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Development of Time of Flight Systems at Fermilab

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Fermilab

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Time Of Flight (TOF).

I. Best timing photodetectors:

1. MCP PMT (Photek240, Photonis XP85011 (12), Hamamatsu…)
2. SiPMs (almost all SiPMs produced in the world tested).
3. LAPPD?, 6x6 LAPD?

II. Readout:

1. DRS4
2. Ortec
3. DSA7125

Hydra?, (PSEC???)

III. Application:

1. Beam line TOF (FTBF, Minerva, CERN…)
2. Calorimeters, Showers maximum (SEC, Crystals, "shashlik")
3. Medical (PET TOF, pCT).

References, used algorithms is of importance

Very good news for TOF team at Fermilab (also Caltech, UC, CERN…)

We got less of 10 picosecond time resolution (TR) at last test beam (TB).

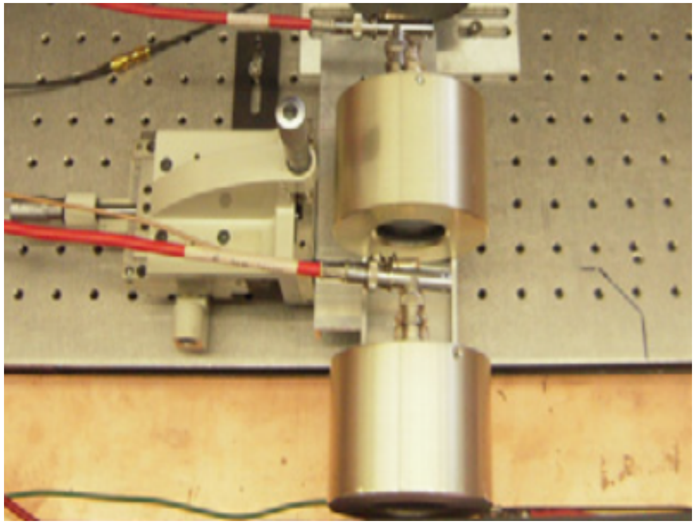
It is important for us because the results obtained with only standard industrial equipment (nothing “special”, see below…)

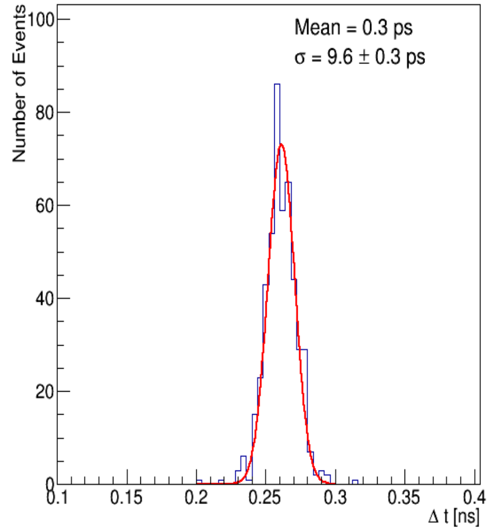
Conditions:
TB at Fermilab, starting January 24 up to February 3, 2015, 120 GeV p).

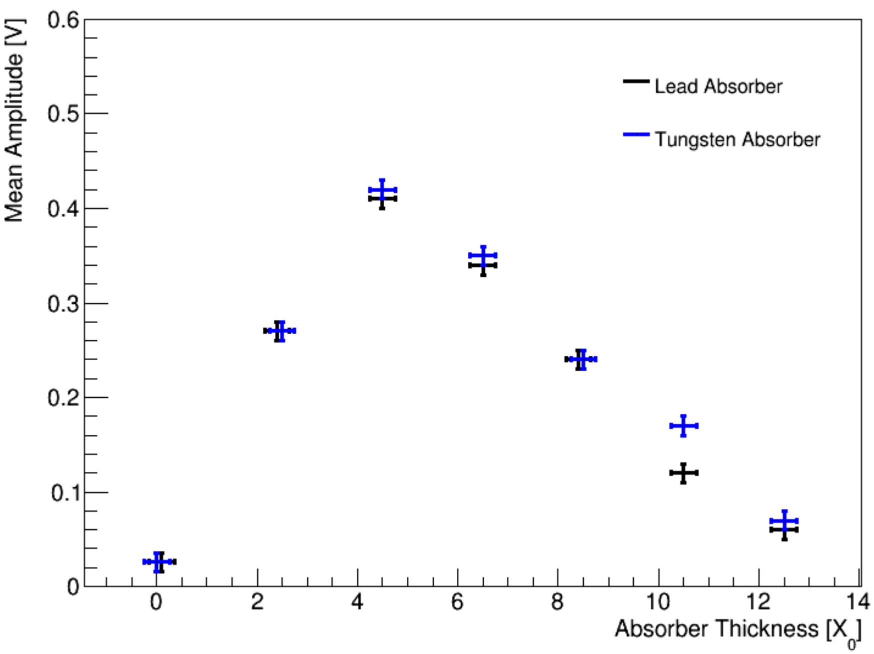
Both start and stop counters are Photek240, 41 mm diameter of input quartz window with photocathode (PC), blue QE ~27%, ~ 1.7 ps timing non uniformity across the PC, SPTR ~37 ps, pore diameter 10 um. The rest you can see at Photek240 specs (the Photek with gating also as w/o). Readout: DRS4, SMA signal cables length less of 3”.

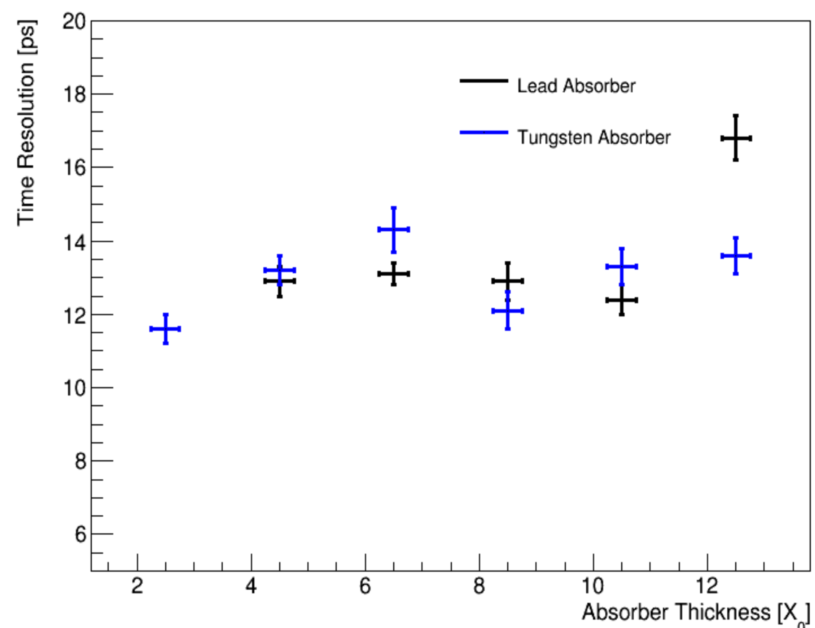
References, used algorithms

9.6 ps obtained for TOF, based on Photek 240









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- 3. A SiPM - based TOF - PET detector with high speed digital DRS4 readout.
- A. Ronzhin, M. Albrow, S. Los, M. Martens, P. Murat, E. Ramberg, H. Kim, C.-T. Chen, C.- M.Kao, K. Niessen, A. Zatserklyaniy, M. Mazzillo, B. Carbone, G. Condorelli, G. Fallica, A. Piana, D. Sanfilippo, G. Valvo, S. Ritt.
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- 4. Development of an alkali transfer photocathode for large area micro channel plate-based photodetectors.
- Zikri Yusof, Klaus Attenkofer, Marcel Demarteau, Henry Frisch, Joe Gregar, Sharon Jelinsky, Seon Woo Lee, Jason McPhate, Richard Northrop, Alexander Paramonov, Anatoly Ronzhin, Greg Sellberg, Oswald Siegmund, Robert Wagner, Dean Walters, Xie.
- Nuclear Instruments and Methods in Physics Research, Physics Procedia 37 (2012) pp. 733– 739.
- 5. Waveform digitization for high resolution timing detectors with silicon photomultipliers.
- A. Ronzhin, M.G. Albrow, S. Los, E. Ramberg, Y. Guo, H. Kim, A. Zatserklyaniy, M. Mazzillo,B. Carbone, G. Condorelli, P. Fallica, A. Piana, D. Sanfilippo, G. Valvo, S. Ritt. Nuclear Instruments and Methods in Physics Research, A 668 (2012) pp. 94-97.
- 6. Electro-Optical Performances of p-on-n and n-on-p Silicon Photomultipliers.
- Massimo Mazzillo, Anatoly Ronzhin, Sergey Los, Salvatore Abbisso, Delfo Sanfilippo, Giusy Valvo, Beatrice Carbone, Angelo Piana, Giorgio Fallica, Michael Albrow and Erik Ramberg.
- IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 59, NO. 12, DECEMBER 2012, p. 3419
- 7. Waveform analysis of SiPM signals with DRS4 board.
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- 8. High Fill Factor P-on-N Silicon Photomultipliers for Blue Light Detection.
- Massimo Mazzillo, Anatoly Ronzhin, Sergey Los, Salvatore Abbisso, Delfo Sanfilippo, Giusy Valvo, Beatrice Carbone, Angelo Piana, Giorgio Fallica, Mike Albrow and Erik Ramberg.
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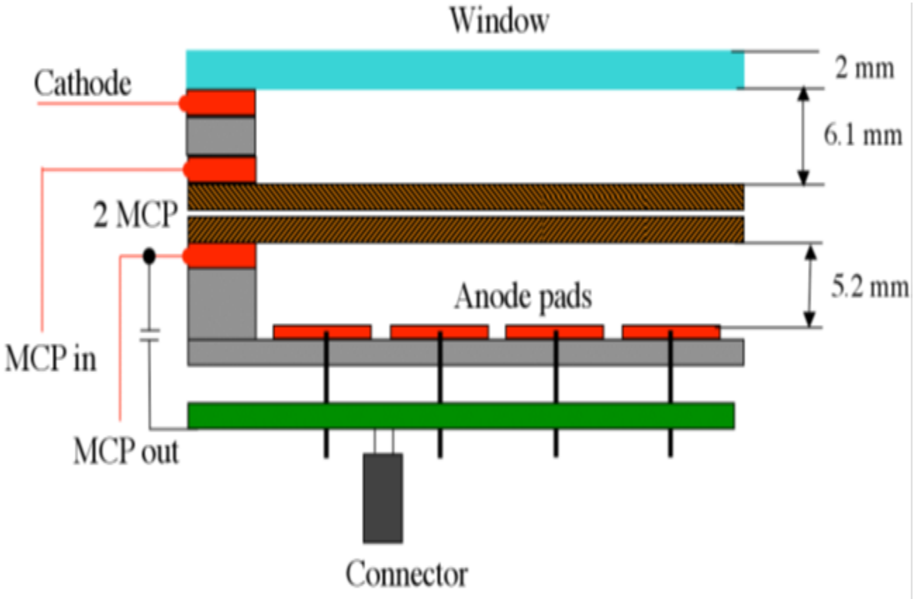
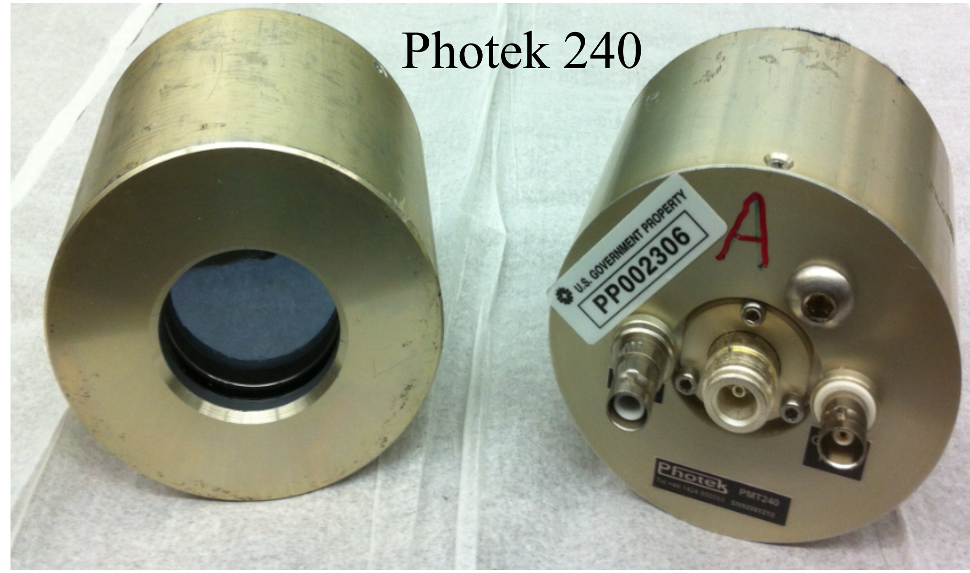
- Photodetectors timing properties almost totally could be characterized by three parameters: a) Single Photoelectron (SP) output pulse shape (we name it "SP response function"; b) SP time resolution (SPTR); c) SP noise rate.
- We always use some electronics for readout in timing systems.
- "Electronic" time resolution is the time jitter for two portions of the same signals applied as "start" and "stop" (from the same source) to electronic system measuring the time interval between them. The "electronic" time resolution is the one of the main parameters of such a systems and should be much smaller that time jitter of used detectors.

  We achieved ~2 ps "electronic" time resolution for our timing systems. New method to calibrate readout proposed and tested.

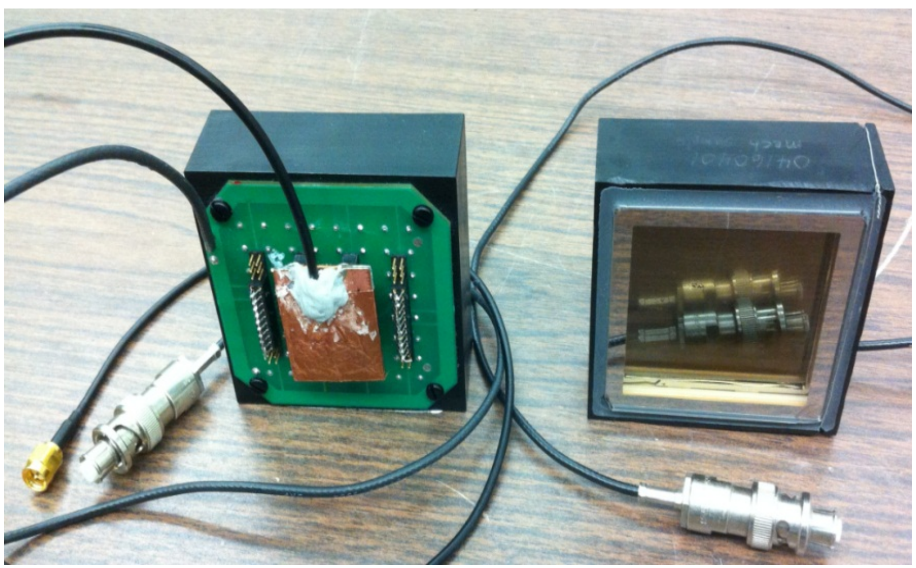
  We use Pilas laser as light source (17 ps, sigma light pulse) with 405 nm (blue) and 635 nm (red) light in our photodetectors bench test.

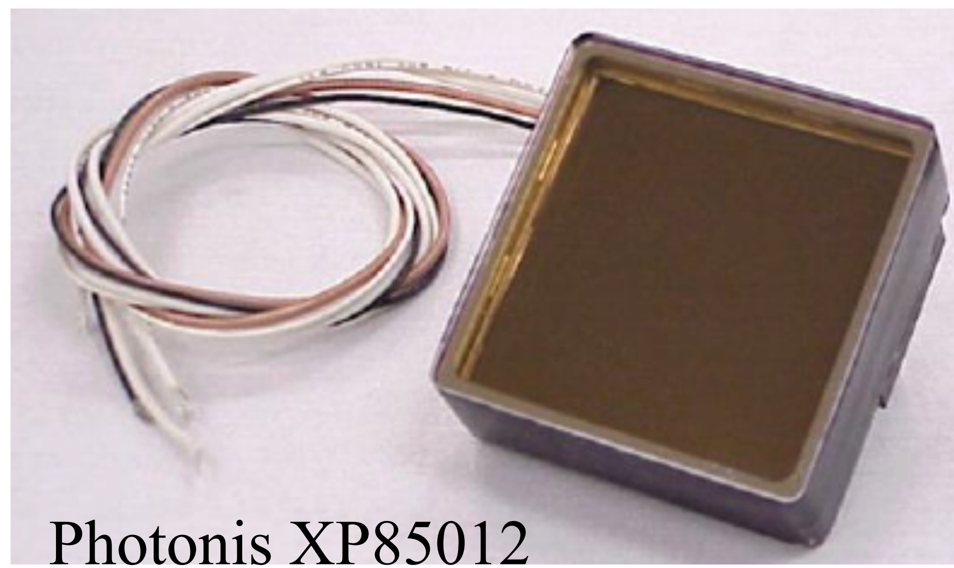
Photek 240 and Photonis MCP-PMT as the SM active element





Timing uniformity across 41 mm diameter PC is ~3ps

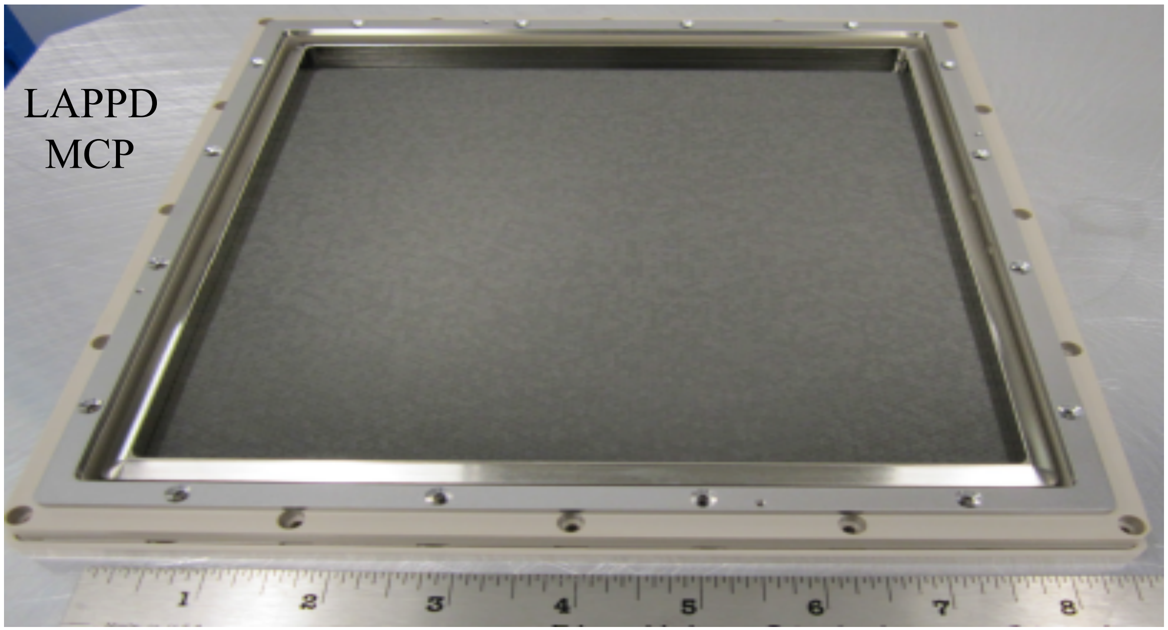




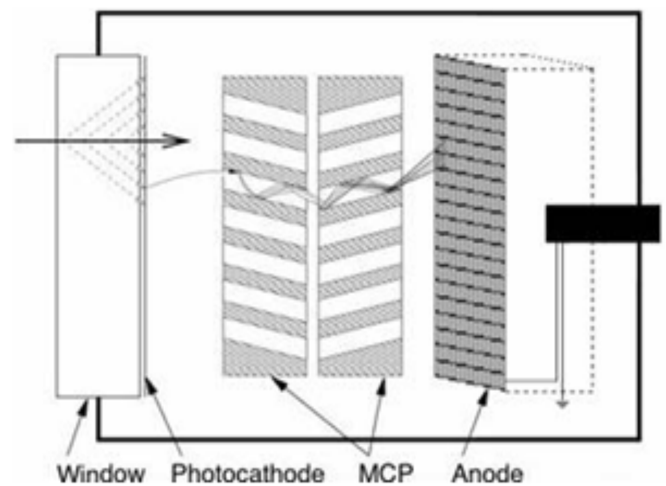
Timing uniformity across 25x25 mm2 ~37 ps

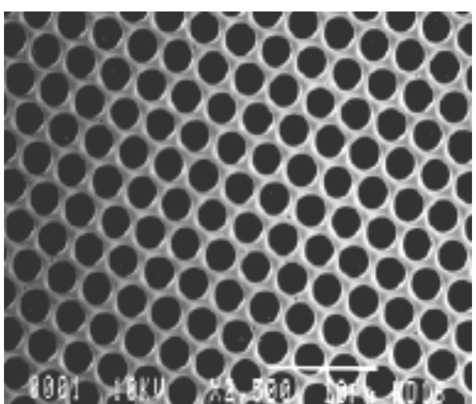
What is micro channel plate (MCP)?

