# Timing Resolution of SiPM technologies before and after neutron irradiation

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ABSTRACT: In recent years, silicon photomultiplier (SiPM) technology has been getting attention from various applications due to its low cost, immunity to magnetic field, compactness and ruggedness. However, its applicability in experiments with harsh radiation environments is still limited due to lack of corresponding radiation damage studies. A 10-year lifetime operation in a typical Small Angle Neutron Scattering (SANS) experiment with an acceptable degradation in photon detection efficiency has already been reported.

In this article, we will discuss the feasibility study of SiPM technology in neutron time of flight experiments. For this purpose, two analog SiPMs, developed by *SensL* and *Hamamatsu*, have been irradiated with cold neutrons (5 Å) up to a dose of $6 \cdot 10^{12}$ n/cm$^2$ at the KWS-1 instrument of the *Heinz Maier-Leibnitz Zentrum (MLZ)* in Germany. After irradiation, the timing resolutions of the SiPMs have been measured under pulsed laser beam with a few hundred photons (405 nm) per single pulse, and a degradation of up to 6 ps has been observed. The degradation might be a result of noise increase, introduced by surface defects caused by neutron exposure damage. Additionally, variation of the excess voltage helped to reveal the difference in the timing resolutions between irradiated and non-irradiated SiPMs, which remained almost constant.

KEYWORDS: Silicon Photomultipliers; Single-photon avalanche diode; Timing resolution; Time jitter; Cold / Thermal neutrons; Time of flight

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## Contents



## 1. Introduction

Neutron time of flight scattering plays a vital role in various research fields (e.g. neutron spectroscopy), probing neutron-nucleus interaction. These studies focus on exchange of kinetic energy between a neutron and a sample under investigation, utilizing the time of flight measurements i.e. a time, the scattered neutron required to hit a detector. Therefore, the timing resolution of a detector employed in such measurements is a crucial parameter. The state of the art spectrometers [1] [2], based on using $^3$He detector tubes, offer time resolutions in sub ns range. Position sensitive scintillation neutron detector using Silicon photomultipliers (SiPM), as proposed in [3], are capable of having better time resolution along with possibility of scaling it for large area detection, mainly due to SiPM's low temporal resolution of a few tens of ps FWHM (full width at half maximum) [4] , and general scalability of silicon detectors.

SiPMs are solid-state devices, capable of single photon detection [5]. They represent arrays of single photon avalanche diodes (SPAD) connected in parallel to offer gains comparable to traditional photodetectors like photomultiplier tubes (PMTs) along with better form factor, lower operating voltages, insusceptibility to magnetic field, lower cost, and higher robustness. Moreover, in a recent study [6] a time resolution of 7.8 ps FWHM has been reported for a SPAD. The SiPMs are available from various manufacturers and are widely used in applications such as medical imaging, automotive, astrophysics, high-energy physics etc. However, their applicability in radiation environments is a matter of concern due degradation of SiPM performance caused by radiation damage [7].

A previous investigation [8] of changes in the dark current of cold neutron (E = 3.27 meV) irradiated SiPMs from three different manufacturers concluded, that for a typical 10 year operation in SANS the sensor can be a potential replacement candidate to PMTs. After irradiation up to a dose of $6\cdot10^{12}$ n/cm$^2$, the same SiPM arrays have shown a degradation in photon detection efficiency not higher than 11% [9].

This paper builds upon these findings by analysing the effect of cold neutron irradiation on timing performance of SiPMs. We measured and compared the time resolution of non-irradiated and irradiated (the ones from the previous campaign) SiPM arrays (*SensL* and *Hamamatsu*) for a few hundred photons events per laser pulse, which is roughly the number of photons expected to hit a pixel during a neutron event in our detector [10].

## 2. Method and materials

The timing resolution (TR) of SiPM represents a statistical distribution of registered photon events, characterized by its precision and accuracy. The accuracy of the SiPM signal is measured with a reference signal, and the precision of this measurement is referred to as TR. Evaluation of TR has been performed here by correlating the laser pulse synchronized reference signal to the SiPM output signal [11] [12].

