Ultrafast Detection in Particle Physics and Positron Emission Tomography Using SiPMs

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RICH 2016

University of Ljubljana

IJS

Motivation

Silicon photomultiplier (SiPM) is becoming the detector of choice in many applications, including particle and medical physics.

SiPM advantages:
- high photon detection efficiency
- good timing properties
- insensitivity to high magnetic fields
- low operating voltage
- compactness, robustness
- potentially low cost

Main remaining issues:
- high dark count rate (~100 kHz/mm²)
- not the best single photon timing (~ 200 ps FWHM)
- limited radiation hardness

Two examples, where the use of SiPMs as photodetectors has been successfully demonstrated:
- Ring imaging Cherenkov counters (RICH)

NIM A 787 (2015) p.203

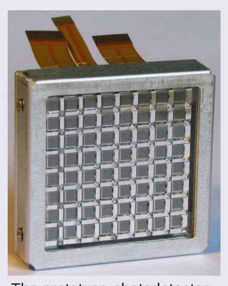
- Time-of-flight positron emission tomography (TOF PET) using Cherenkov light

NIM A 804 (2015) p.127

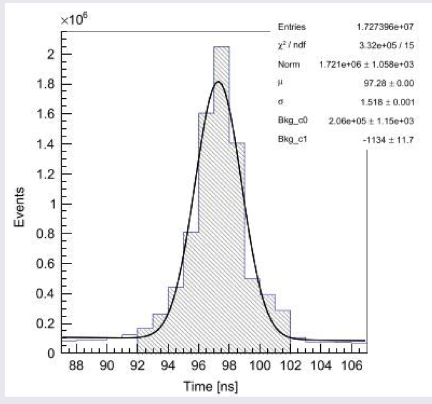
Poster: Measurements of 511 keV annihilation photons with ulitmate timing resolution

RICH

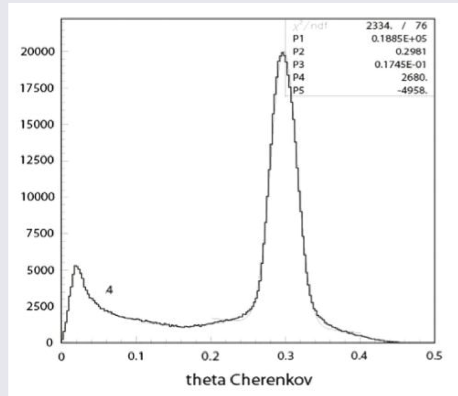
Modules of SiPMs were developed and tested as candidate photodetectors in proximity focusing ring imaging Cherenkov counters using aerogel radiators (ARICH) for the upgraded Belle II spectrometer.
Main requirements for the photodetectors are:
- good single photon sensitivity
- position resolution ~ 5 mm
- operation in magnetic field of 1.5 T



The prototype photodetector: Hamamatsu Photonics MPPC S11834-3388DF 64-channel SiPM array coupled with light concentrators



Time of arrival distribution of hits. By selection only events inside 10 ns window, SiPM dark count contribution was reduced to acceptable levels.



The Cherenkov angle distribution, obtained in a beamtest experiment with aerogel radiator in proximity focusing arrangement.

Excellent detector performance was demonstrated (equivalent of 36 hits/ring). Improvements in timing resolution could be used to improve dark count background rejection.

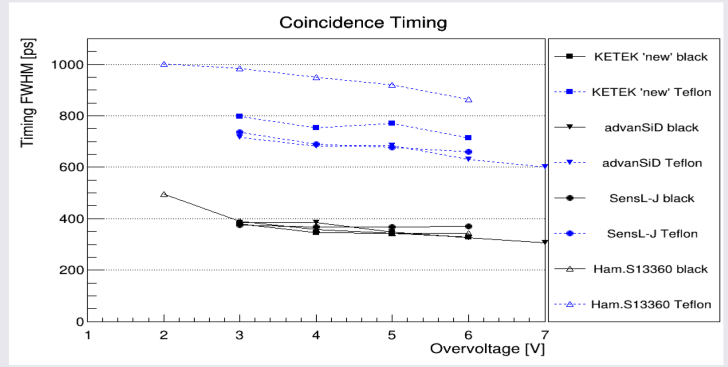
Cherenkov TOF PET

Positron emission tomography (PET) is a medical physics modality, enabling in-vivo imaging of biological processes via coincident detection of 511 keV annihilation gamma rays.