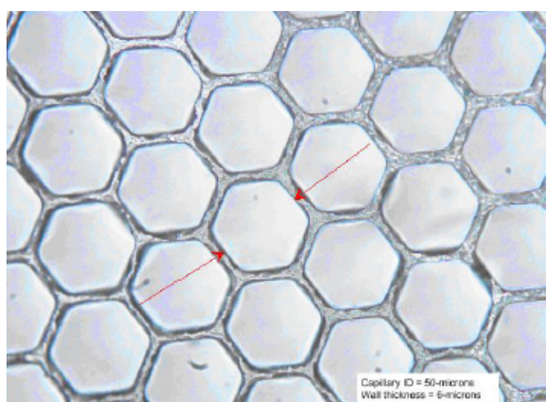
A micro-channel plate (MCP) is a slab made from highly resistive material of typically 1 mm thickness with a regular array of tiny tubes (micro channels) leading from one face to the opposite, densely distributed over the whole surface.



MCP materials: lead glass, borosilicate glass, aluminum oxide… Different technology developed. Metallization process is covering MCP by NiCr, to make electrical contact for HV leads.

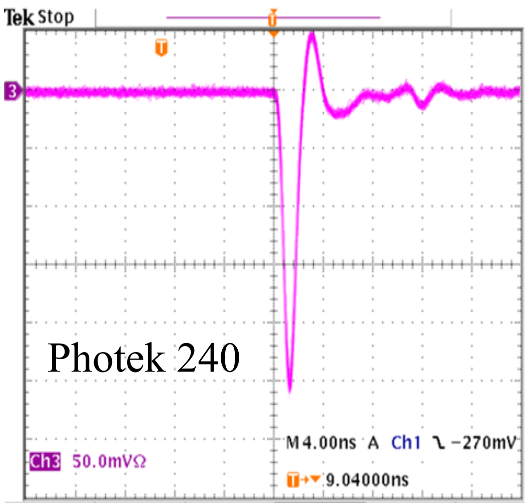


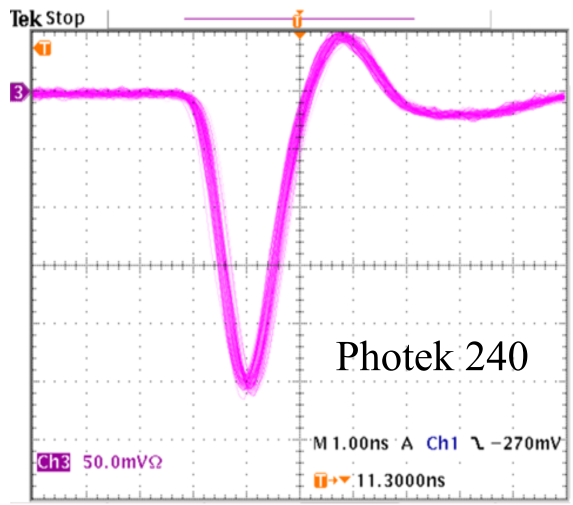


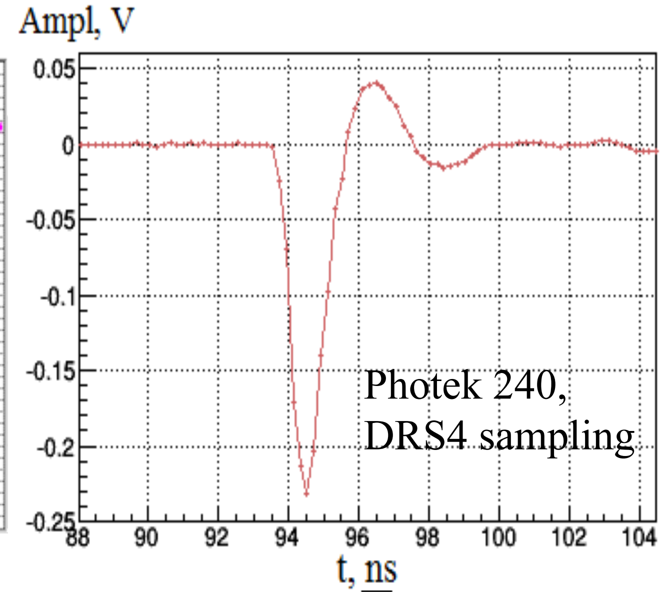


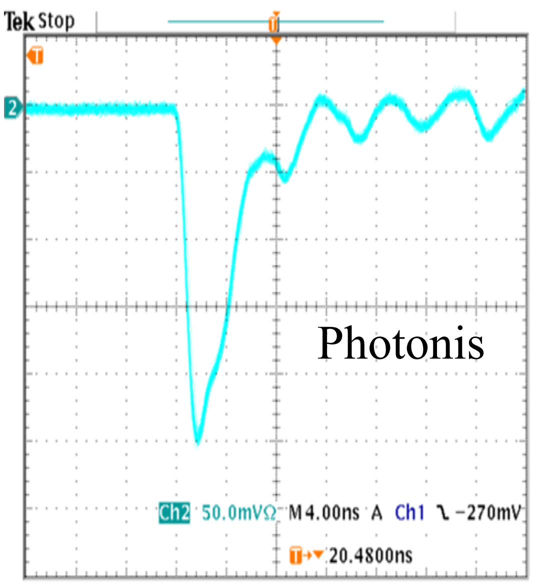
A standard MCP is produced by chemical etching of a fused fiber optic that is produced using specialized (and expensive) core and clad glass. The core glass is etched away from the plate and the cladding is hydrogen fired to produce a thin layer of semi-conducting reduced lead oxide on the surface of the MCP pores. INCOM’s MCP is fabricated using a unique hollow draw process that eliminates the need for a specialized core glass that needs to be removed

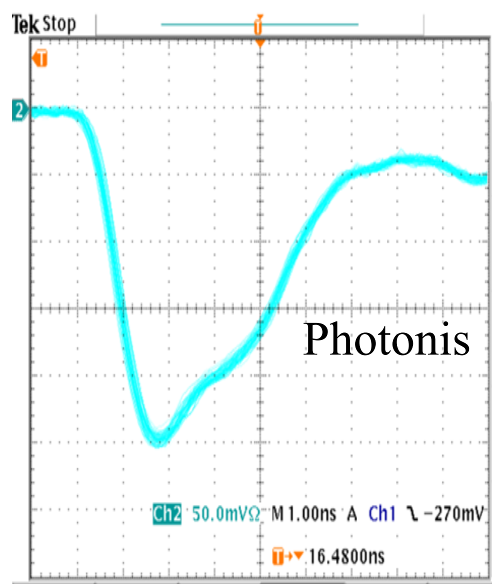
MCP-PMT output signal shapes, FWHM ~ 1 ns, rise time <1ns

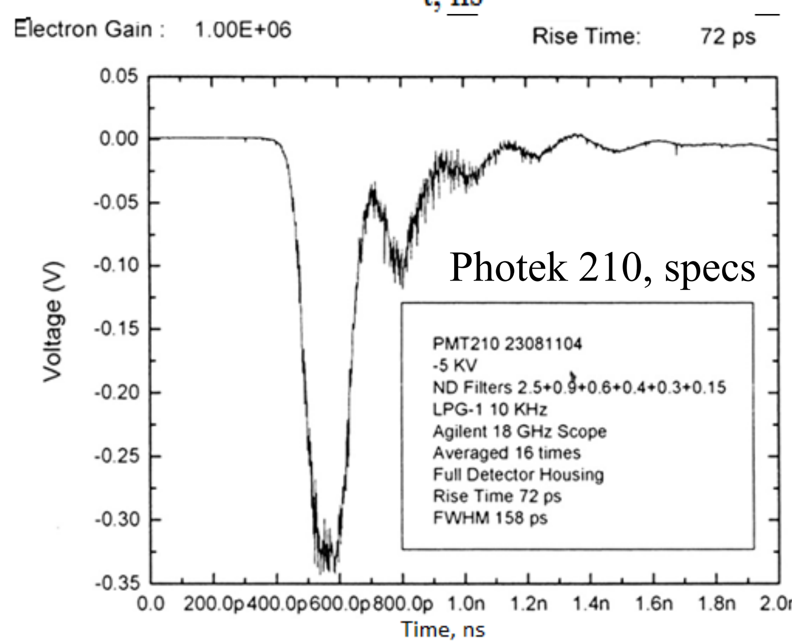




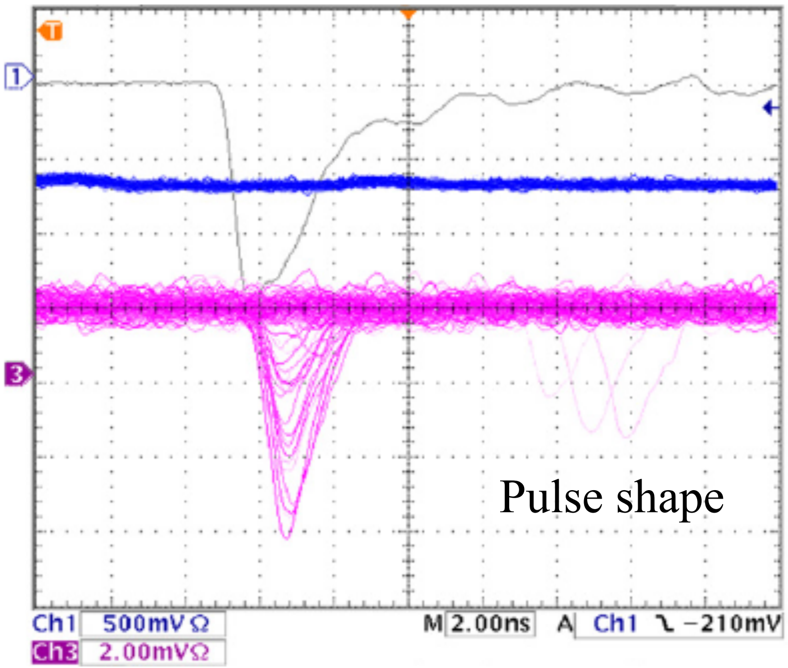


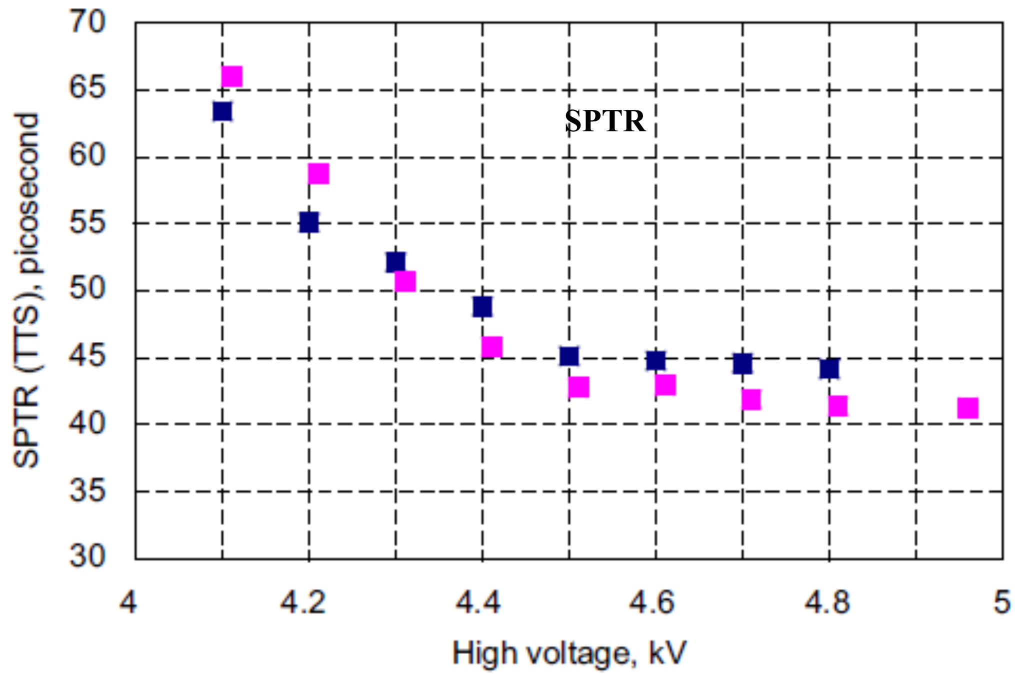


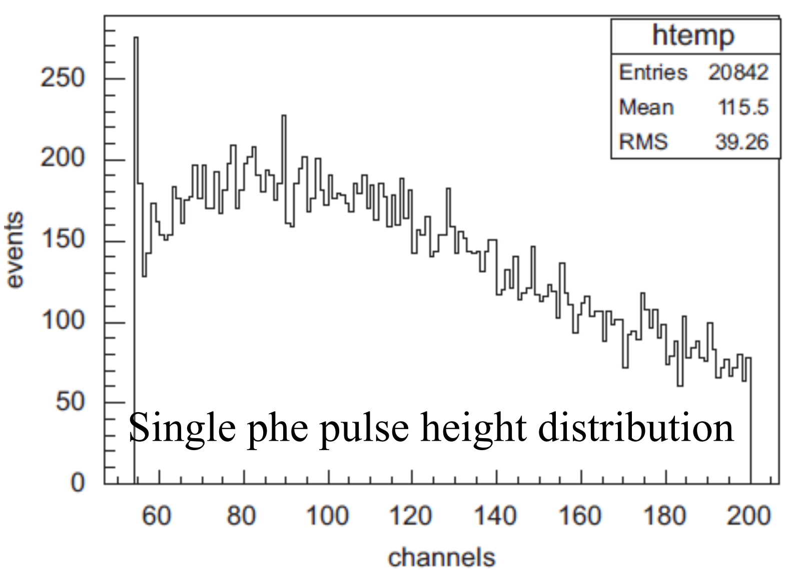


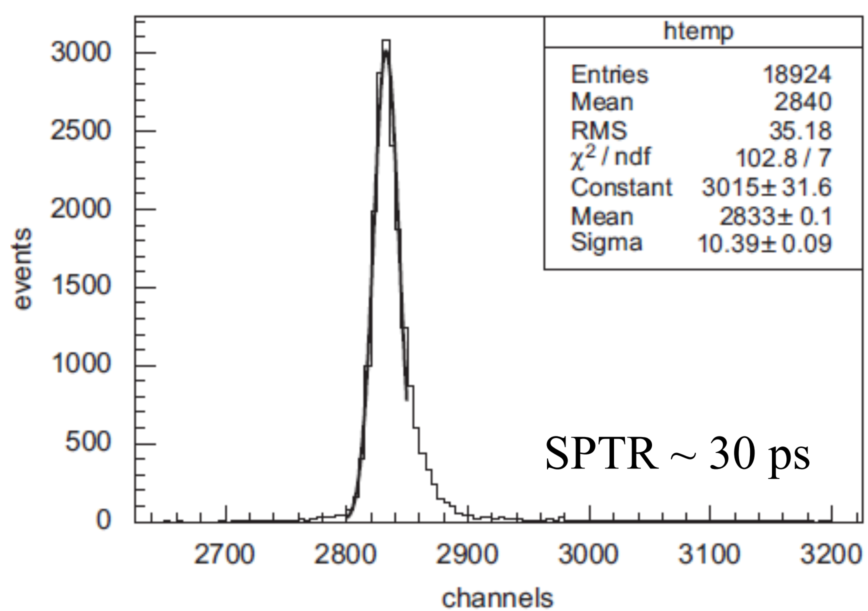


Photek240 output signal shape, SPTR

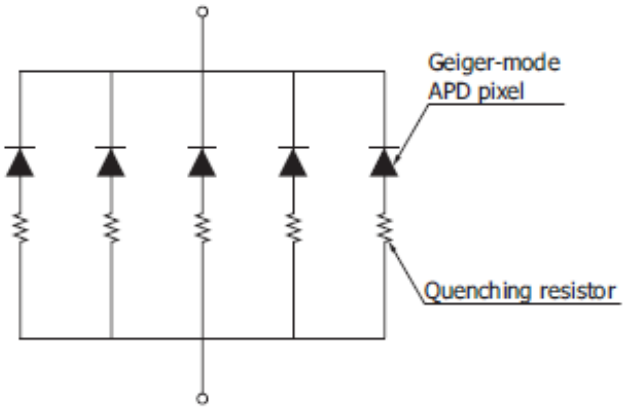


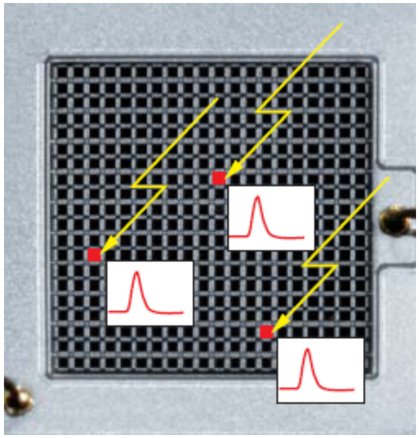


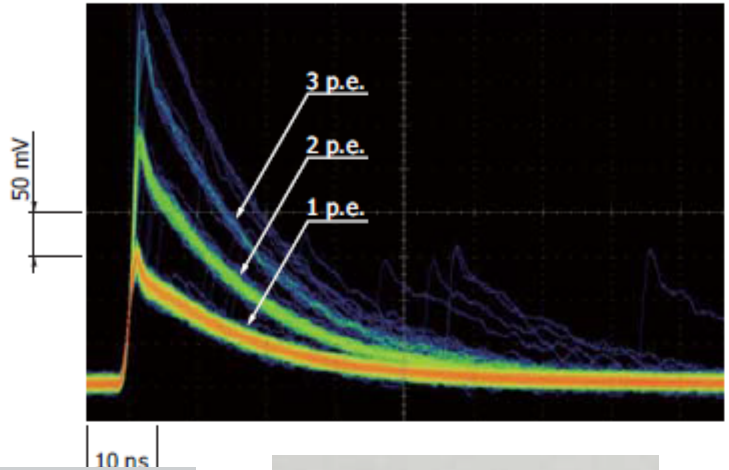


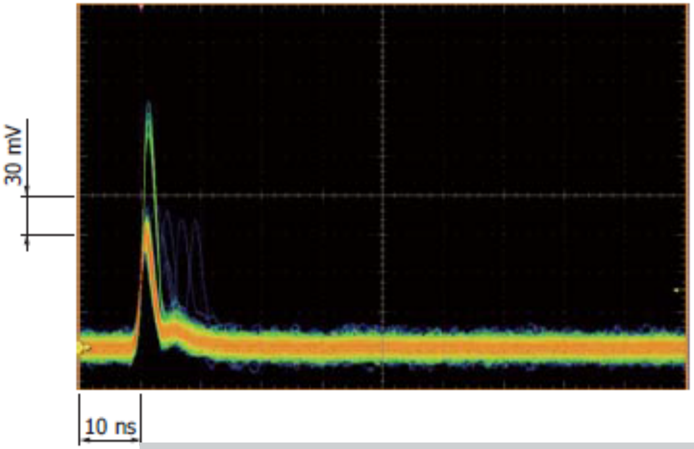


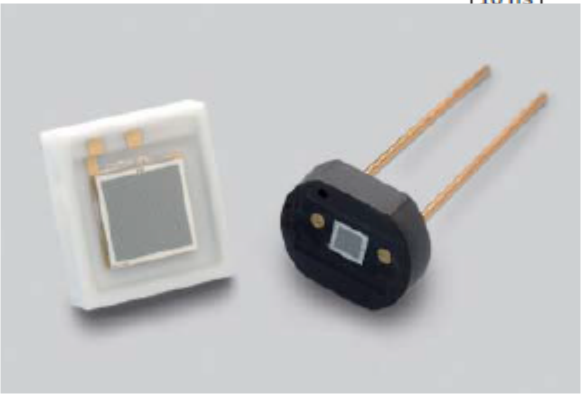
Silicon Photomultiplier (SiPM)

