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Study of timing performance of Silicon Photomultiplier and application for a Cherenkov detector

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Outline

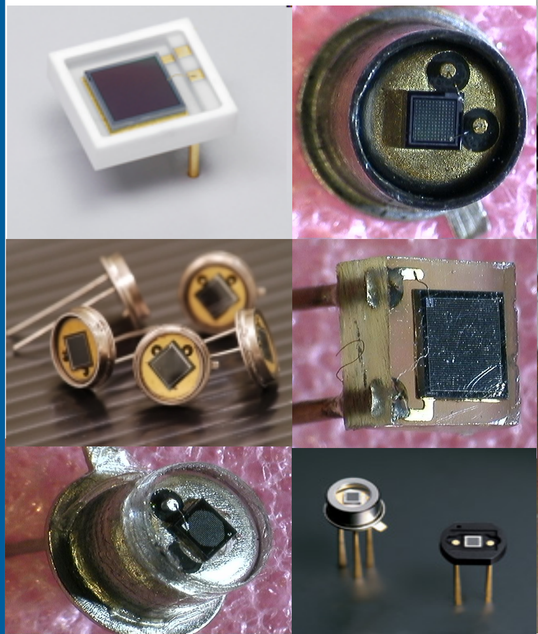
- Motivation.
- SiPM timing performance.
- Cherenkov counter prototype
- Beam test and results.
- Summary & conclusion.

Motivation

- Start detector working in a magnetic field with time resolution in the range of 100 ps is highly required, this motivated us to think about using SiPM for this purpose.
- Readout of promptly emitted Cherenkov light with SiPM is a promising combination, the idea is to benefit from the promptly emitted light to study the performance of the Cherenkov counter prototype based on the SiPM readout.
- If such a counter works and demonstrates a sufficient timing performance, it could be a valuable alternative for a beam line TOF-start counter, due to the advantages like cheapness, compactness, magnetic field resistance and simple operation.

SMI activities

- Test different types of SiPM (MAPD-Zecotek, SiPM-Photonique, MPPC-Hamamatsu, ….)

