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Study of Timing Properties of Multi-Pixel-Photon-Counter's Illuminated by 630 nm and 405 nm PiLas Laser Light.

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Abstract. **Timing measurements of Multy-Pixel-Photon Counters (MPPC's) at the picosecond level were performed at Fermilab. The core timing resolution of the amplifiers, discriminators and TAC/ADC combination to perform these measurements is approximately 2 picoseconds. The single photoelectron time resolution (SPTR) was measured for the signals coming from the MPPC's. An SPTR of about one hundred picoseconds was obtained for MPPC's illuminated by picosecond laser pulses. The SPTR depends on applied bias voltage and on the wavelength of the light. A simple model is proposed to explain the difference in the SPTR for blue and red light. Finally, requirements for the MPPC's temperature and bias voltage stability to maintain the time resolution are discussed.**

I. INTRODUCTION

1.1 Time-of-Flight

Time-of-flight (TOF) measurement is a very useful technique to distinguish between subatomic particles. To make a particle identification (ID) means to define the particle's mass. This is possible by measuring the particle momentum by using radius of curvature in a magnetic field and the particle's velocity measured by TOF. Typical resolutions for TOF have been on the order of 100 picoseconds (ps). Partly this is due to the use of scintillators for light generation, which have extended generation times. Partly this is due to the inherent limitations of large size phototubes, whose intrinsic transit time spread (TTS) is large.

1.2 Multi-pixel Photon Counting

The multi-pixel avalanche photodiode, also known as Multi Pixel Photon Counter (MPPC) for those produced by Hamamatsu, could be an option for upgrading capabilities of TOF systems. Another name often used for such a device is silicon photomultiplier (SiPM). The MPPC's are blue sensitive photosensors, which fit well to the light from scintillators and Cherenkov radiators. The blue photon detection efficiency of the devices can be about 65%. The TTS of the MPPC is about 100 ps for a single photoelectron. MPPC's with a sensitive area of 3mm x 3mm are already on the market. We discuss here measurements of MPPC timing characteristics performed at the Fermi National Accelerator Laboratory (Fermilab).

II. SETUP TO STUDY MPPC TIMING

2.1 LED Setup

Two setups at the Silicon Detector Facility (SiDet) at Fermilab were created for studying MPPC timing characteristics (Figure 1). The first one contains a dark box where MPPC's under study are located. The parts of the setup are a picosecond-level pulse generator (Picosecond Pulse Lab, model 2000) used to power a fast blue light emitting diode (LED) driver, with the MPPC hooked up to a VT120 Ortec fast preamplifier and Ortec 934 Constant Fraction Discriminator (CFD). The LED light level was changed by a rotating wheel with light attenuation filters and monitored by PIN diodes. The LED attenuated light was delivered to the MPPC's by optical fiber. The MPPC's housing was mounted on a Peltier cooling element which was used to change and stabilize the MPPC's temperature. The Peltier allowed changing the temperature in the range of 0 C to +25 C with 0.5 C of accuracy. The trigger output of the picosecond pulse generator was used as the timing start signal and the CFD

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signal as the stop. The time difference between the start and the stop signals was measured by an Ortec 567 Time to Amplitude Converter (TAC), whose analog output was fed into an Ortec AD114 14 bit Analog to Digital Converter (ADC), located in a CAMAC crate with PC readout. This system had 50 ns of dynamic range, with a single channel resolution of 3.1 ps.

2.2 Laser Setup.

The second setup also consisted of a dark box where MPPC's were placed. The electronics chain was identical to the setup described above. The MPPC's were illuminated by a PiLas laser (635 nm and 405 nm heads with light pulse duration of 34 ps, FWHM). The PiLas allowed changing of the light intensity in the dynamic range 0-100%. We monitored the laser light by a PIN diode and a small size photomultiplier. A Peltier element was also used to stabilize the MPPC's temperature, but was eventually replaced by a Ranque-Hilsch vortex tube to increase the temperature dynamic range and improve the temperature stability. The range of temperature was +25C to -20C inside of the dark box. Four thermocouples were installed in different places inside and outside the box to achieve better temperature control. The temperature could be changed, stabilized and monitored with about 0.1C accuracy by hardware and software managed by a PC using LabView software. The PiLas trigger signal is used as the timing start and the CFD signal is used as the timing stop. The timing measurement is the same as with the first setup. A Keithley supply was used for the MPPC's as a bias supply. The unit maintains the supplied voltages with 10 mV accuracy.

