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Development of Picoseconds Time of Flight Systems in Meson Test Beam Facility at Fermilab

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Abstract

The goal of the work is to develop time of flight (TOF) system with about 10 picosecond time resolution in real beam line when start and stop counters separated by some distance. We name the distance as "base" for the TOF. This "real" TOF setup is different from another one when start and stop counters located next to each other. The real TOF is sensitive to beam momentum spread, beam divergence, etc. Anyway some preliminary measurements are useful with close placement of start and stop counter. We name it "close geometry". The work started about 2 years ago at Fermilab Meson Test Beam Facility (MTBF). The devices tested in "close geometry" were Microchannel Plate Photomultipliers (MCP PMT) with Cherenkov radiators [1]. TOF counters based on Silicon Photomultipliers (SiPms) with Cherenkov radiators also in "close geometry" were tested [2, 3]. We report here new results obtained with the counters in the MTBF at Fermilab, including beam line data.

1. Introduction

Typical TOF resolutions have been of the order of 100 picoseconds (ps) due to used "slow" detecting media, also as to "poor" single photoelectron time resolution (SPTR) of used photodetectors. New generation of solid state photomultipliers (SiPms) allows get much better time resolution because of fast avalanche spread (at the level of 100 ps) and therefore very high SPTR. As substitute for the SPTR is often used term transit time spread (TTS). Among the unique properties of the SiPms are perfect single photoelectron pulse height spectra, quantum efficiency up to 65%, non sensitivity to magnetic field, low amount of material when locating into a beam, very low applied bias voltage (at the level 30-70 Volts), sensitive area up to 5x5 mm2, good enough radiation stability. Another advantage is that a lot of company already involved into SiPms production [4]. The dependence of SiPms parameters on temperature and bias voltage can be overcome by applying standard technique [5]. The SiPM, Hamamatsu (Multi Pixel Photon Counters or MPPCs)

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could be an option for upgrading capabilities of TOF systems. Unique properties reveal the SiPms produced by STMicroelectronics, Catania, Italy [6], which are also good candidates. We will present test beam results obtained with both types of SiPms. Another type of very promising photodetectors are Photek MCP PMTs. Bench test of the devices and test beam data are also presented.

2. Photek 240 and Photek 210 study

The setup at the Silicon Detector Facility at Fermilab to study photodetector timing at picoseconds level has been already described [2-5]. The same setup was used to study timing properties of the Photek 240 [7] and Photek 210 MCP PMTs. The "2" stands for 2 micro channel plates, the "40" and "10" means 40 mm and 10 mm diameter photocathode. The Photek 240 SPTR which taken from specifications was 100 ps, a parameter that we investigated more precisely. The input window material is fused silica with extended UV quantum efficiency (Fig. 1), the window thickness is 9 mm. The MCP pore size diameter is 10 um. The Photek 210 window thickness is 5.6 mm and pore size diameter is 3 um. Photek 240 was mounted inside a dark box and was illuminated by 405 nm PiLas laser light. The intensity of the laser light was changed by optical filters also as by TUNE setting of the laser. Bertan (model 380N) was used as the high voltage (HV) unit with 10 kV maximum HV. The PiLas laser trigger out signal was used as a start signal and the Photek 240 signal passed through an Ortec 9327 unit ((constant fraction discriminator (CFD) with preamplifier in the single unit)) was used as the stop signal. A time to amplitude converter TAC 567 plus AD114 pulse height digitizer was used to measure the time interval between start and stop signal with 2 ps of the "intrinsic electrical time resolution". The AD114 is a 14 bit ADC with 16 K of channels, 3.1 ps per channel. The Le Croy 2249 ADC was used to measure the Photek 240 pulse height distribution. This ADC has about 1000 channels with 250 fC per channel. We used Ortec 120 C (noninverting, gain of 20) in series at the input of the ADC for the single photoelectron pulse height measurements.

We planned to measure SPTR as a function of the high voltage (HV) and a position of the spots illuminating the photocathode. The SPTR was measured in the units of standard deviation (sigma) of the fitted Gaussian distribution (everywhere below). Another parameter to measure was the dependence of the time resolution on the number of photoelectrons. The light filters allowed attenuate laser light in a few decades of dynamic range. To insure the single photoelectron regime we required more than 90% pulses taken by 2249 ADC resulted in pedestal events. Typical oscilloscope trace (red) of the Photek 240 pulses in a single photoelectron mode and a single photoelectron pulse height distributions are shown in Fig. 2 and Fig. 3. The trace was taken by Tektronix TDS 3054B oscilloscope with 500 MHz bandwidth. In the Fig.3 one distribution corresponds to whole photocathode (PC) illumination (the full 40 mm diameter (a), and another one to a 5 mm optical hole in the center of the photocathode (b). SPTR dependence on HV is shown in Fig.4. The two sets of points correspond to a 1 mm diameter "open hole" in the center of photocathode and then shifted aside by 18 mm. Our "working HV" was in the range of 4.4 – 4.9 kV based on this data. The SPTR of the Photek 240 worsens below 4.5 kV due to the used frontend electronics. The output signal is outside the best timing range of the Ortec 9327 CFD for that voltage. Red and blue squares correspond to the PC's center illumination and 18 mm away from the center. The illuminated area is 1 mm diameter. Typical SPTR distributions are presented in Fig. 5 (a, b correspond to the whole PC illuminated and 5 mm area in center of the PC illuminated).

We also studied shifts in the mean value of the SPTR distribution depending on the position of the spot of the illumination on the PC. The open hole of 5 mm diameter, displaced by 16 mm from center was moved to 3, 6, 9, 12 clock positions around the center. Corresponding SPTR spectra are presented in Fig. 6. We observe no significant dependence on the position, i.e. the photocathode is very isochronous.

We present the Photek 240 dependence of the time resolution on the number of photoelectrons in Fig. 7. The diamonds and squares correspond to illumination of 5 mm area in the center of the PC and whole PC. The number of photoelectrons was changed by optical filters applied to the output light of the PiLas laser head. We used attenuators between the Photek 240 output and the 9327 input depending on the amplitude of the signal of the Photek 240 to accommodate the signal in the best timing range of the 9327. We calculated the number of photoelectrons by measuring the width of the pulse height spectra. Another approach was to normalize the Photek 240 output signal on the single photoelectron amplitude. We estimate the accuracy of the first method to be about 10%. The time resolution improves as inverse square root of the number of photoelectrons when the number is more than four. But an overall level of the resolution is about two times worse than provided by an extrapolation from the single photoelectron result. This is different from our previous SiPms study where we observe clear inverse square root dependence in whole range, starting with single photoelectron [2].

We learned that time resolution of silicon photomultipliers depends on the signal amplitude when using the 9327 Ortec CFD. The same study was repeated for the Photek 240. We present the dependence of the time resolution on the 9327 Ortec input amplitude in Fig. 8. The 9327 input amplitude was changed by attenuators. These data were taken with about 80 photoelectrons.

We studied the Photek 210 timing properties in the same setup. The SPTR spectra were taken (Fig. 9). The better SPTR was obtained if to compare with Photek 240 (sigma of the fitting Gaussian distribution about 9 channels instead of 11), but with more noticeable tail. This could be addressed to photoelectron recoils from top MCP surface [1]. The trace of the Photek 210 output signal taken with fast scope (low illuminating light level) presented in Fig. 10.

3. MPPC and STM bench test main results

We described already main bench test study of SiPms [2-5]. Among the main results obtained earlier were dependences of SPTR for different SiPms as functions of overvoltage (difference of bias and breakdown voltage) and wavelength of an illuminating light. SPTR were improved with overvoltage increase and reveal different dependences on wavelength related with used silicon structure. We have to highlight here the results which we consider as new ones. We got SPTR for MPPC Hamamatsu, 3x3 mm^2 of sensitive area at the level of 120 – 150 ps, (overvoltage was up to 2.2 Volts). This is better than we had before for another delivered samples. We present MPPC SPTR in Fig. 11, a. Another type of SiPms tested produced by STMicroelectronics, Catania, Italy. The STM were thoroughly described in [6]. For the STM (3.5x3.5 mm^2 of the sensitive area) we got about the same SPTR value with 5 V of overvoltage (Fig. 11, b). The STM traces of signals with low light level illumination presented in Fig. 12. The pulse height distribution was measured at a higher light intensity (Fig. 13). The device was biased at 3.5V of the overvoltage and illuminated by 405 nm light. An Ortec VT120 preamplifier with gain 20 was used to amplify the signals and a Lecroy 2249 Analog to Digital Converter (ADC) to measure the charge integrated for a fixed gate time of 50 ns. About 30 photoelectrons peaks are clearly separated in the spectrum.

4. Test beam results

We used the test beam facility in the Meson Detector Building at Fermilab. The beamline can be tuned for 120 GeV/c protons from Fermilab’s Main Injector, or the beam can be brought onto a target providing lower momentum secondary beams.

As in the bench tests, the signals from detectors under test were delivered to the 9327 Ortec CFD, followed by the time measurement of the TAC567/AD114 combination. A single ADC count in the AD114 corresponds to 3.1 ps, total amount of channels about 16,000 with total dynamic range of 50 ns. The schematic diagram of the test beam is shown in Fig. 14. A, B and C are detectors based on MCP PMTs or SiPms. This is the setup with “close geometry” of the A, B, C, which is different from “real” time of flight system, when start and stop counters must be placed on some “big” distance between them. The trigger counter was based on two small size PMT looking at a single scintillator with 2x2 mm^2 transverse size, 16 mm along the beam. The counter was located on a movable stage allowing it’s alignment with 30 μm accuracy The “veto” counter had “octagon shape”, 10 cm side to side size of scintillator, with 7 mm diameter hole in the scintillator geometrical center. The scintillator was viewed by 2 photomultipliers from opposite sides. The dark box with G10, acting as an RF shielding was used to accommodate counters under test, trigger and veto counters (Fig. 15). Sometimes C counter was placed outside of the dark box. The readout schematic is shown in Fig. 16. The only A and C detectors are shown here for simplicity.