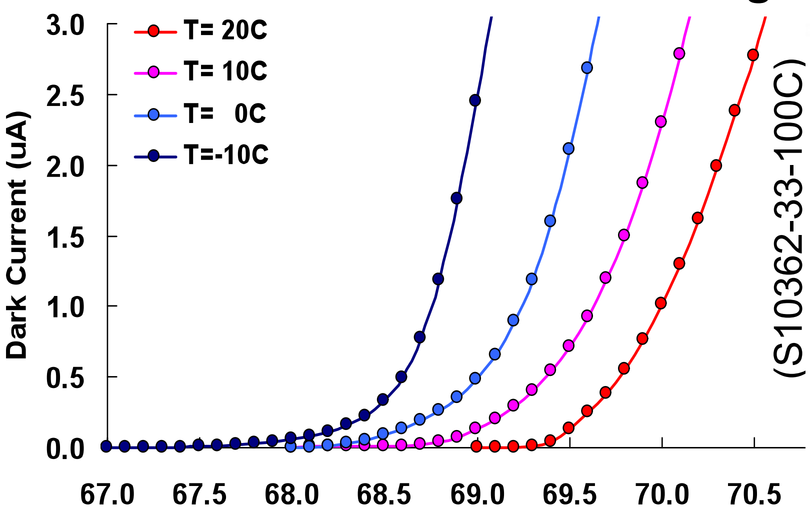


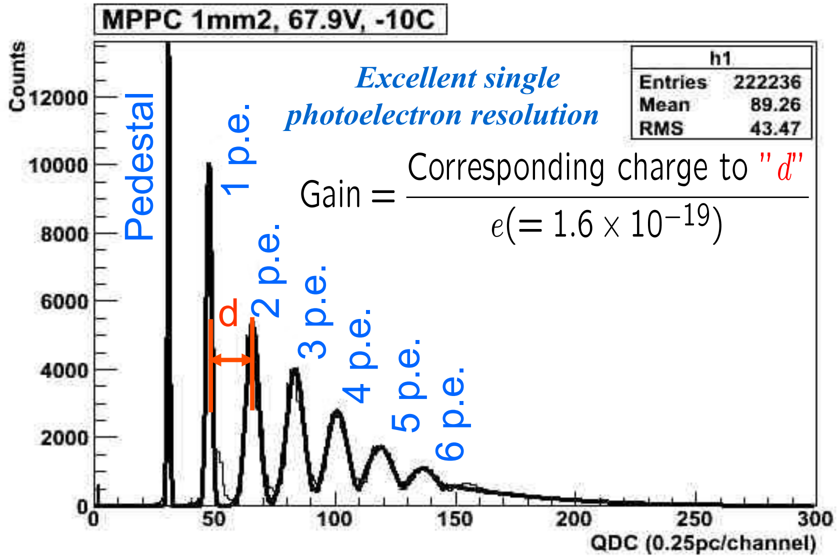
Hamamatsu MPPC, Zecotek MAPD different sizes

Dark box, Keithley 617 programmable electrometer, Pico second laser system

SiPM parameter measurements

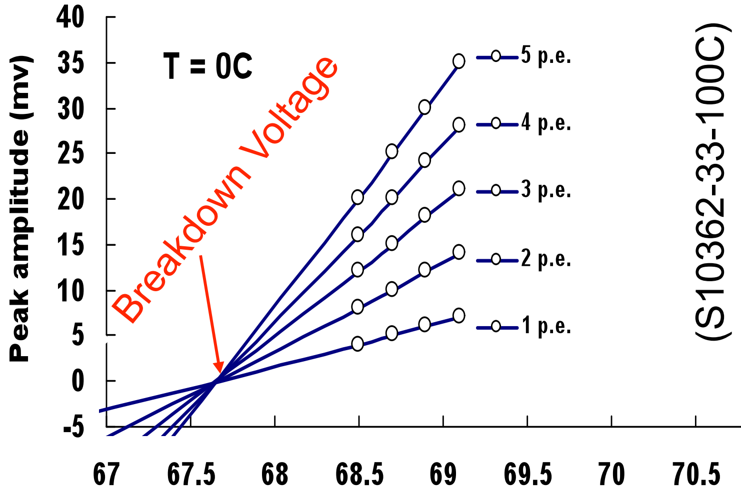
Dark current vs Bias Voltage

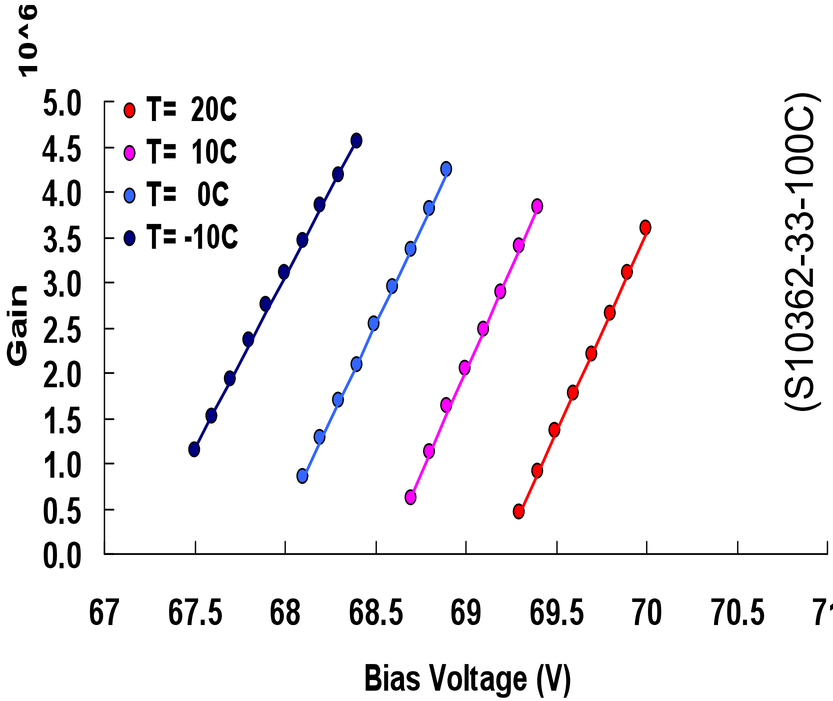




$$\text{Gain} = \frac{\text{Corresponding charge to "}d\text{"}}{e(= 1.6 \times 10^{-19})}$$