Quality of images can be improved by limiting the reconstructed position of annihilation with time-of-flight measurement of the two gammas.

An excellent coincidence time resolution of < 100 ps FWHM can be achieved by detecting Cherenkov photons produced by gamma interactions in a suitable radiator (PbF_2).

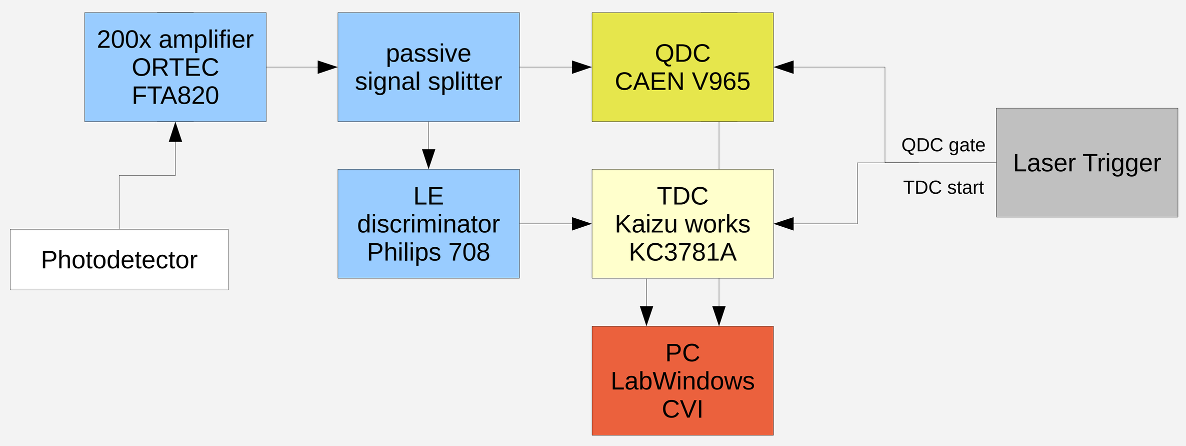
By using SiPMs very good detection efficiency was demonstrated, but cooling was required (dark noise) and the timing was slightly limited by 3x3 mm² SiPMs tested.

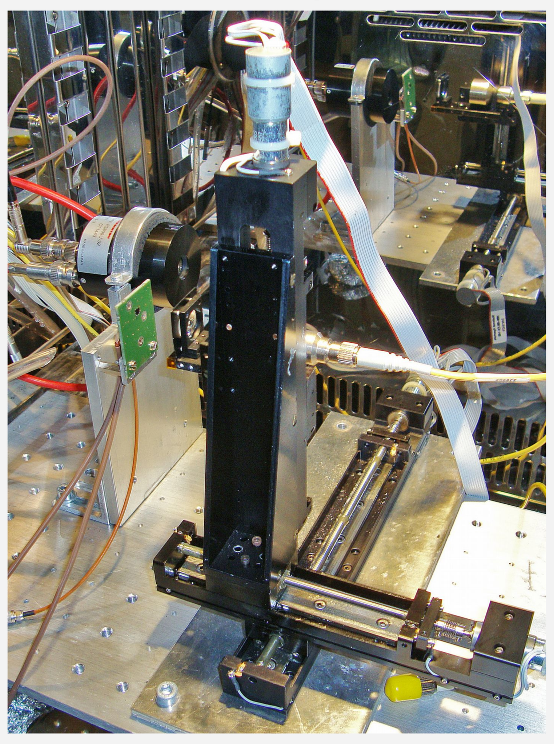


The coincidence time resolution measured with different SiPMs and Cherenkov radiator surface treatments (bare crystal, black painted or Teflon wrapped).