III. INITIAL TEST OF THE SETUP.

3.1 Time Stability

Schematics of the initial test are shown in Figure 2. A start and stop signal were delivered to the TAC567 and AD114 from the same generator (Figure 2a). The electronics time resolution was measured in this case and turned out to be 2 ps. Two peaks were obtained by introducing a 1000 ps delay into the stop signal (Figure 3). The warming up time of the TAC567 plus AD114 is about 20 minutes. After half an hour the peak position of the time difference measurement is stable to within +/- 1.5 ps at room temperature (25 C).

3.2 Temperature and Over-Voltage Stability

The next test was performed with a Hamamatsu MPPC with 1x1 mm^2 sensitive area. This MPPC was illuminated by an intense LED. The driver pulse was used as a start signal and the MPPC as a stop signal (Figure 2b). The amount of LED light was enough to observe 10 ps time resolution. The mean timing peak position with respect to temperature and bias voltage was taken. A time shift of 11.5 ps per 1/2 degree C (at ambient room temperature of 24 degree C) was measured. Then, 1 Volt of overvoltage was applied to the MPPC. (The 'overvoltage' is defined as the difference between the applied bias voltage and the breakdown voltage for a given device.) A 6.2 ps time shift per 10 mV of overvoltage change was detected. These preliminary tests showed the conditions needed to keep a 10 ps level of time resolution. We attempted to maintain these conditions in future tests.

3.3 Amplifier/Discriminator Settings

A few tests were performed to evaluate the Ortec 9327 amplifier/discriminator dynamic range to get the best timing. The unit's timing parameters depend on pulse duration and amplitude, according to the 9327 specifications. The 9327 unit should accept pulse widths up to 5 ns (FWHM). A simple clipping circuit was used to shorten the MPPC pulses to this value (Figure 4). The 9327 has an internal jumper which allows it to operate in one of two ranges of accepted signal amplitudes: 0 – 30 mV or 1 -150 mV. An initial test was performed to see the 9327 time resolution dependence on the overvoltage. The measurement's conditions were:

- Hamamatsu MPPC sample 1, 3x3mm^2 active area
- Ortec preamp (VT120) and Ortec 9327 CFD in the 0–150 mV range
- 635 nm PiLas head
- About 100 photoelectrons
- At room temperature (+25 C)

The result is shown in figure 5. Analogous dependences were taken with another MPPC, sample 1**.** 20 db (FP-50 Texscan attenuator) was introduced into signal line starting with 1.2 Volt of the overvoltage (Figure 6). Time resolution was measured in dependence of the signal amplitude, sample 44. Both range (0-30 mV and 0-150 mV) were tested. FP-50 Texscan attenuators used to change the MPPC amplitude in the case. The result presented in figure 7. We tried to keep amplitude spectra inside of the 10-40 mV area based on these preliminary results in further data taking.

IV. THE MPPC TIMING STUDY

We tested a few Hamamatsu MPPC samples of 1x1 mm^2 of sensitive area. These included 100x100 μm^2 of pixel size (100 pixels on the device in total), 50x50 μm^2 pixel size (400 pixels) and 25x25 μm^2 (1600 pixels). A single photoelectron's time resolution (SPTR) as a function of the overvoltage were taken. Both 405 nm and 635 nm of the PiLas laser heads were used to perform the SPTR measurements. The efficiency of the single photon registration was less than 10% for each pulse with the chosen PiLas light intensity. Thus the number of events with two photoelectron's amplitude in the timing distribution could be neglected. The time jitter due to the PiLas light pulse could be neglected in these measurements (the 34 ps of the FWHM of the laser light pulse). The results are presented in Figure 8**.**

The general tendency is an improvement of the time resolution with the overvoltage increase. Another result is that the SPTR is better with 635 nm of the PiLas illumination in comparison with 405 nm for these devices. This effect is just opposite to the data obtained with IRST SiPM's, which revealed better time resolution for 405 nm laser light, as shown in Figure 9.