Breakdown Voltage



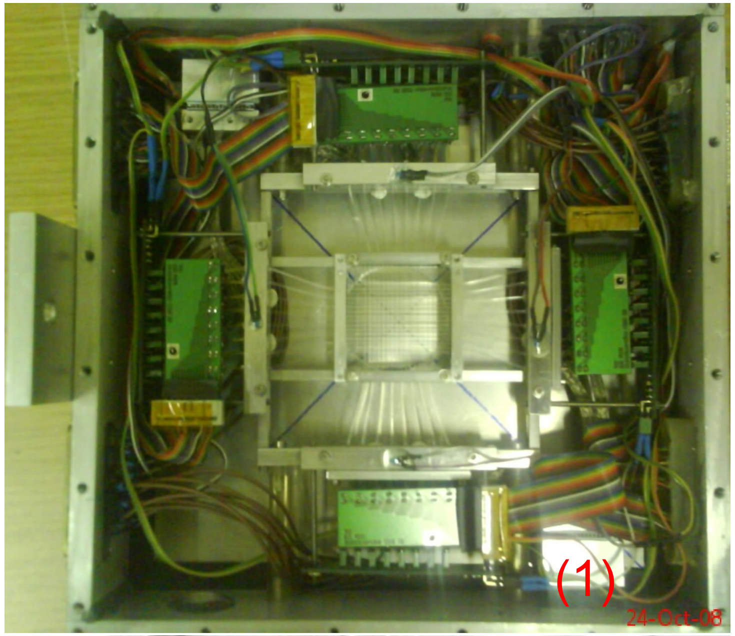


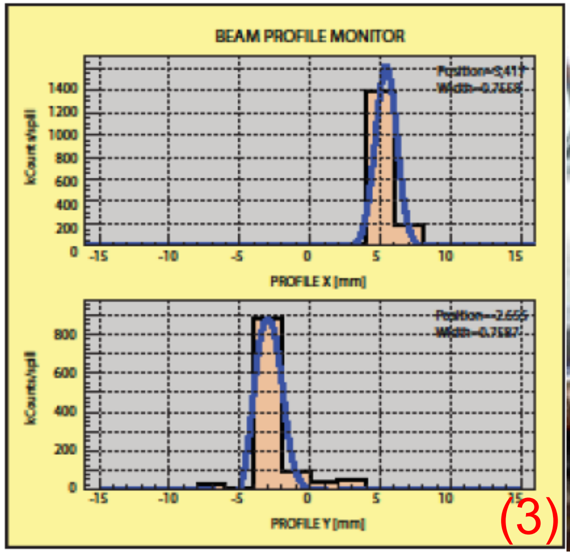
Beam profile monitor

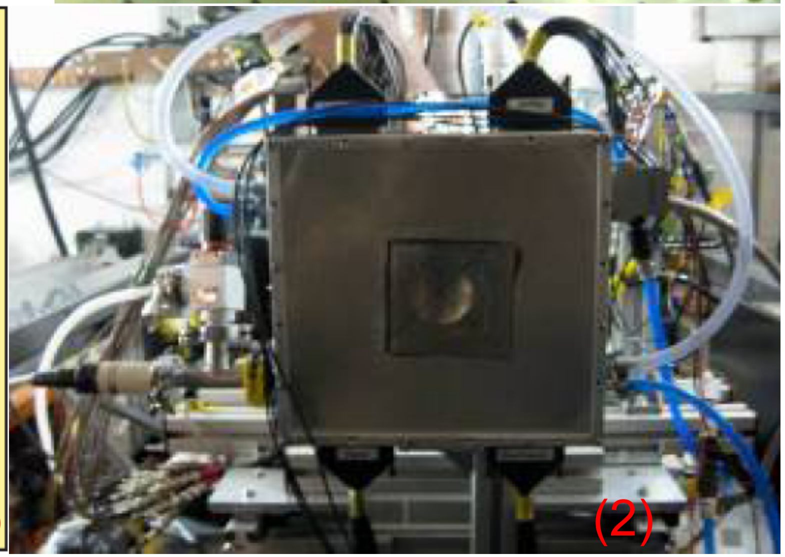
SiPMs in combination with a 16×16 scintillating fiber grid in 2 planes were used for a beam profile monitor for the FOPI experiment (1).

Beam profile monitor mounted at FOPI/GSI (2).

Proton beam profile measured in x- and y-axis (3).