We had 2 runs of TOF study in beamline. First one took place on May – June 2009 and second one was on March 2010. We will describe the results obtained on 2009 test beam.

Let’s start with Photek MCP PMT study on the beam. Data were taken on May – June 2009 run. We located A, B, C inside of the dark box. 120 GeV/c protons passed through all 3 MCP PMTs, Photek 210 (A, B) and Photek 240 (C). All three input windows of the photodetectors were positioned normally to the beam and served as Cherenkov radiators.

The measured values were three time differences T_{12}=tA-tB, T_{13}=tA-tC and T_{23}=tB-tC and pulse height distributions of A, B and C. Suppose the intrinsic time resolution in terms of sigma of corresponding Gaussian distribution of the detectors are I, II, III. We neglect "electrical time resolution" of the readout. Our SiDet and previous test beam data shows it is up to 2-4 ps.

We have 3 equations with 3 variables:

$I^2 + II^2 = T_{12}^2$ (1)

$I^2 + III^2 = T_{13}^2$ (2)

$II^2 + III^2 = T_{23}^2$ (3),

The result of unfolding will be:

$I = \mathrm{sqrt}\ \{(T_{12}^2 + T_{13}^2 - T_{23}^2)/2\}$

$II = \mathrm{sqrt}\ \{(T_{12}^2 + T_{23}^2 - T_{13}^2)/2\}$

$III = \mathrm{sqrt}\ \{(T_{13}^2 + T_{23}^2 - T_{12}^2)/2\}$

We got 12.0 ps for both Photek 210 and 7.7 ps for Photek 240 after applying these equations to experimental data. T_{12}, T_{13} and T_{23} are sigma of Gaussian distribution fitting to the measured time spectra. Soft amplitude cuts (about 10%) and time-walk correction to the CFD (Ortec 9327) was applied. The results clearly indicate that CDF's time-walk correction improve time resolution by about 10%. [1]. We got 18 ps time resolution if to consider A and B as one start counter when A and B were Photek 210, both with quartz radiators, located at Cherenkov angle, about 48^0 to the beam (Fig. 17), The quartz radiators when used were optically coupled with photocathode by UV transparent optical grease (Dow Corning). Note that such configuration of the start counter allows eliminate time jitter due to 2 mm of the horizontal size of the trigger counter. 2 mm corresponds to about 10 ps of the eliminated time jitter.

We got 35 ps of time resolution when using MPPC Hamamatsu, 3x3 mm2, 50x50 um2 pixel size, 3600 pixels with 6 mm of length quartz radiator, normal incidence. We used the MPPC as A counter [3] in the case. The time spectrum presented in Fig. 18. The MPPC with Cherenkov radiator was the start counter and Photek 240 (normal particle incidence) was the stop counter in the measurement.

These measurements allowed us to define the time jitter of each of the counter and to choose the best option for the last measurement. In that case the Photek 240 as a stop counter was located by about 8.7 meters (base distance between start and stop counter) downstream from the start counters. The start counters, (two Photek 210 with the quartz bars as Cherenkov radiators, fig.17) were placed inside the dark box. We used the best front end configuration (e.g. the 9327 CFDs were placed close to Photek MCP PMTs). The measured value was a sum of two time intervals (each of them is the time difference between start and stop counters) divided by two. The sum eliminates the time spread due to the beam size in the horizontal direction. The result obtained with positive charged particles beams at 4, 6, 8 GeV/c momentum is presented in Fig. 19. The dominant peak arbitrarily placed at the time equal to zero (horizontal scale is in picoseconds) is mainly due to positrons and pions. The time of flight difference between muons, pions, kaons, protons and positrons for 4, 6, 8 GeV/c momenta at different base distances are presented in table 1. The measured TOF time resolution was 24 ps.

Now we will describe the results obtained on March 2010 test beam. We received one more Photek 240. We installed two Photek 240 and one Photek 210 in line. Same electronic used, beam momentum was 120 GeV/c with normal incidence to all of 3 counters (Photek 240, A, B) and (Photek 210, C). The measured time spectra T_{12}=tA-tB, is shown in Fig 20. Soft amplitude cut (10% of cutting events) and slew correction applied to raw data. The result was about 10% of the time resolution improvement due to the procedure. We can estimate the time resolution of the Photek 240, A as 7.7 ps and Photek 240 B as 9.4 ps. The Photek 240 B had slightly worse time resolution, what was in accordance with our bench test measurements. No correction on “electronics” time resolution applied.

Another measurement was done with two Photek 240. 5 quartz bars were optically coupled with the Photek 240 PC (Fig. 21). A and B counters were Photek 240, both with 5 quartz radiators (5x5x90 mm^3), located at Cherenkov angle, about 48^0 to the beam (Fig. 22). The beam passed through all 5 bars in each counter. We obtained 11.2 ps/counter time resolution if to consider A and B as one start counter.

We replaced Photek 210 by MPPC (3x3 mm^2) with Cherenkov radiator 3x3 mm2 of the cross section, 7 mm of the length for normal particle incidence. Fig. 23 presents measured timing spectra with 7 mm of the radiator’s length. We performed the next measurement with 30 mm of the radiator length and obtained 16.3 ps time resolution (Fig.24, a). If to subtract the deposit of the time jitter introduced by Photek 240 (7.7 ps) the time resolution of the MPPC with the radiator will be 14.4 ps/MPPC. Measured amount of photoelectrons was about 60 (Fig. 24, b).

We measured also STMicroelectronics SiPm time resolution [6] with 3.5x3.5 mm^2 sensitive area and 3x3x30 mm^3 fused silica quartz radiator. We obtained about 20 ps/STM time resolution. This is slightly worse than MPPC result, what is mostly due to the lower photo detection efficiency (PDE) of the STM. Nevertheless STM is already revealing some unique properties and PDE can be improved with geometrical fill factor increase [6]. The best time difference measured between STM and MPPC was 29 ps (Fig. 25). This is good indication to use SiPms for positron emission tomography (PET), [8].

The next TOF measurement was done with the “base” distance 7.12 meters between start (Photek 240, A) and stop (Photek 240, B) counters, normal particle incidence. The beam momentum was 8 GeV/c. The measured TOF time difference between particles is shown in Fig. 26. The calculated time of flight differences between muons, pions, kaons, protons and positrons at 8 GeV/c momentum at the base distances are presented in table 1. The measured TOF resolution was 14.5 ps for “light” particles peak (mostly positrons and pions). Some worsening of the time resolution (if to compare with 12.4 ps in “close” geometry) can be addressed to different particles contained in the “light” particles peak, beam divergence, etc. The calculated and measured results are in very good consistency.

One more TOF measurement was done with MPPC (30x3x3 mm^{3}of fused silica, normal incidence, counter C) and Photek 240 (counter B). Base distance was 7.21 meters. Measured time interval was T_{23}=tC-tB (the case corresponds to inverse time scale). The result presented in Fig. 27.

5. Discussion

The measured SPTR of the Photek 240 is about 40-45 ps and does not depend on the position of the PC illumination. Note that the diameter of the PC is 40 mm. The SPTR mean time shift is less of 3.5 ps for different positions of the PC illumination, which enables one to locate several Cherenkov radiators on the same phototube and maintain excellent timing. We measured almost no time change in signal appearance across the 40 mm diameter of the PC. This is due to special “isochronous” anode structure developed by the factory. We used that fact when placing 5 quartz fused silica bars on both Photek 240 photocathodes in the measurement described above.

We usually started beam test measurements with normal positioning of photodetectors with respect to the beam. This allowed us to calibrate tested devices, have good comparison with previously obtained data, check the “electronic readout”, which should be about 3 ps, etc.

The estimated time jitter (sigma of the fitting Gaussian spectrum) of the Photek 240 for normal incident particles is 7.7 ps/device (this is without correction on “electronic” time jitter). The input window thickness of the 240 is 9 mm, The MCP’s pore diameter is 10 um. A charged particle passing through the PC window with normal incidence produces about 70-80 photoelectrons or 8-9 photoelectrons per mm. This large number is mostly due to the high quantum efficiency extended into UV (Fig. 1).

For the Photonis MCP PMT [1] we had about 4 photoelectrons per mm of input window as radiator, a factor of 2 less than for the Photek 240. So the Photek 240 could be considered as the stop TOF counter producing the best timing signal, because usually the amount of material does not matter for the stop counter.

The measured SPTR of the Photek 210 is about 33 ps. Photocathode diameter is 10 mm, pore size is 3 um. The input window thickness of the 240 is 5.6 mm. The best obtained test beam time resolution is 12 ps/device. It is worse than for Photek 240 due to less thick window. The time resolution measured on the beam line was 14.5 ps when two Photek 240 used as start and stop counters with “normal” particle incidence. Some worsening of the time resolution (if to compare with 12.4 ps in “close geometry”) can be addressed to different particles contained in the peak we used to extract the sigma, beam divergence, etc. The best time resolution for the Photek 240 was 7.7 ps/device.

We obtained 16.3 ps time resolution for MPPC with 3x3x30 mm3 of fused silica quartz radiator as start counter and Photek 240 as stop counter. This corresponds to 14.5 ps/MPPC time resolution. The time resolution improved with radiator’s length increase. We observe the inverse square root behavior of the time resolution vs. number of photoelectrons. This should be true for fixed light pulse shape. In our case the number of photoelectron increase is partially due to increase of a pulse duration as far as we understand. We plan to simulate the results to clarify this effect. Measured time resolution of the STM with the same size radiator (3x3x30 mm^3) is 20ps/STM.

We have to note that the TOF system based on Cherenkov light detection has a threshold dependent on particle’s momentum (Fig. 28). This is the difference with the case when scintillation light detected.