The SiPM signal (arrival of a photon) is generated by illuminating it with a pulsed laser beam. The laser trigger output is used as the reference signal. An oscilloscope is then utilized to measure the temporal characteristics of these two signal by building a histogram. Further, the sigma (standard deviation) of this histogram is calculated to evaluate the TR of the SiPM.

### 2.1 Device and characteristics

The measurements have been carried out on two analog SiPMs arrays. The pixel size of *SensL* and *Hamamatsu* arrays were both 3 mm × 3 mm with pixel pitch of 4.2 mm and 3.2 mm respectively. The number of SPADs in a pixel for *SensL* and *Hamamatsu* were 4774 and 3884 with as SPAD size of 35 µm and 50 µm respectively. The detailed specifications can be found in [9]. Four pixels around the centre of both *SensL* (12 × 12 pixels) and *Hamamatsu* (8 × 8 pixels) arrays were considered for this investigation, which where irradiated with neutrons in 2015 by direct exposure to the beam line [8].

A picosecond pulsed laser (PiLas) with a pulse width of 45 ps and wavelength of 405 nm was used as light source. The laser was operated with a repetition rate of 1 MHz and tuning setting of 80%. A fast digital oscilloscope from *KEYSIGHT* (sampling rate of 40 GSa/s and bandwidth of 13 GHz) was used for signal analysis.

The positioning of the SiPM pixel under investigation, in the laser beam was achieved by an automated optical measurement system. The details of this system can be found in [9]. During the measurements, SiPMs have been maintained at a constant temperature in dark environment using the dark box that was a part of the optical measurement system.

### 2.2 Experimental Setup

The diagram of the performed experiment is shown in Fig. 1. The laser optical pulse has peak power of 300 mW and the output of the laser head is connected to a multimode fiber to illuminate the SiPM. In order to attenuate the intensity of the beam to a few hundred photons per pulse, absorptive neutral density filters along with a 1mm pinhole were used. Approximately 600 photons were impinging the pixel of the SiPM array, which corresponds to pixel occupancy of around 12% for *SensL* and 15% for *Hamamatsu*.

The response of the SiPM (see Fig. 2(a)) was obtained from the standard read out circuitry recommended by the manufacturers [13]. For both *SensL* and *Hamamatsu* arrays, a load resistor of 50Ω was used along with a decoupling capacitor of 10 nF and 0.1 µF respectively. Furthermore, a constant threshold at 50% of the signal amplitude was set during the measurements. The biasing of the SiPM was provided by a programmable power supply (*EA-PSI-6150-01*) with a resolution of 10 mV.

