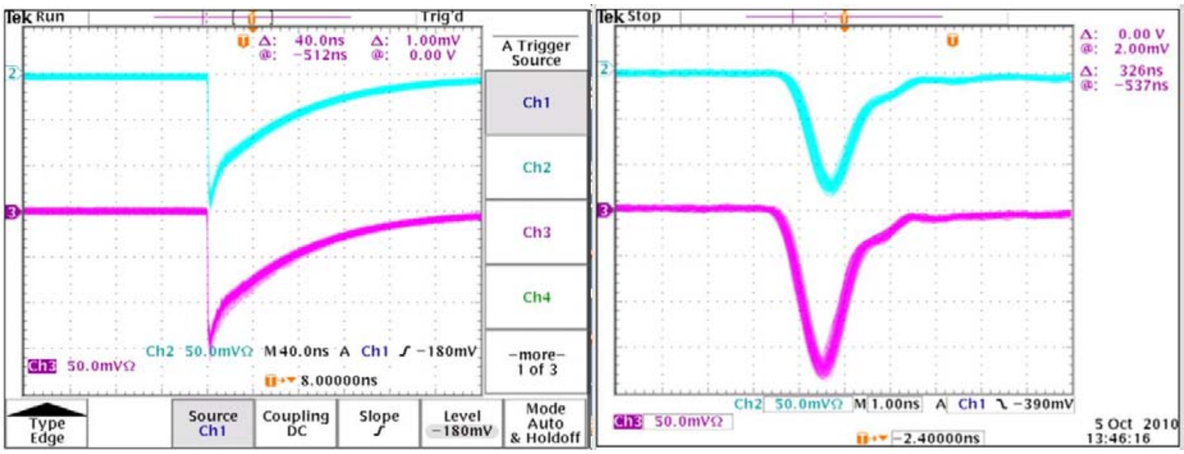

Fig. 2. Traces of STM signals. The SiPMs illuminated by PiLas laser light. Traces are taken without (a) and with (b) a clipping capacitance.