Acknowledgements

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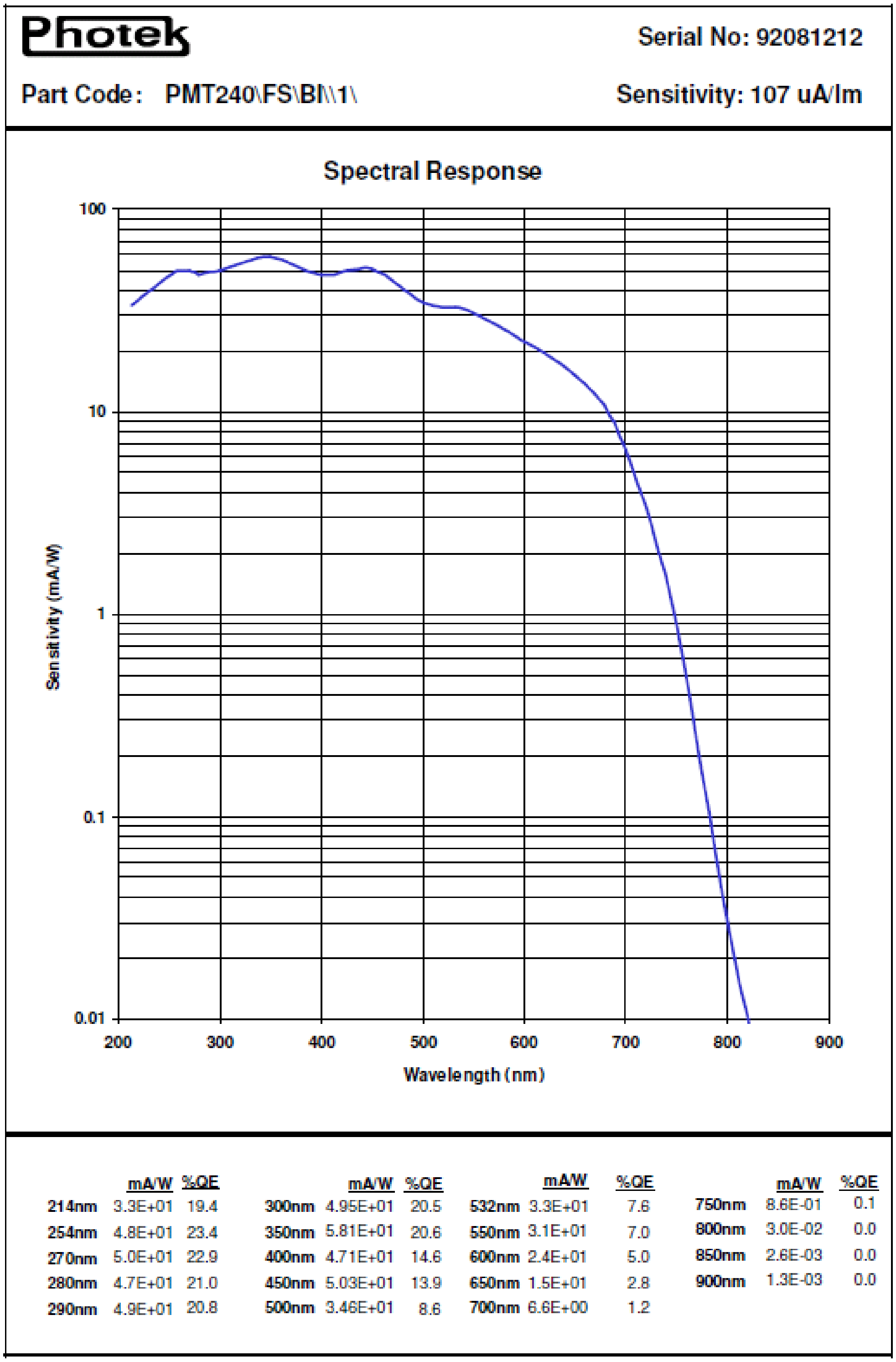
8. http://en.wikipedia.org/wiki/Positron_emission_tomography



Photek

Serial No: 92081212

Part Code: PMT240\FS\BI\\1\

Sensitivity: 107 uA/lm

Spectral Response

	mA/W	%QE		mA/W	%QE		mA/W	%QE		mA/W	%QE
214nm	3.3E+01	19.4	300nm	4.95E+01	20.5	532nm	3.3E+01	7.6	750nm	8.6E-01	0.1
254nm	4.8E+01	23.4	350nm	5.81E+01	20.6	550nm	3.1E+01	7.0	800nm	3.0E-02	0.0
270nm	5.0E+01	22.9	400nm	4.71E+01	14.6	600nm	2.4E+01	5.0	850nm	2.6E-03	0.0
280nm	4.7E+01	21.0	450nm	5.03E+01	13.9	650nm	1.5E+01	2.8	900nm	1.3E-03	0.0
290nm	4.9E+01	20.8	500nm	3.46E+01	8.6	700nm	6.6E+00	1.2			

Fig. 1. Photek 240 quantum efficiency versus wavelength.

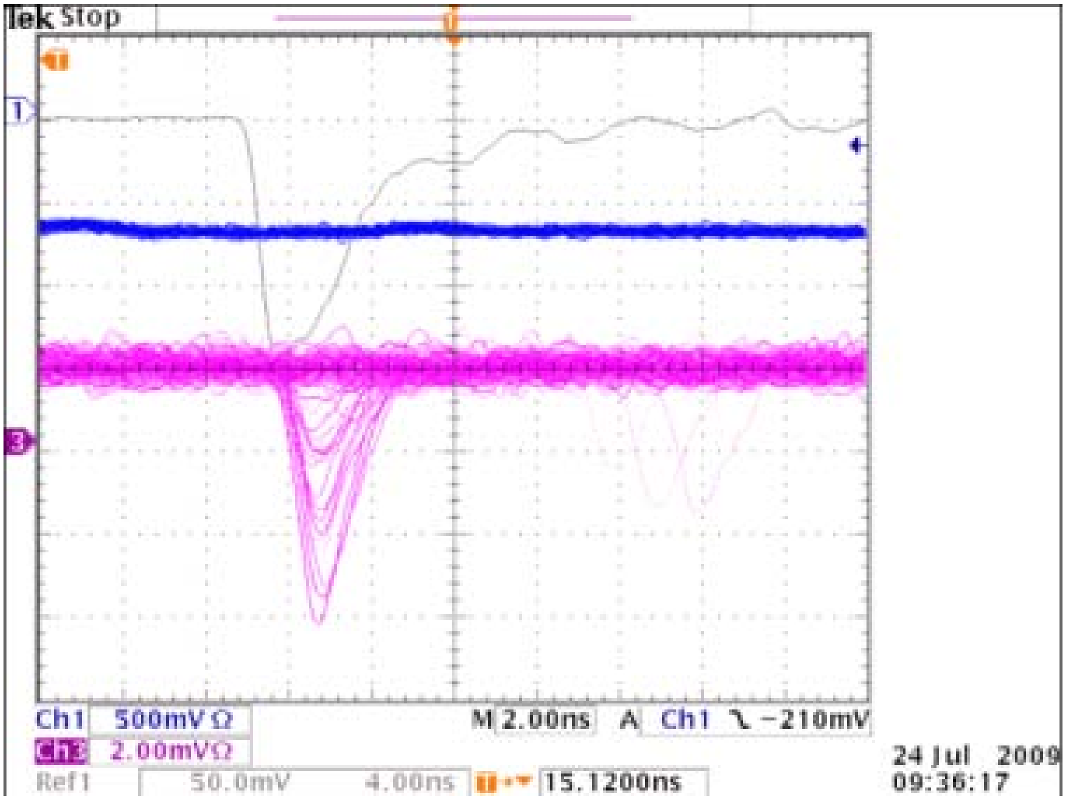


Fig. 2. Oscilloscope traces (red) of the Photek 240 signals corresponding to single photoelectrons.

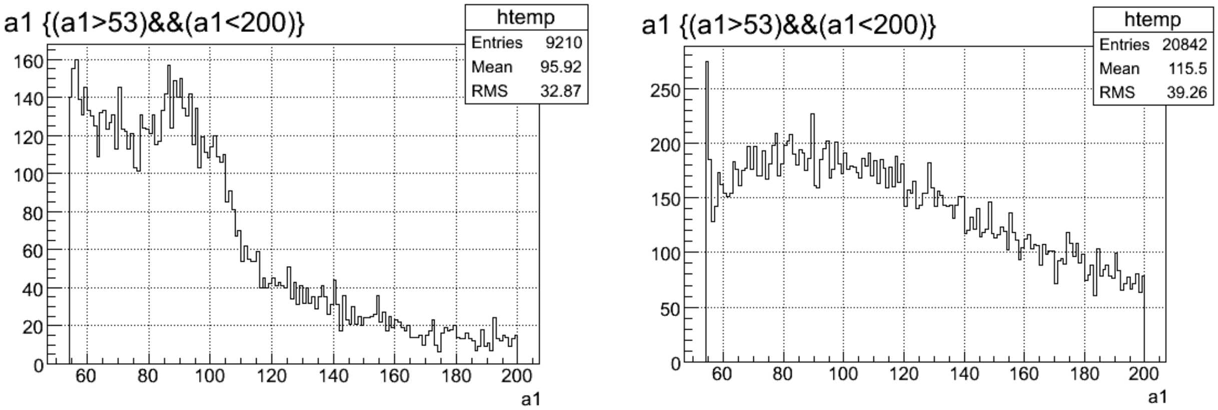


Fig. 3. Single photoelectron pulse height distributions (a1 is a channel number). A cut to exclude pedestal events was applied (a1>53). One distribution (a) corresponds to whole 40 mm diameter photocathode (PC) illumination, and the other (b) to a 5 mm diameter area in the center of the photocathode.