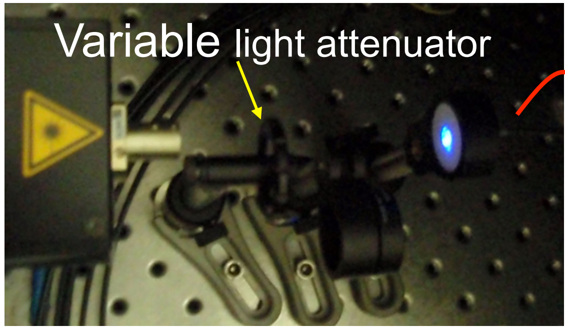


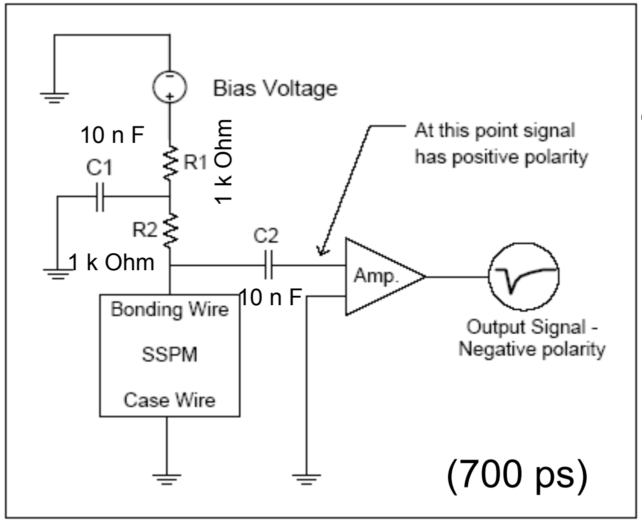




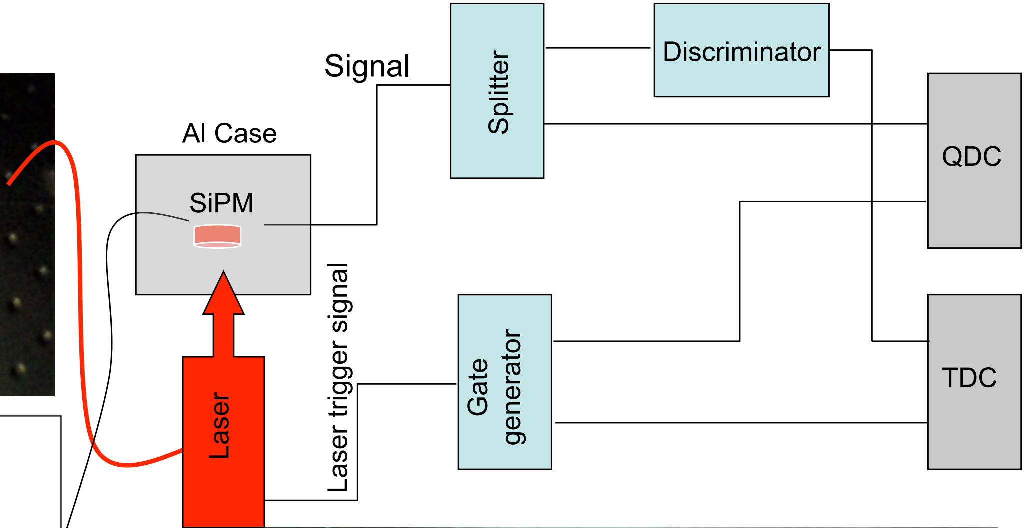
SiPM time resolution measurements

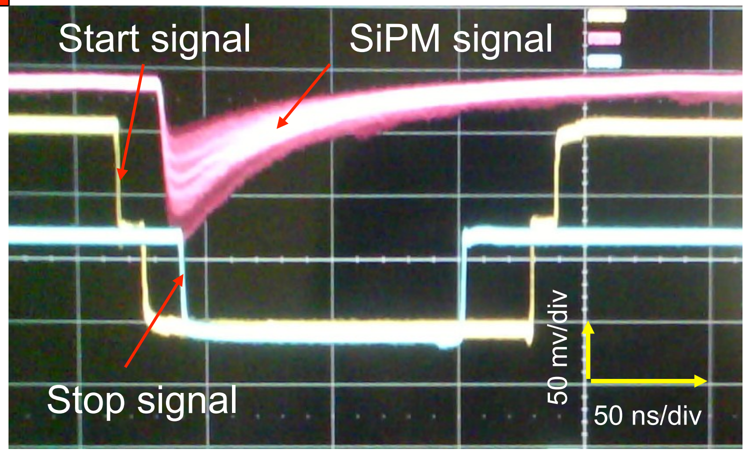
