

Silicon timing response to particles and light.

Anatoly Ronzhin*, Maria Spiropulu+

Fermilab*, Caltech+.

Abstract

It is observed growing interest to fast timing detectors in high energy physics, related, for example, with collider luminosity increase (LHC) [1]. The options of CMS [2] calorimeter upgrade based on silicon detectors renewed interest to the timing study of this type of detectors. The article is devoted to study of silicon timing response to particles and light.

Keywords: silicon detectors, time resolution, electrons and holes.

1. Introduction

Few factors determine the timing response of silicon detectors. One of them defines time constant and depends on series resistance of the silicon, load resistance and terminal capacitance. The other are due to silicon intrinsic properties: the silicon thickness, the carrier's velocity and its collection time, dependent on depletion voltage and type of the carriers. The carriers drift time in fully depleted silicon determines the carrier's collection time. This time determines the silicon time

response in case of small time constant, but the response could be mostly dependent on time constant for silicon with large capacitance.

We studied earlier the influence of signal rise time on time resolution (TR) of detectors. The shorter the signal rise time the better time resolution can be obtained [3-7]. The fact that the rise time of semiconductor detectors is minimal when the detector is totally depleted is well known [8]. The signal rise time is mostly dependent on silicon capacitance and velocity of carriers. But it is also dependent on source of irradiation (e.g. charged particles or photons). The photons produce much more compact ionization in silicon what could lead in turn to fast timing response. Applied bias voltage in silicon is usually high enough ($E > 10^5$ V/cm) to get saturation velocity for carriers [8]. We consider main sources of signal time jitter in silicon both for particles and light illumination. In case of silicon the density of the carriers define the minimum achievable time jitter like for other type of detectors [3-7].

The paper is organized as follows. The general silicon timing properties described in section 2. Special attention is taken to the main source of the time jitter in silicon. Some details related with influence of silicon thickness, transverse size, depletion voltage, also as type of irradiation on silicon time jitter considered. In section 3 presented some results on time resolution (TR) of silicon measured at the FTBF beams. The results of the study of the silicon illuminated by picosecond laser pulses presented in section 4. Discussion and conclusion presented in sections 5 and 6 respectively.

2. General silicon timing properties

Electric field applied to silicon results in the built-in junction voltage ($\sim 0.6\text{V}$) which is typical for silicon diodes. The high electric field in silicon leads to total depletion which is formed from a conducting region by removal of all free charge carriers. When *charged particle* pass through the totally depleted silicon region it produces carriers collecting on corresponding electrodes and producing output signal.

Silicon detectors can be used when high time resolution is needed. Suppose applied bias voltage (reverse bias) made total depletion of the silicon. When charged particle pass through the silicon it produces electron hole pair, **Fig. 1**. The electrons and holes drift in electric field which is directed across the diode junction from cathode to anode in opposite directions and make up output signal on corresponding electrodes.

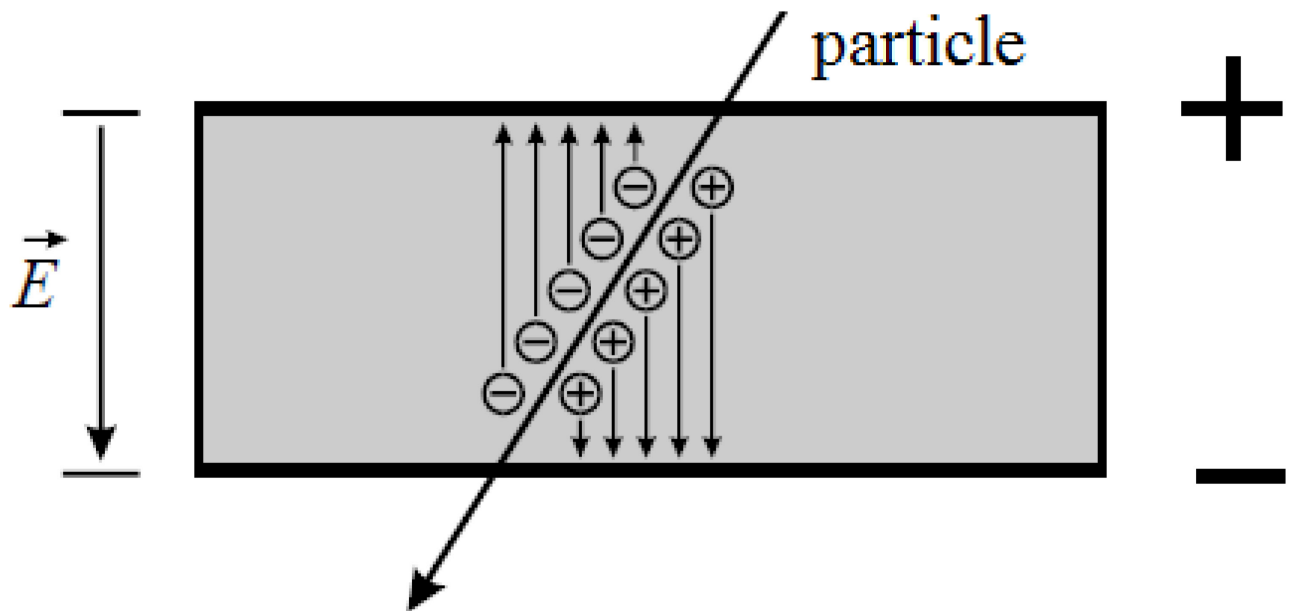


Fig.1. Illustration of building of electrons and holes, produced in silicon by passing particle.

We will consider silicon parameters, which have most influence on its time resolution (TR). Suppose the thickness of the silicon is 300 μm . The relativistic particle passes the 300 μm by 1 ps, so we can neglect this time (and jitter) in the consideration. An electron-hole pair is created by 3.6 eV energy deposit of the particle. At high fields $E > 10^5 \text{ V/cm}$ the mobility of the carriers attains a constant drift velocity of 10^8 mm/s for electrons ($300\mu\text{m}/3000\text{ps}$) in the silicon [8]. The amount of electrons produced in the 300 μm by minimum ionizing particle is $\sim 30,000$ or $\sim 5 \text{ fC}$. The electrons produced by the particle collected on positive electrode and the holes on the negative. When the bucket of the carriers (produced all along the track of the particle) started to move in the electric field it induces signal on electrodes collecting the charge.

Another part of the signal produced simultaneously by electrons and holes, collected on positive and negative electrodes. The time needed to collect all electrons in the 300 μm is $\sim 3\text{ns}$. We can assume that the rise time of the signal should be close to the same value if not to take into account the influence of discharge produced at the same time. The value of the time jitter of the signal can be estimated as the rise time of the signal divided on the signal to noise ratio, or

$$\text{Time jitter} = t_r \times 1/S/N$$

where t_r is rise time and S/N is signal to noise ratio.

The silicon signal should be amplified because of a small value of a charge produced in the silicon by particle. This mean that S/N in silicon will be also dependent on amplification and noise of used amplifier. The silicon thickness and it transverse size define another important TR silicon parameter – its capacitance. The capacitance is going down when increasing the bias voltage value up to full depletion, as

$$1/\sqrt{V},$$

where V is the magnitude of the bias voltage.