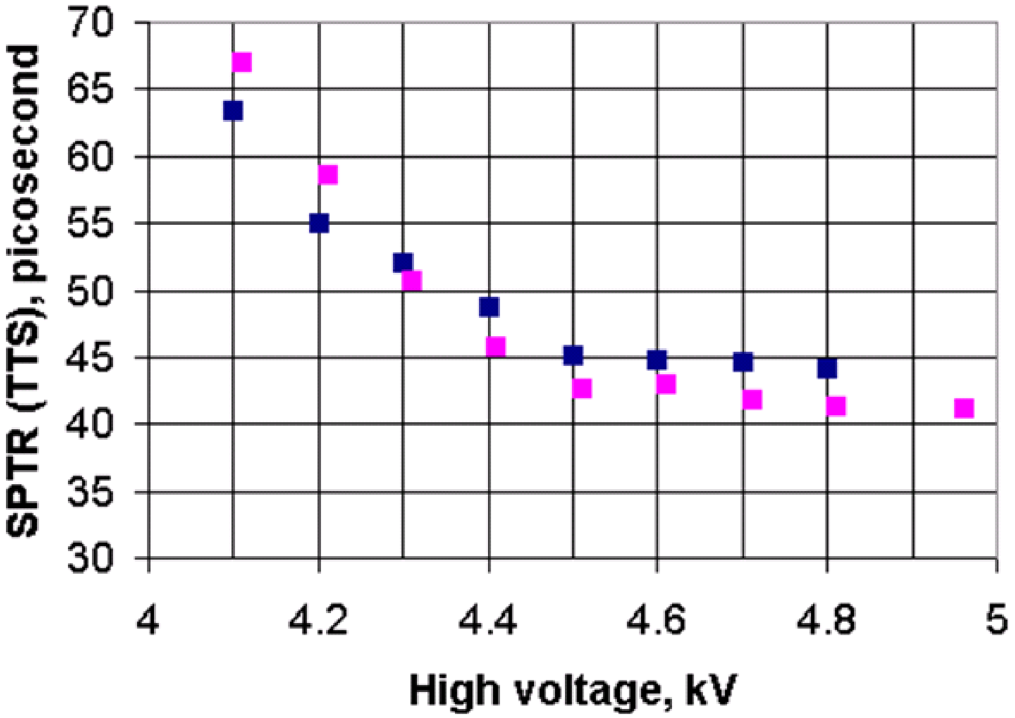


Fig. 4. SPTR vs HV. Red and blue squares correspond to the PC's center illumination and 18 mm away from the center. The illuminated area is 1 mm diameter.

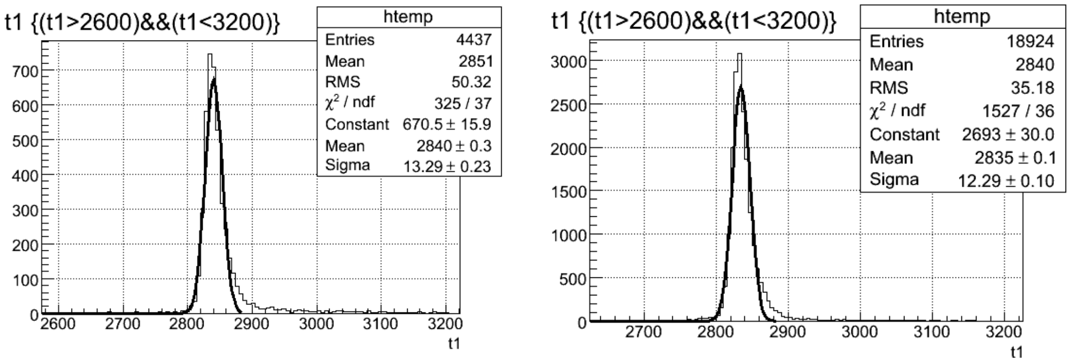


Fig. 5. SPTR for the whole PC illuminated and 5 mm in the PC center illuminated (a, b).

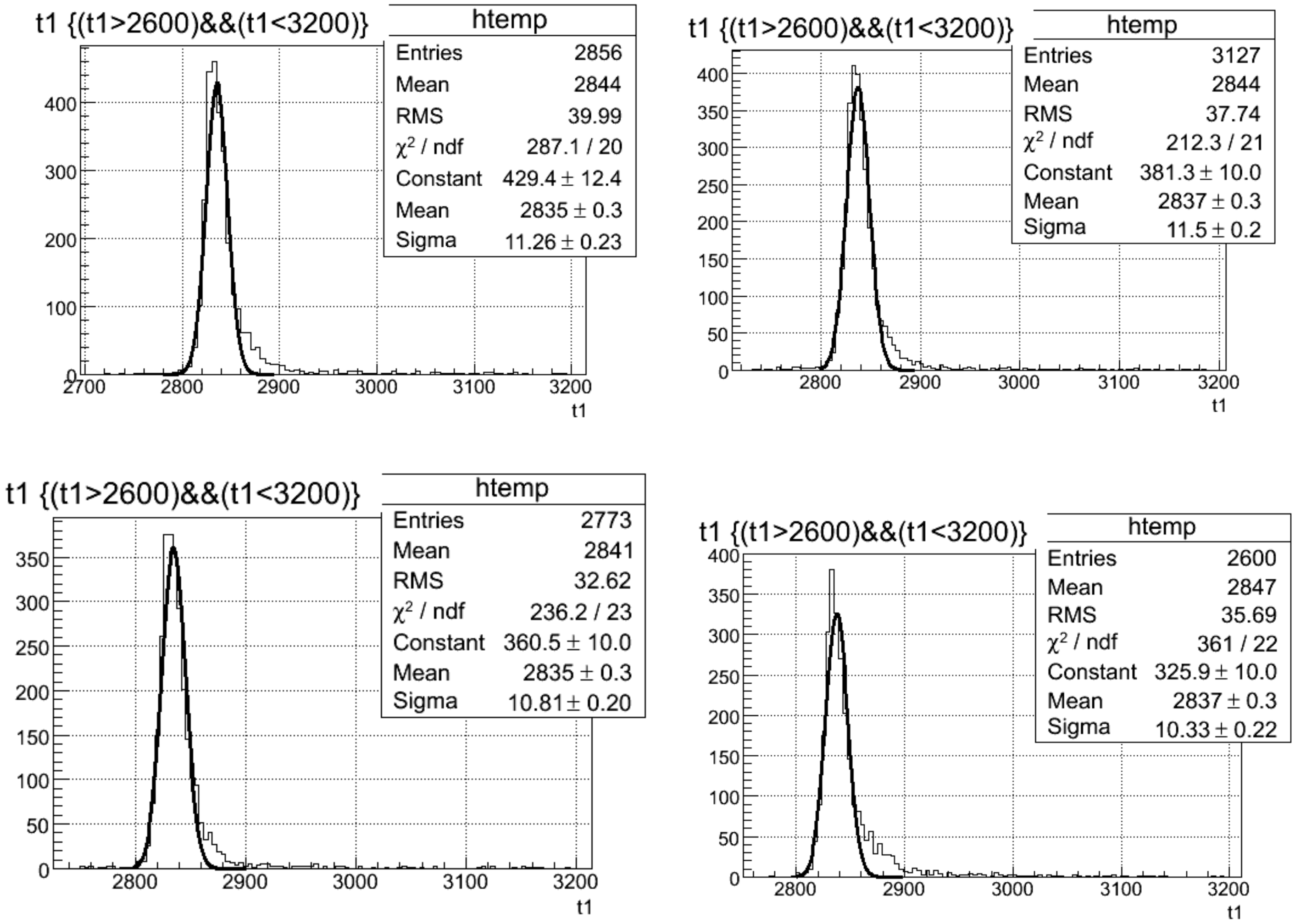


Fig. 6. SPTR distributions for different illuminated positions on the PC. (see text).

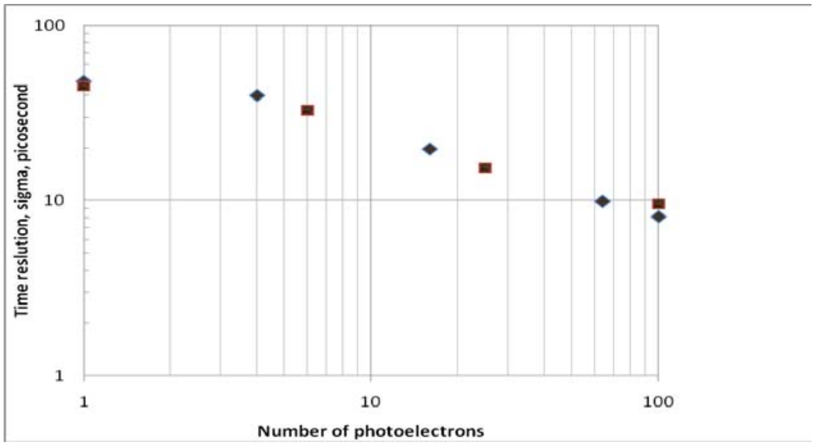


Fig.7. Time resolution (sigma) of the Photek 240 as function of the number of photoelectrons. The data are from the test bench.

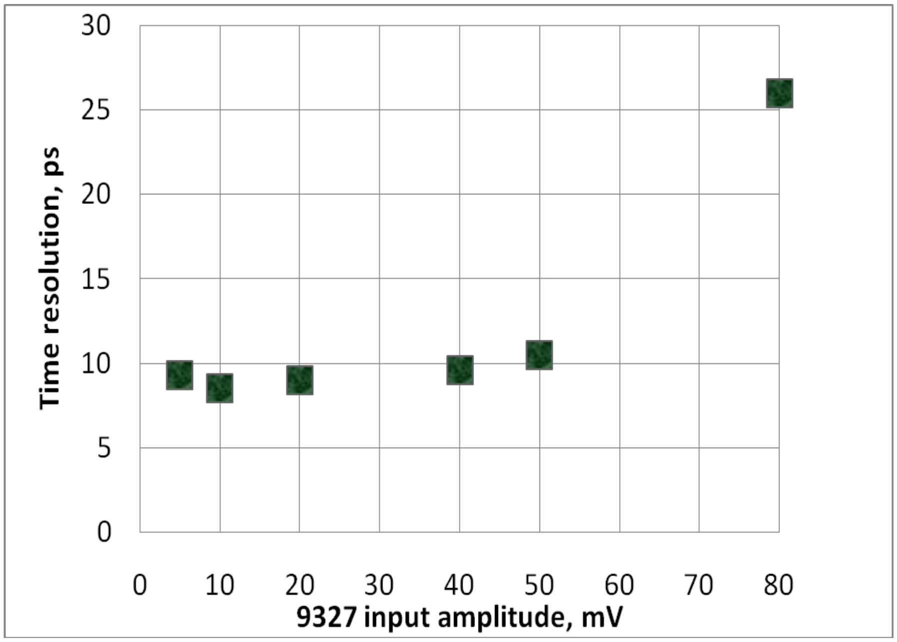


Fig. 8. The Photek 240 time resolution as a function of the signal amplitude.