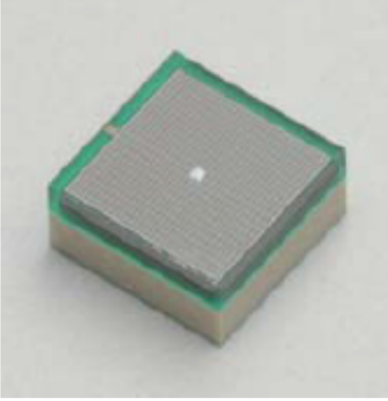


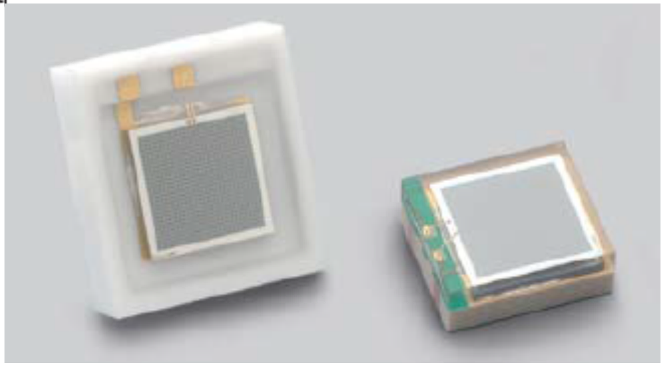




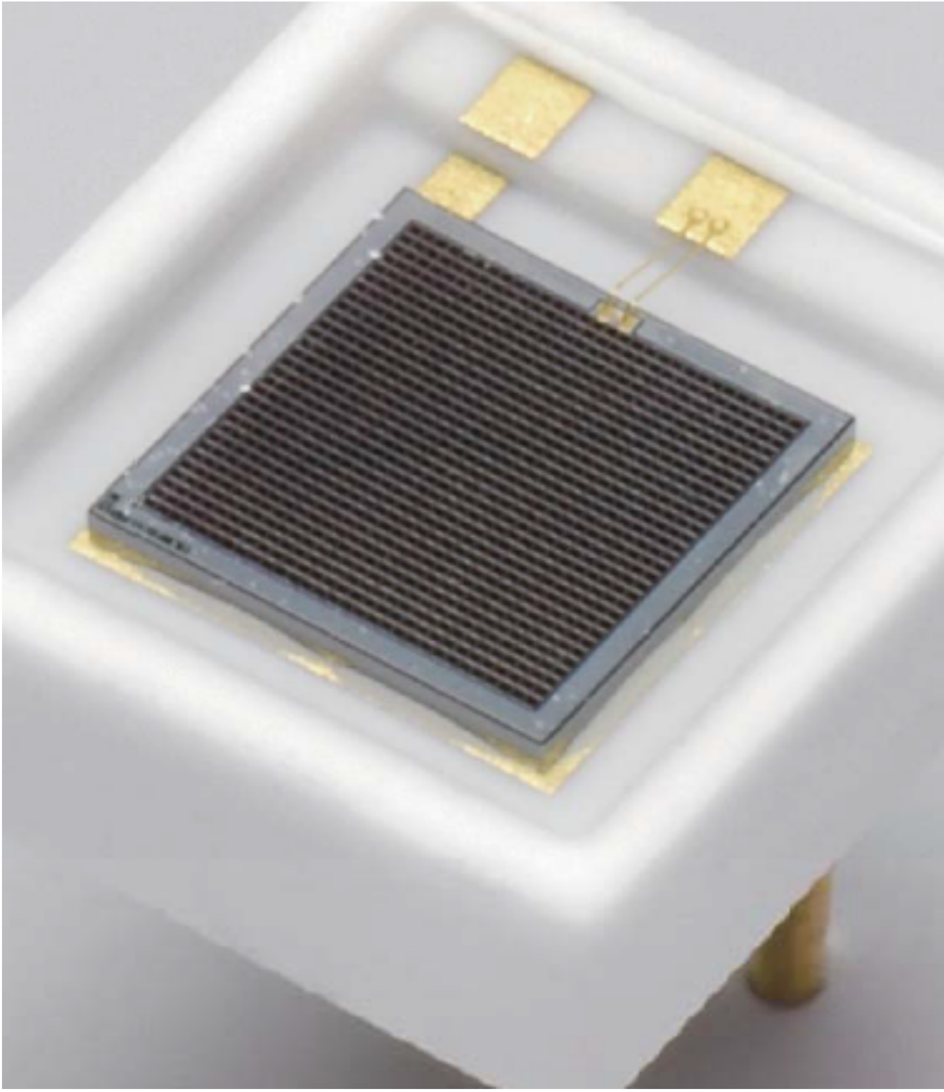
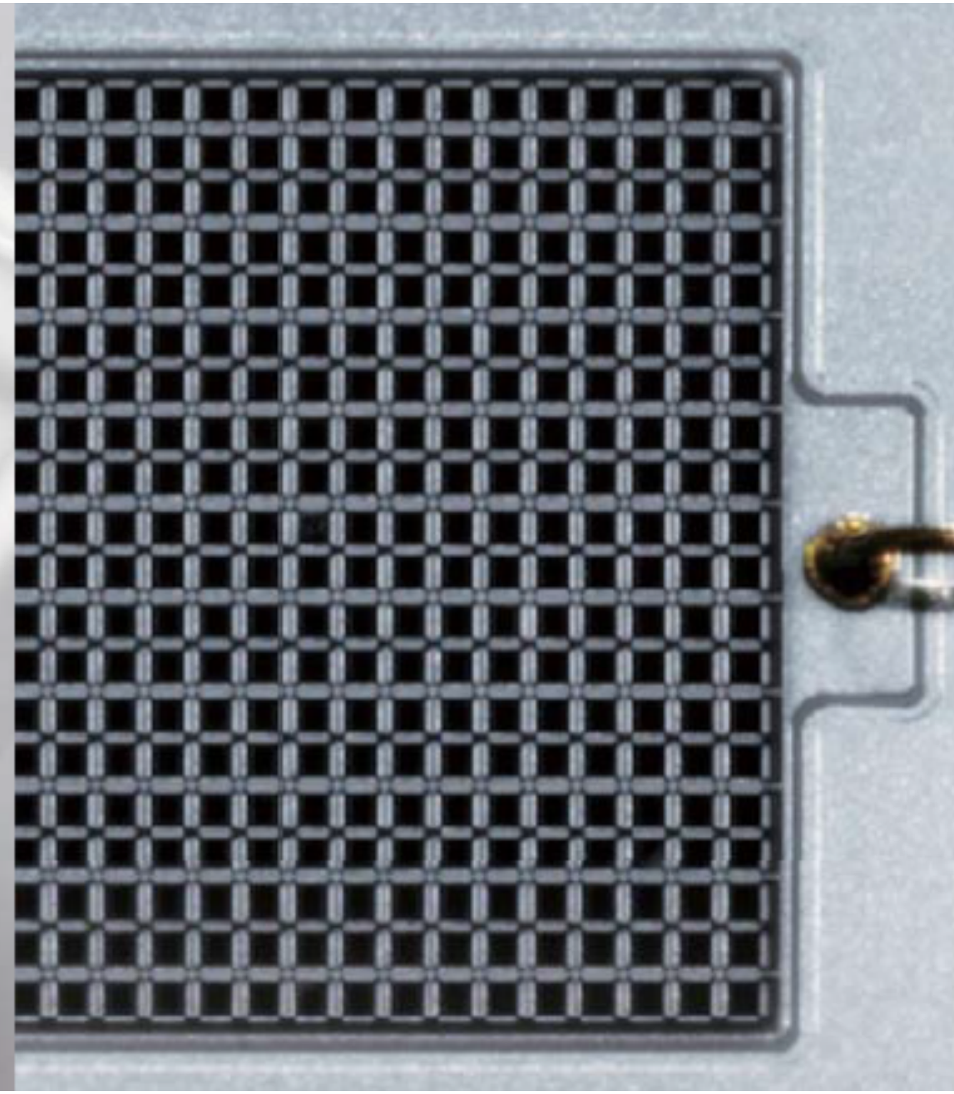








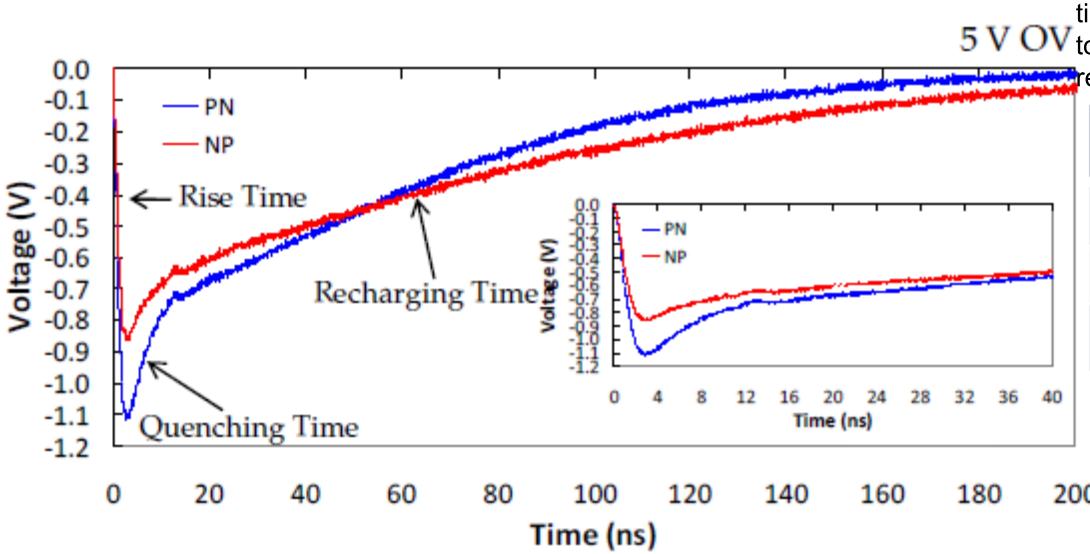
Some SiPMs

Pulse Shape Analysis

- 4x4 mm² SiPMs, 4100 microcells, 45% fill factor, BV≈28 V, R_Q≈265 KΩ
- Illumination and bias condition corresponding to about 1500 p.e. in N on P SiPM

Tau rise – avalanche propagation, collection of carriers in drift region and at the contact across the bulk region. Tau quench - time for avalanche current to decrease from max to zero due to discharge of capacitance of the quenching resistor . Tau recharge - time to recharge all caps thru quenching resistors



Parameter	P on N	N on P
τ_{Rise} (ns)	≈ 1	≈ 1
τ_{Quench} (ns)	2.3	2.5
τ_{Rech} (ns)	78	92

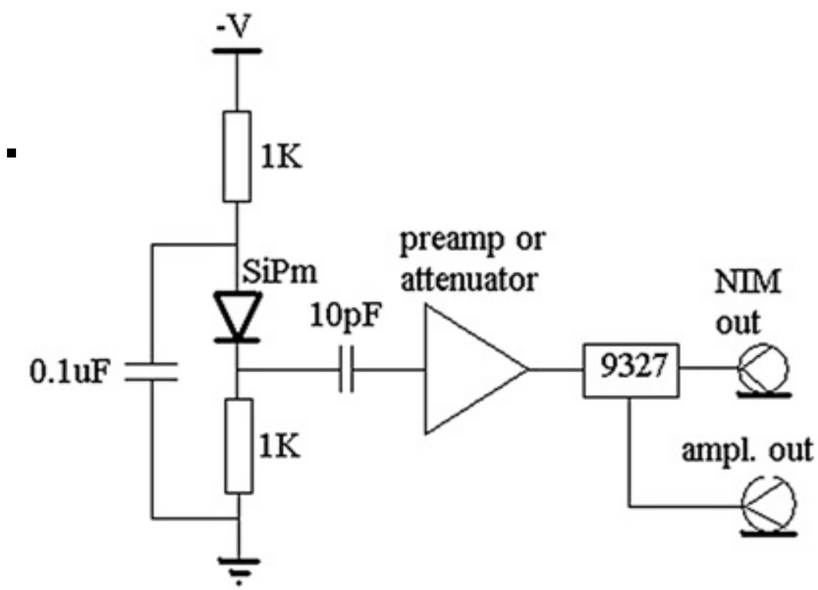
The SiPms signal shape play crucial role for SiPm timing. The influence of main parameters on the shape is understood now. STM can technologically change shaping according to requirements. SPICE analysis. Noise counted.

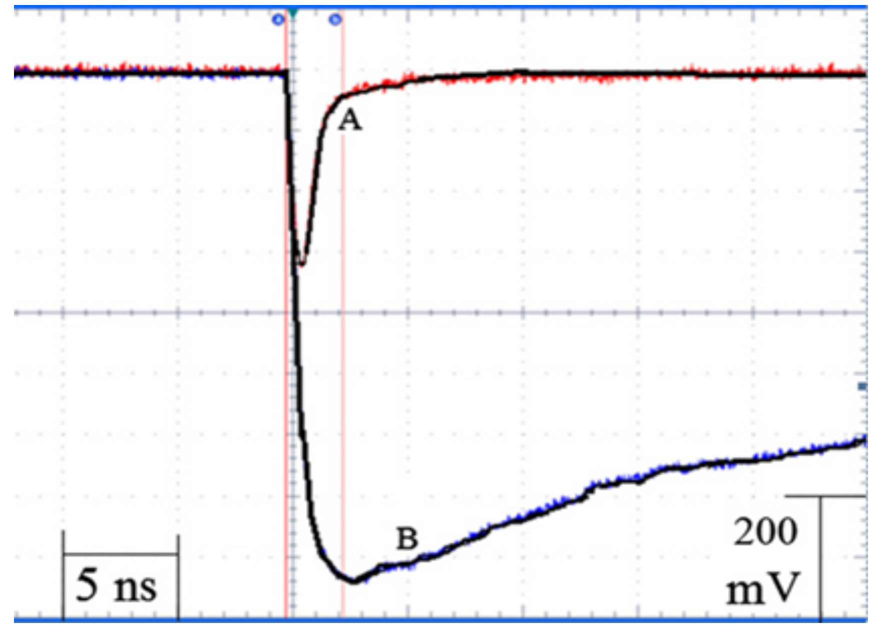
P on N SiPMs

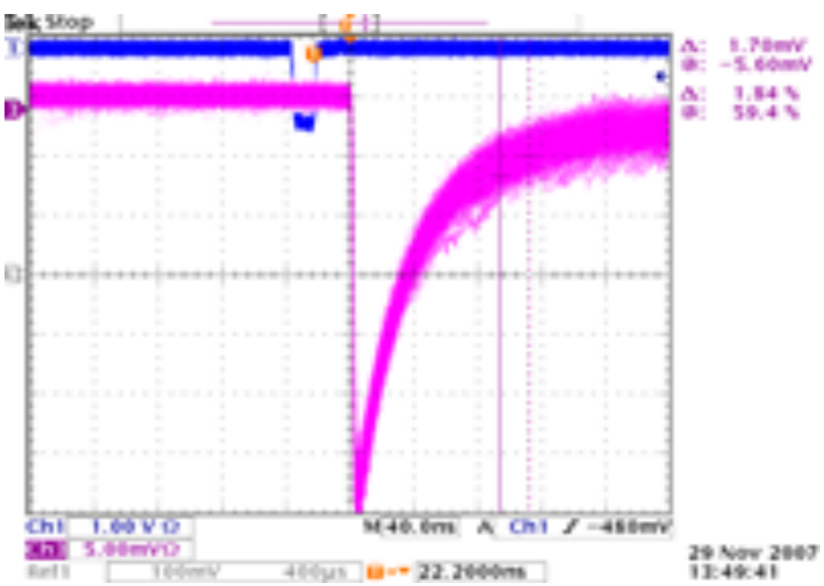
- Lower τ_{Rech} → Lower $C_{microcell}$ → Higher Depletion Layer Thickness
- Higher signal → Higher number of fired microcells → Higher PDE

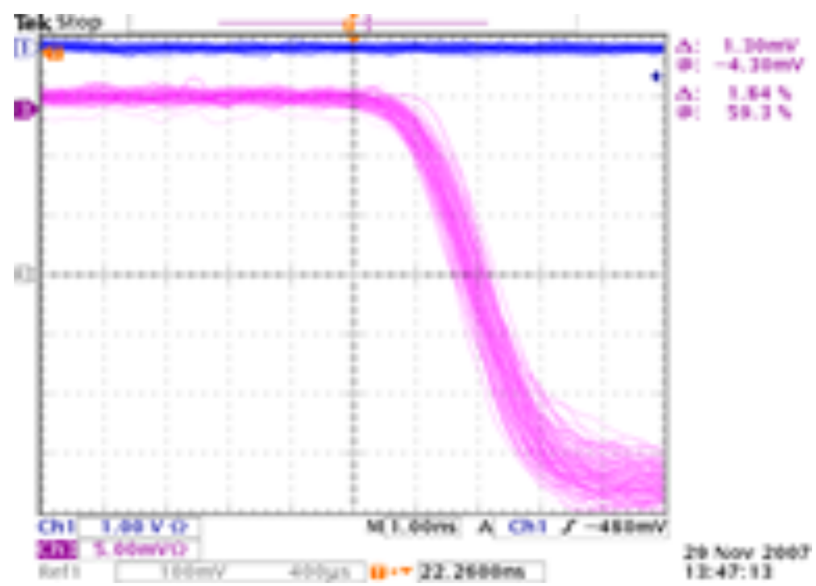
Results to be confirmed by PDE and gain measurements