The capacitance behaviour with the bias increase is almost flat after the bias is above the silicon full depletion. The value of the capacitance in the region is dependent on the transeverse size of silicon and geometrical size of electrodes, collecting the charge. The capacitance above the full depletion increased when the silicon thickness decrease.

The noise in a silicon detector system depends on various parameters: temperature, geometry of the detector, the biasing scheme, the readout electronics, etc. Noise is typically given as equivalent noise charge (ENC). This is the noise at the input of the amplifier in elementary charges. The most contributions into the noise are detector capacitance, leakage current, parallel and series resistors.

The detector capacitance at the input of a charge sensitive amplifier is usually the dominant noise source in the detector system. Segmented detectors with short strip or pixel structures could be used to reduce this component of the silicon noise.

3. Test beam results.

Test beam setup presented in Fig. 2. Details of the experimental setup are thoroughly presented in reference [9].

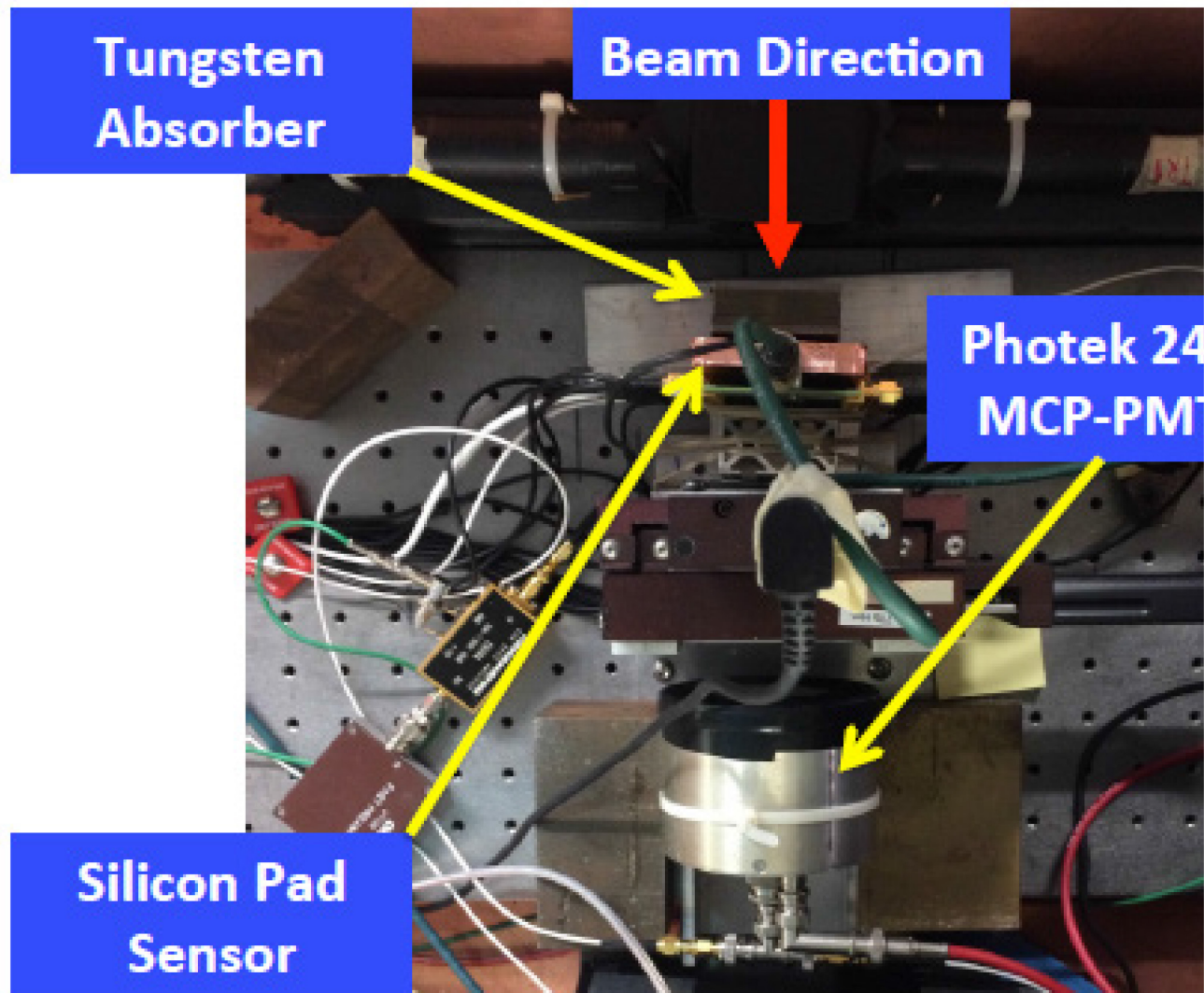


Fig. 2. Test beam setup.

Test beam measurements were performed at the Fermilab Test-beam Facility (FTBF), which provided a

proton beam from the Fermilab Main Injector accelerator at 120 GeV, and secondary beams composed of electrons, pions, and muons of energies ranging from 4 GeV to 32 GeV. A small plastic scintillator of transverse dimensions 1.8 mm x 2 mm is used as a trigger counter to initiate the read out of the data acquisition (DAQ) system and to select incident beam particles from a small geometric area, allowing to center the beam particles on the silicon sensor. Next, a stack of tungsten absorbers of various thicknesses for measurements of the longitudinal profile of the electromagnetic shower was placed.

The silicon pad sensor is located within a metal box covered by copper foil, and is placed immediately downstream of the absorber plates. The electric diagram for the silicon diode connections presented in **Fig. 3**.

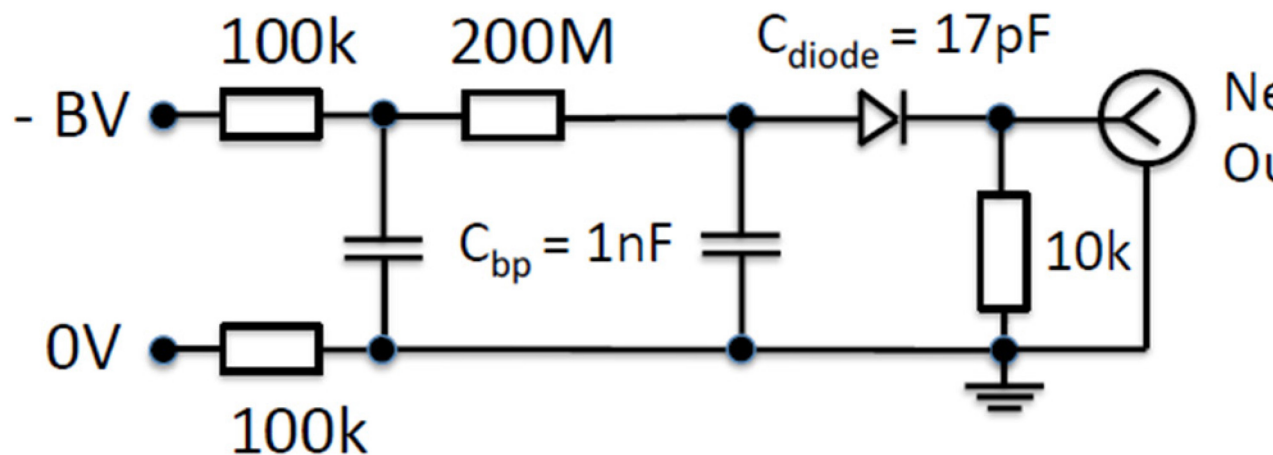


Fig. 3. The electric diagram for the silicon diode connections.