Some tendency for improvement of the SPTR was observed for the smaller pixel size for the MPPC's with 1x1 mm2 of sensitive area. Worse SPTR was measured for the 3x3mm2 MPPC (50x50 um2 of the pixel size). The SPTR obtained for 635 nm laser light is a little bit better than for 405nm (Figure 10).

An inverse square root dependence of the SiPM's time resolution was observed when the number of the photoelectron's detected was increased (Figure 11). The number of photoelectrons was estimated on the base of the single photoelectron's signal which is perfectly defined for the MPPC's. Most of the data were taken at room temperature (23-25 C) under the temperature control (accuracy is about +/- 0.1 degree C). Figure 12 presents dependence of a time resolution, time delay change and signal amplitude versus temperature for MPPC with 3x3 mm^2 illuminated by the blue light (405 nm). It worth to note the worsen of the time resolution with temperature increase is due to simultaneous overvoltage decrease. The time resolution is about the same with restored overvoltage.

V. DISCUSSION

We feel that the differing absorption lengths of light in silicon SiPM's may play a dominant role in their timing characteristics. The dependence of the absorption length versus the wavelength of light in silicon is shown in figure 13. The electric field dependence on distance from the SiPM surface is also modeled on the same picture. The picture is taken from an article of H-G Moser, MPI [1]. A more precise picture of the electric field distribution for the shallow junction SiPM produced by IRST, Italy (Claudio Piemonte report at Fermilab [2]) is presented in Figure 14.

For the IRST SiPMs the n+ side of the silicon faces to the light. One can see that if a photon absorbs close to the SiPM surface then the originated carriers will be holes. Likewise, the carriers will be electrons if the photon is absorbed deep into the silicon. The absorption length is about 100 nm for the 405 nm photon (blue light PiLas head) and 4 μm for the 635 nm (red light PiLas head). So the blue photons produce mostly holes which travel to the high electric field and produce an avalanche. The red photons produce mostly electrons traveling into the high field from the opposite direction. The mobility of holes in silicon's electric field is about 3 times less than for electrons but the hole's traveling distance is 40 times less. So the combined time spread of carriers originated by blue photons should be about one order of magnitude less than originated by red photons. We feel that this may be an explanation for why the SPTR could be better for the blue light in this case. The magnitude of the velocity of carriers inside of silicon is about 1-10 ns per 300 um depending on the electric field applied to silicon, silicon impurity, temperature [3]. The spread of the order of a few microns of traveling distance could provide 100 ps of the corresponding time spread according to a rough estimation. This simple picture does not take into consideration the time jitter due to an avalanche development, lateral avalanche size, etc, but only considers the initial carrier's time spread [4]. Nevertheless, this naïve model describes to some extent the data obtained for the IRST SiPM (Figure 10).

For the Hamamatsu MPPC's, the p+ side faces to the light. The electrons are the carriers for the 405 nm, and the holes are for the 635 nm in the case. The MPPC time spread for the single photoelectron should be better than for the IRST SiPM when illuminating by 405 nm light according to the model presented above. But just opposite was observed experimentally, i.e. the 1mmx1mm Hamamatsu MPPC's show about 15% better SPTR for the 635 nm. Almost no significant SPTR difference is measured for 3mmx3mm MPPC's for 405 nm and 635 nm illumination (Figure 11). One arising question is where the high field area for the MPPC structure is located. It is evident the location of this region should have influence on the SPTR. If the high field area is deep within the device, then one would expect a more equal SPTR between red and blue light, as observed, with a measured difference of only about 20% at a maximum. Figure 8 shows some SPTR improvement with smaller pixel size of the MPPC's. This effect is likely due to the MPPC's capacitance.