Setup

- PiLas diode laser system EIG1000D, 404nm and 635nm laser heads (35 ps FWHM)
- Light attenuated to single photon levels using ND filters
- Focusing optics (minimum spot size σ ~ 3μm)
- 3D computer controlled stage (< μm accuracy)
- Temperature controlled chamber (-70°C to 100°C)
- Hamamatsu R3809 MCP PMT reference photodetector (25 ps FWHM)
- Readout system (SiPM signal preamplified using NEC uPC2710TB preamp):





- All of the SiPMs tested so far (all 3x3 mm²):

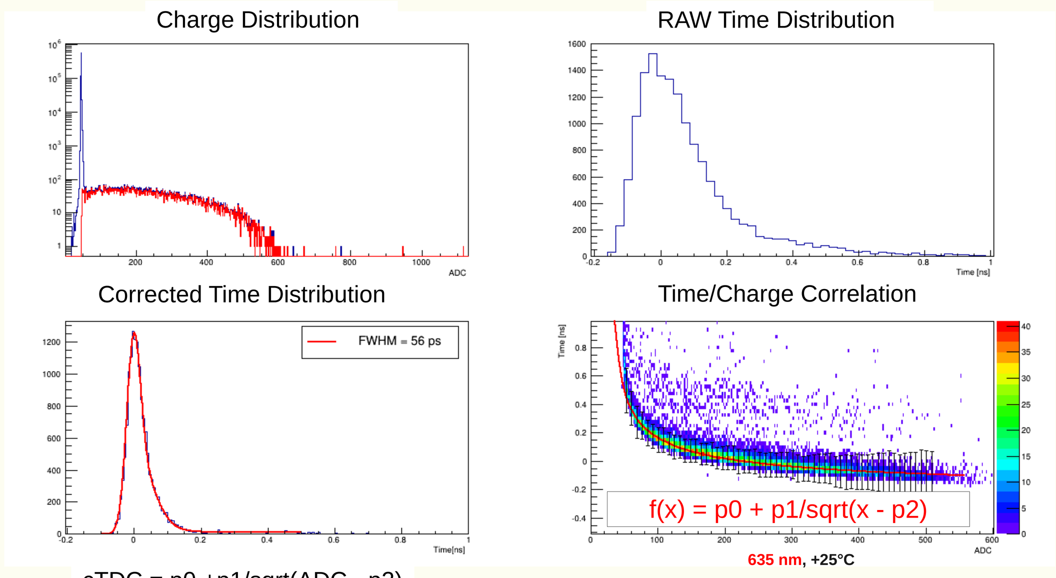
Label	Producer	Model	Pixel Pitch [μm]	Breakdown [V]
Ham.S10931	Hamamatsu	S10931-050P	50	69
Hamamatsu	Hamamatsu	S12641-PA-50	50	65
Ham.S13360	Hamamatsu	S13360-3050CS	50	50
AdvanSiD	AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK 'old'	KETEK	PM3375TS-SBO	75	25
KETEK 'new'	KETEK	PM3350TP-SBO	50	25
SensL	SensL	MicroFC-30050-SMT	50	25
SensL-J	SensL	MicroFJ-30050-TSV	50	25

Results

Time resolution with reference detector

Hamamatsu R3809 microchannel plate photomultiplier tube (MCP PMT)