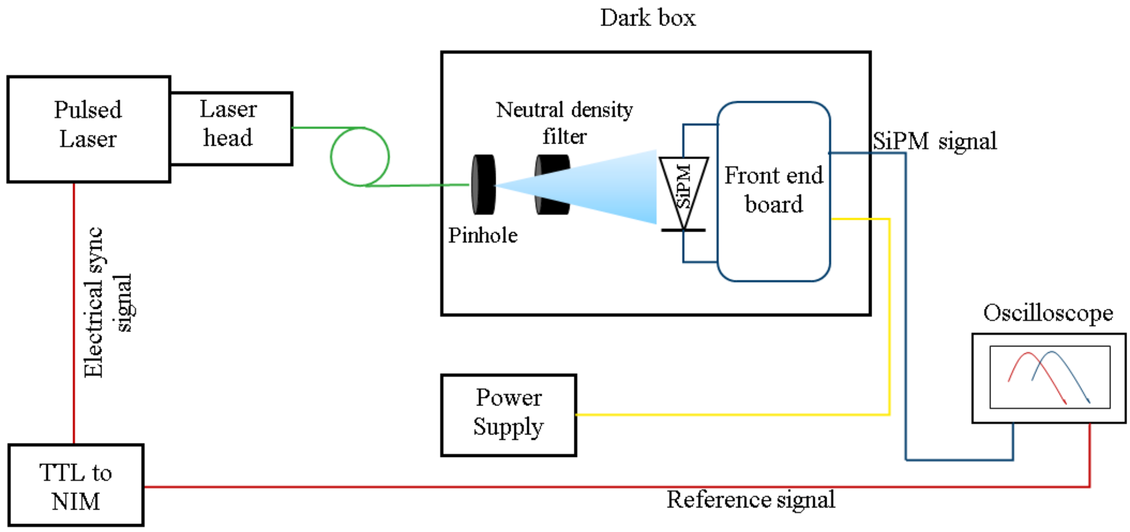



**Figure 1.** Diagram of the measurement setup utilized for the comparison of time jitter of irradiated and non-irradiated SiPMs. The system consists of a laser source and optical setup attenuating the light used for the analysis of SiPM output obtained from the readout electronics.

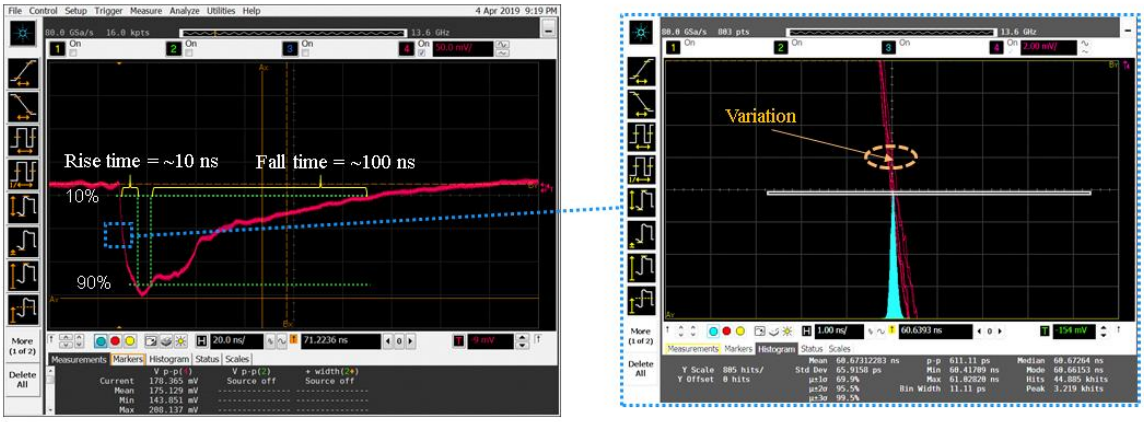
The values of the breakdown voltage ($V_{BD}$) for non-irradiated and irradiated SiPMs (~25 V for *SensL* and ~65 V for *Hamamatsu*) were taken from the previous measurement at the given temperature [9], which were obtained from the I-V curve method. Different biasing voltages ($V_{bias}$) were applied during the experiment.

The trigger output pulse of the laser module, which were used as the reference, represents a 5 V TTL (transistor-transistor logic) signal, and for signal reconditioning we converted it into a -1 V NIM (nuclear instrumentation module) signal, using a NIM-TTL-NIM adapter (*EG&G*, LA8000). The pulse width of the trigger signal was measured to be 9 ns and the rise time was 4 ns, which was reduced to 3 ns after reshaped from the adapter. This signal was used to trigger the oscilloscope on one channel and the SiPM output signal was fed into another channel. The trigger threshold was kept constant at 50% for all the measurements.

Finally, the SiPM signal were analyzed in the oscilloscope to obtain a timing response histogram (refer to Fig. 2(b) and 3), whose root mean square values are reported here. TR were plotted at various excess voltages ($\Delta V = V_{bias} - V_{BD}$): 2 to 5 V for *SensL* and 3 to 6 V for *Hamamatsu*. All measurements were performed at 21°C.