Clipping capacitance to improve SiPm timing



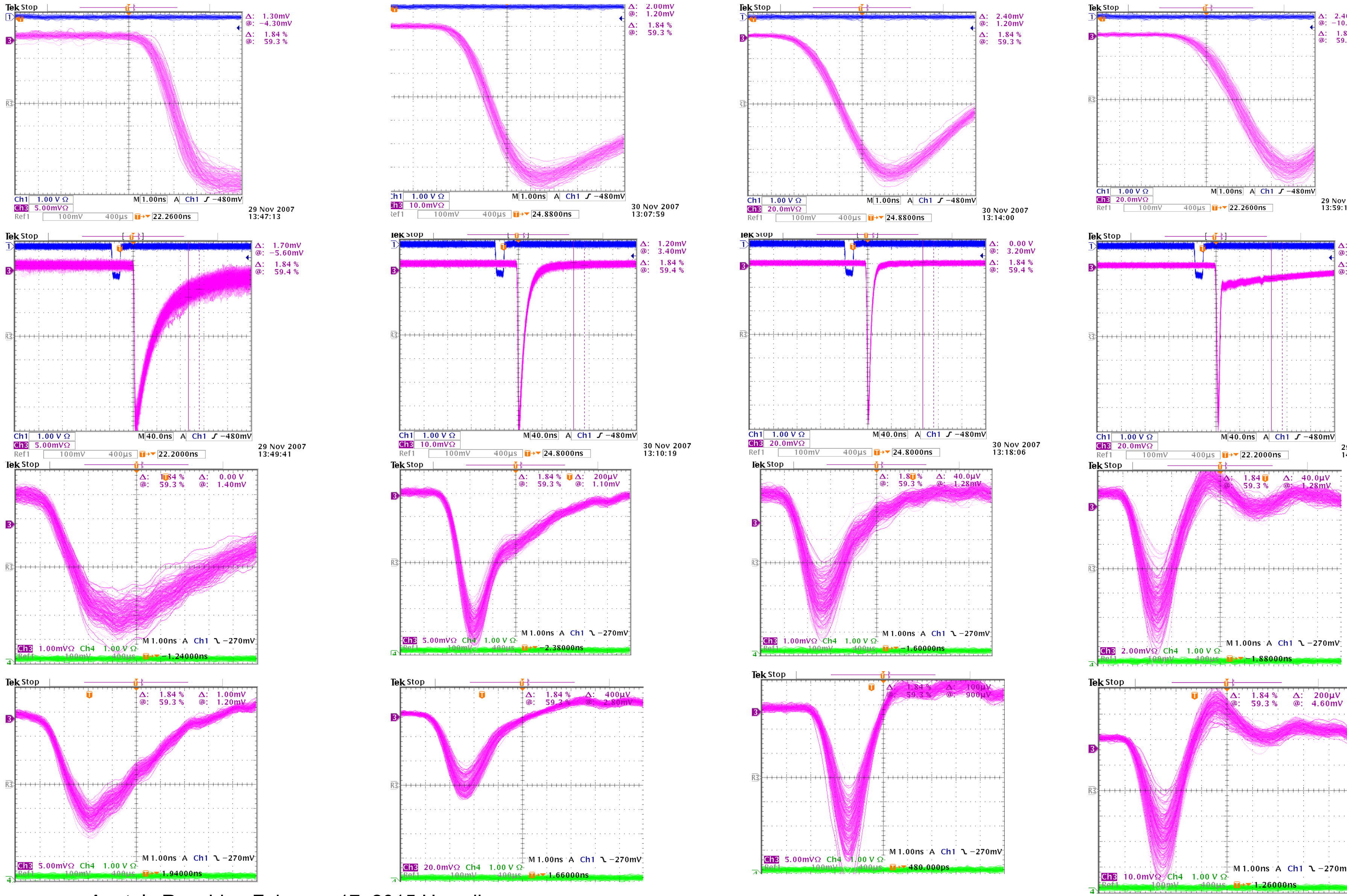




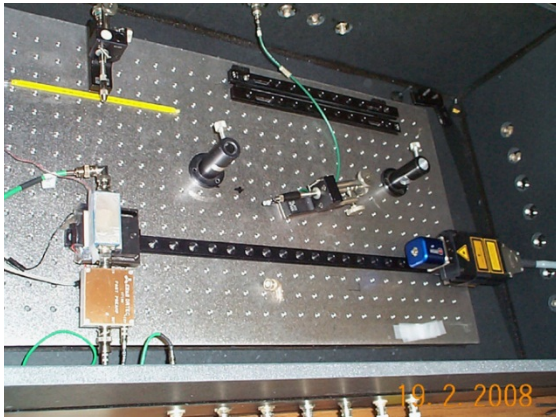


500 MHz TEK, 1ns, 40 ns – raw signals, 1 ns – differ. Signals and 9327 out

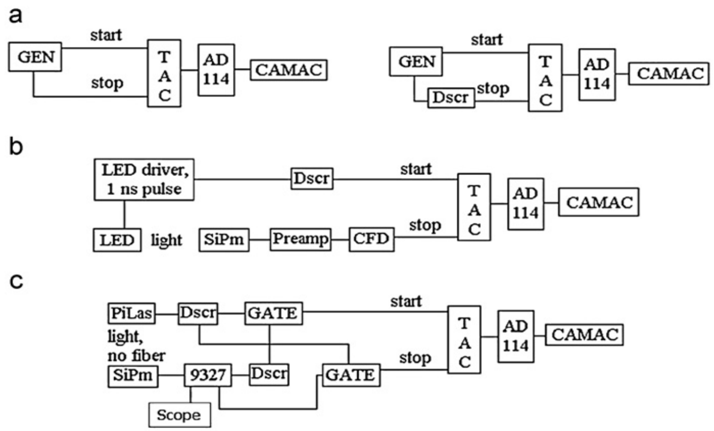
HAM-100U-10 | HAM-050U-9 * | HAM-025U-10 | MRS



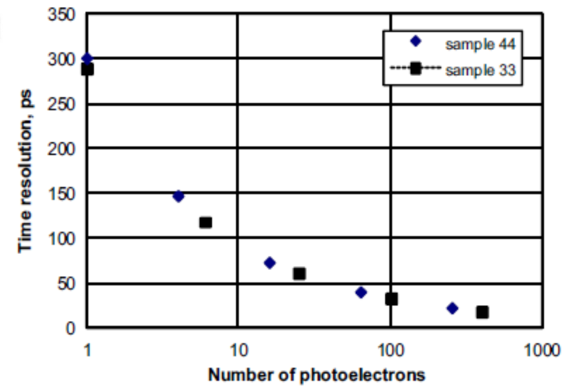
Study of SiPms timing properties. SPTR, sigma.



Setup at SiDet with PiLas, SiPm with preamp, laser head are shown. Light strongly suppressed for SPTR measure



Few readout schematics at SiDet, Ortec TAC567+AD114, 3.1ps/ch, ~16k of chs, 9327 Ortec CFD



Time resolution dependence on photoelectrons number, MPPC

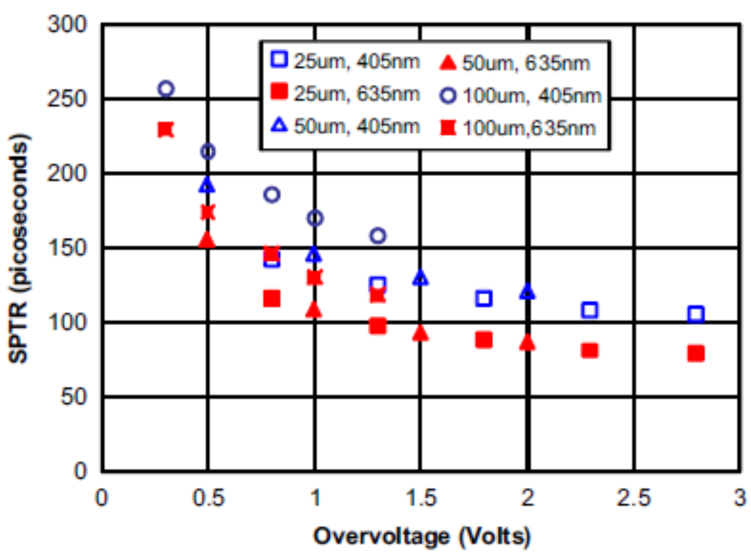


Fig. 7. SPTR of various MPPC's ($1 \times 1\,mm^2$ sensitive area) illuminated by blue (405 nm) and red (635 nm) PiLas light versus overvoltage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

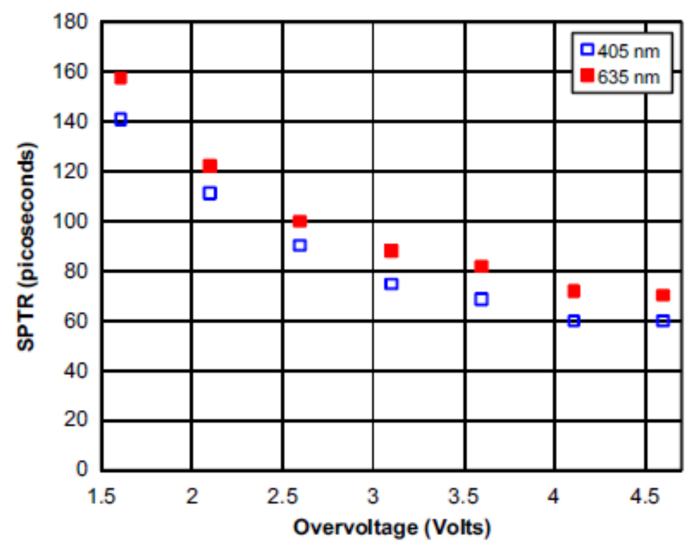


Fig. 8. SPTR of the IRST SiPM ($1 \times 1\,mm^2$ sensitive area) illuminated by blue and red laser light versus overvoltage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The influence of WL on SPTR was noticed Dependent on SiPm structure. Left slide is MPPC. SPTR is better for red light. Right side is IRST. SPTR is better for blue light. The effect was understood and explained. Depends on SiPm structure. STM made P on N, results presented.

Study of new STM timing properties. SPTR dependence on WL, structure.

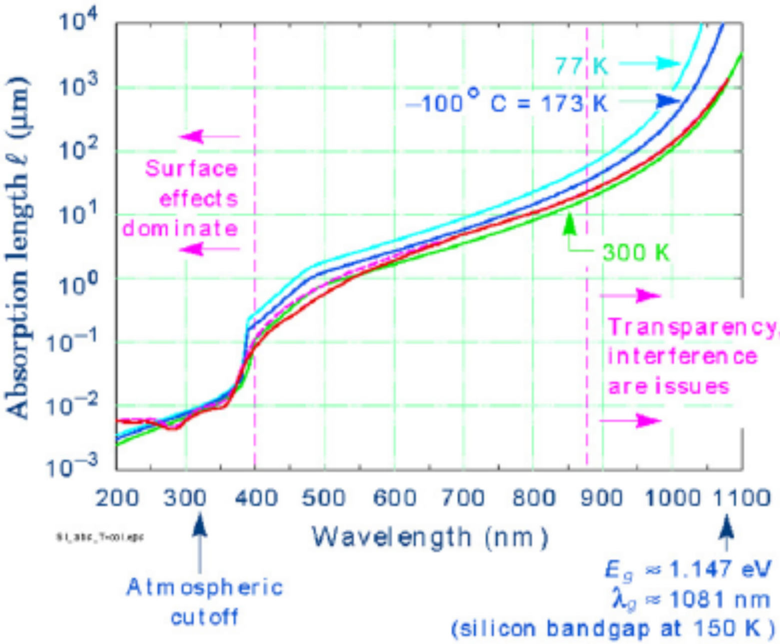
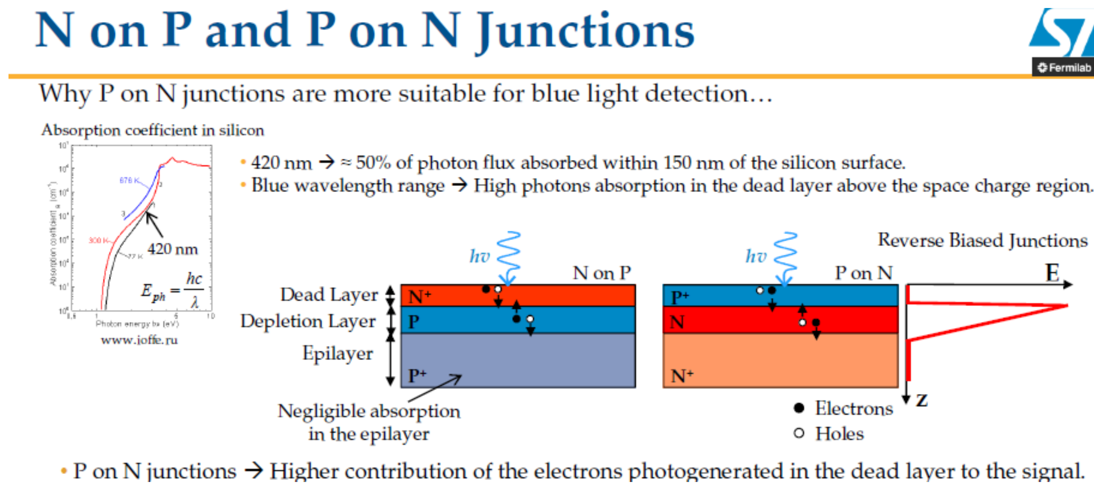
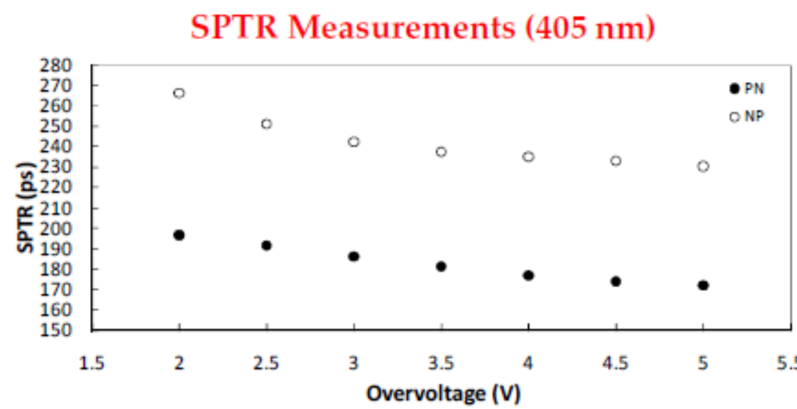


Fig. 12. Absorption length in silicon as a function of photon wavelength. Different colored curves correspond to different temperature [5].





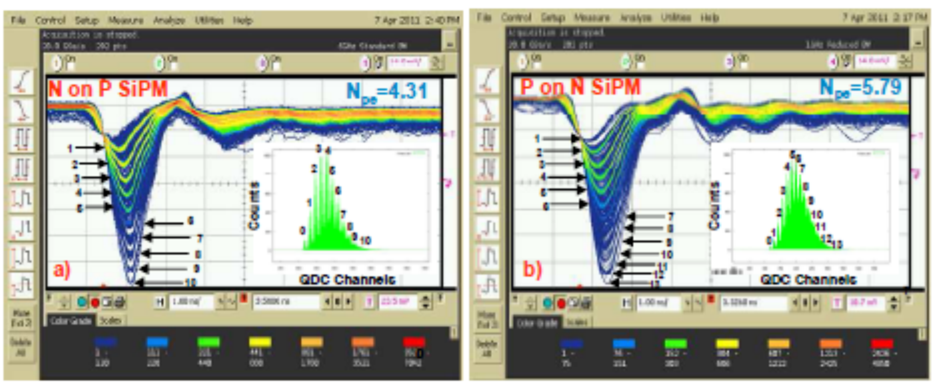


Fig. 2. Typical oscilloscope persistence snapshots obtained on N on P (a) and P on N (b) 10x10 SiPMs biased at 5V-OV and illuminated with very low light intensity at 405 nm. In the pictures single photoelectron charge spectra obtained in the same operating conditions are reported.

The P on N structure tested only with PiLas at Fermilab and shows better SPTR timing than N on P. The presented test beam results refer only to N on P. P on N test will be next. Noise amplitude <1 mV/50 Ohm.

SPTR is also dependent on SiPm size, pixel size, OV, temperature. Better for smaller SiPm size. SPTR is about 70 ps for 1x1mm2 diode size, 170ps for 3.5x3.3mm2. SPTR Improved with overvoltage increase.

N on P and P on N Performances Summary

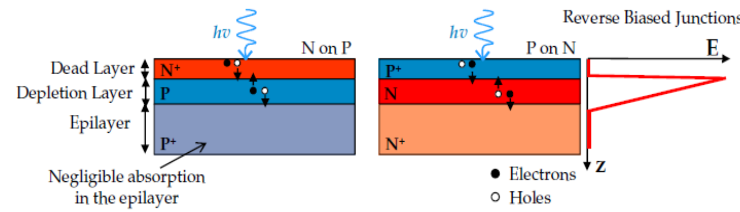
SiPMs with 45% fill factor

405 nm, 5 V OV, RT

Parameter	N on P SiPMs (standard)	P on N SiPMs (prototypes)
BV (V)	28.3	28.8
R_{Quench} (KΩ)	265	265
τ_{Rise} (ns)	≈ 1	≈ 1
τ_{Quench} (ns)	2.5	2.3
τ_{Rech} (ns)	92	78
C_{micr} (fF)	186	158
Gain	5.80×10^6	4.95×10^6
PDE (%)	21.7	31.1
QDE (%)	48.2	69.1
DNR Density (MHz/mm^2)	0.65	1.25
SPTR (ps)	231	174

Better Performances
Similar Performances
Worse Performances

420 nm ~ 50% of the photons absorbs in 150 nm of Si



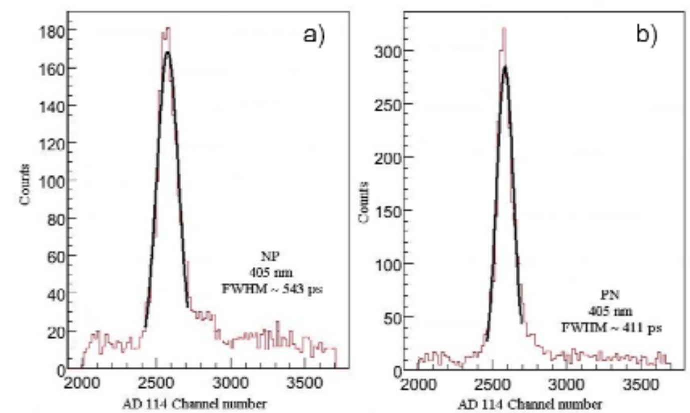


Fig 9. Typical single photoelectron timing spectra obtained on 4x4 mm^2 N on P (Fig. 9 a) and P on N (Fig. 9b) SiPMs at 24 °C, 5 V OV and illuminated at 405 nm.

Results confirmed on different area SiPMs.
Characterization in progress!

N on P SPM30 and SPM42– Layout Characteristics

SPM 30

Parameters	Unit	SPM30-60	SPM30-75	SPM30-100
Pixel size	μm^2	3000 x 3000	3000 x 3000	3000 x 3000
Pixel active area	mm^2	9.0	9.0	9.0
Number of cells in one pixel		2500	1600	900
Cell fill factor	%	45.4	55	66
Cell size	μm^2	60 x 60	75 x 75	100 x 100

SPM 42

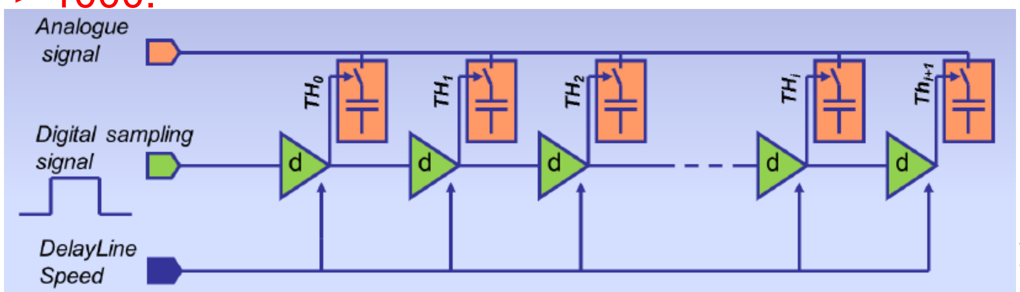
Parameters	Unit	SPM42-60	SPM42-75	SPM42-100
Pixel size	μm^2	3960 x 4440	3976 x 4476	3976 x 4470.4
Pixel active area	mm^2	17.6	17.6	17.6
Number of cells		4866	3342	1742
Cell fill factor	%	45.4	54.2	66.1
Cell size	μm^2	60 x 60	71 x 75	100 x 100

Why SiPms and DRS4 for the fast TOF application?

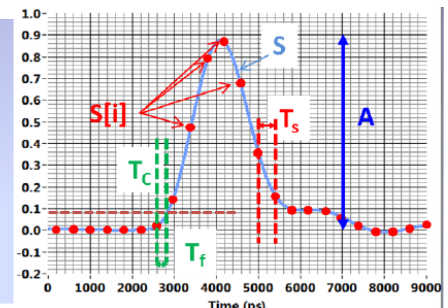
• the avalanche spread very fast || to surface. The avalanche size is ~10um. Single photoelectron time resolution (SPTR) is at the level of 100 ps, our SPTR measurements approved it.
• perfect single photoelectrons spectra which allows easy calibration.
• PDE for the blue light is at the level of 50%. For TOF we don't care too much about optical crosstalk. But we also studied SiPm with tranches.
• non sensitivity to magnetic field, what extend SiPm TOF application.
• low amount of material introduced into the particle's path to get few tens picosecond time resolution.
• "high" voltage bias applied to SiPms is only 30-70 Volts.
• the industrial sensitive size of SiPms is 5x5mm2 is currently available
• SiPms produced with almost edgeless design, which allows produce different geometry, like matrix, cells in line, etc.
• temperature and bias voltage stability requirements defined to keep few ps level. It is not a problem now for TOF application.
• we involved in STM study and have perfect feedback with producers.
• DRS4, waveform digitizer, 5Gs/s (200 ps/sample), 500 MHz BW, 10 bits depth/ch.; allows to measure time interval with few ps accuracy and pulse height (PH) simultaneously at low cost (wrt. Ortec). Last version #4 with ~1 mV/50 Ohm noise floor.