- Time resolution was studied by illuminating SiPM with blue laser light pulse width 32 ps at wave length 408nm.





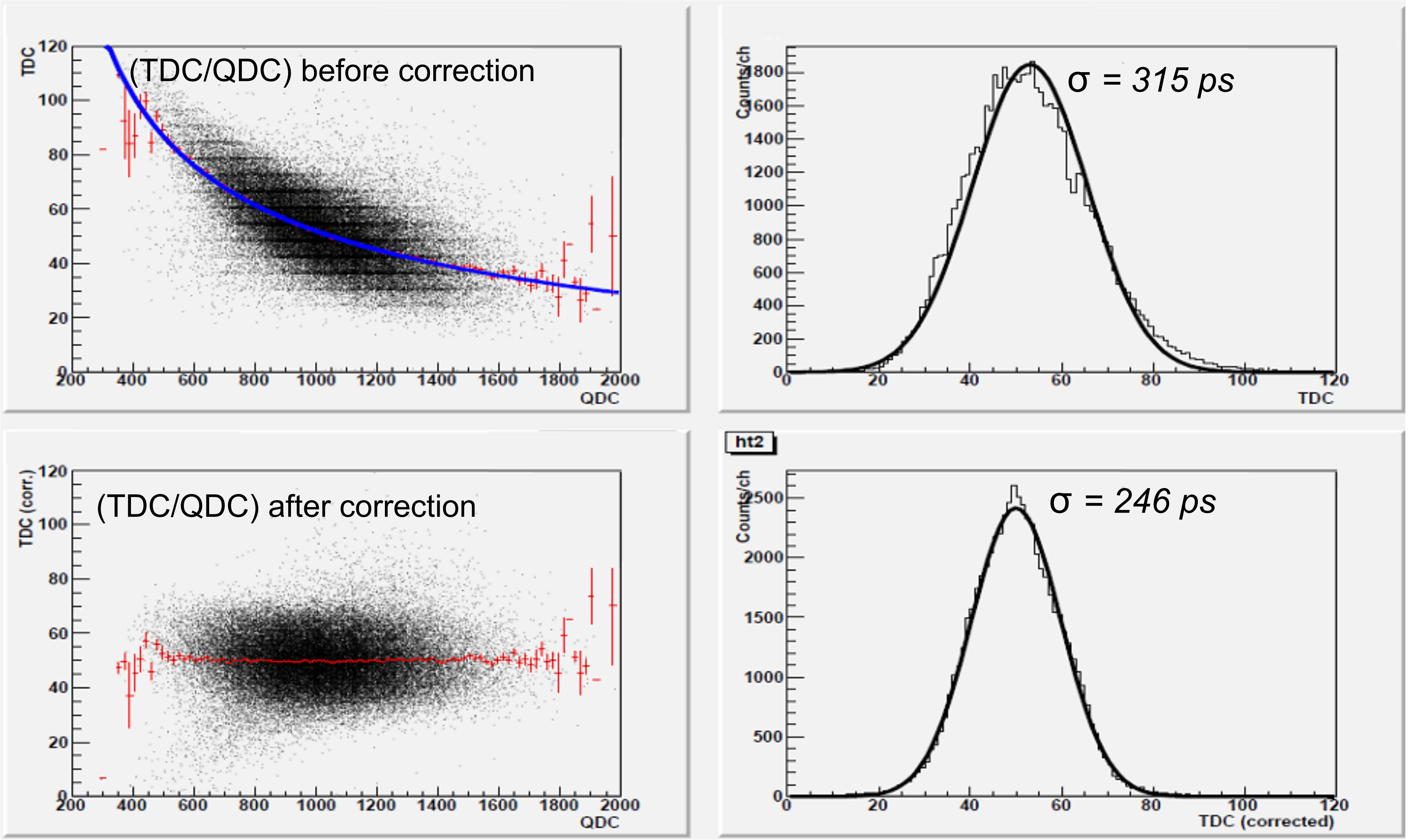
Photonique preamplifier (AMP-0611)