Photek 240 micro-channel plate photomultiplier detector was placed furthest downstream, and serves to provide a very precise reference timestamp. Its precision was previously measured to be less than 7 ps.

The DAQ system was based on a CAEN V1742 digitizer board [10], which provides digitized waveforms sampled at 5 GS/s. The metal box containing the silicon sensor was located on a motorized X-Y moving stage allowing to change the location of the sensor in the plane transverse to the beam at an accuracy better than 0.1 mm. A nominal bias voltage of 500 V was applied to deplete the silicon sensor in most of the studies shown below, unless noted otherwise.

The thickness of the silicon was ~ 325 μm , transverse size is 6×6 mm^2 , capacitance is 17 pF. The signal was produced by 32 GeV electrons making shower in 6 radiation length of tungsten upstream of the silicon. The Ortec120C [11] with Hamamatsu C5594 amplifier [12] in series used to amplify silicon signal (Fig. 4). The signal has a rise time of about 2 ns, and a full pulse width of around 7 ns. This rise time is consistent with a time constant of a silicon sensor coupled to a 50 Ohm amplifier. The time resolution ~ 25 ps was obtained with the signal. This mean the S/N was ~ 75 , what was in agreement with rough estimation.

Examples of the signal pulse waveform for the silicon sensor (left) digitized by CAEN V1742 digitizer board [10] presented in Fig. 4.

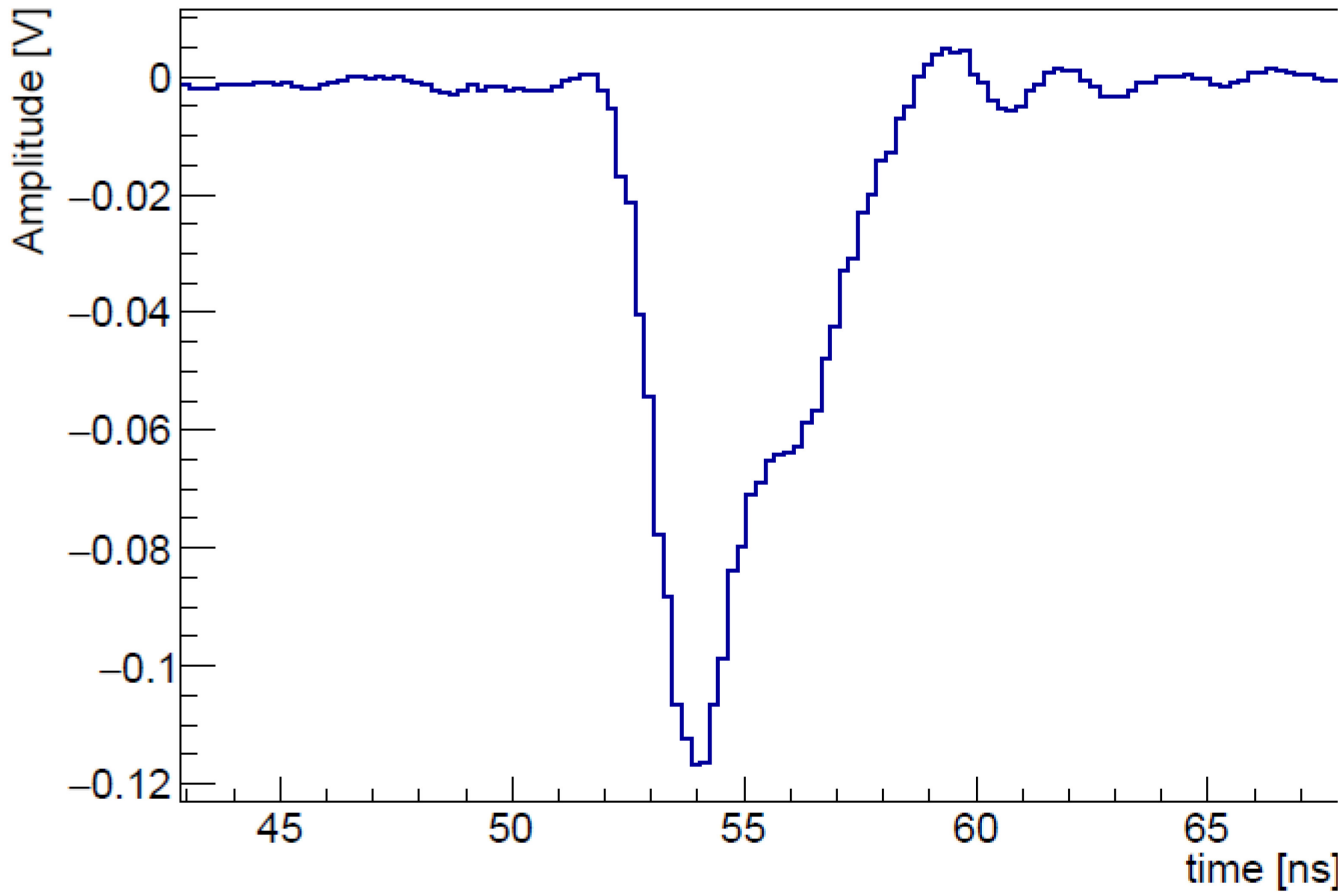


Fig. 4. Example of silicon signal taken by CAEN V1742 digitizer. Conditions: 32 GeV electron beam, 6 radiation lengths of tungsten upstream of the silicon pad.

We can estimate the amplitude of the silicon signal for 120 GeV proton. The amount of electron produced is ~ 30000 in 300 μm silicon. The gain of used amplifiers (Ortec 120C [10] and Hamamatsu C5584 [11] in series) was about a few hundred. The total gain of the circuit was 6×10^6 electrons. The corresponding charge is 1 pC/proton. Taking into account the pulse duration (which is $\sim 7\text{ns}$), external load 50 Ohm and factor of 2 for triangular signal shape we obtain $\sim 10\text{ mV/proton}$ the silicon signal amplitude.

In the **Fig. 5** presented measured PH distribution and TR for the silicon. The distributions were taken with 32 GeV electron beam, and 6 radiation lengths of W. For the signal produced by the shower a few hundreds mV signal, which corresponds ~ 50 particles in terms of the protons units, was obtained.