DRS4, (Domino Ring Sampler), introduced by Stefan Ritt, PSI

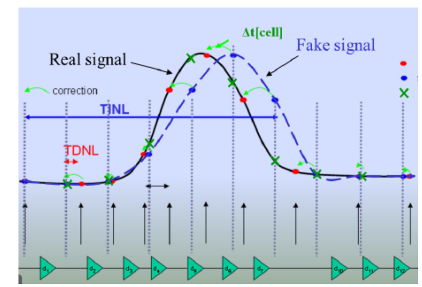
Principle: Sample & Store an incoming signal in an array of capacitors, waiting for (selective) readout and digitization= bank of Track & Holds. DRS4 can replace old classic TDC, ADC traditional readout. PH and TR measured by the same unit. Used one is capable to digitize 4 input channels at sampling rates 5 Giga-samples per second (GSPS, 200ps/cell). Individual channel depth of 1024 bins and effective range of 12 bits. BW is up to 850 MHz. DRS4 is based on Switch Capacitor Array (SCA). "Aperture" and "random" time jitter. Correction of "aperture" jitter. Noise floor ~1 mV/50 Ohm (Slides below taken from Stefan Ritt (DRS4) and Eric Delagnes (LAPPD). S/N > 1000.



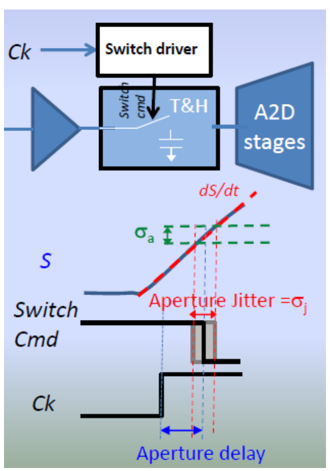
Switch Capacitor Array (SCA).



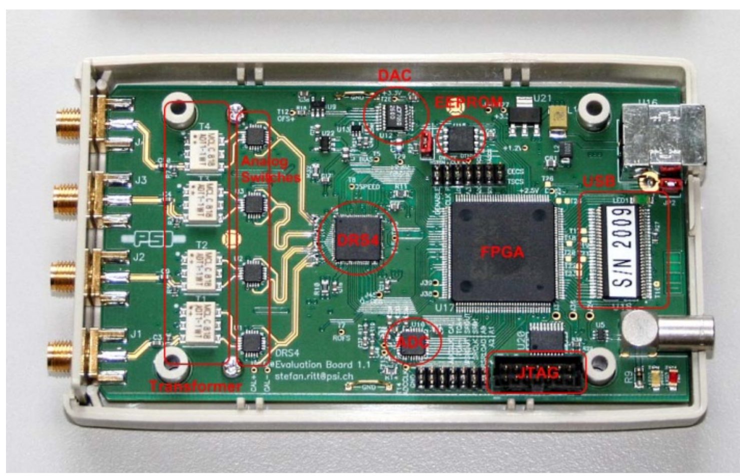
Signal sampling



Correction of "aperture" jitter



Key parameters of DRS4



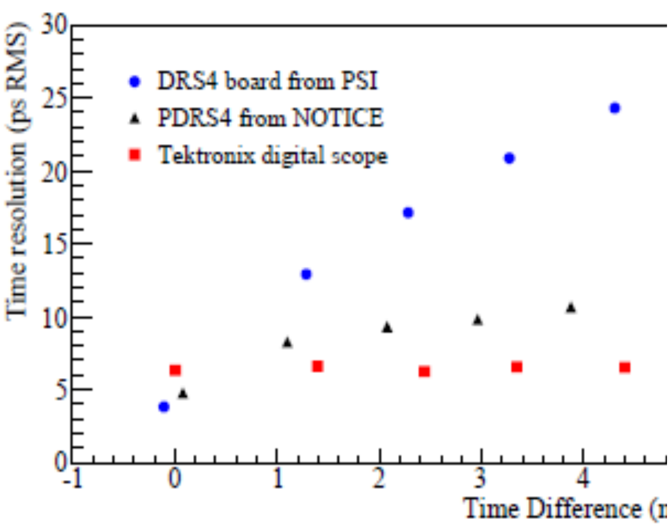
DRS4 unit open, (old) version

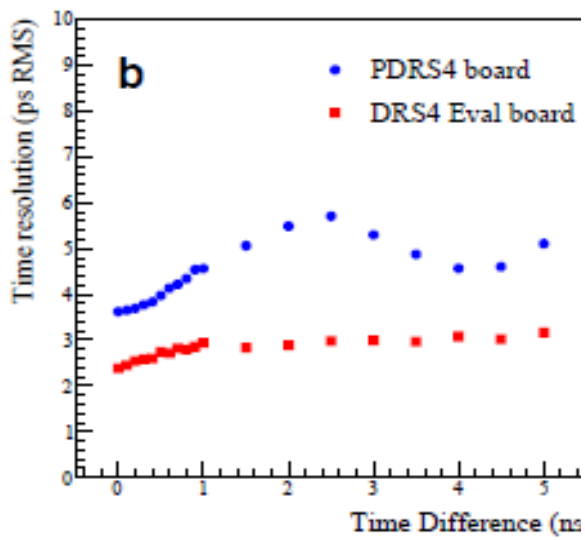
DRS4, last version

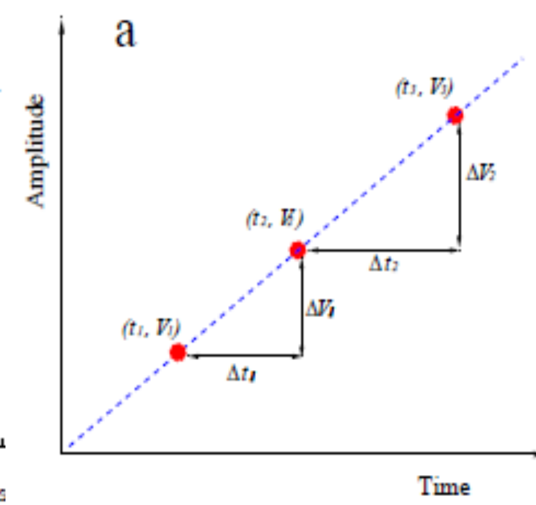
CAEN V1742

New DRS4 calibration method

- Each of 1024 sample has different time length, so called “aperture” jitter which can be corrected. “Random” time jitter is another issue.
- We report a new time calibration method for DRS4-based waveform sampling electronics. Based on the linearity of the sawtooth-shape pulse, the method can calibrate the individual sampling intervals associated with the 1024 capacitor cells of the DRS4 from differential-voltage measurements. After applying this method, the large variation in the sampling interval of the DRS4 chip is clearly revealed. The dependence of the time resolution on the time difference of two pulses, which has been observed by using other time calibration methods, is significantly reduced after applying the proposed calibration method, and we are able to achieve 2.4 - 3.2 ps RMS time resolution for the time difference in the 0-5 ns range. The proposed time calibration method was applied to two different readout boards using the DRS4 chip and could be applicable to other waveform sampling electronics based on switched-capacitor-array technology. We got “electronic” time resolution for the DRS4 (200 ps/bin) close to the Ortec readout 3.1 ps/bin).





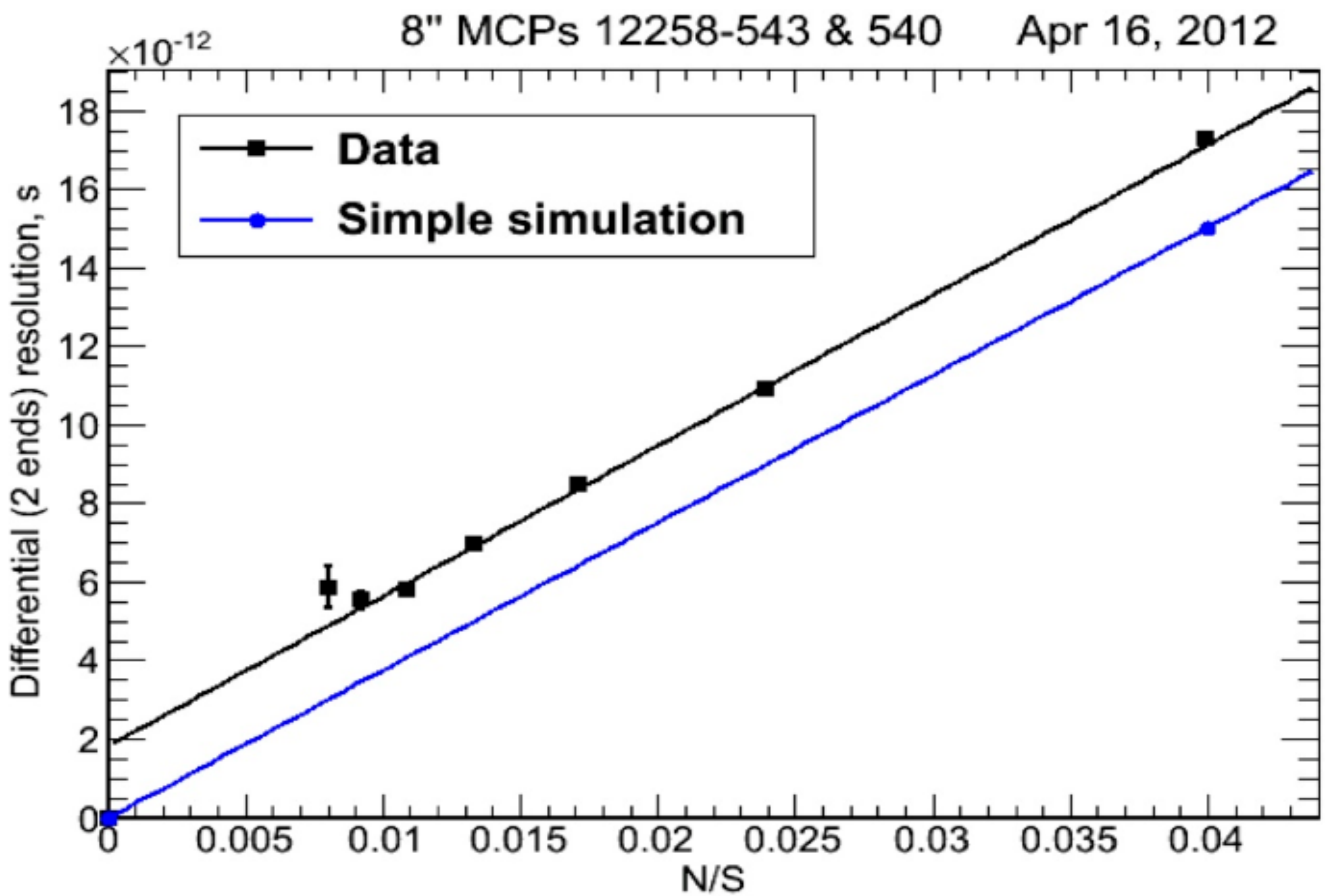


Noise floor still deposit into the DRS4 time resolution (e.g. for zero delay).

Time resolution vs noise level

•

LAPPD result

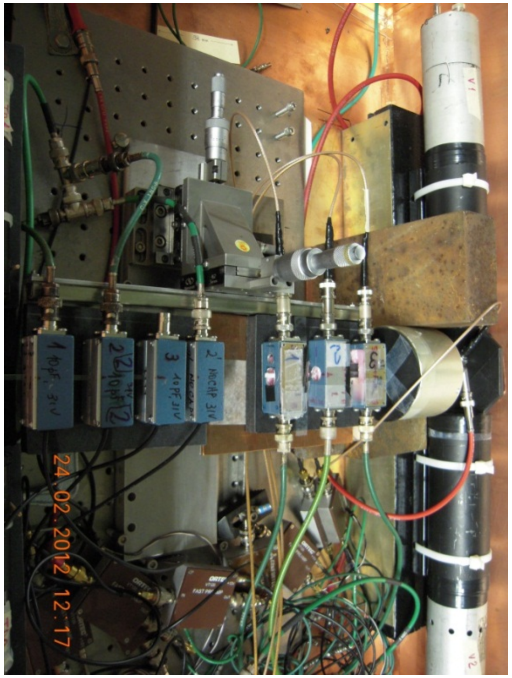


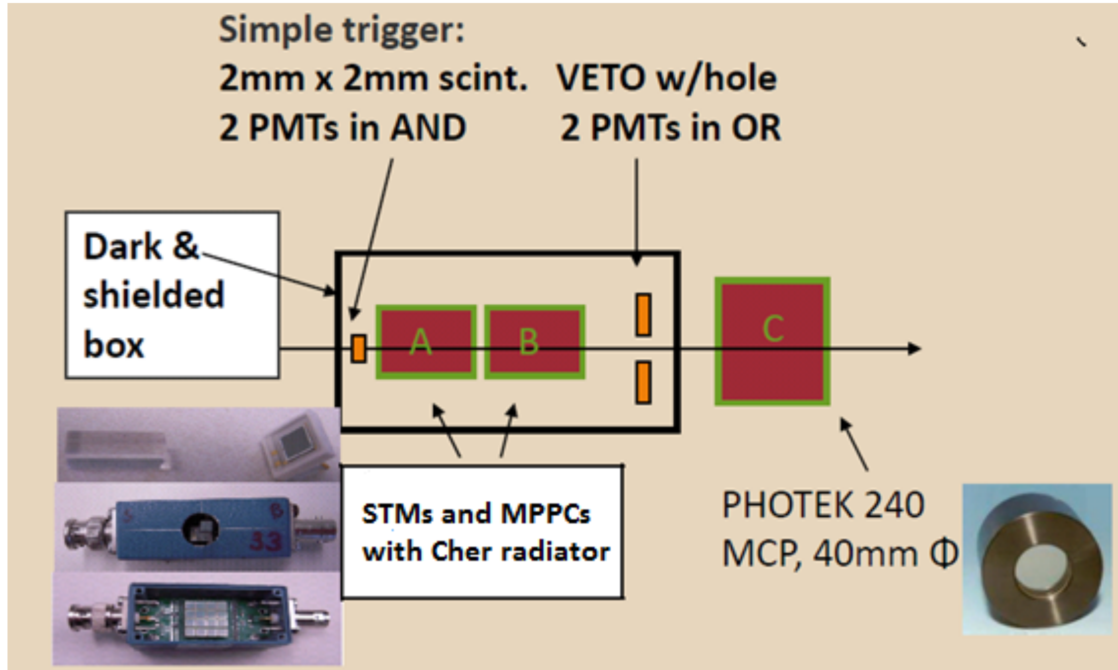
N = RMS of the noise; S = signal amplitude

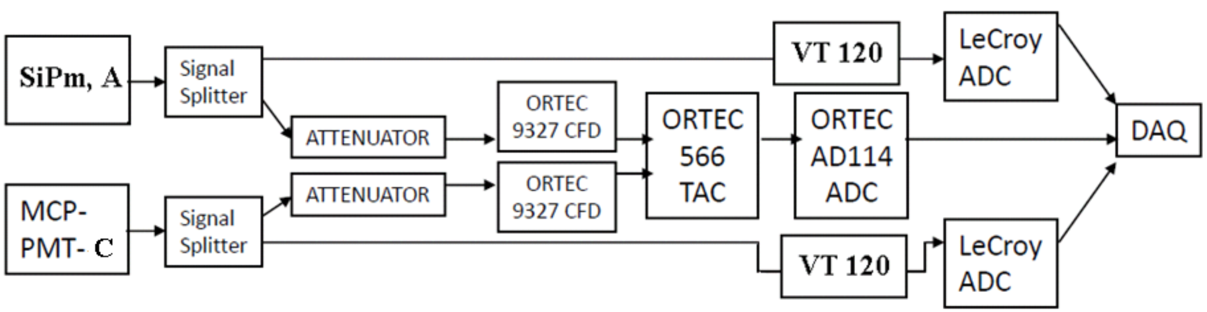
Simulation has many more points than shown. All are very well consistent with the blue line.

T-979 Setup in Fermilab Test Beam Facility (FTBF)

Time interval between “start” (SiPm) and “stop” (SiPm or Photek 240) signals is measured value. Beam: 120 GeV protons. Light is generated in fused silica radiator for the SiPms and in the Photek 240 input window at normal particle incidence.

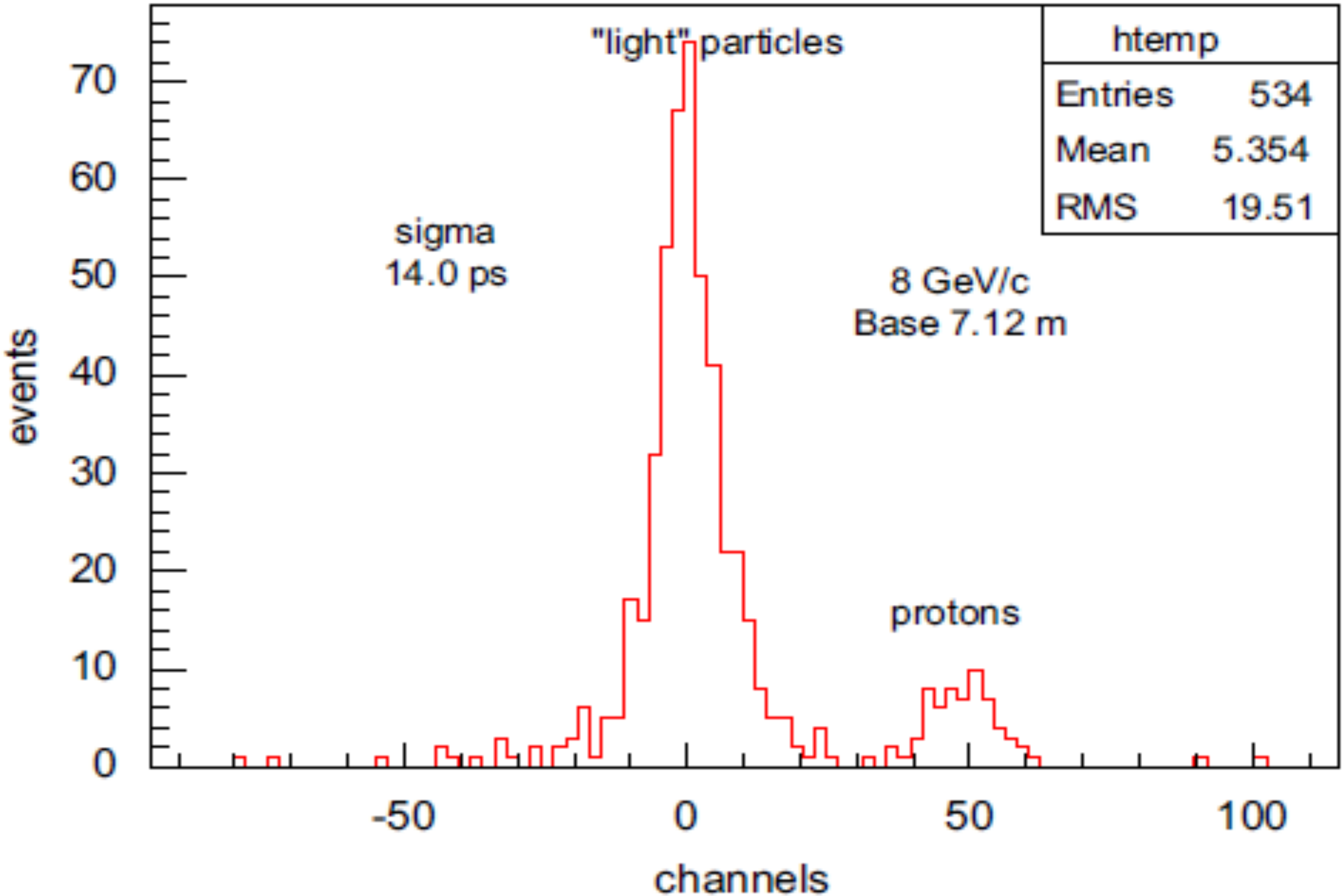




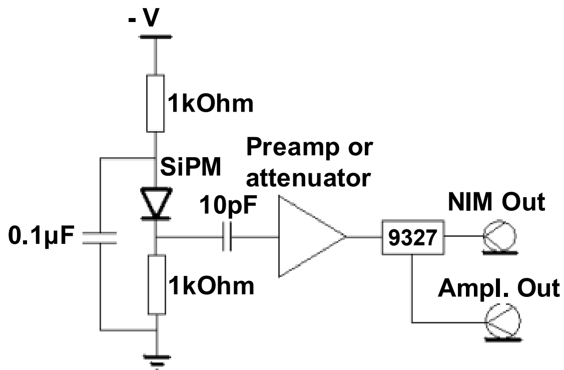


ORTEC readout:
CFD – constant fraction discriminator,
TAC – time amplitude converter,
ADC – analog to digital converter, ~16,000 channels, 3.1 ps/ch
“Electronic” time resolution (ETR) is 2 ps.