IV. SUMMARY OF RESULTS.

A new setup for timing measurements at the picosecond level has been arranged at Fermilab. The core timing resolution of the amplifiers, discriminators and TAC/ADC combination is approximately 2 picoseconds. The temperature and bias voltage stability requirements to maintain a few picoseconds time resolution was discussed. We have made a study of single photoelectron time resolution (SPTR) for signals coming from Hamamatsu MPPC's and IRST SiPM's. We used a laser with blue (405 nm) and red (635 nm) heads for the study. The SPTR improved with the overvoltage increase. The SiPM's time resolution is inversely proportional to the square root of the number of photoelectrons. A simple model is proposed to explain the difference in the SPTR when illuminating the silicon photomultipliers by 405 nm and 635 nm laser light.

References

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2. Claudio Piemonte. Development of Silicon Photomultipliers at IRST. FNAL report, October 25th 2006
3. T. Ikoma, K. Hara. Temperature Dependence of Hole Saturation Velocity in Silicon. Appl.Phys., 3, 431, 1974.
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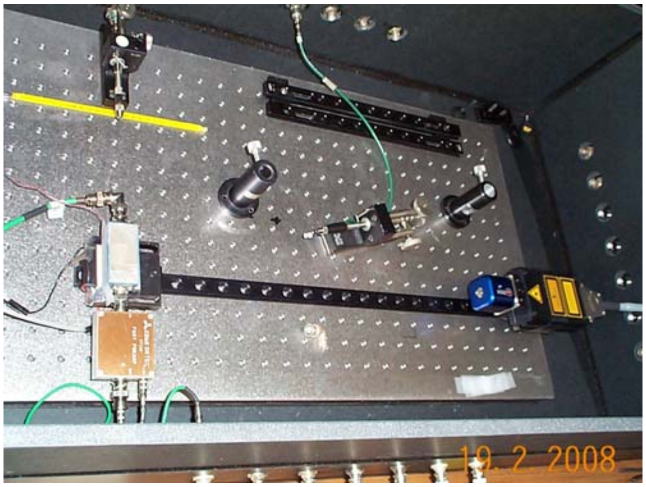

Fig. 1. Setup for the SiPm timing study. Optical table located in a dark box. Picosecond Laser (PiLas) head attached to rail on the right side, and SiPm box with Ortec preamplifier is on the left side.

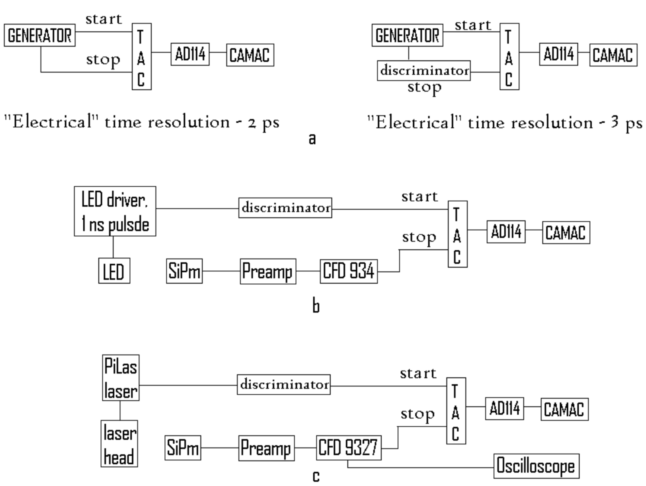

Fig. 2. Schematics of the SiPm readout. TAC – time – amplitude convertor, AD114 – amplitude digital convertor, LED – light emitting diode, CFD 934 – ORTEC constant fraction discriminator, PiLas – picosecond laser, SiPm – silicon photomultiplier, 9327 – 1 GHz ORTEC AMP & TIMING DISCRIMINATOR.