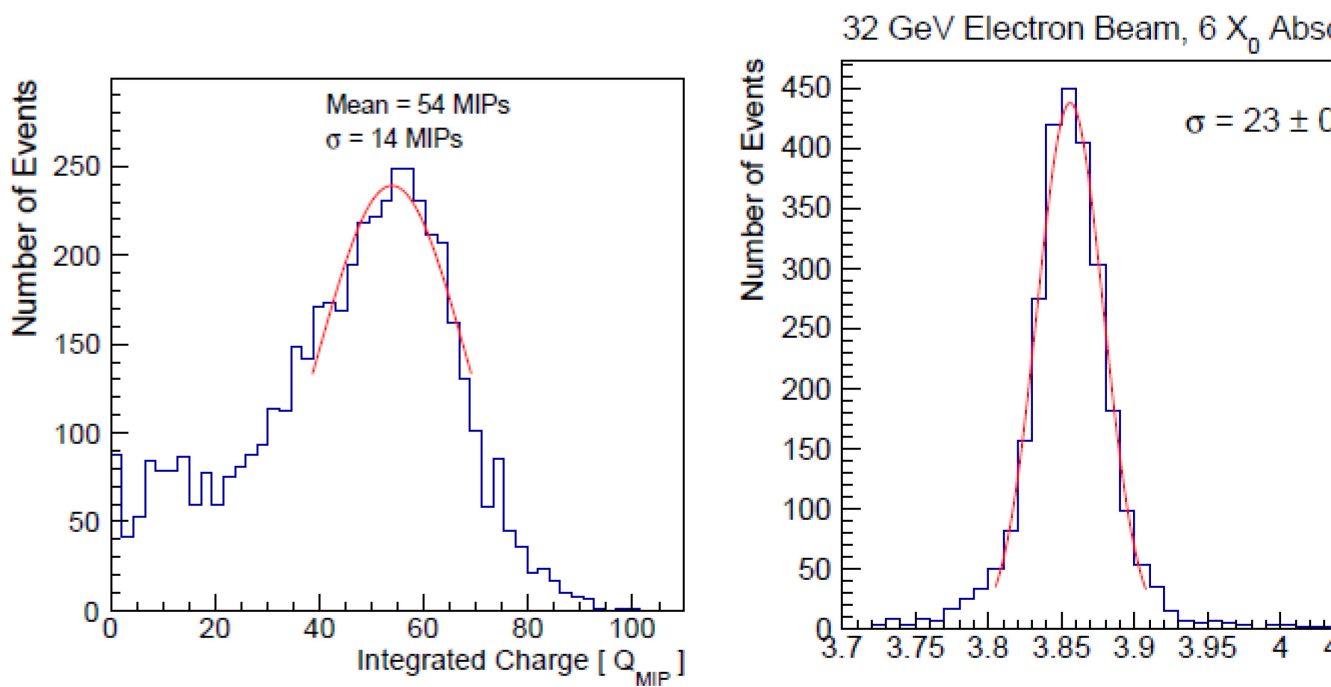


Fig. 5. An example of the distribution of integrated charge in the silicon sensor shown in units of charge measured for a MIP. Right: The distribution of Δt between the silicon sensor and the Photek MCP-PMT. A 32 GeV electron beam is used, and the silicon sensor is placed after 6 radiation length of tungsten as absorber.

The dependence of the integrated silicon charge on bias voltage presented in **Fig. 6**.

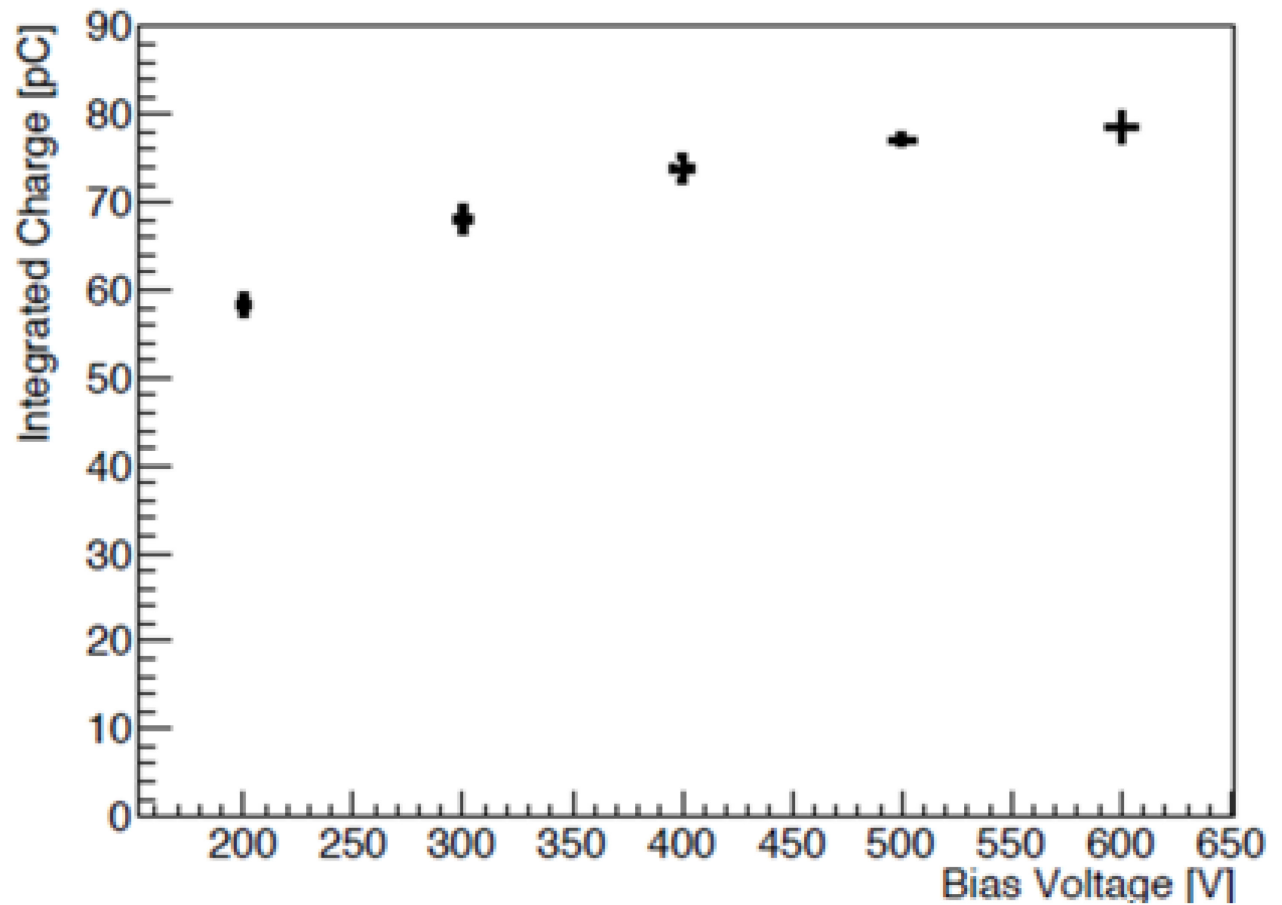


Fig. 6. The dependence of the integrated silicon charge vs applied bias voltage. Conditions: 32 GeV electrons, 6 radiation length of tungsten.

4. Results of the silicon illumination by picosecond laser pulses (PiLas, [13]).

The visible photons produce much more compact ionization along the direction of the photon incidence (a contrary to relativistic particles). That could lead in turn to fast timing response [14], Fig. 7.