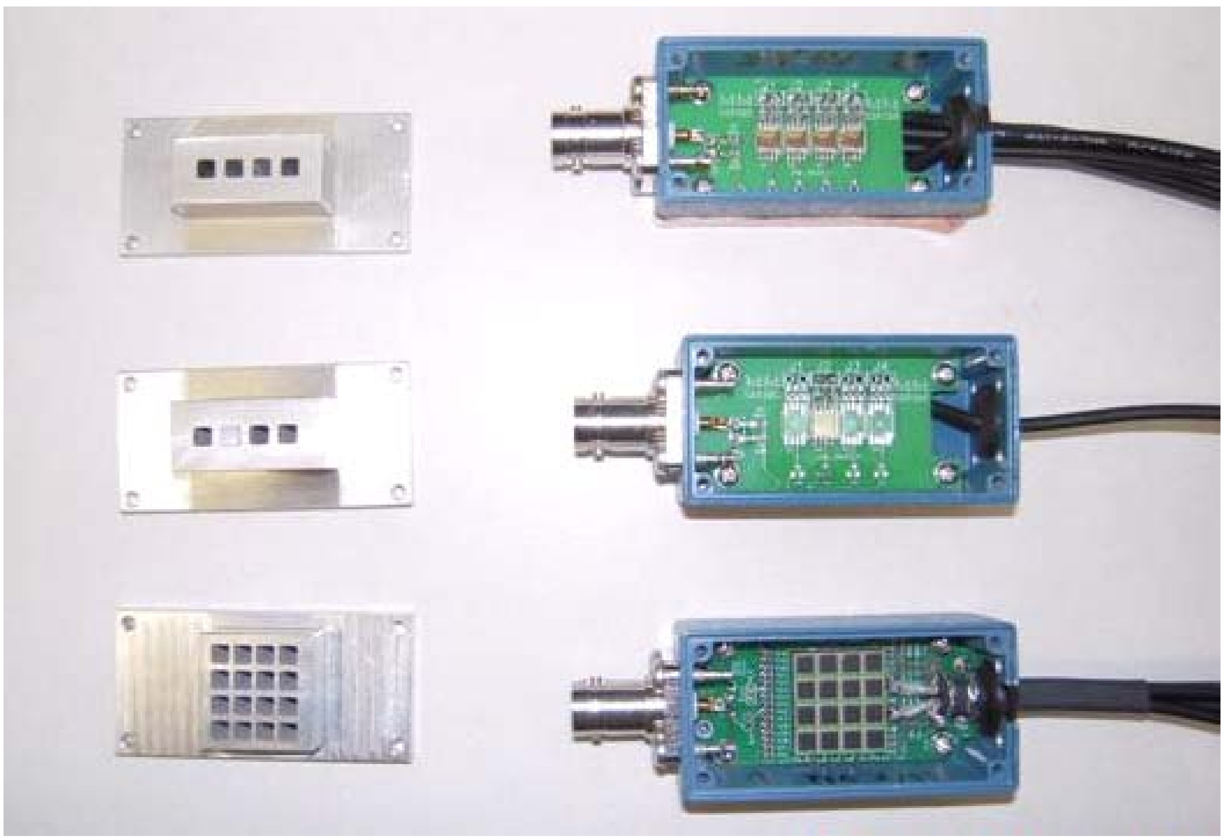

Fig. 3. Pomona boxes with SiPms mounted inside. From the top, on right: 4 STM SiPMs inside the Pomona box with printed circuit board. The support for Cherenkov radiators or scintillating crystals is on the left. Center: The same for one STM SiPM. Bottom: The MPPC matrix, 4x4 cells inside the Pomona box with printed circuit board and support for radiators.