Time-walk correction

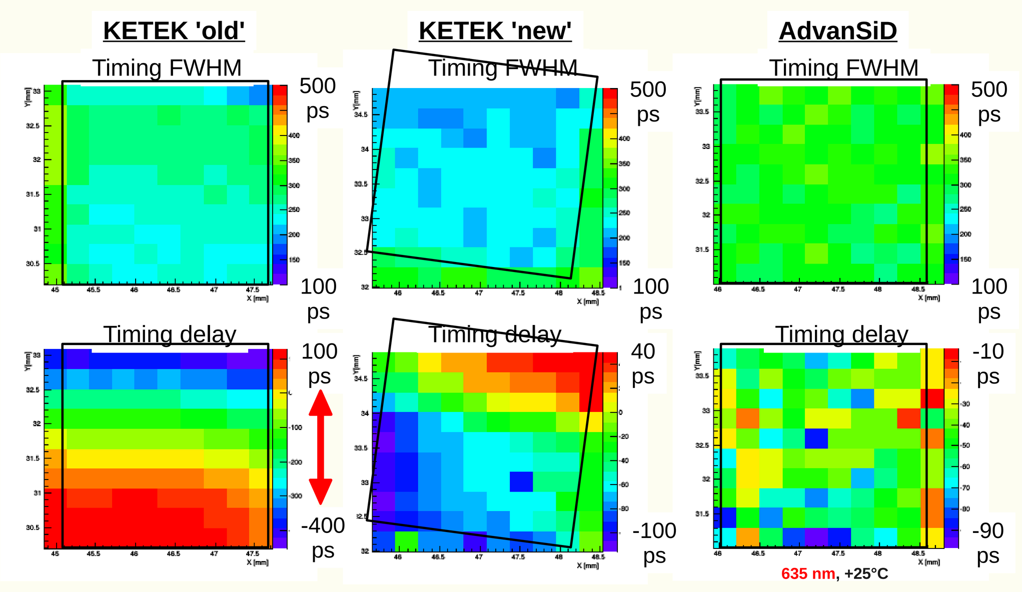


cTDC = p0 +p1/sqrt(ADC - p2)

56 ps FWHM (measured) = **35** ps (laser) ⊕ **25** ps (MCP PMT) ⊕ **36** ps (electronics)

Timing and signal delay vs. position

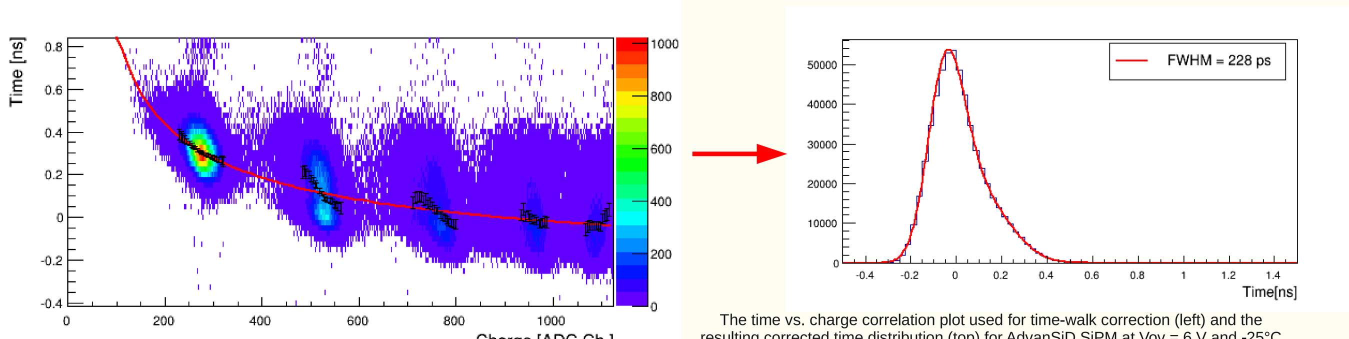
Laser defocused to ~ 300 μm and scanned over whole SiPM surface:



Variation in path lengths from different cells to common output can lead to timing degradation of the whole device.