### 2.3 Time jitter

The measured jitter values ($\sigma_{measured}$) had contribution from two more components in addition to the time jitter of the SiPM ($\sigma_{SiPM}$). The first component ($\sigma_{noise}$) is the jitter produced by the associated electronics and can be evaluated as the ratio of the sigma of the baseline noise and the slope of the rising edge of the signal [14]. The second component is the overall contribution due to the setup ($\sigma_{setup}$), e.g. due to laser trigger output, which is considered as the reference signal here, and TTL to NIM adapter. In order to estimate this, we split the electronic signal output from the laser via the adapter into two channels. Then employed the same principle of triggering the




**(a)** **(b)**

**Figure 2.** An oscilloscope image of the (a) temporal characteristics of *SensL* (non-irradiated) output signal with the standard readout employed and (b) a zoomed region of the rising edge of the signal along with the histogram of the output pulse variation with respect to reference signal at a given threshold. The uncertainty of the timing of the registered photon events is the jitter.


**Figure 3.** Image showing an example for the measurement performed using the oscilloscope (not to scale), where blue signal refers to SiPM output and red is the trigger signal. A threshold is also seen on the blue curve and the histogram (in cyan) build up below it.

oscilloscope on one channel and measuring the sigma of the histogram obtained from the other channel. Furthermore, the jitter in the optical pulse width of the laser should also be taken into account and have been obtained from the data sheet (3 ps). Thus, the measured value can be written as the quadrature sum of all the individual contributions as:

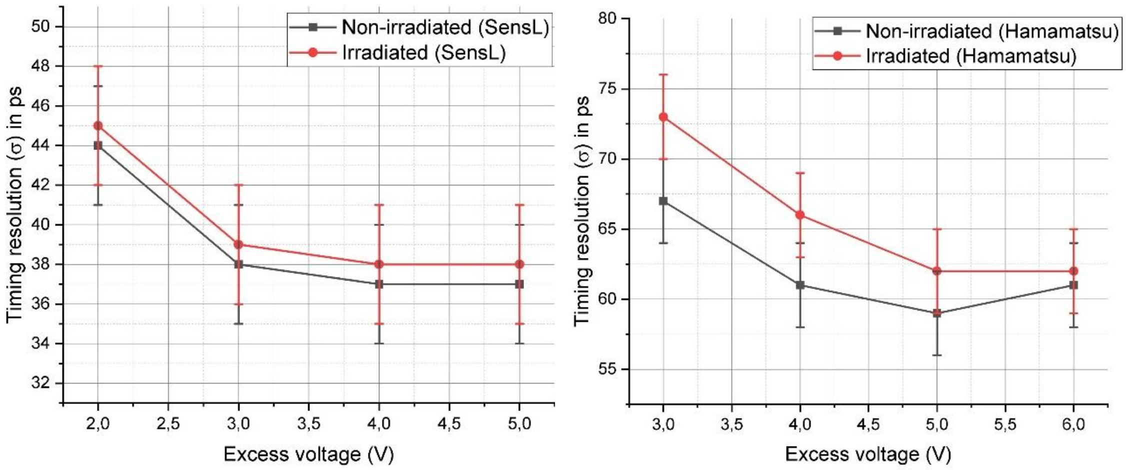
$$\sigma_{measured}^2 = \sigma_{SiPM}^2 + \sigma_{noise}^2 + \sigma_{setup}^2 \qquad (1)$$

Furthermore, $\sigma_{SiPM}$ can be divided into the intrinsic jitter of a SiPM and the transit time spread that is defined as the timing skew of the SPAD arising from distance mismatch between individual SPADs and SiPM output [15]. However, this is out of the scope of this study as we were not evaluating the absolute value of the $\sigma_{SiPM}$.

The goal of this work is the relative comparison of TR for the irradiated and non-irradiated SiPMs. Therefore, we report the values of $\sigma_{measured}$ only, consisting of all individual components along with $\sigma_{SiPM}$ as per Eq. 1. Nevertheless, we evaluated $\sigma_{setup}$ and $\sigma_{noise}$ to ensure that they do not dominate over $\sigma_{measured}$, but for the sake of ease of measurements we assumed them constant as the same experimental conditions and equipment have been used at all times during this study. Additionally, the significance of these two contributions start reducing with higher number of photons illuminating the SiPM, as this is the case in this study. This implies that for all the measurements discussed below, we can assume that comparison of $\sigma_{measured}$ is the comparison of $\sigma_{SiPM}$.