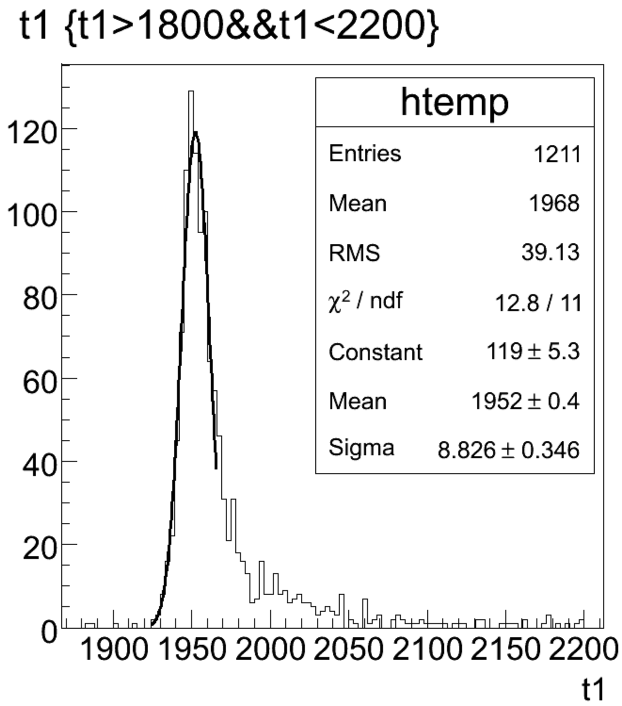


Fig. 9. SPTR for the Photek 210, 10 mm diameter PC illuminated.

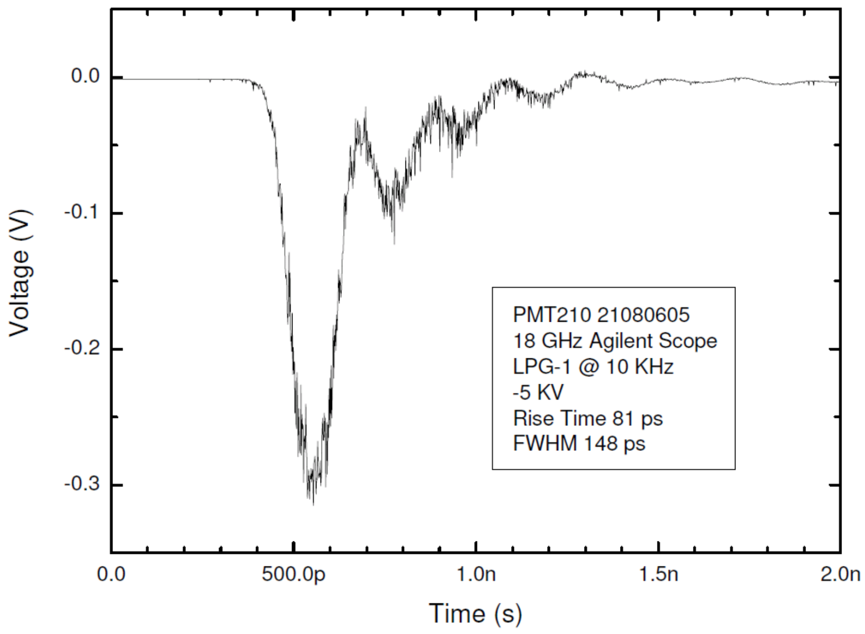


Fig. 10. Oscilloscope (18 GHz Agilent) trace of the Photek 210 signal.

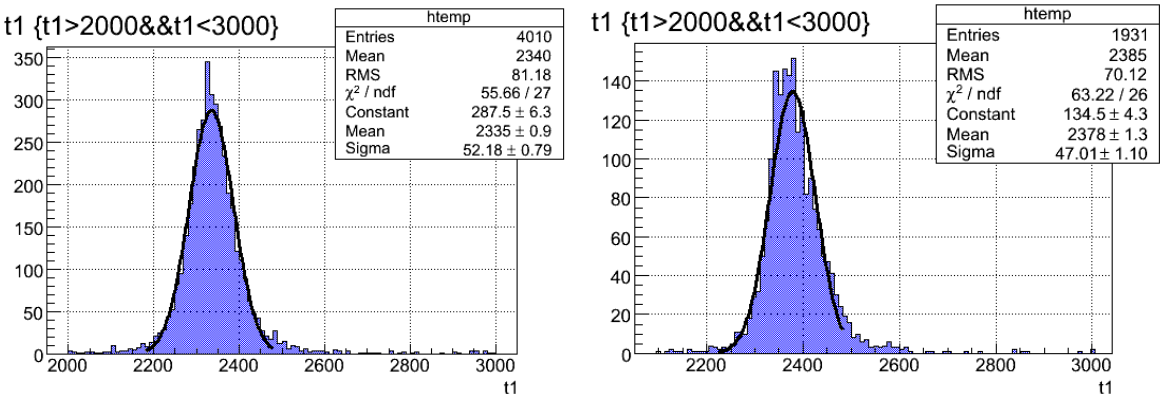


Fig. 11. SPTR's of MPPC (3x3 mm^2 sensitive area), left and SPTR of STM (3.5x3.5 mm^2 sensitive area), right (see text for more details).

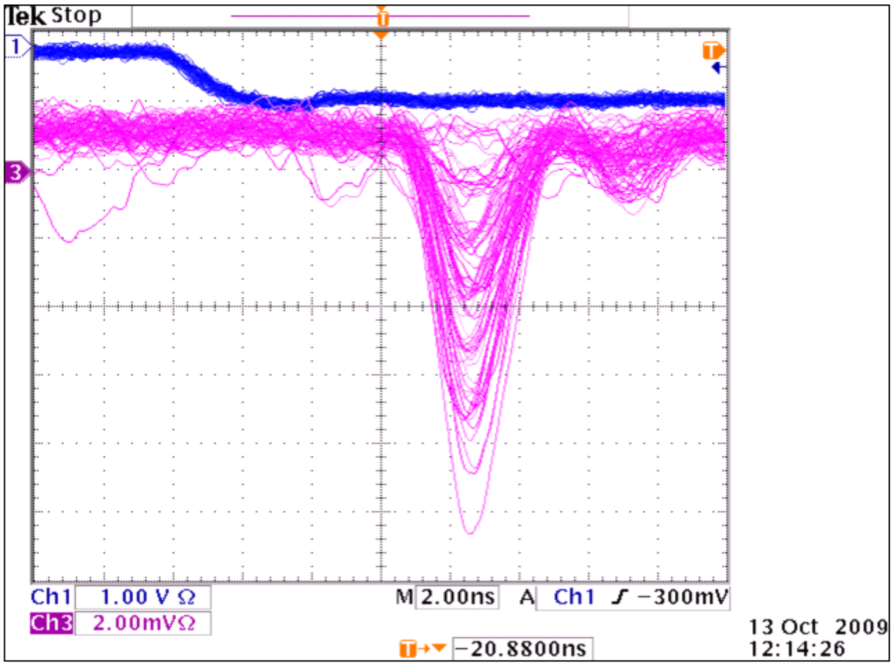


Fig. 12. Snapshot of STM output signal with a few photons illumination. The signal is clipped to fit the Ortec 9327 input signal requirements.

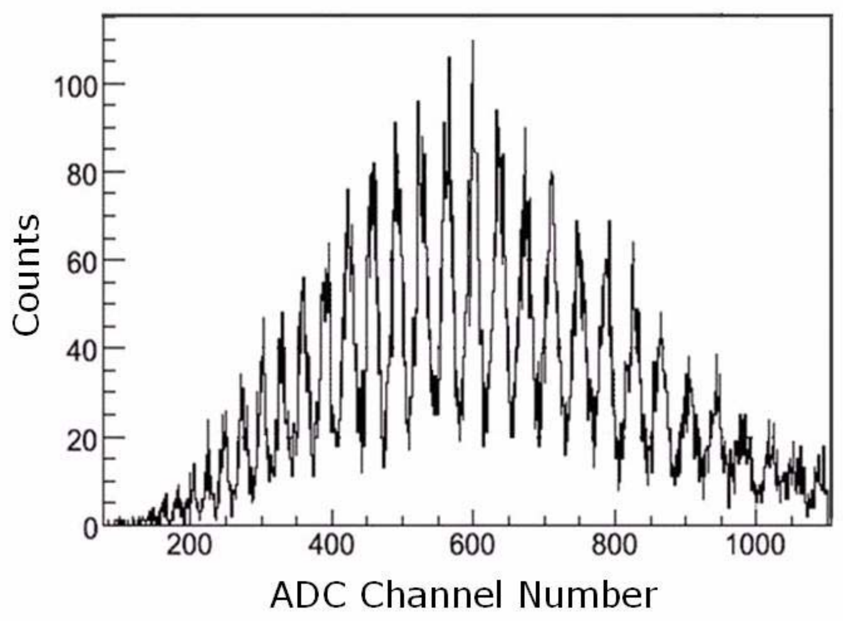


Fig. 13. Single photoelectron spectrum from a 3.5x3.5 mm^2 STM biased at 3.5 V overvoltage and illuminated by laser light at 405 nm. The charge was integrated for a fixed gate time of 50 ns (250 fC per ADC channel). About 30 photoelectrons peaks are clearly separated in the spectrum. ADC channel number 600 corresponds to 17 photoelectrons.