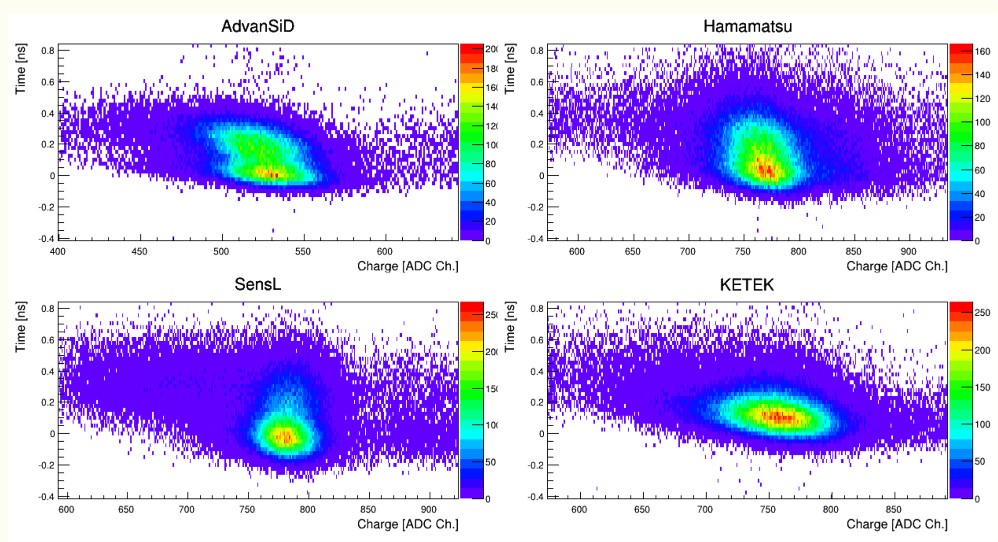
Timing

Overvoltage dependence of time resolution was measured for different SiPMs
- a second, delayed contribution in multiple cell signal height distributions degrades the timing and reduces the performance of time-walk correction

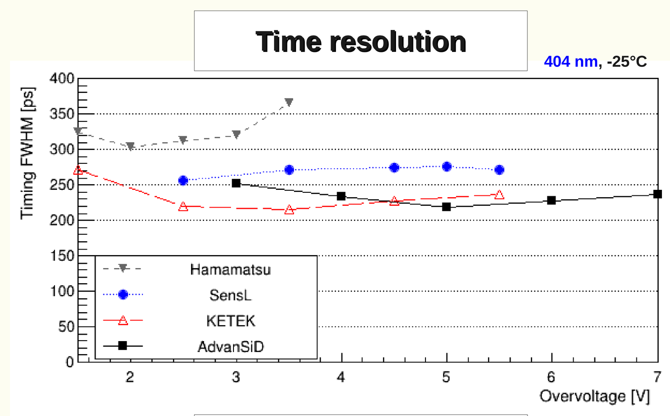


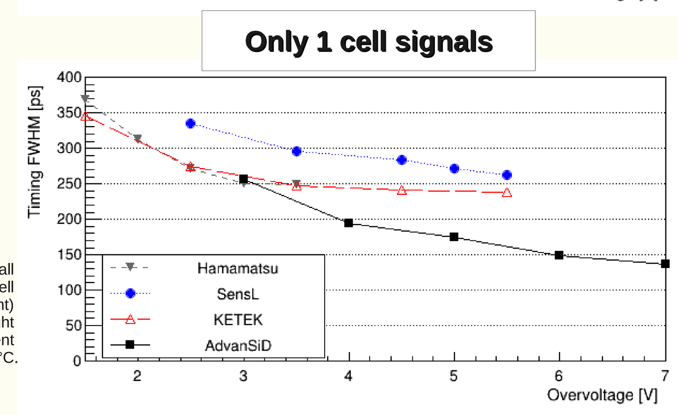
The time vs. charge correlation plot used for time-walk correction (left) and the resulting corrected time distribution (top) for AdvanSiD SiPM at Vov = 6 V and -25°C.