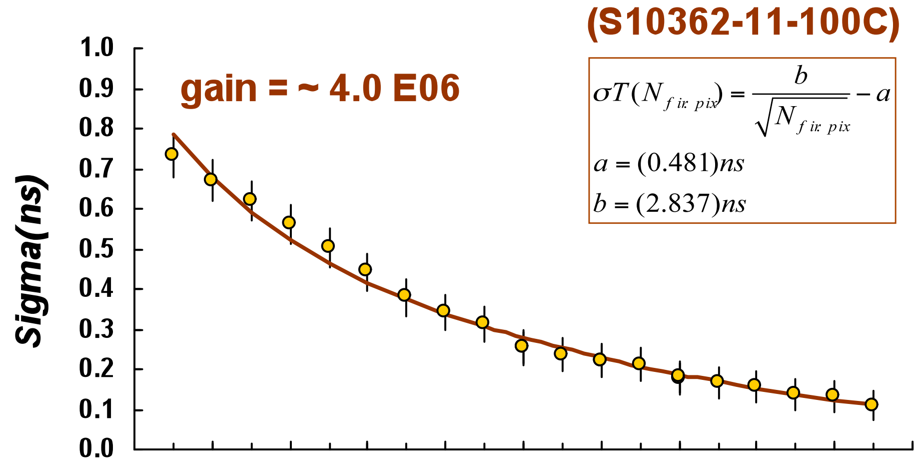
Time resolution measurements

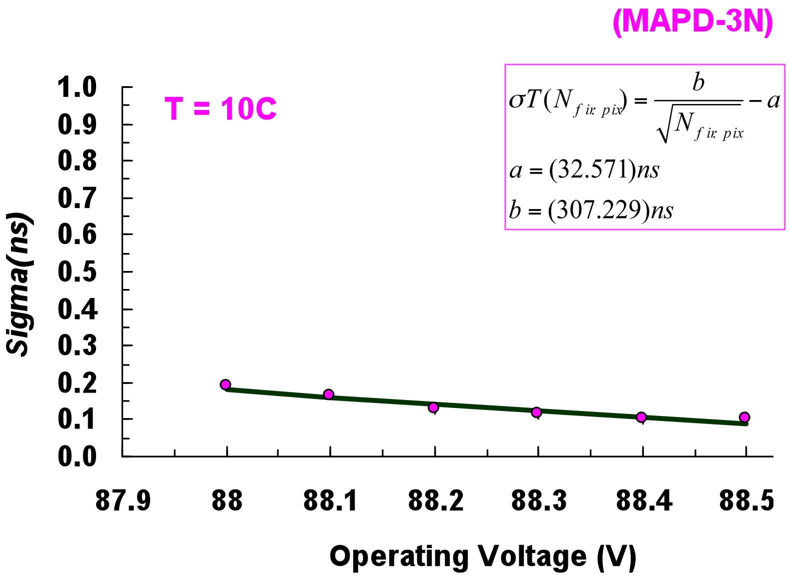
- Time resolution was calculated after slewing time corrections as sigma (σ) value by Gaussian fitting for TDC distribution.