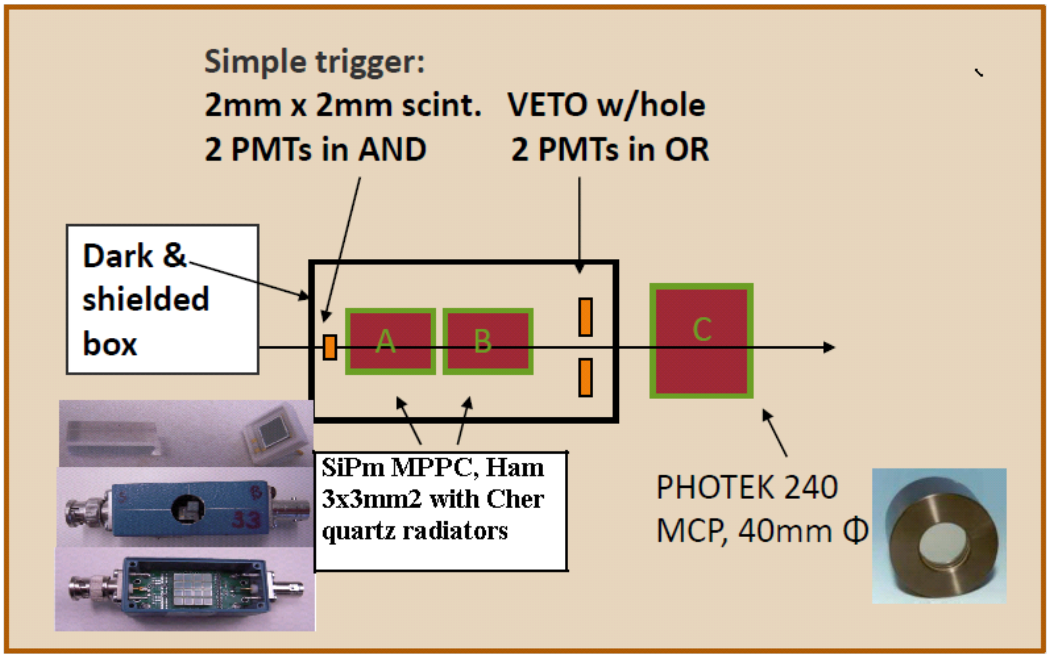


Fig. 14. The schematic diagram of the test beam.

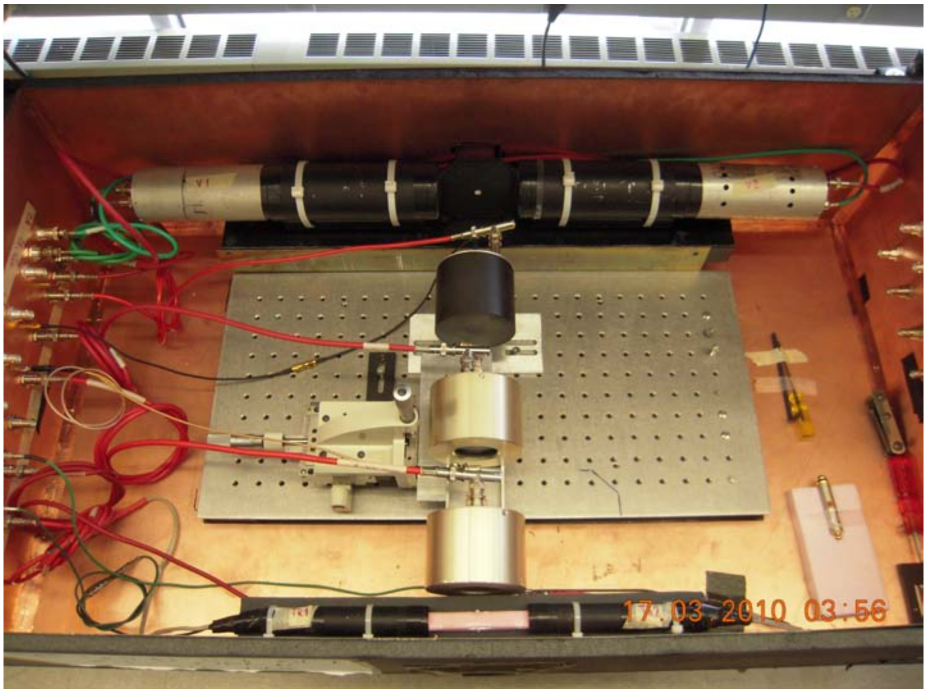
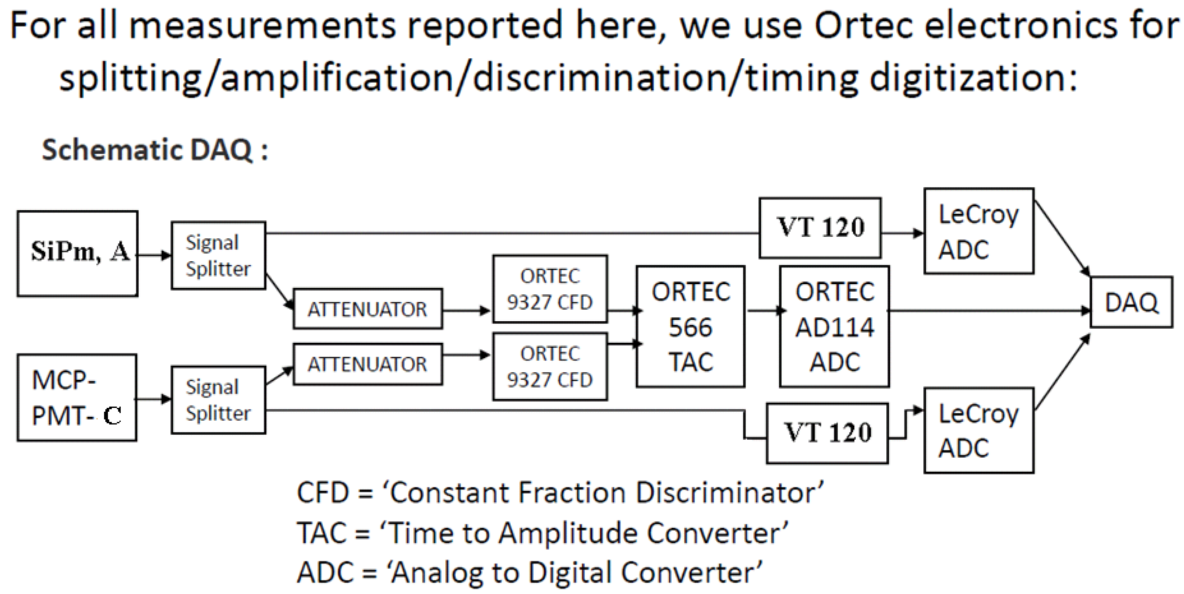


Fig. 15. The setup at the beam, 120 GeV protons. Two Photek 240 PMTs and one Photek 210 were placed on the optical table (normal incidence). A 2mm x 2 mm trigger counter is located upstream, and a veto counter (a scintillator paddle with a 7 mm diameter hole) is downstream.



For all measurements reported here, we use Ortec electronics for splitting/amplification/discrimination/timing digitization:

Schematic DAQ :

CFD = 'Constant Fraction Discriminator'
TAC = 'Time to Amplitude Converter'
ADC = 'Analog to Digital Converter'

Fig. 16. Simplified schematic of the readout.

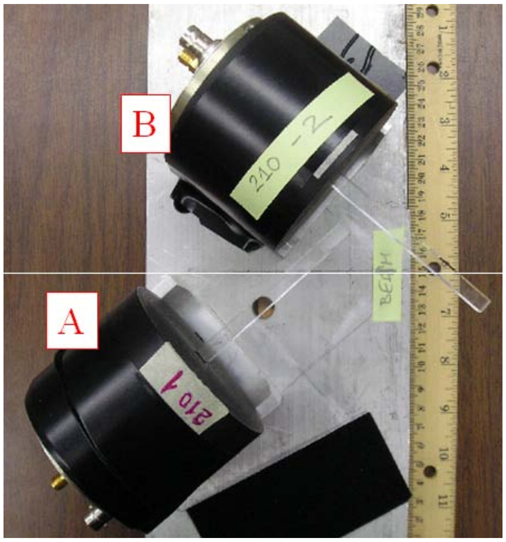


Fig. 17. Photek 210 with quartz radiators (bar's size 6x6x100 mm3) aligned at 48^0 to the beam. The measured time difference is (t_A-t_C) $+(t_B-t_C)/2$. The time jitter, due to the beam size in the horizontal direction cancels.

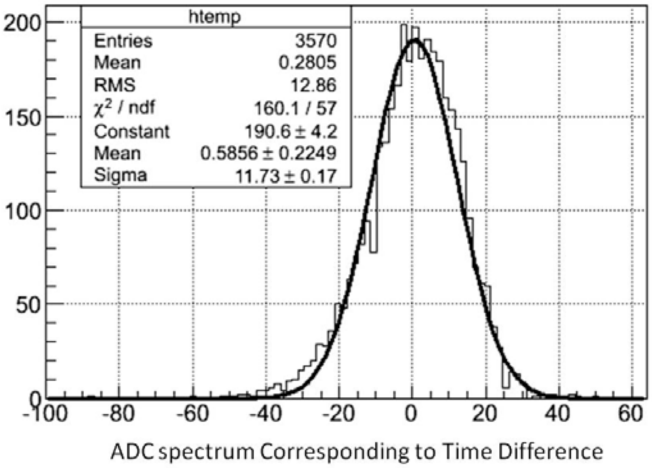


Fig. 18. Timing spectrum, obtained with 120/c GeV protons. Devices used were MPPC’s (3x3 mm2) with Cherenkov radiator as start counter and a Photek 240 (normal particle incidence) as a stop counter. Time resolution (sigma) is 11.7 channels, or 35 ps, per SiPM.