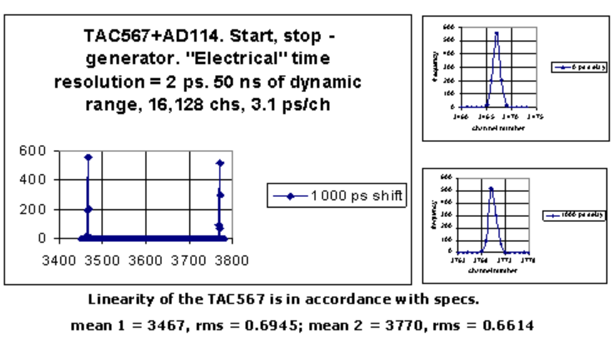

Fig. 3. "Electrical time resolution" is 2 ps. Time delay with and without additional 1000 picosecond delay in "stop" channel.

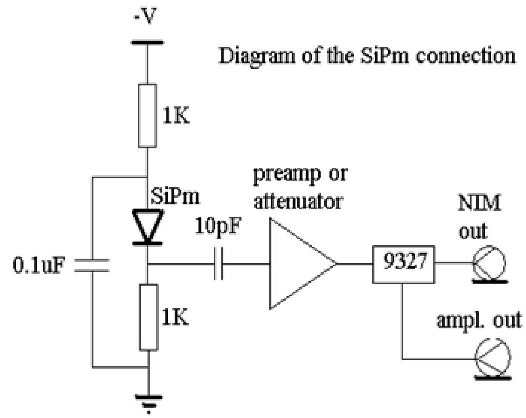

Fig. 4. Schematics of a SiPm signal's clipping.

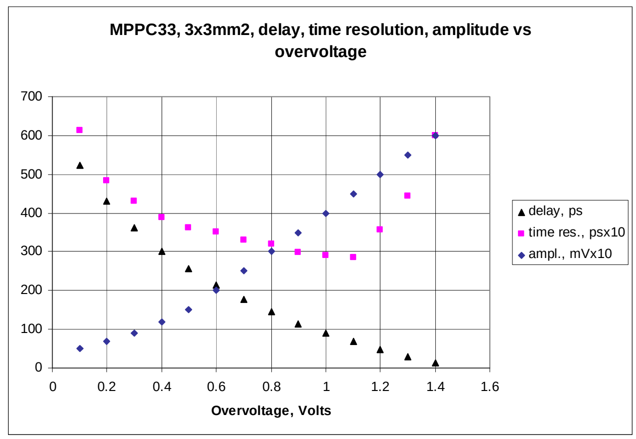

Fig. 5. The MPPC33 delay, time resolution and signal amplitude dependence on overvoltage.

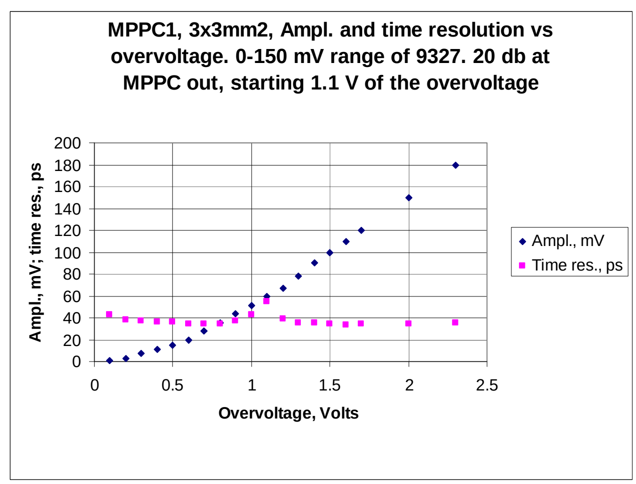

Fig. 6.. The MPPC 1 signal amplitude and time resolution dependence on overvoltage.