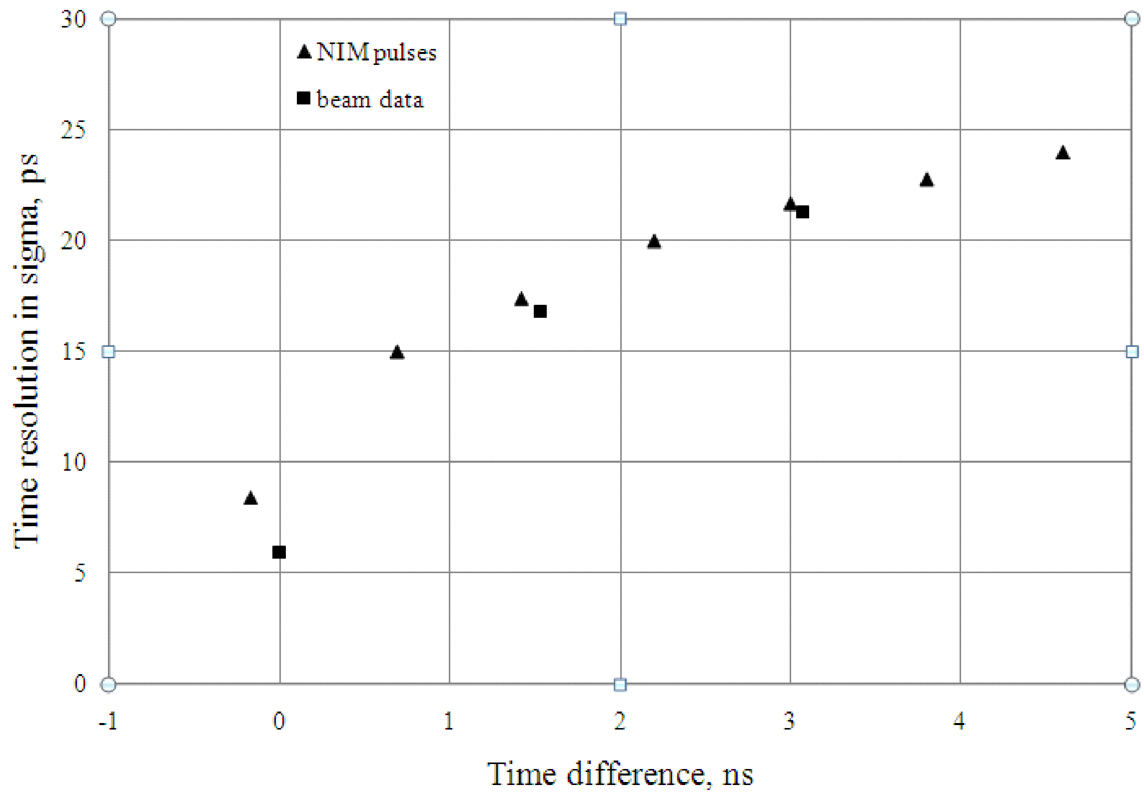

Fig. 4. Dependence of intrinsic “electrical” time resolution on the delay $t_1 - t_2$ between signals, DRS4, #2040. Data are presented as circles; both signals have an amplitude of 400 mV. Data taken in the test beam setup are also presented as squares, 450 mV amplitude maximum (see text for details).

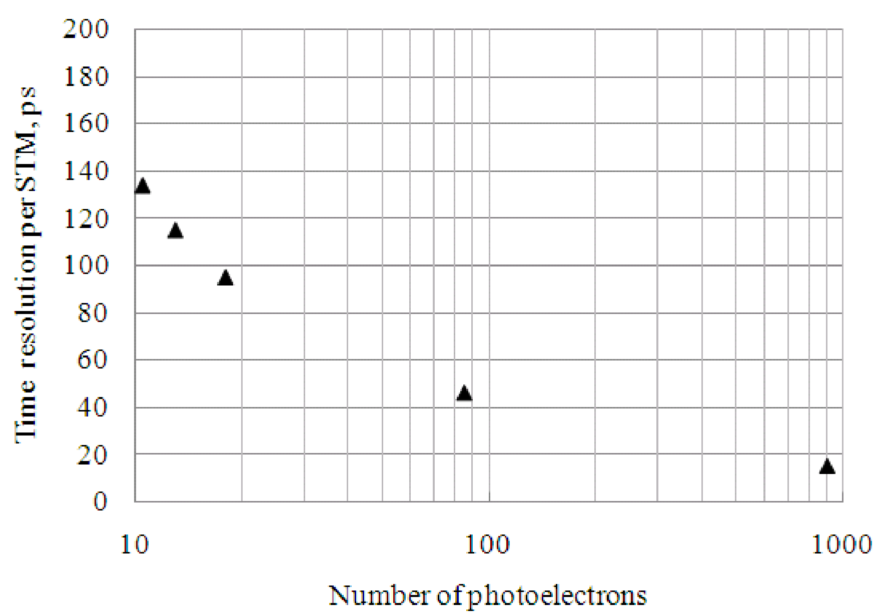

Fig. 5. Dependence of the time resolution on the number of photoelectrons per single STM.