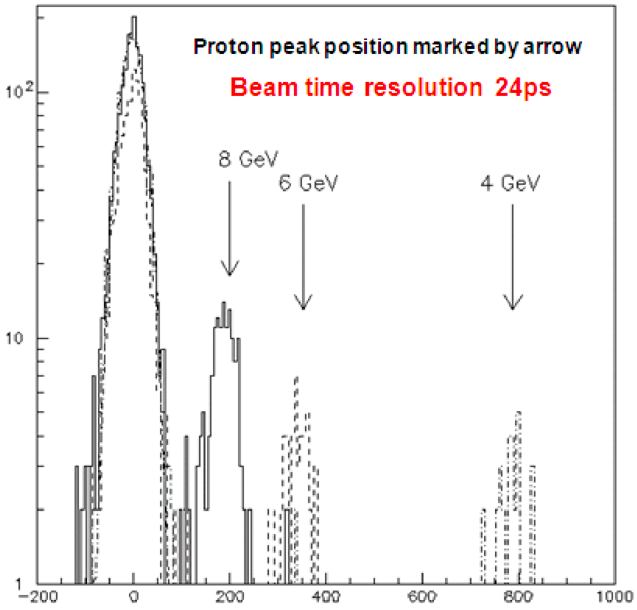


Fig. 19. Time of flight (TOF) spectra obtained with the beams of 4, 6 and 8 GeV/c momentum. The proton peak positions are marked by arrows. The distance between the start and stop counters was 8.7 meters. The time resolution from the Gaussian distribution fitting the “light” particles peaks (mostly positrons and pions, left peaks) is 24 ps (sigma).

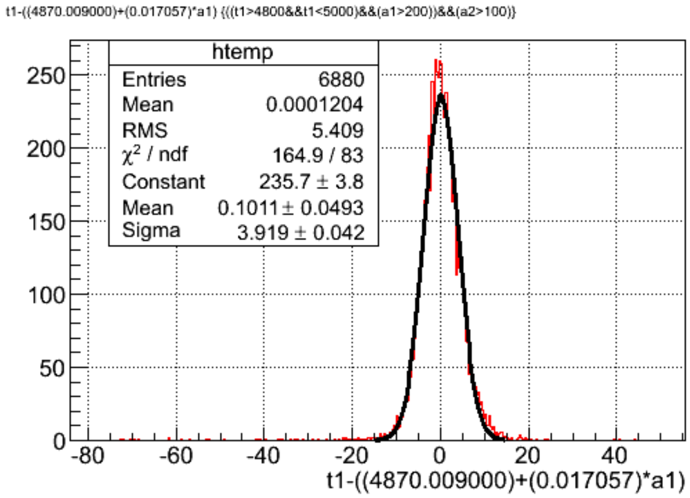


Fig. 20 Timing spectrum, obtained with 120/c GeV protons. Devices used were two Photek 240 (normal particle incidence) in line. Time resolution (sigma) is 12.4 ps.

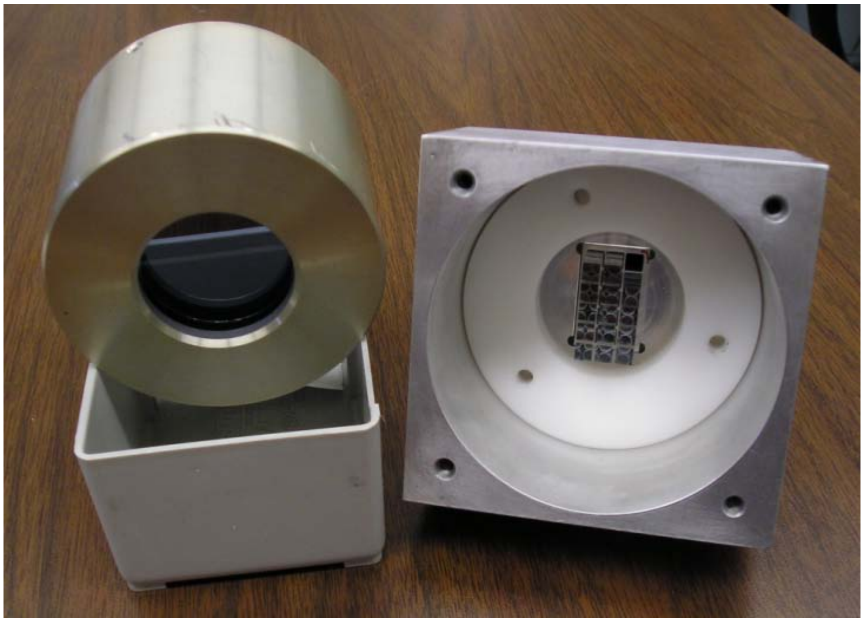


Fig. 21. External view of the Photek 240 (left) and matrix (5x3) of the bars (right).

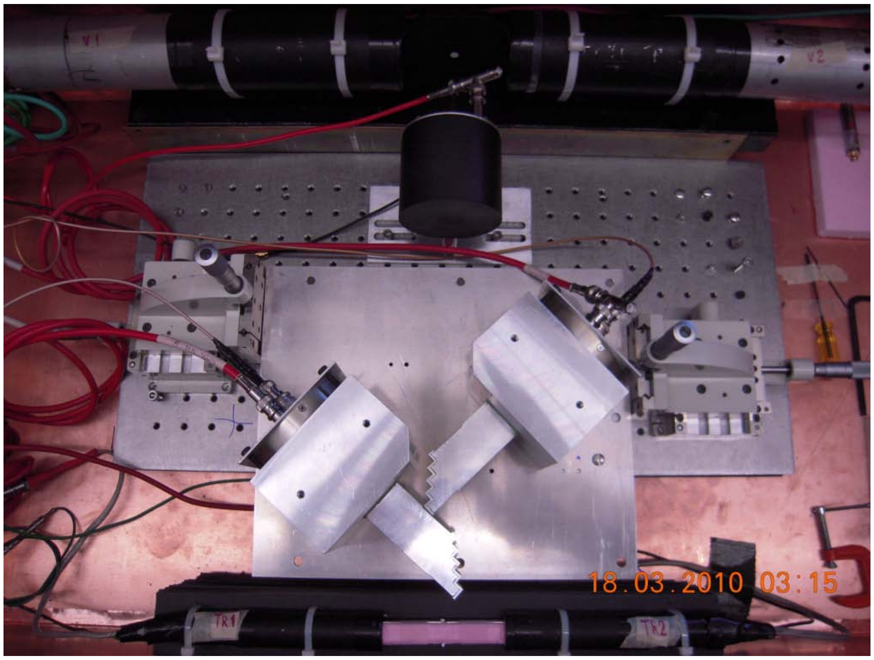
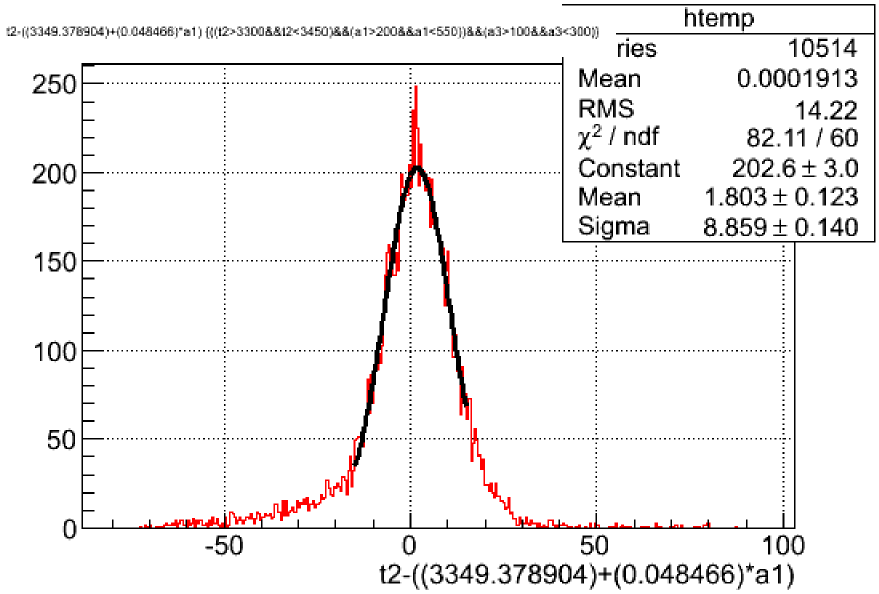


Fig. 22. The setup with two Photek 240s. The MCP PMTs are optically coupled to 5 quartz bars (all the bars are located in the horizontal plane along the beam). Each bar placed at 48^0 (Cherenkov angle) with respect to the beam. The bars are 5x5 mm^2 cross section with different lengths, on average 90 mm. Also shown in the figure are the optical table, trigger, veto and Photek 210 counters inside the RF shielded dark box.



Fis. 23. Timing spectra. The start counter is the MPPC with 7 mm of fused silica as Cherenkov radiators. The stop counter is a PMT240 at normal incidence.