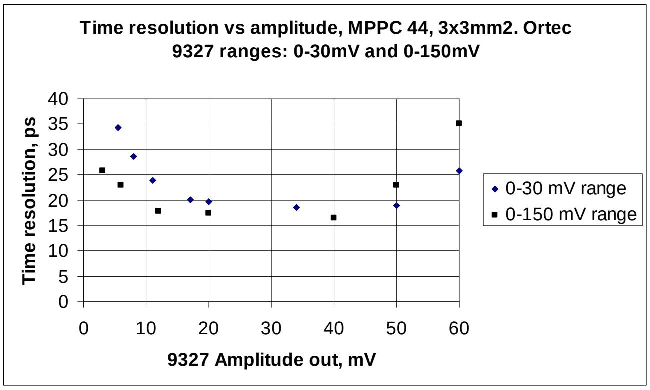

Fig. 7. The MPPC 44 time resolution dependence (in picoseconds) vs. the signal amplitude.

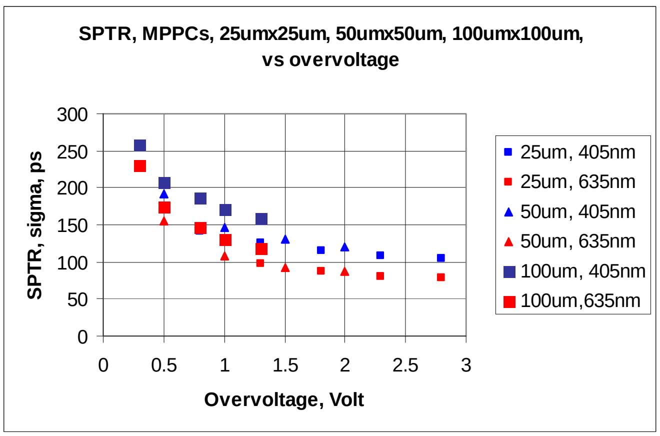

Fig. 8. SPTR of the MPPCs (1x1mm2 of the sensitive area) illuminated by the blue and the red PiLas light vs. overvoltage.

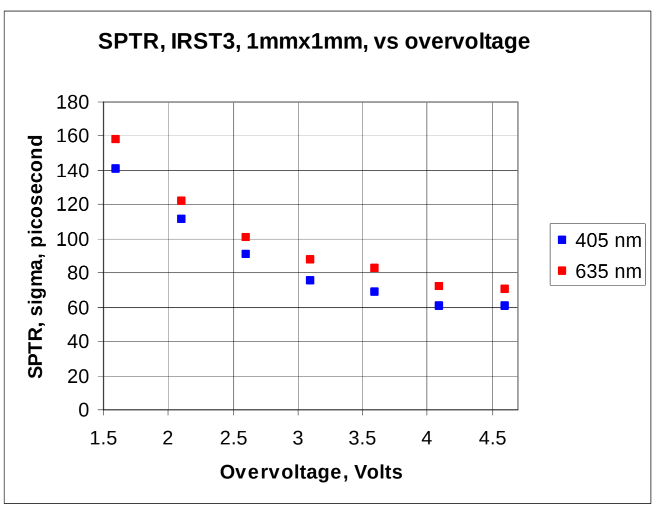

Fig. 9. SPTR of the IRST SiPm illuminated by the blue and the red light vs. overvoltage.

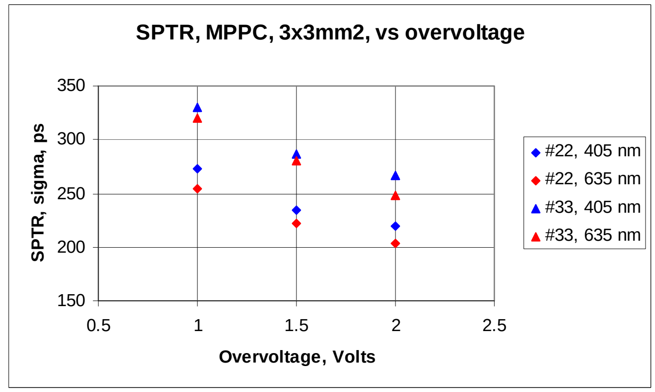

Fig. 10. SPTR of the two MPPCs samples illuminated by the blue and the red light.