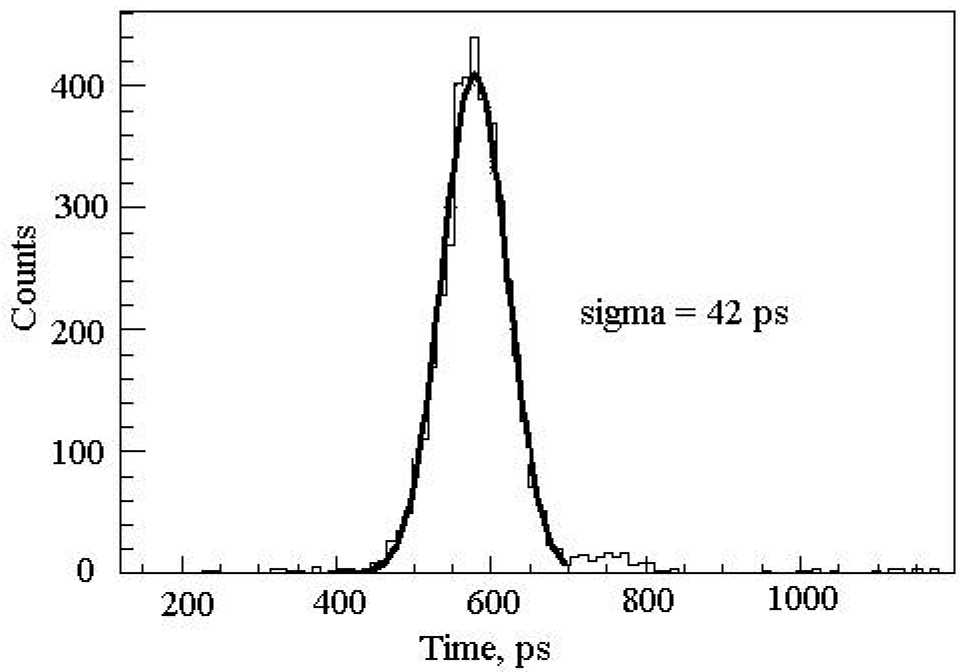

Fig. 6. Distribution of the time difference between channels 5 and 6, Hamamatsu MPPCs.

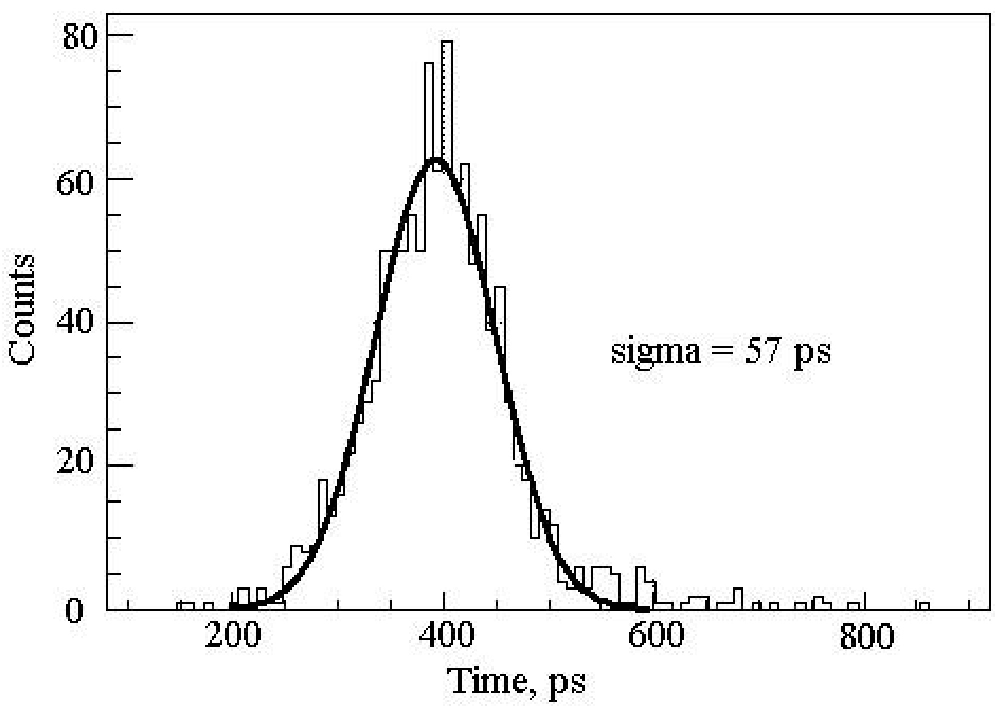

Fig. 7. Distribution of the time difference between channels 5 and 6, STM SiPMs.