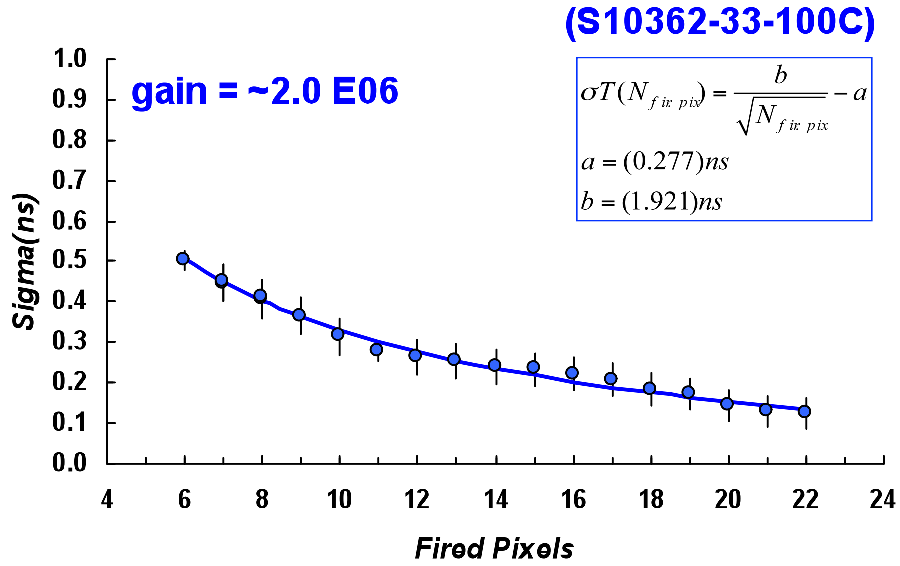


Time resolution measurements

- MPPC (1, 3 mm^2) Hamamatsu.
- MAPD-3N, Zecotek.





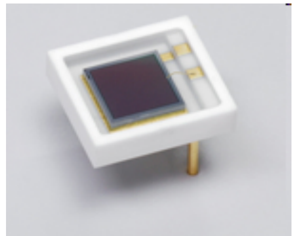


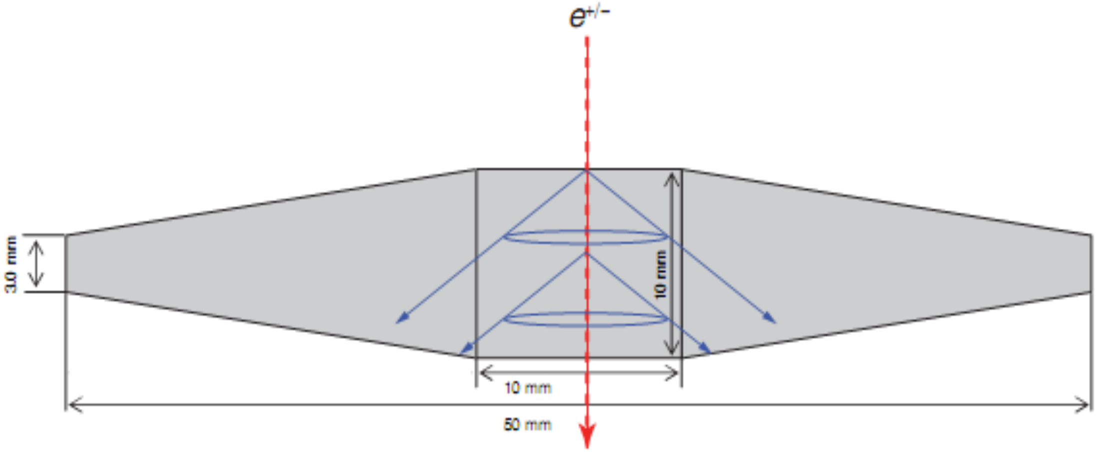
- Time resolution improves with increasing the number of photons and/or operating voltage.