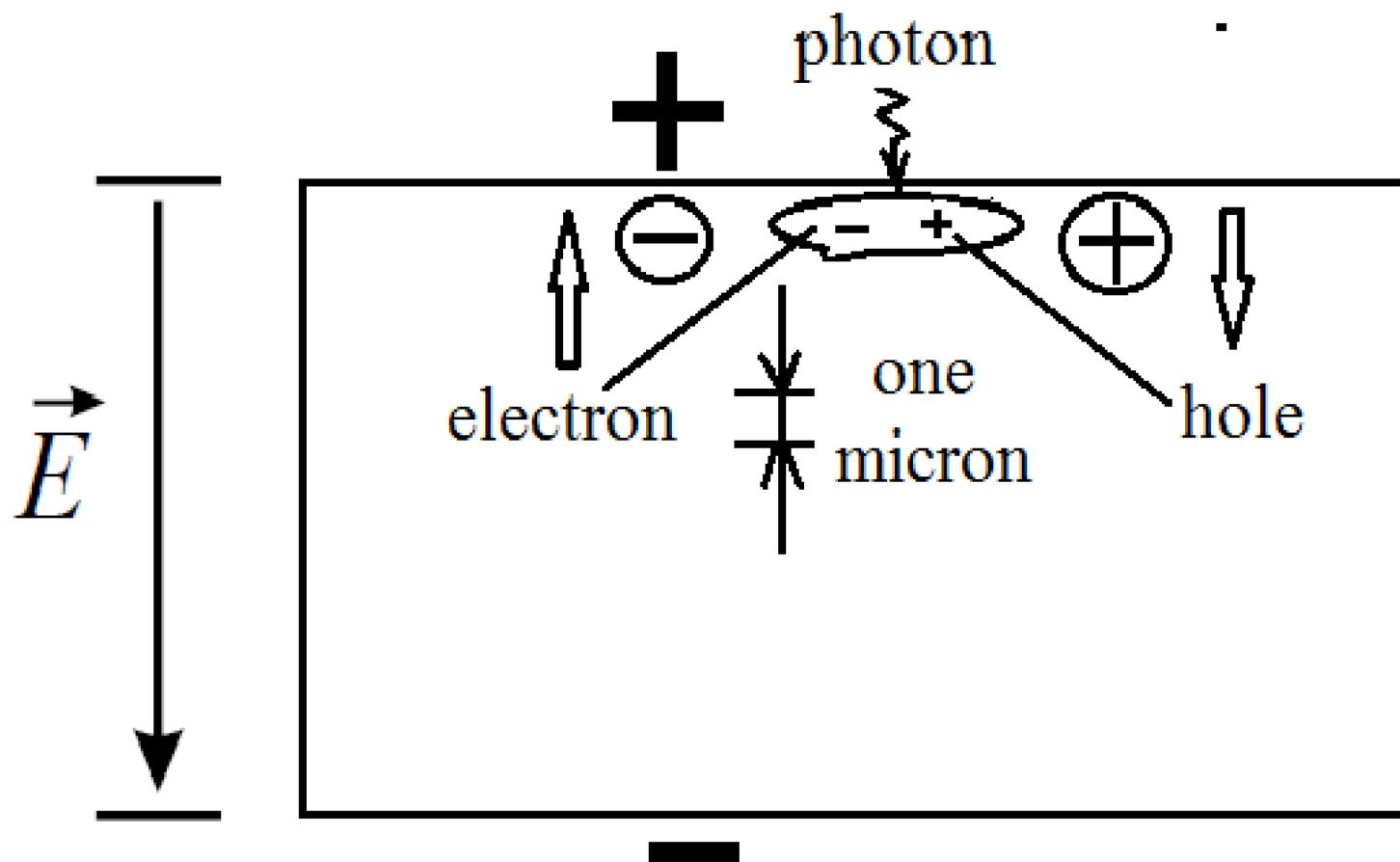


Fig. 7. Illustration to case when visible photon hits the silicon.

With the goal to measure silicon timing parameters the PiLas laser heads with 405 nm and 635 nm wavelengths [13] was used. The laser light pulse (sigma) is ~ 15 ps. DRS (version 5), was used for these measurements. The part of the used setup is shown in Fig. 8.

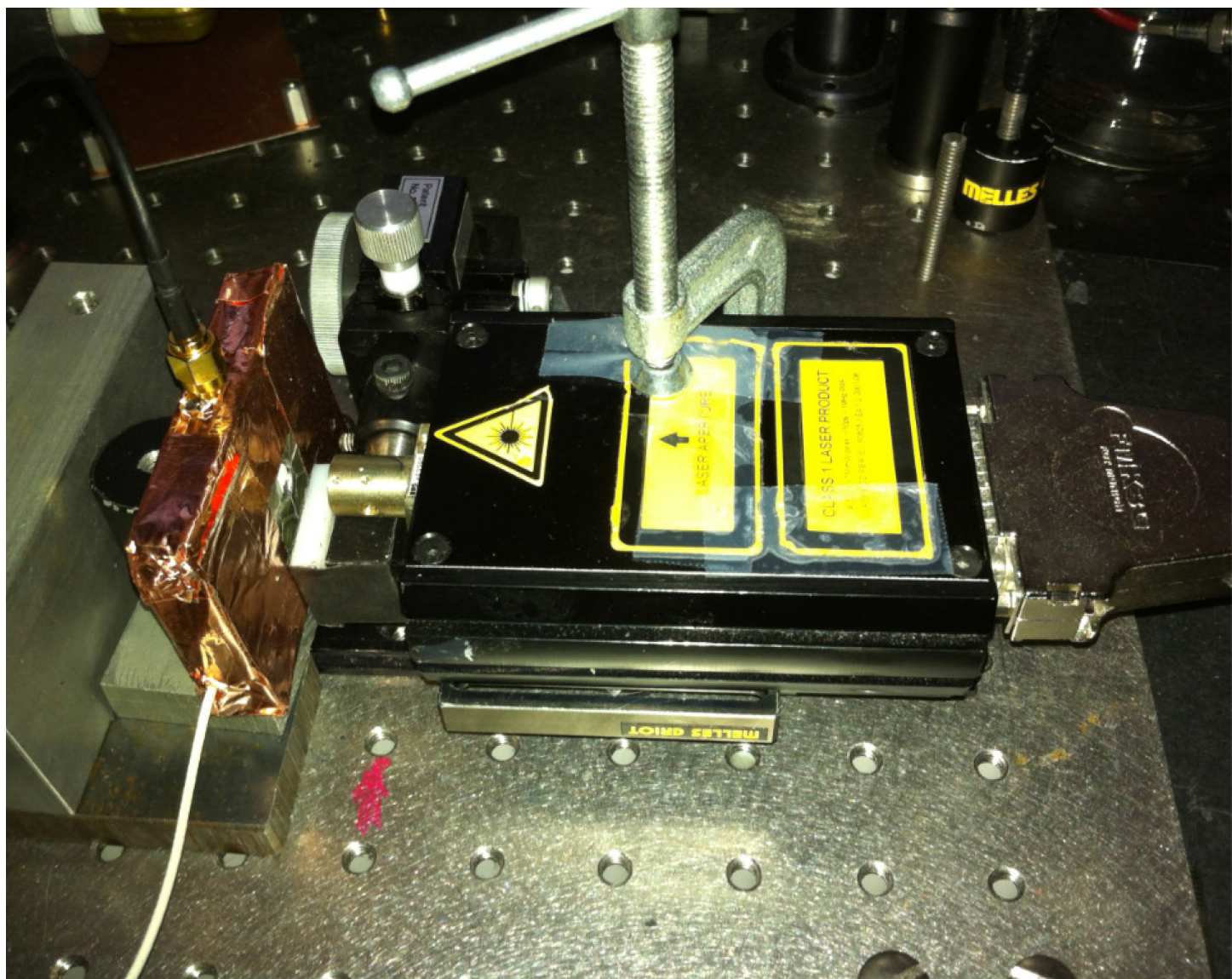


Fig. 8. Setup to measure timing response of the silicon illuminated by Pilas laser light.