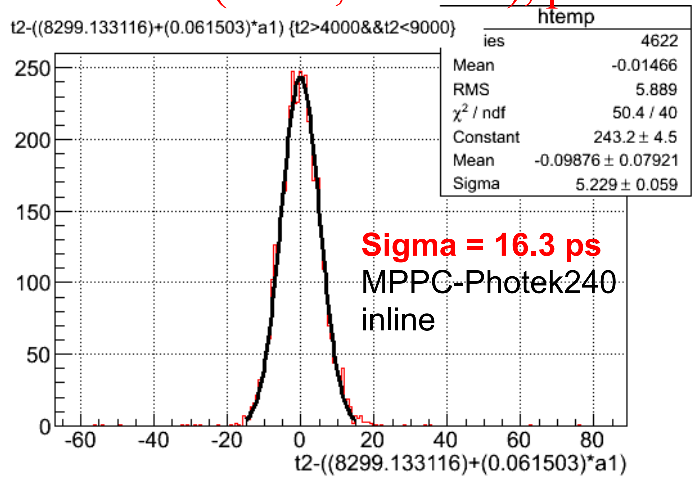
TOF system at FTBF based on Photek 240, ~13 ps time resolution



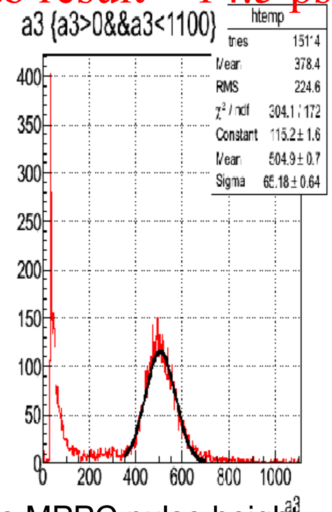
STM signal clipped to fit Ortec 9327 CFD (<5 ns, FWHM), previous best tb result – 14.5 ps



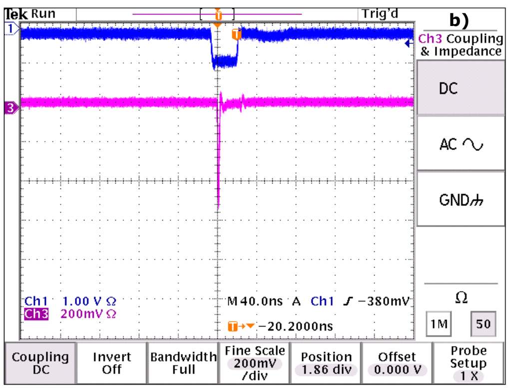
Schematic of STM biasing and readout

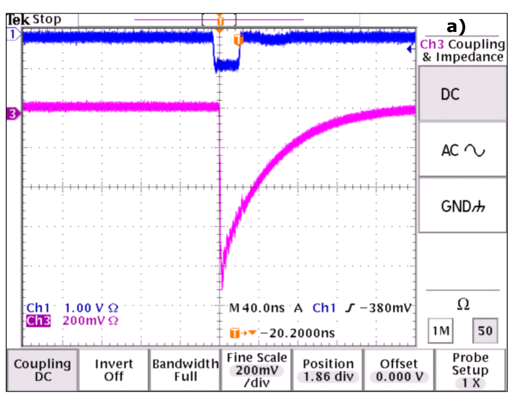


Timing difference spectrum for signals coming from MPPC (radiator is fused silica, 3x3x30 mm3) and Photek 240 (radiator is input window, 9.6 mm thick). 120 GeV protons. Normal incidence. The MPPC time resolution is 14.5 ps. Soft pulse height cuts and slewing correction applied. Both “start” and “stop” counters located next to each other.

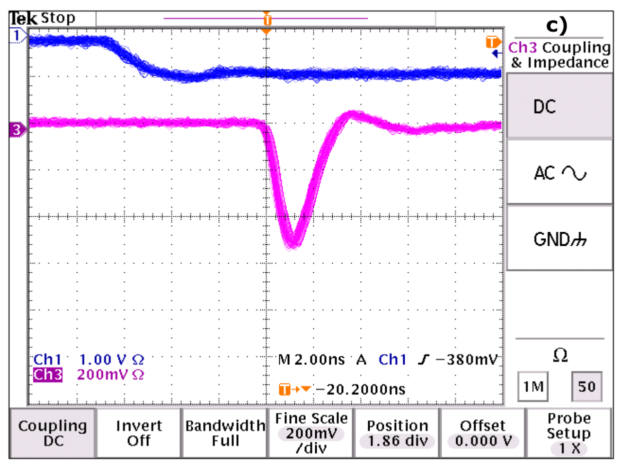


The MPPC pulse height spectrum, 120 GeV protons. Quartz radiator, 3x3x30 mm3
N of photoelectrons ~ 60 phes

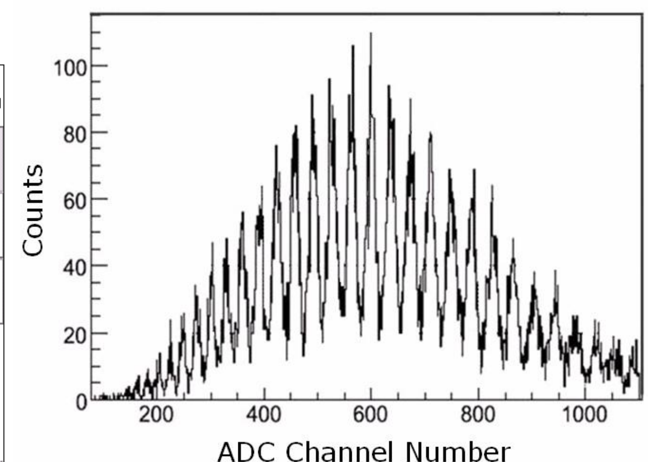




STM signals with (top) and w/o (b) clipping capacitance, 40 ns scale

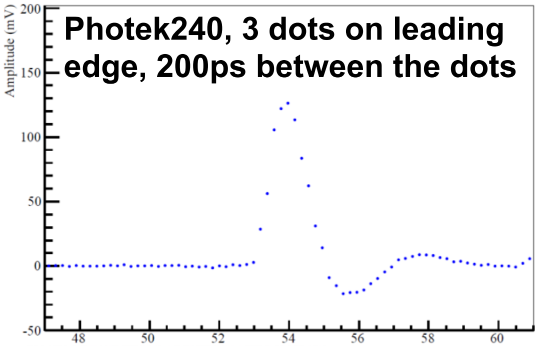


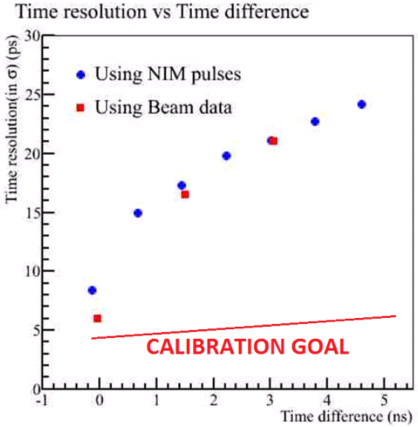
STM signal with clip cap, 2 ns scale

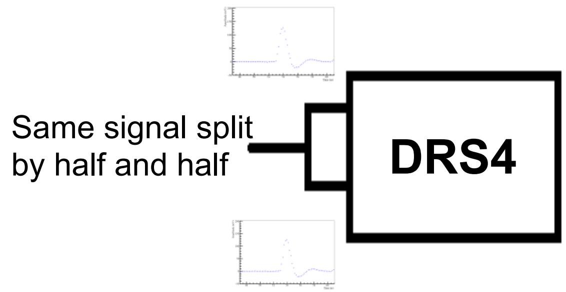


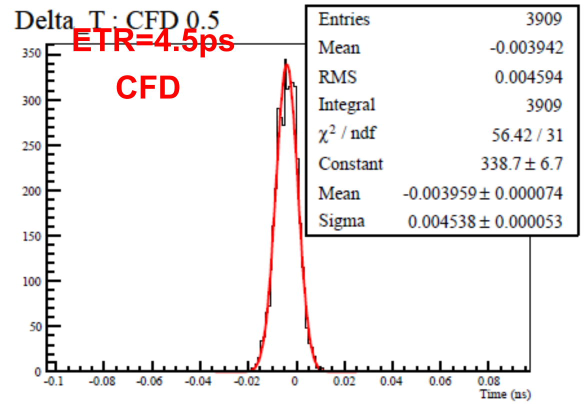
STM pulse height spectrum, mean number of photoelectrons = 17 phes. STM is 3.5x3.5mm2, 4900 pixels, 48x48um2 pixel size, 3.5V of OV.

Test Beam results (2001). ETR. New STMs. DRS4 readout.



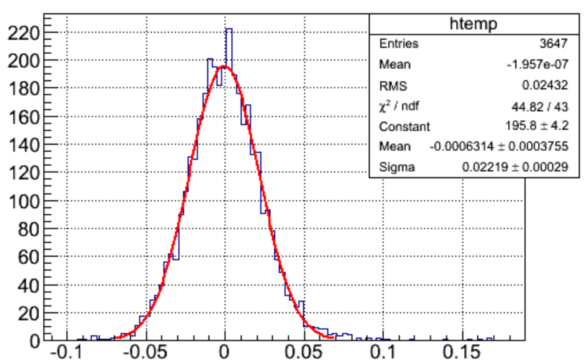




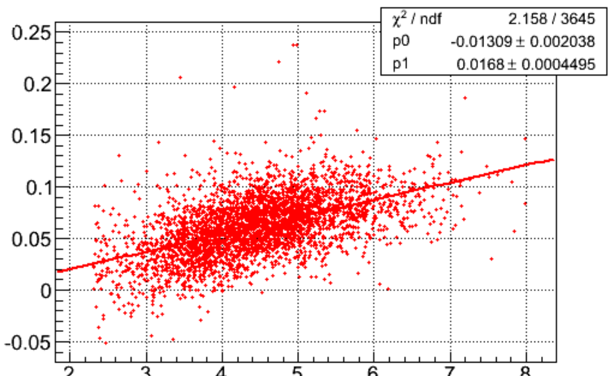


Electronic Time Resolution (ETR) of the DRS4 depends on delay between "start" and "stop" signals. Start and stop signals are halves of the same signal (Photek240 on the beam or NIM pulse". DRS4 should be calibrated for the time resolution. For the result shown above the delay was ~ 0ps. Noise floor is still deposit into the DRS4 ETR. TR is the same for both "clipped" and "non clipped" STM signals (also as with PiLas). This allow to get the same high TR without clipping capacitance and amplifier for STM

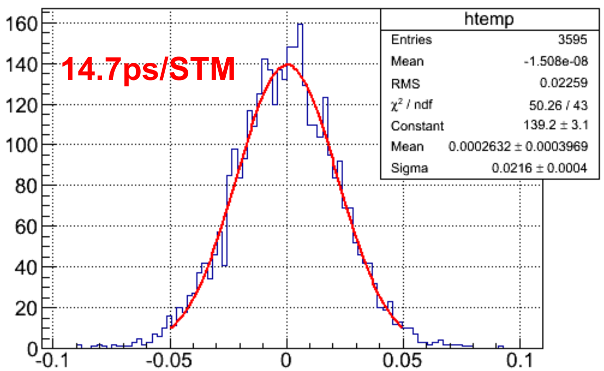
Example of TB data are below. Conditions: 2 STMs with 30mm long quartz radiator, both along the beam line, (second behind first), 120 GeV protons, normal incidence, TR at the level of 14-15 ps.



Time resolution (TR), 2 STMs



TR (ns) vs. amplitude, skew



TR after skew correction

 Anatoly Ronzhin, February 17, 2015, Hawaii

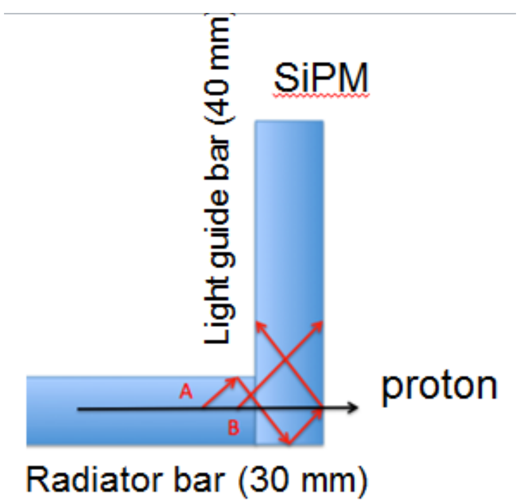
QUARTIC Timing detectors for HPS240

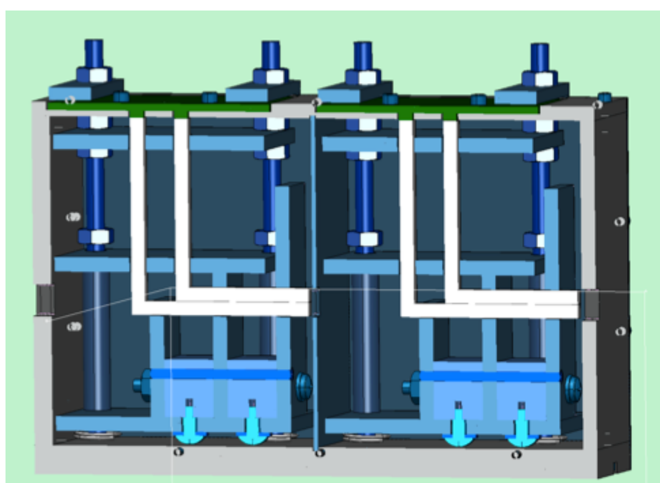
Baseline for timing is : **GASTOF** (very fast, but not segmented) plus **QUARTIC** (segmentation for multi-hit timing, less resolution). Both in series. GASTOF in front (less material).

Requirements of system:
Time resolution ~ 10 ps
Area ~ 10mm (V) x 20 mm (H)
Segmentation for > 1 proton/bunch
Edgeless, active to ~ 200 um from pipe
Radiation hard
Lifetime > ~ 1 year at LHC at 10^{34}
Rate: 25 ns sensitivity

At Fermilab we have built and tested (14-18.2) in beam a **QUARTIC** prototype, solving technical issues and achieving 20 ps in a 4-bar (in z) module with 3mm x 3mm elements. It uses quartz (fused silica) L-shaped bars: 30 mm radiator bar and 40 mm light guide bar read by a silicon photomultiplier (SiPM).

Team: M. Albrow, A. Ronzhin, S. Los, E.Ramberg, A.Zatserklyanyi, J.Kim, S. Malik



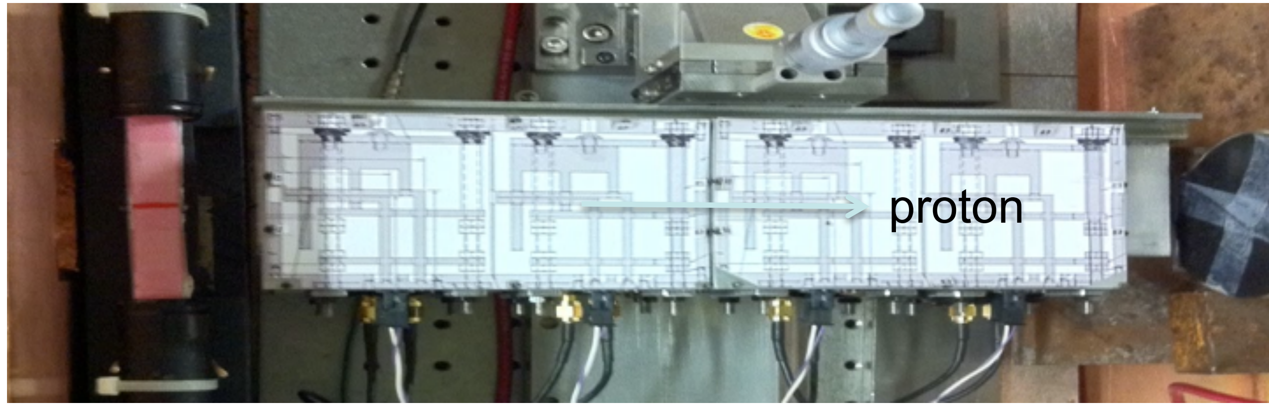


Principle: All Cherenkov light is totally internally reflected to back of radiator bar. ~ 50% goes up LG.

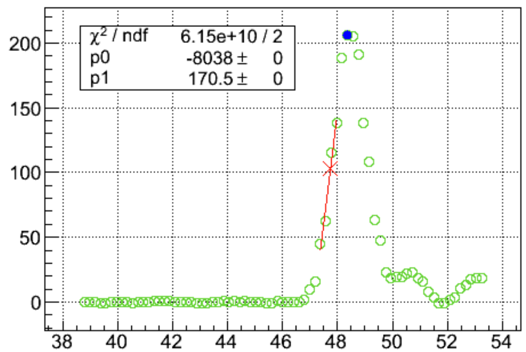
Maintain TIR: nothing touches surfaces,
except minimal at corners. Bars separated by
fine wire (100 um) ... keep TIR.

Four units in test beam, 2mm x 2mm trigger counter + Photek240 reference (7<ps)

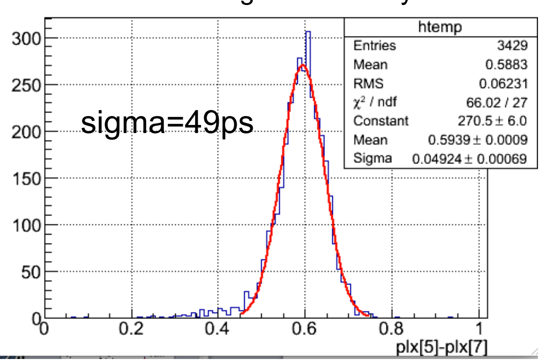
70V on SiPMs, Clip signals (9pF) & x 20 preamp.
→ DRS4 5 GHz waveform digitizer. Read 8 traces (200 ps/point)20 mV/div.