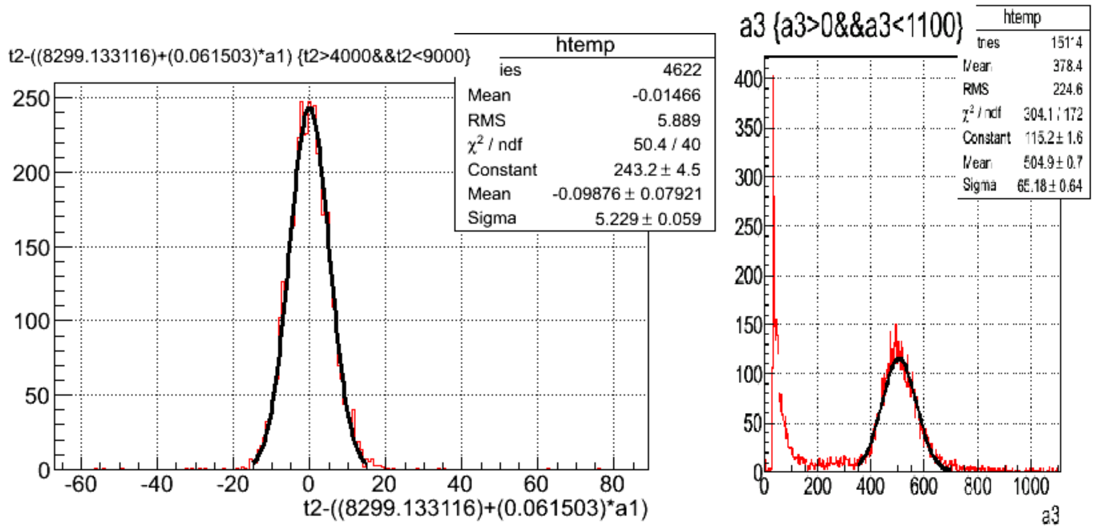


Fig. 24. Timing spectrum (a) and pulse height amplitude spectra (b). The time resolution is 16.3 ps or 14.5 ps/MPPC. Start counter is MPPC with 30 mm of fused silica as Cherenkov radiator. Stop counter – PMT240 at normal incidence. The MPPC amplitude spectrum shows about 60 photoelectrons.

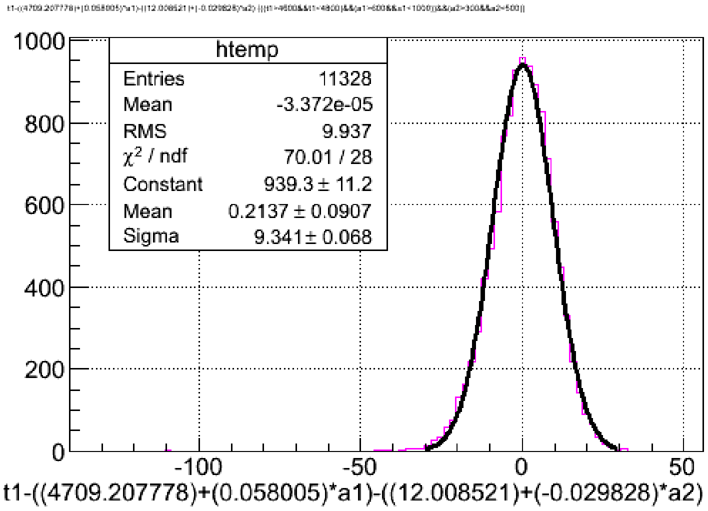


Fig. 25. Distribution of the time difference between STM and MPPC. Both are with 3x3x30 mm^3 fused silica quartz radiators. Time resolution is 29 ps.

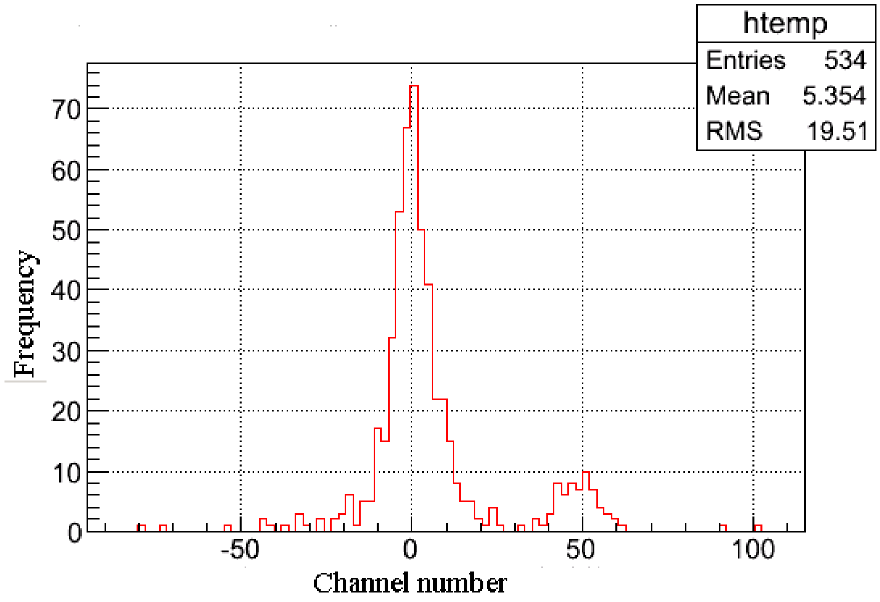


Fig. 26. Time of flight (TOF) spectra obtained with the beam of 8 GeV/c momentum. Both start and stop counters are PMT240 with normal particle incidence. The left peak corresponds mostly to positrons and pions and the right (small) peak corresponds to protons. The width of the left peak fitted by a Gaussian distribution is σ = 14.5 ps. The distance between the start and the stop counters was 7.12 meters (see text for more details).

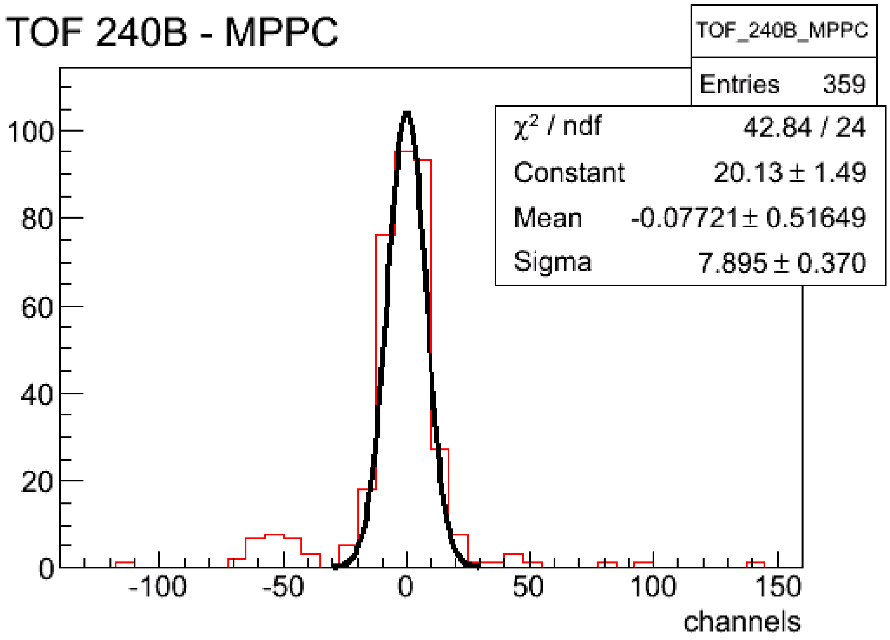


Fig. 27. Time of flight (TOF) spectra obtained with the 8 GeV/c beam. One counter is an MPPC with a Cherenkov radiator and the other is a Photek 240, at normal incidence. Increasing time-of-flight is from right to left in this plot. The larger right peak corresponds mostly to positrons and pions and the small left peak corresponds to protons. The width of the right peak fitted to a Gaussian distribution is σ = 24.5 ps. The distance between start and the counters was 7.21 meters.

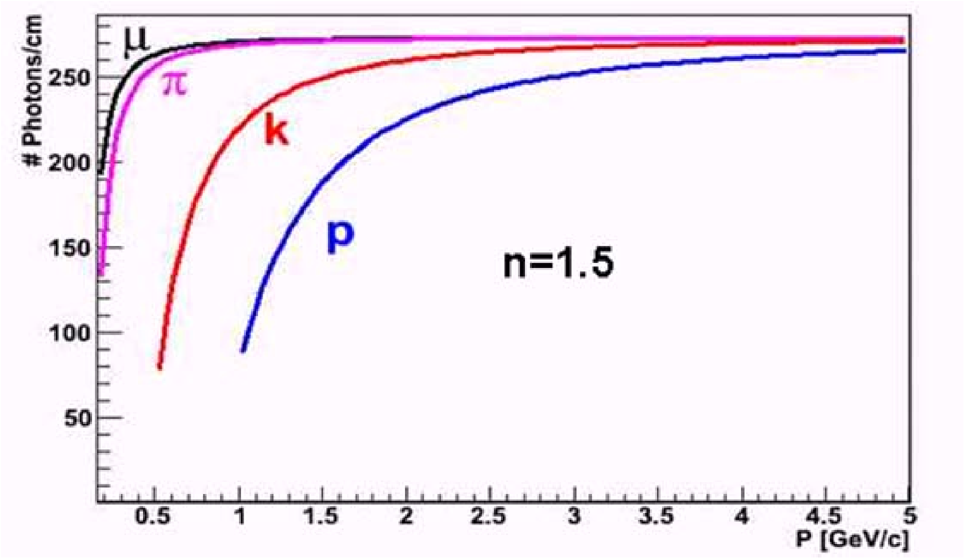


Fig. 28. The number of photons produced in 10 mm of a medium with refractive index n=1.5 by different particles versus momentum ((Hans Wentzel (Fermilab)).

Table 1. The table present time of flight difference between start and stop counters in picoseconds dependent on momentum (in GeV/c) and distance between them in meters for the particles. The base distance is slightly different due to different location of the start and stop counters on the beam (see text).

P, GeV/c	4	6	8	4	6	8	8	8
Base, meters	8.71	8.71	8.71	8.65	8.65	8.65	7.12	7.21
dT, u-e, ps	10.1	4.5	2.6	10.1	4.5	2.6	2.1	2.2
dT, pi-e, ps	17.7	7.9	4.4	17.6	7.8	4.3	3.6	3.6
dT, K-e, ps	220.5	98.2	55.7	219.0	97.5	55.2	45.6	46.1
dT, p-e, ps	788.9	353.2	199.4	783.5	350.8	197.6	163	165