The “electrical” time resolution was measured first. The NIM signal was splitted by two halves and applied to the DRS as “start” and “stop” signals. The obtained time resolution (TR) was ~ 4.8 ps (**Fig. 9**).

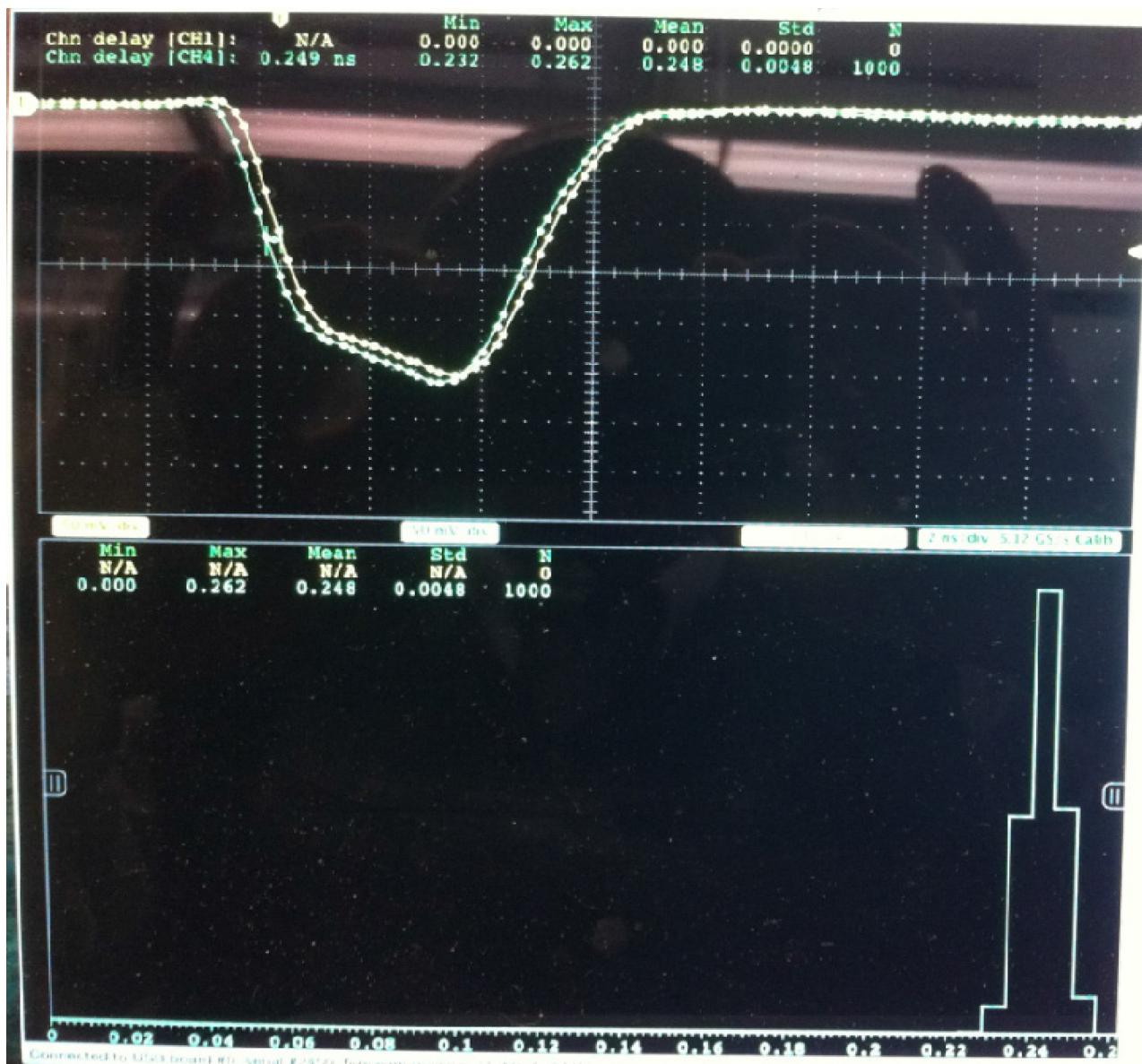


Fig. 9. Traces of two halves of the NIM signals. Histogram below present “electronic” TR, which is 4.8 ps.

It is worth to note that the obtained TR allow to measure the difference in the cable length with better of 1 mm accuracy (~ 5 ps delay in the used cable).

Few measurements with silicon illuminated by laser light were performed. The goal was to estimate some timing parameters (signal shape, time resolution and it dependence on

applied bias voltage, etc.). It was observed small change of the silicon signal shape when bias voltage was changed. The results below present signal peak amplitude in dependence on bias voltage.

The trace of the silicon signal (blue color) presented in Fig. 10. The trigger signal is of rose color in the figure. The time jitter was measured between the trigger signal and silicon signal. The “time stamps” for both signals was settled on ~ 0.5 of signals amplitude. The histogram below presents the time spread between these two signals (5.8 ps, standard deviation). The time TR of the silicon detector, corrected on “electronic” time resolution is ~ 3.3 ps. The trigger was the Pilas laser out.