- this is apparent when comparing time resolutions obtained for events with only single and only double cell signals
- the effect is different for SiPMs from different manufacturers

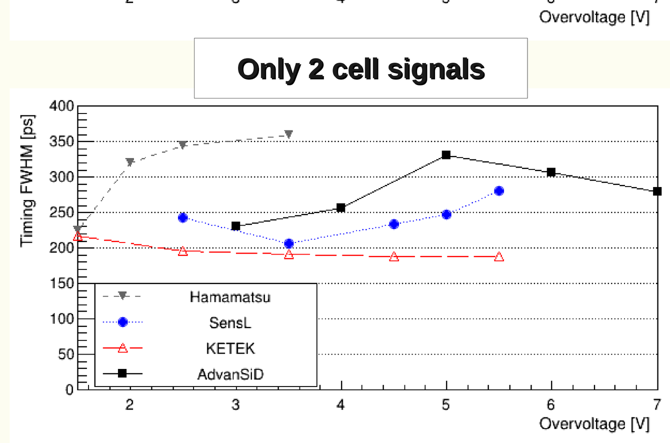


Time vs. charge correlation plots for only double cell height signals corresponding to four different SiPMs (left) at -25°C.



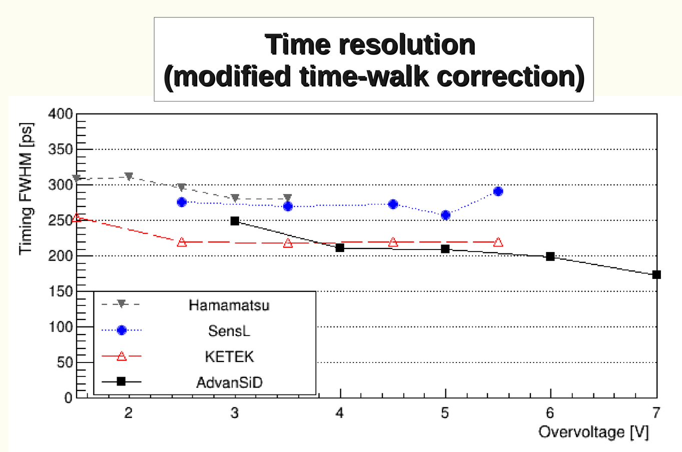


Measured time resolutions for all events (top right), only single cell pulse height signals (middle right) and only double pulse height signals (bottom right) at different overvoltages and -25°C.



Improving the time resolution

First attempt to improve the time resolution by modifying the time-walk correction:
- data was split into subsets corresponding to a certain number of fired cells (i.e. subsets composed of events with only 1, 2, 3,... cell pulse height)
- time-walk function obtained and correction applied for each subset individually (but with the same fit function shape as before)
- corrected time distributions for all subsets were then combined and the time resolution was obtained for the whole dataset
- improvement from 218 ps FWHM to 173 ps FWHM (AdvanSiD SiPM @ 7 V overvoltage)



Conclusions

Time resolution < **200 ps FWHM** achieved using improved time-walk correction algorithm (< 150 ps FWHM using only single cell height signals)

Time resolution of SiPMs tied mainly to the:
- intrinsic cell resolution
- variation in time that signals need to get from cells to output (worse for larger devices, much improved in newer SiPMs)
- at single photon levels, degradation due to additional, delayed contribution in multiple cell height signals (depends strongly on devices/technologies and time pickup used)

The presumed source of the second contribution are optical crosstalk events, which cause delayed detection of multiple cell signals by influencing the shape of the signal.

Possible improvements:
- SiPM technology (less crosstalk)
- reducing the effects of second contribution with suitable time-walk correction algorithm
- separating the second contribution by improved time pickup (multiple-threshold measurement, waveform sampling)