(Drawings glued on boxes for alignment only)

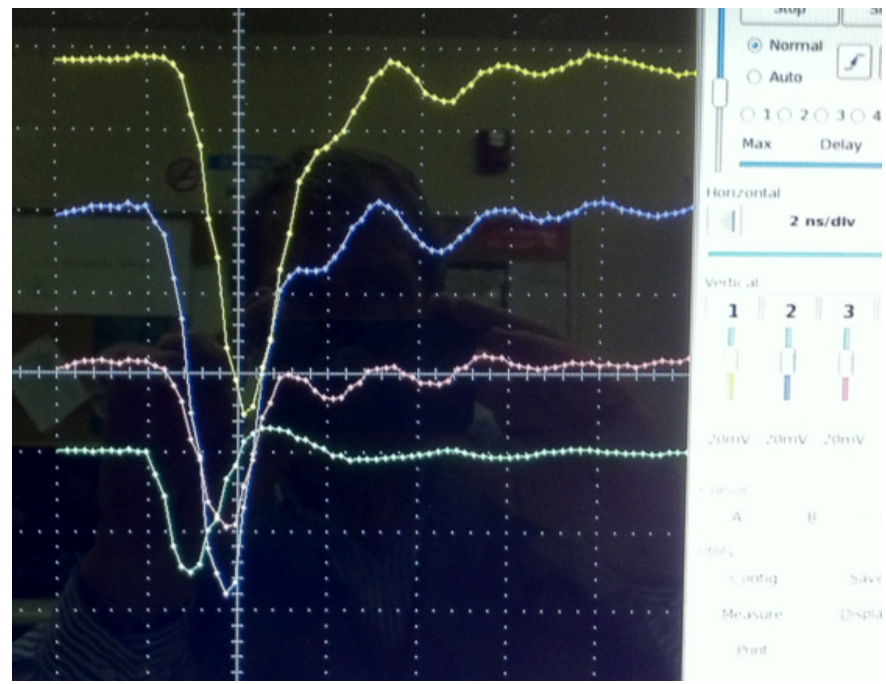


Preliminary fit for t:
50% point, interpolate -2 & +2 points
No time slewing corrections yet.



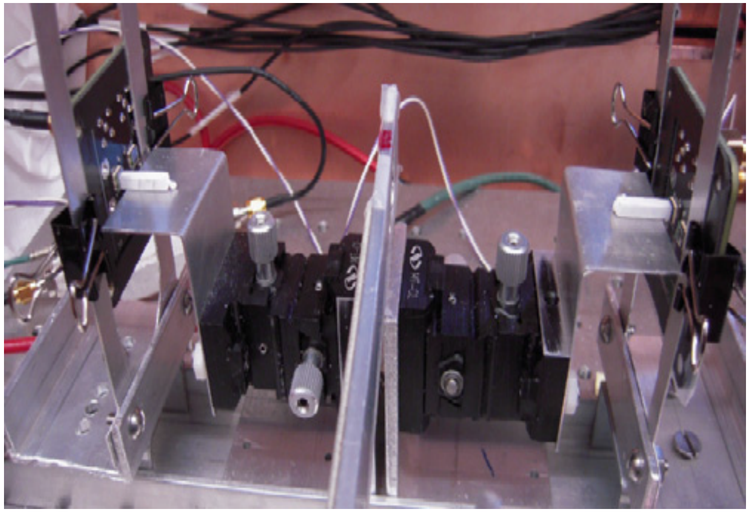
Bar 1S – Ref, σ = 49 ps.
Bar intrinsic 42 ps
With PH slewing correction < 40 ps

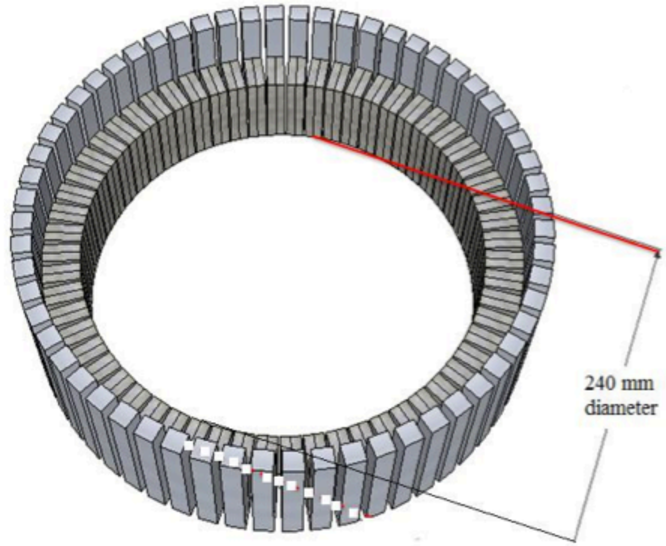
We have now ~40 ps/bar, and with 4 (independent) bars that is sigma(t) = 20 ps &
combined with GASTOF we are there. That is today, but there are possible improvements (later).

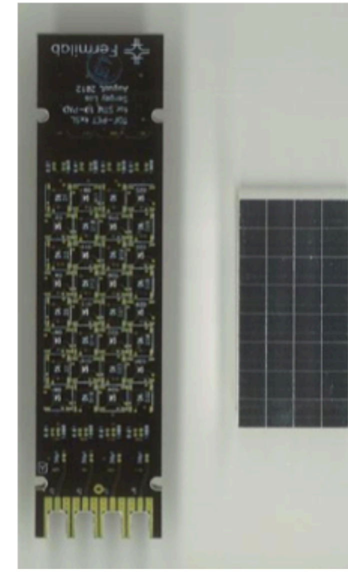


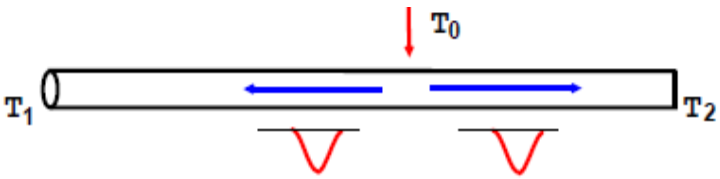
DRS4 readout. One event: 3 bars in line, STMs, channels 1,2,3. Ch4 – Photek240, reference

Medical application, R&D phase. “Helmet brain scanner”. Strip Line (SL) readout.

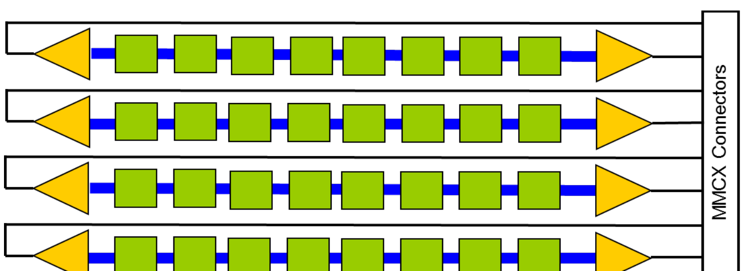


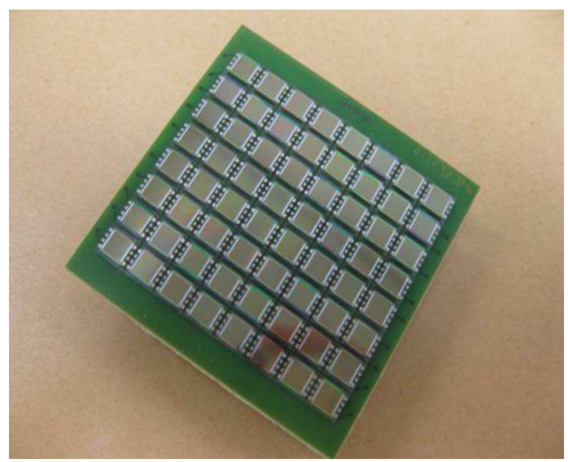


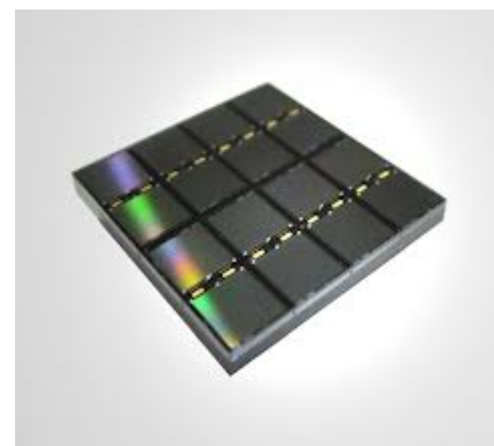




Strip Line (SL) principle. T1-T2 time difference measured to define place of particle pass along the SL







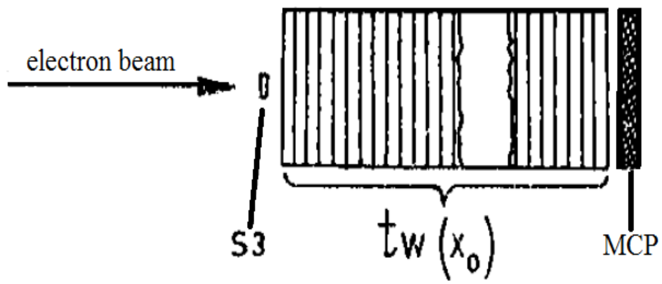
We have performed a study of silicon photomultipliers (STM and MPPC) with 3x3x15 mm3 LYSO crystals for TOF-PET applications. We obtained 75 ps, sigma, best result in the world.

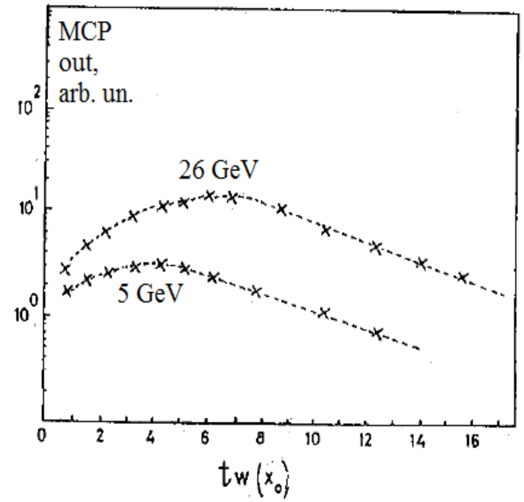
Two main options of the “final helmet”: SiPMs matrix or Strip lines (SL) readout.

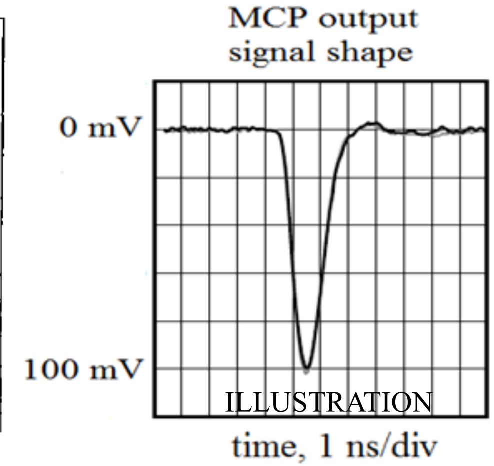
Shower Maximum (SM) detectors and Secondary Emission Calorimeter (SEC) based on micro channel plate (MCP)

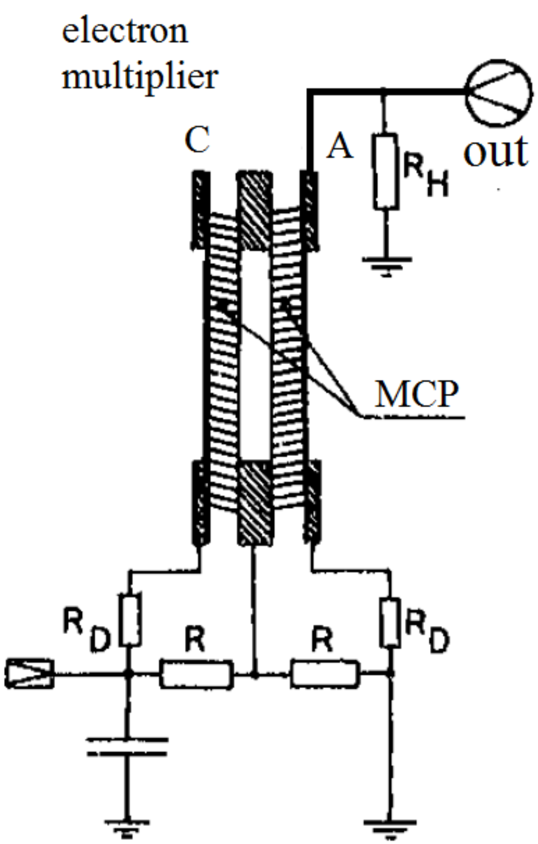
- The active materials used in shower maximum (SM) detectors and calorimeters at high luminosity hadron colliders are scintillators, crystals, quartz fibers, etc. These materials suffer from damage after experiencing radiation dose larger of 50 Mrad and need to be replaced by more radiation resistant materials as integrated luminosity increases. An additional big challenge is to improve the timing properties of the detectors. They should operate at counting rate ~107/s and be capable to reduce the background from multiple collisions. The proposal described below could satisfy these requirements.
- The use of secondary emitter materials as an active element in sandwich type calorimeters allows the development of a new type of detector that is highly radiation resistant and fast. One of the options is to use micro channel plate (MCP) as secondary emitter. But the high cost of the MCPs has limited its application in practice. With the recent progress of the Large Area Picosecond Photo Detector collaboration, the cost may decrease sufficiently to allow practical construction of this type of detectors.
- In 2014 we have successfully measured time resolution of a single layer of the device based on micro channel plate photomultiplier (MCP-PMT). The detector's time resolution dependence on absorber thickness placed upstream of the MCP-PMT was measured. The measurements were performed at FTBF. We used secondary beams with 12 GeV and 32 GeV of energy. This initial study allowed us to estimate deposit of Cherenkov light and direct secondary emission in the detector response. We can see that MCP secondary emission in the detector response is very high (70% for the Photonis 85011 MCP PMT). We got ~20 picosecond time resolution with Photek 240 MCP-PMT (best in the world so far).
- In this LDRD, we plan to measure the main parameters of the similar detector but without photocathode (just bare MCP). Another part of the project is to make calorimeter prototype with many layers of secondary emitters based on a big size MCP (200x200 mm2) which produced in frame of the LAPPD project. We also plan to test the secondary emitter based on PMT dynode system. Radiation hardness of the secondary emitters described above should be measured. We can use few Fermilab radiation area for that. We can answer three important questions in frame of the project.
- 1. What limit of time resolution and counting rate of such a detectors.
- 2. What the magnitude of the radiation dose which still allow the detectors survive.
- 3. Estimate the cost of the detectors.
- The performances of the shower maximum detector with secondary emission layer as an active element is already well understood and demonstrated. We have fully operational setup for the planned measurement (except of radiation hardness test) at the FTBF. Therefore, the LDRD funding, if awarded, will be mainly used for the installation and operation for the calorimeter prototype, M&S and technical/engineering efforts of setting various detector's options, and efforts for the scientists for the data taking and analysis. Part of the funding can be used for the radiation study.
- We believe this is an innovative idea can find a lot of application in calorimeters for physical experiments. We see requirements of fast and radiation resistant calorimeters for the CMS LHC upgrade, as well as for Fermilab experiments with high beam intensity (e.g. Mu2e). This is the first step towards producing a new type of calorimeter which can be very useful for future experiments.

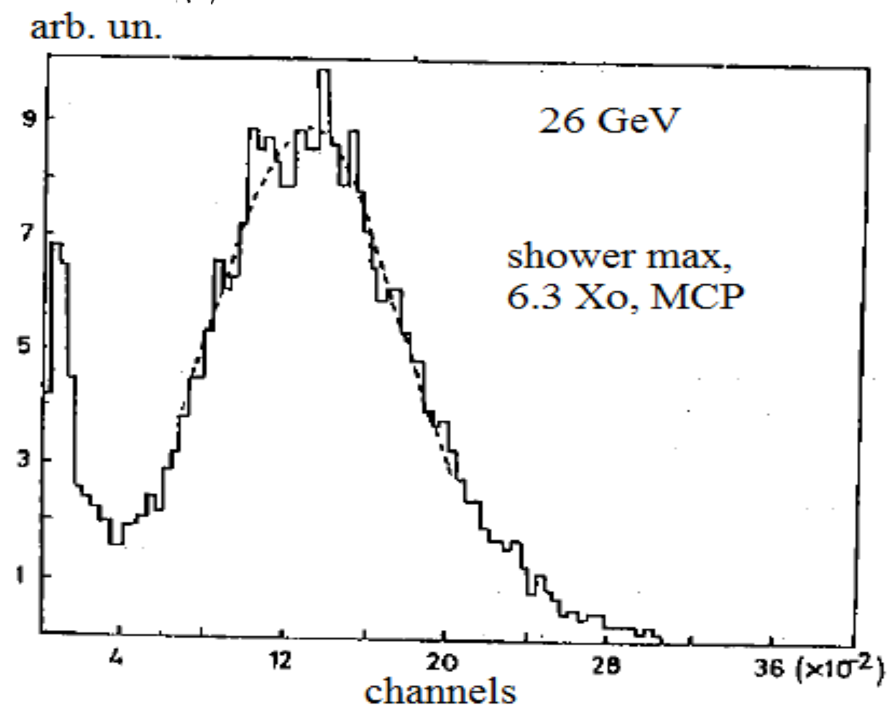
New type of Shower Max (SM) detector. Radiation resistant and fast.







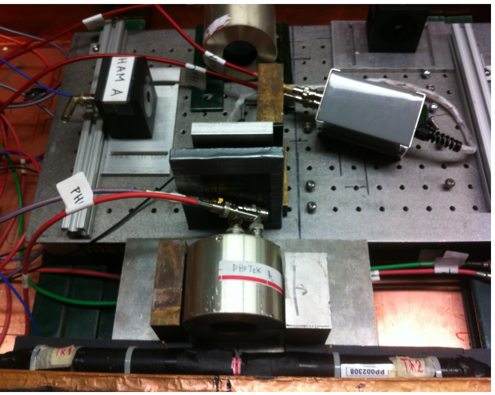


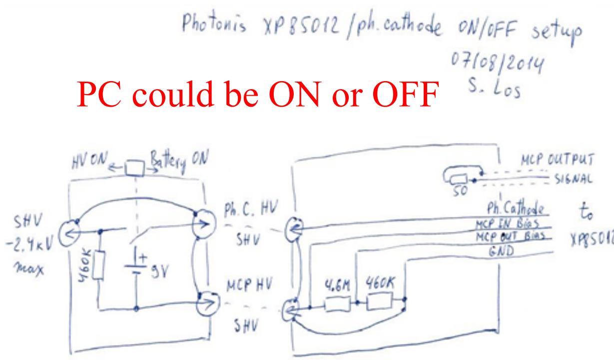


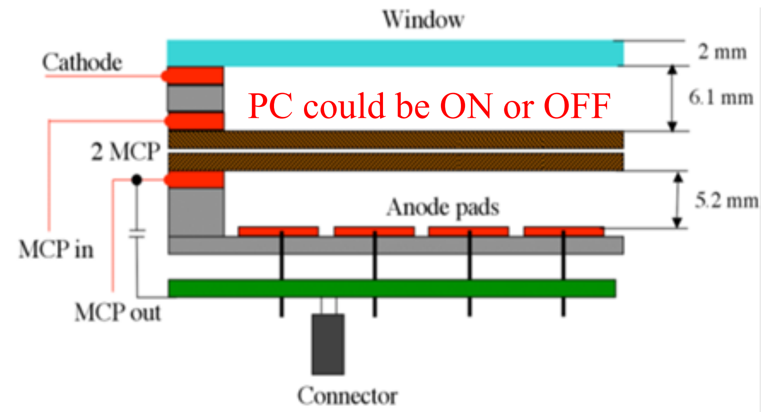
Just narrow slot (~10 mm) needed to insert the SM into existing calorimeter (CMS upgrade?)