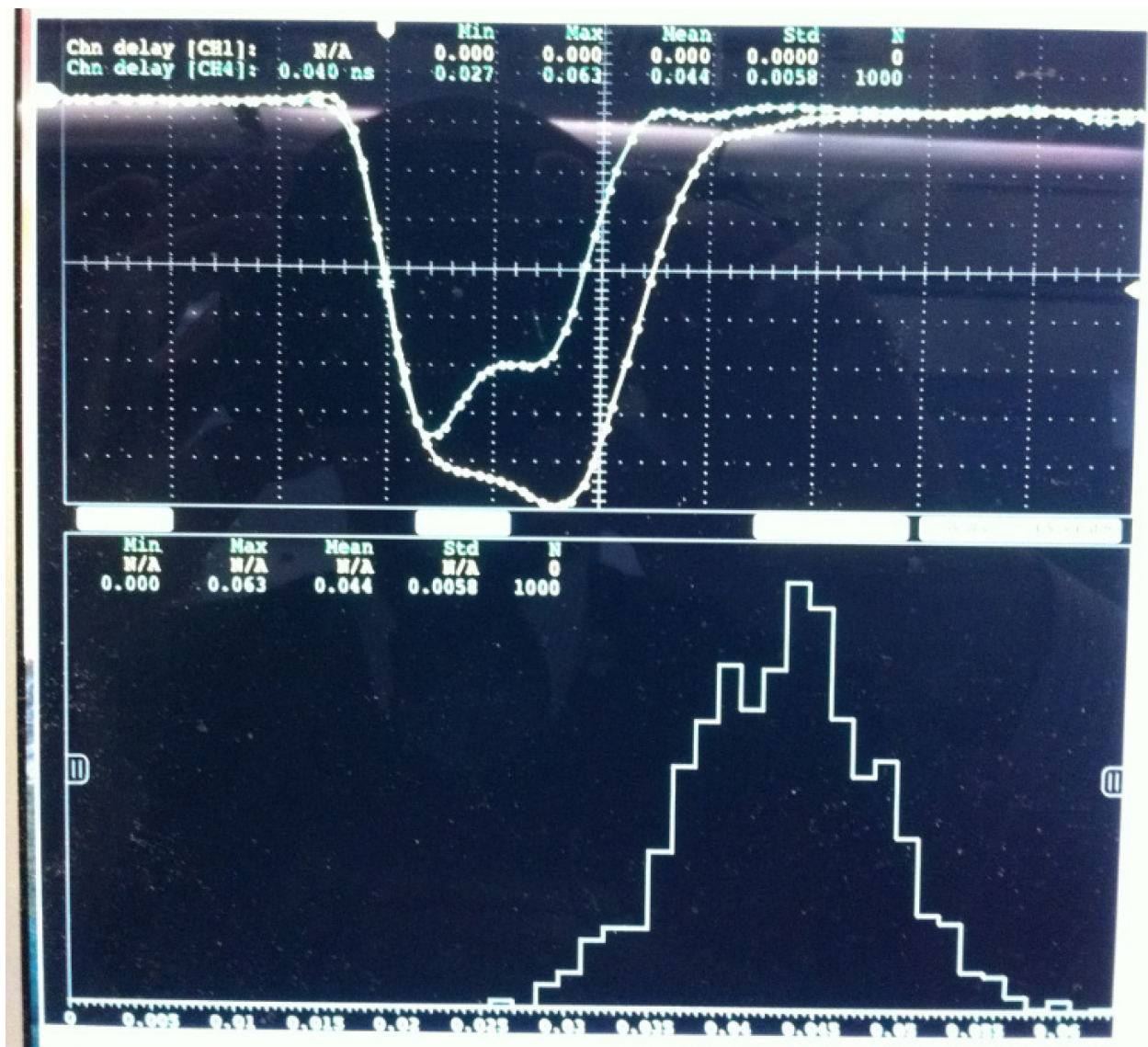


Fig. 10. Example of the silicon signal shape, blue trace. The trigger signal is a rose trace.

The peak amplitude of the silicon signal and TR vs bias voltage presented in the **Fig. 11**. Dependence of the TR on bias voltage was measured with both of blue and red laser light.

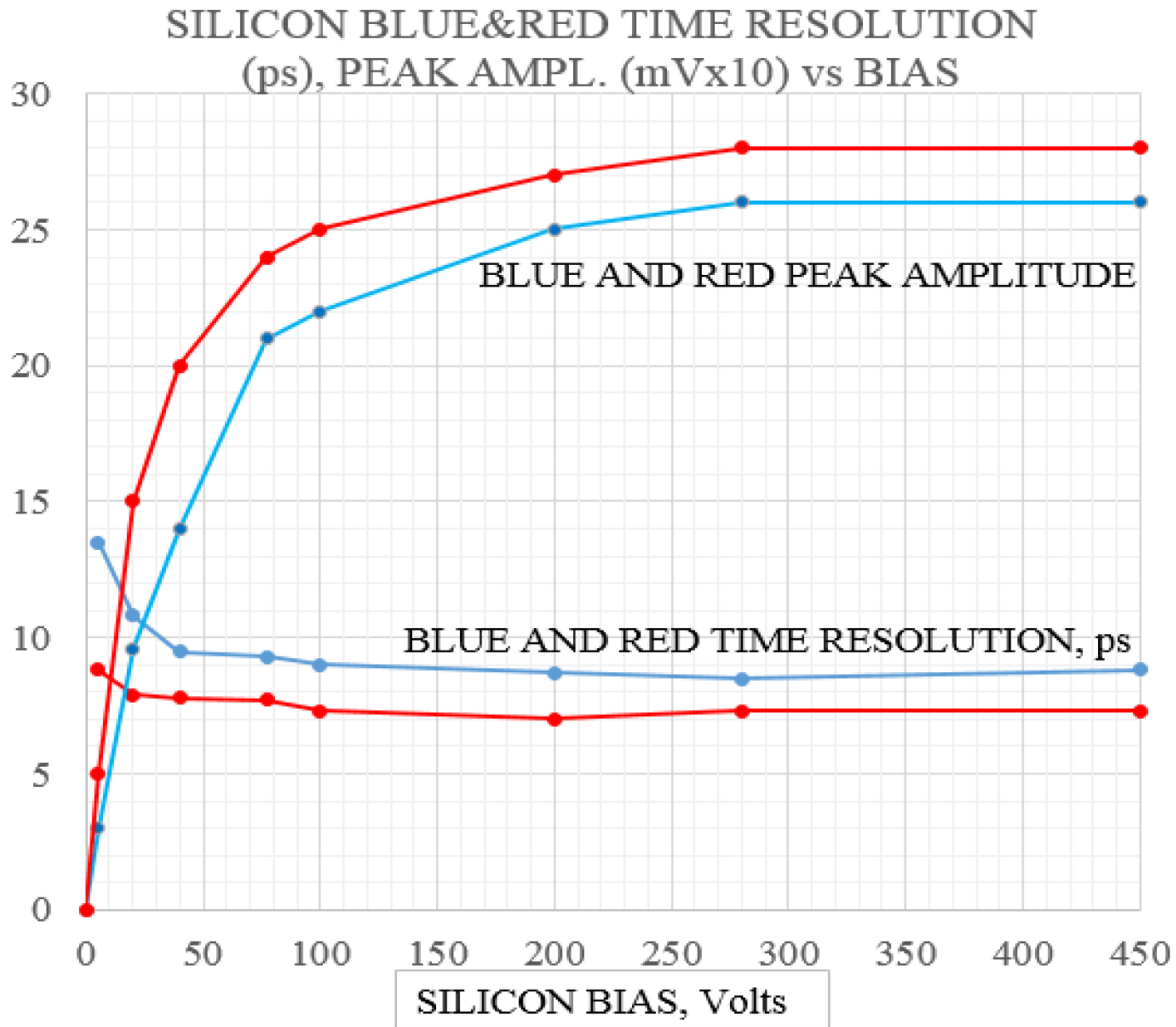


Fig. 11. Time resolution of the silicon in dependence on bias voltage. Laser light was 405 nm (blue) and 635 nm (red).

The attempt was made to see changes of the output signal shape and TR on the silicon illuminated area. Changes diameter of Iris diafragm (with minimal diameter of open area of 1 mm) of the silicon illuminated area was used. No any noticeable

signal shape changes were observed.

The dependence of the TR on the laser light intensity was measured. The uniform light attenuators of the laser light were used. Close inverse square root dependence of the TR on the amount of the light was observed. The best time resolution about 3.3 ps was observed with biggest possible amount of the Pilas laser light illuminated the silicon.