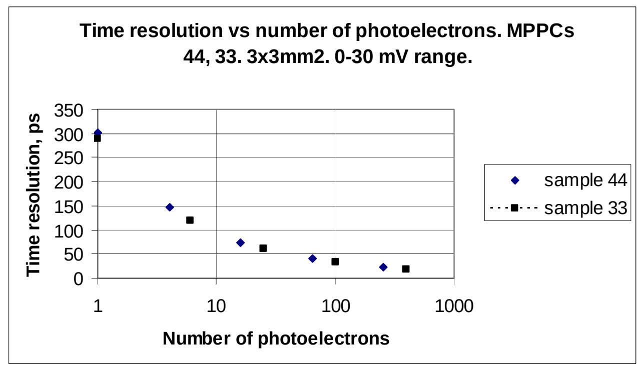

Fig. 11. Time resolution (sigma) of the two MPPCs samples in dependence on the number of the photoelectrons.

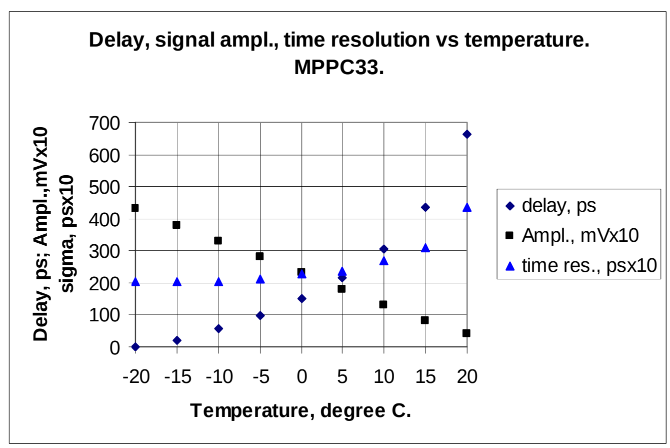

Fig. 12. The MPPC 33 delay, signal amplitude, and time resolution vs. temperature.

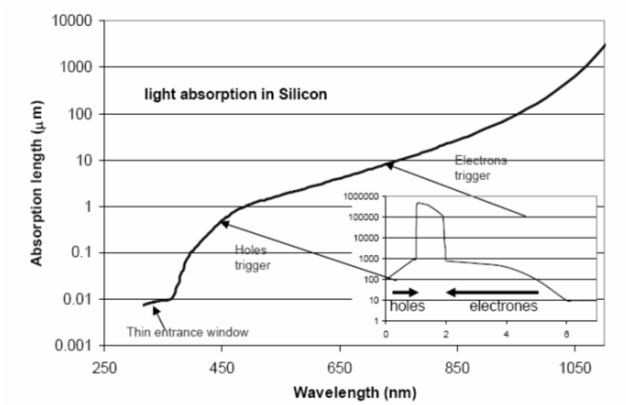

Fig. 13. Absorption length in silicon in dependence of photon's wavelength. Schematics of the electric field distribution inside of a SiPm (n+ side faced to the light, distance X from the SiPm surface is in microns) in the right bottom part of the drawing.

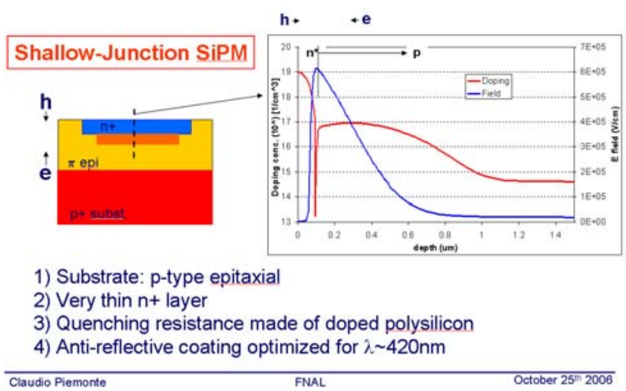

Fig. 14. Distribution of the electric field and doping inside of IRST SiPm (top right) and the shallow-junction SiPm structure (left side of the drawing). Data presented by C. Piemonte at Fermilab.