## 3. Measurement results

We measured the four pixels of each of the non-irradiated and irradiated SiPM array. The comparison of the average $\boldsymbol{\sigma_{measured}}$ of these pixels of non-irradiated and irradiated SiPM are plotted in Fig. 4 (a) (b) for of *SensL* and *Hamamatsu* respectively.




**(a)** **(b)**

**Figure 4.** Time jitter of average of four pixels versus different excess voltages for non-irradiated and irradiated SiPM at 21°C for 600 photons per pulse and at a constant threshold of 50% for both signals, i.e. trigger and SiPM for (a) *SensL* array (b) *Hamamatsu* array. The error bars represent a square root summation of systematic and statistical error.

## 4. Discussion and summary

Although we didn't use low noise front end electronics (with out amplifiers), the results obtained for $\sigma_{measured}$ are lower compared to the SPTR (single photon timing resolution) values reported so far for similar SiPMs [11] [12] [16]. The reason is that the TR value decreases with a higher number of photons illuminating a SiPM, due to reduced jitter in the avalanche generation at SPAD level [17]. A similar effect is also responsible for the decrease in timing resolution with increase in excess voltage, which can be observed in Fig. 4. As the gain of an SiPM is directly proportional to the excess voltage, the carrier multiplication process due to impact ionization mechanism increases with higher bias voltage. This results in higher photon detection efficiency that leads to faster signal generation and improved resolution.

This improvement is limited because after a certain excess voltage the noise increases rapidly. With increase of $V_{bias}$, the dark current (noise) generated due to both temperature-assisted processes (thermal generation of free carriers) and field-assisted processes (direct band-to-band tunneling and trap-assisted tunneling) starts dominating over the photon generated current. A similar behavior of saturation in TR over excess voltage was also reported previously in [12] [16].

As it can be seen from Fig. 4 (a) (b) the irradiated SiPMs show an increase in TR. This might be attributed to the n-type doping, which is introduced when silicon captures a cold or thermal neutron and transmutes into phosphorus. This leads to a decrease of recombination time of the minority carriers (holes). Additionaly, the neutrons introduce some defects in the silicon crystal, creating traps that can act as recombination-generation centers or trapping centers. Those traps may release the charge carriers with a delay [18].

Furthermore, these trap-assisted carriers contribute to an increase in the dark current of the irradiated SiPMs, as reported in [8]. Moreover, the trapping centers leads to increase in the capacitive coupling between the SPADs, thus resulting in higher charge collection sharing between SPADs and small increment of the noise [18]. This altogether might have resulted in a slight degradation in the TR of irradiated pixels as can be observed from Table 1. Nevertheless, further investigation on radiation damage in SiPMs needs to be performed to have a better understanding of the phenomenon happening at the microscopic level, explaning the mechanism in macroscopic property changes.

| **SiPM arrays** | **Timing Resolution (σ) in ps** | | **Received overall neutron (5Å) dose (× $10^{12}$ n/cm$^2$)** |
|---|---|---|---|
| | **Non-irradiated** | **Irradiated** | |
| *SensL* | 38 ± 3 | 39 ± 3 | 1.9 |
| *Hamamatsu* | 67 ± 3 | 73 ± 3 | 6 |

**Table 1.** Comparison of time resolution of average of four pixels of SiPM arrays before and after exposure to cold neutrons. The values represented here were performed at an excess voltage of 3 V for around 600 photons, and at constant threshold of 50% for trigger and SiPM signal.

From these results we can conclude that the SiPMs discussed above can be used in neutron time of flight experiments with an acceptable (up to 9%) degradation in timing resolutions over a long term of operation (dose up to $10^{12}$ n/cm$^2$ @ 5 Å).

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