5. Discussion

The presented results show that the time stamp associated with electromagnetic showers induced by electrons with energy between 20 GeV and 30 GeV can be measured with a precision better than 25 ps. Subtracting for the resolution of the reference photo detector yields a precision close to 20 ps. Moreover, we observe an improvement of the time resolution with the energy of the electron, and more generally with an increase in the signal amplitude. These measurements demonstrate that a calorimeter based on silicon sensors as the active medium can achieve intrinsic time resolution at the 20 ps level, as long as noise is kept under control. Time jitter arising from intrinsic properties of the silicon sensor is demonstrated to be well below the 20 ps level.

The high electric field in silicon leads to total depletion which is formed from a conducting region by removal of all free charge carriers. When charged particle pass through the totally depleted silicon region it produces carriers collecting on corresponding electrodes and producing output signal. The

thickness of the silicon tested is 325 μm . The electrons produced closer to the positive electrode are collected first. The time needed to pass 1 μm in silicon by electron is ~ 10 ps. The measured silicon signal leading edge is ~ 2 ns corresponds to 200 μm of the silicon thickness. The two parameters defined detector time resolution are signal rise time and signal to noise ratio. The signal to noise ratio ~ 100 is our case. The corresponding time resolution is ~ 20 ps, if to take these parameters for the TR calculation. It is pretty close to measured value. So, we can say that the “rest of the silicon thickness” which is ~ 125 μm ($125\mu\text{m} = 325\mu\text{m} - 200 \mu\text{m}$) does not participate in the silicon time jitter, because these electrons are coming “too late”. This simple model can explain in general obtained results.

The size of the “*charged cluster*” produced by visible photon inside of silicon is relatively small in comparison with trace length produced by *charged particle*. [14, 15]. When energetic photons penetrate the active region of silicon, some (or in certain cases all) of the photons' kinetic energy may be absorbed through interactions with bound electrons resulting in ionization -- liberation of unbound charge in the form of hole-electron pairs. 3.6 eV of photon energy absorbed in silicon are required to liberate one electron-hole pair. The pair is located in the area limited by a few microns. The produced charge is better “localized” and should have in general less time jitter.

When silicon detector illuminated by photons which have enough energy to excite an electron from the valence to the conduction band, is incident upon the detector, the resulting

accumulation of charge leads to a flow of current in an external circuit. The photon energy should be larger of small energy gap between the valence and conduction bands of the detector in the case. Since light is not the only source of energy that can excite an electron, detectors will have some amount of current that is not representative of incident light. For example, fluctuations in thermal energy can easily be mistaken for light intensity changes. A variety of these “non-light” contributions are present and, when summed up, make up the total noise within the detector.

Obtained TR with silicon light illumination do not significantly differ for blue and red light. It may be due to **shallow** penetration of the light into silicon, which is ~ 100 nm for 405 nm and ~ 1 μ m for 635 nm [16]. Another obtained result is that the TR almost does not depend on applied bias (in the range 30-450 V) in both case. May be it is due to small size of area with carriers in both case. The TR resolution improves with Pilas laser light. The measured value is at picosecond level with high light intensity illuminated silicon.

6. Conclusion.

The time resolution for the silicon ~ 20 ps at FTBF obtained. 32 GeV electron beam and 6 radiation lengths of W upstream of the silicon detector was used. This could correspond to **~ 50** shower's particle registered. The 120 GeV proton amplitude corresponds to ~ 10 mV according to measurements and estimation (with amplifiers, see above). It was observed significant amplitude increase when absorber used. This open an

opportunity to use the silicon as active layer in calorimeter, for example in CMS HGC upgrade [2].

The results obtained with PiLas laser illumination of the silicon shows possibility to get few picosecond time resolution (TR). The TR is weakly depends on bias voltage in the range of 30-450V of the bias. The best measured TR was ~ 3.3 ps with correction on “electronic” time resolution. The result was obtained with maximum Pilas laser light intensity. The TR = 3.3 ps turned out to be very sensitive to type of cable, the length of the cable, temperature, etc. The TR might be used as a tool to measure such a parameters with high accuracy.

7. Acknowledgement.

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References

1. CMS Collaboration "Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process", 26 July 2013, arXiv:1307.7135[hep-ex].
2. J. Butler, D. Contardo, M. Klute, J. Mans, and L. Silvestris, Technical Proposal for the Phase-II Upgrade of the CMS Detector," Tech. Rep. CERN-LHCC-2015-010. LHCC-P-008, CERN, Geneva, Jun 2015.

3. A. Ronzhin, S. Los, E. Ramberg, M. Spiropulu, A. Apresyan, S. Xie, H. Kim, A. Zatserklyaniy “Development of a new fast shower maximum detector based on microchannel plates photomultipliers (MCP-PMT) as an active element”. Nuclear Instruments and Methods in Physics Research A759 (2014) 65–73.
4. D. Anderson, A. Apresyan, A. Bornheim, J. Duarte, H. Newman, C. Pena, A. Ronzhin, M. Spiropulu, J. Trevor, S. Xie, R. Zhu. “Precision timing measurements for high energy photons”. Nuclear Instruments and Methods in Physics Research A787 (2015) 94–97.
5. Anatoly Ronzhin. “High time-resolution photodetectors for PET applications”. Nuclear Instruments and Methods in Physics Research A809 (2016) 53-57.
6. A. Ronzhin, S. Los, E. Ramberg, A. Apresyan, S. Xie, M. Spiropulu, H. Kim. “Study of the timing performance of micro-channel plate photomultiplier for use as an active layer in a shower maximum detector”, Nuclear Instruments and Methods in Physics Research, A795 (2015) 288–292.
7. A. Ronzhin, S. Los, E. Ramberg, A. Apresyan, S. Xie, M. Spiropulu, H. Kim. “Direct tests of microchannel plates as the active element of a new shower maximum detector”, Nuclear Instruments and Methods in Physics Research A795 (2015) 52-57.
8. Helmuth Spieler: Semiconductor Detector Systems, Oxford University Press, 2005.

9. A. Apresyan, G. Bolla, A. Bornheim, H. Kim, S. Los, C. Pena, E. Ramberg, A. Ronzhin, M. Spiropulu, S. Xie “Test Beam Studies Of Silicon Timing for Use in Calorimetry”. Preprint Fermilab, FERMILAB-PUB-15-572- PPD, 2015. Submitted to NIM, 2015.
10. CAEN V1742 digitizer.
<http://www.caen.it/csite/CaenProd.jspparent=11&idmod=661>
11. Ortec VT120C fast preamplifier. www.ortec-online.com
12. Hamamatsu high speed amplifier C5594. Hamamatsu catalog, 2015.
13. PiLas Laser, Advanced Photonic Systems, A.L.S Gmb. H Schwarzschild str 6,
Photonic Center, D-12489 Berlin, Germany.
14. Silicon detectors for high energy particles, chapter 10.
https://www.hamamatsu.com/resources/pdf/ssd/e10_handbook_f_or_high_energy.pdf
15. S.M. Sze. Bell Laboratories, Incorporated, Murray Hill, New Jersey, “Physics of Semiconductor Devices” Copyright, 1981 by John Wiley & Sons, Inc.
16. A. Ronzhin et al. “Study of Timing Properties of SiPMs at Fermilab”, report presented at 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference. Record N1-111, NSS/MIC, 2012.