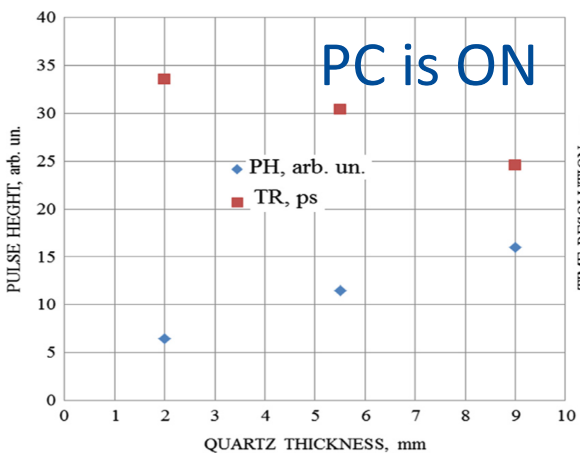
Development of a New Fast Shower Maximum Detector based on Micro Channel Plate as an active element

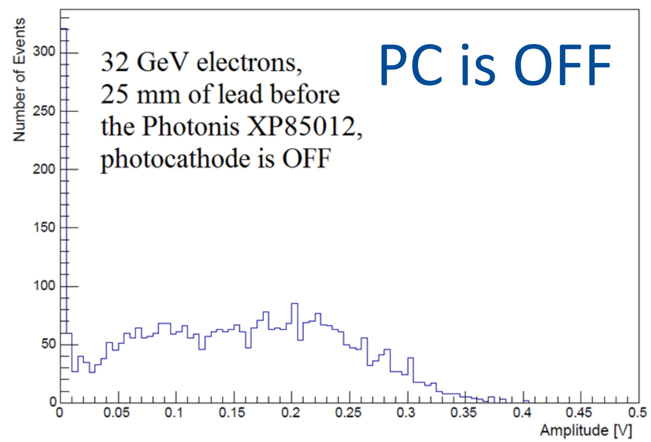
Direct measurements with Micro Channel Plate (MCP) as shower maximum detector performed at the Fermilab Test Beam Facility with 120 GeV primary proton beam and 8 GeV, 16 GeV and 32 GeV secondary beams. We obtained time resolution for the SM detector based on the MCP at the level of ~40 ps and ~100% registration efficiency. This demonstrate that SM secondary particles detect well by the MCP.

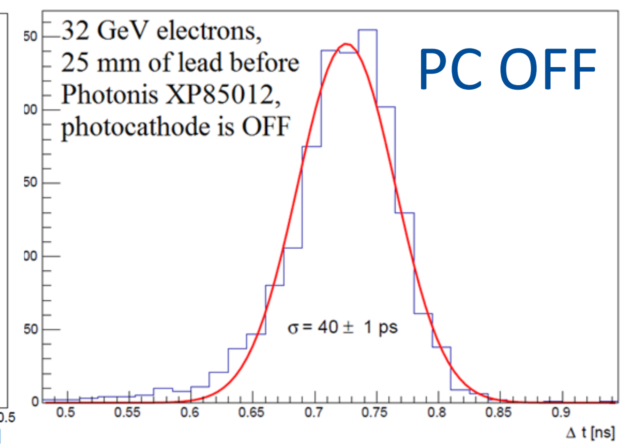






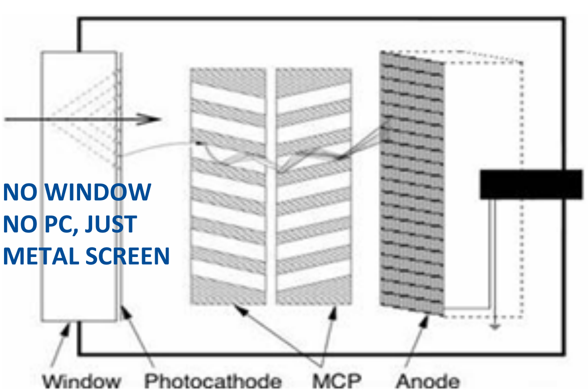


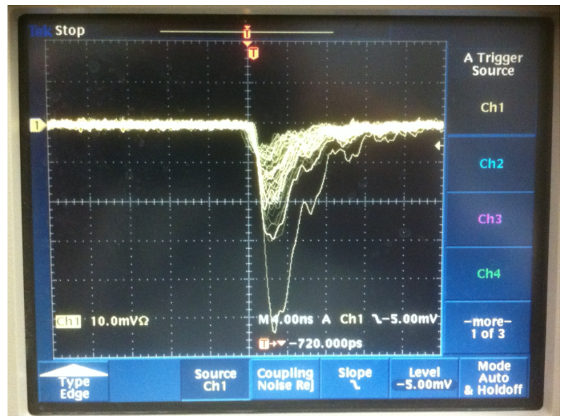


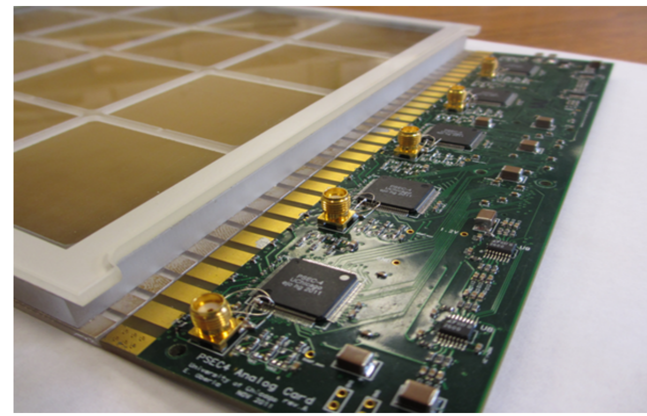


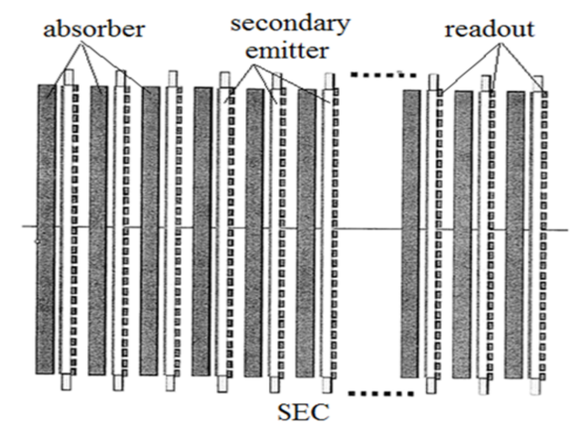
Test of Shower Maximum (SM) Detector at FTBF, TR ~40 ps, it is easy to insert the SM into Calorimeter, needs in ~13 mm of slot size (CMS?)

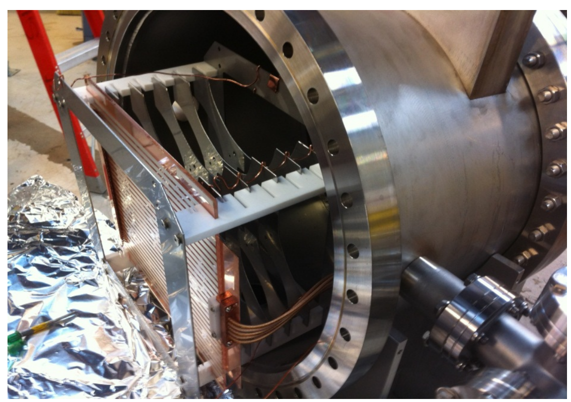
MCP is an electron multiplier that detects and multiplies electrons in two dimensions. MCP is also sensitive to ions, vacuum UV rays, X-rays and gamma rays and so can also be used as devices to detect their position and energy. MCP is a slab made from highly resistive material of typically 1 mm thickness with a regular array of tiny tubes (micro channels) leading from one face to the opposite, densely distributed over the whole surface. A standard MCP is produced by chemical etching of a fused fiber optic that is produced using specialized (and expensive) core and clad glass. The core glass is etched away from the plate and the cladding is hydrogen fired to produce a thin layer of semi- conducting reduced lead oxide on the surface of the MCP pores. INCOM's MCP is fabricated using a unique hollow draw process that eliminates the need for a specialized core glass that needs to be removed.

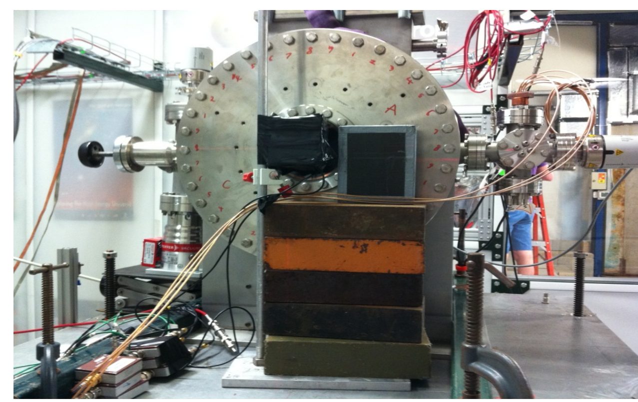








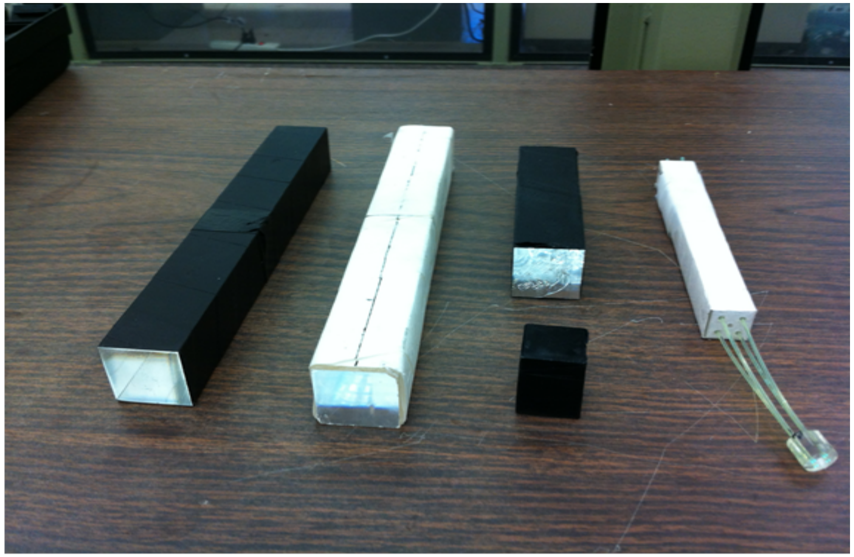




SM on MCP's (chevron), size inside 8"x8" - 2"x2", SL or pixel readout.

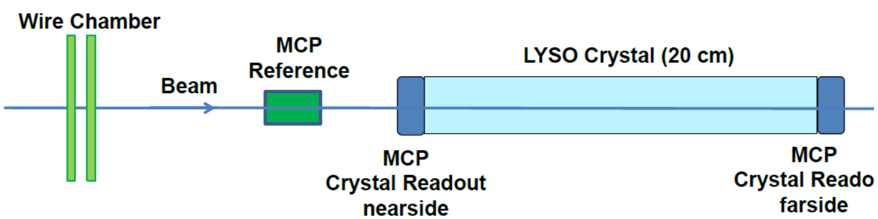
- Our plan is to continue study of the Photonis XP85012 as active element of a Shower Maximum (SM) detector (with photocathode, PC OFF) at the next FNAL test beam. The XP85012 with PC OFF (only MCPs were active element of the MCP-PMT) was already tested as the SM detector. We have obtained ~ 40 ps ps time resolution in the energy range 8 GeV- 32 GeV. The sensitive area was 24x24 mm2 (custom made single anode size). The readout was based on DRS4. We made measurements with different thickness of the lead as absorber upstream of the XP85012 (PC is OFF).
- The current goal is to improve the SM Time Resolution and to measure the SM Space Resolution at different beam energies with better anode pixelization (we have 6x6 mm2 of each pixel size). We plan is to check different thickness and materials of absorbers. The Strip Line (SL) readout also could be OK if we can get such a device. The device could be in between of 8"x8" – 2"x2" size range. We are ready for the beam test with 2"x2" device.
- The next will be study (as soon as it will be complete) of the Secondary Emission Calorimeter (SEC), approved T-1058 experiment at FNAL. Readout could be with DRS4 or PSEC, depending on schedule and budget.

R&D of PSEC Calorimeter with Crystals (Caltech for CMS), MCP-PMTs

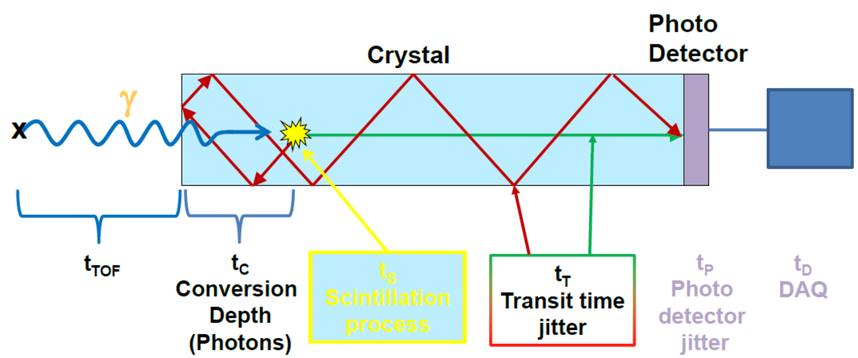


Test Beam – Longitudinal Setup

- Wire chamber used to define 16x16 mm area of the beam and as trigger. Beam size ~2 cm.
- Reference MCP : Photek, 40 mm active area.
- Crystal readout MCP : Hamamatsu, 8mm active area.

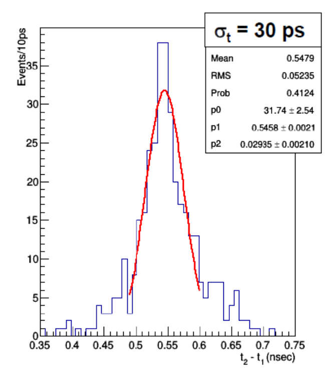


Electromagnetic Type Detection in Crystals

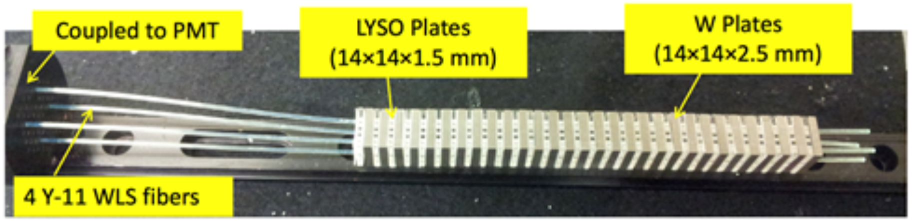


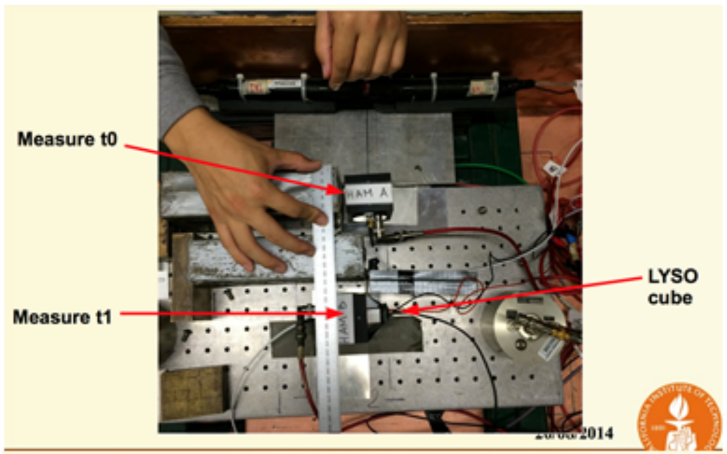
Longitudinal Setup

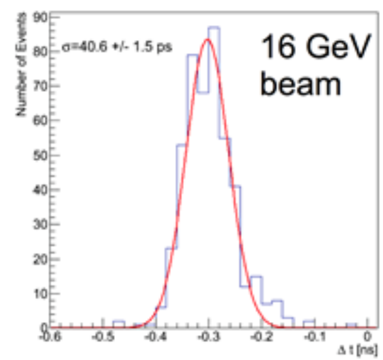
- Electron beam, 8 GeV.
- Differential time (near side – far side crystal readout) resolution : 53 ps, core width 30 ps. To be compared with the 160 ps from the cosmic muon test.
- In the longitudinal setup, transverse geometric spread negligible.
- Longitudinal shower fluctuation may impact timing measurement.

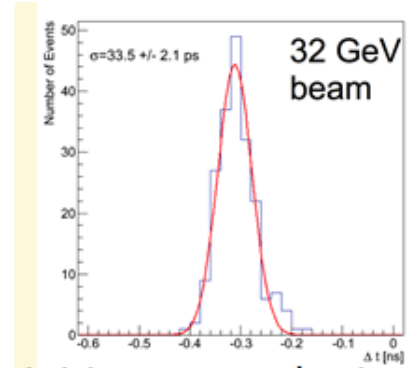


Timing with LYSO, Fibers, MCP PMT (CMS upgrade)

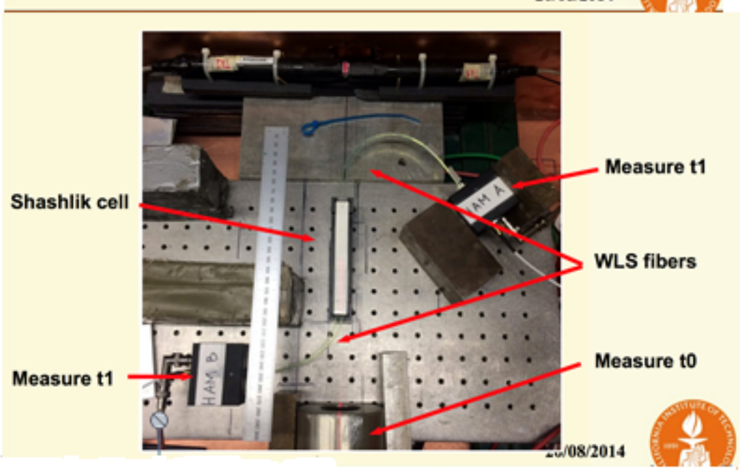


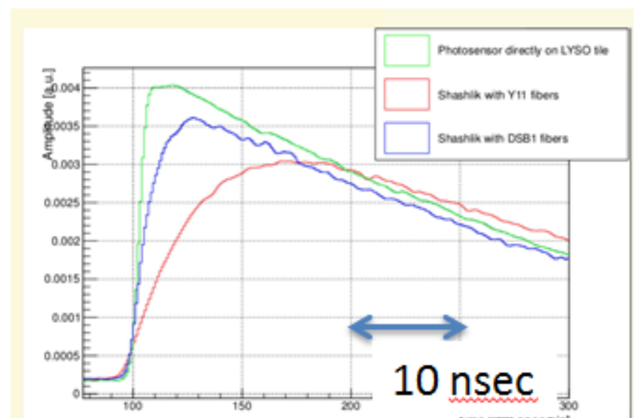






With lead as showering initiator, can obtain ~30 ps





Significant timing differences between fibers

Caltech, Fermilab

Summary

- Continue Fermilab TOF systems development. Our area: MCP-PMTs, silicon photomultipliers and new readout, based on fast wave forms digitizers (e.g. DRS4). Also Crystals now.
- Continue study of Shower Maximum (SM) detectors with active elements as secondary emitters (currently MCPs, may be others). Obtained few tens ps TR of the SM on test beam.
- The best TOF time resolution obtained with MCP-PMT is less of10 ps in beam conditions and is ~14.3 ps with SiPMs (new STMs which are not the best ones, new readout, DRS4, FTBF). Different algorithms to get best signal's timing tested. Leading edge, CF, MF are among them.
- 9 ps time resolution along Strip Line (SL) is obtained on FTBF beam.
- PET-TOF. Our current results, ~77 ps TR and 10% of PH (with MPPCs and 3x3x15 mm3 LYSO crystals) resolution are among the best.
- We have clear plan for FNAL PET-TOF development (depending on funding).
- Work together (including direct contacts) with STM producers (Massimo Mazzillo) and DRS4 inventor (Stephen Ritt). We benefit from direct contact with PSEC4 team in frame of LAPPD.
- Setup for new SiPm study with DRS4 readout arranged at SiDet. We have studied timing properties (Single Photoelectron Time Resolution (SPTR), signal shape dependence on SiPm structure, noise floor of several SiPms producers (STM, MPPC, IRST FBK, SensL, Kotura, MePhy, CPTA, etc.).
- Continue to investigate the influence of WL and SiPm structure on SPTR (PiLas laser) and optimize STM signal shape.
- Continue study of SiPm's TR in dependence on temperature.
- The TOF based on SiPms used in FTBF (FNAL), PET-TOF, HPS in future and in another projects, plans.
- We need to measure rad resistance of the MCP.
- Study the TR and PH resolution of SMs with MCPs different size, different absorber materials and different readout. Currently we are ready with XP85012 (PC OFF) as SM active element.