Cherenkov counter prototype

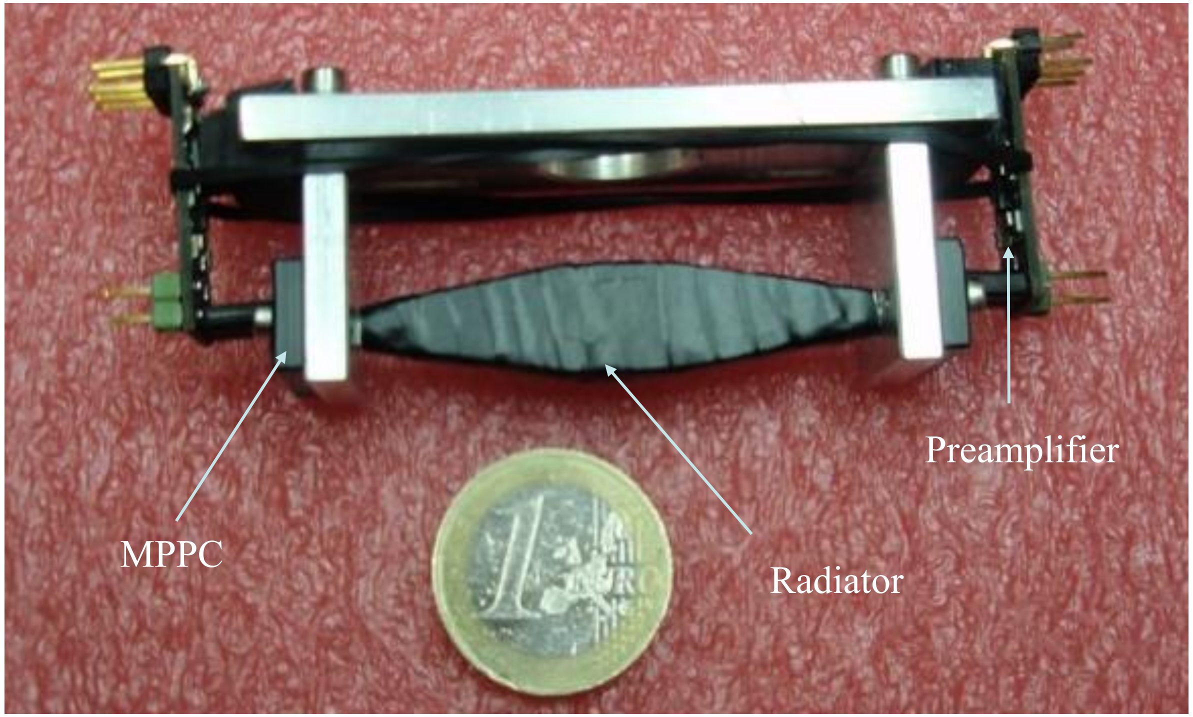
- A radiator made of quartz, 1 cm thick and 5 cm long, optically coupled on both sides to 3×3 mm^2 MPPCs(S10362-33-100C) Hamamatsu, this devices was primarily selected because of its large active area.

The other series (S10362-11) has potentially better intrinsic timing performance, however due to the smaller sensitive area ($1 mm^2$), the reduction of photon collection will have a negative impact on the overall timing performance.





Cherenkov counter prototype



Photograph of the prototype Cherenkov counter

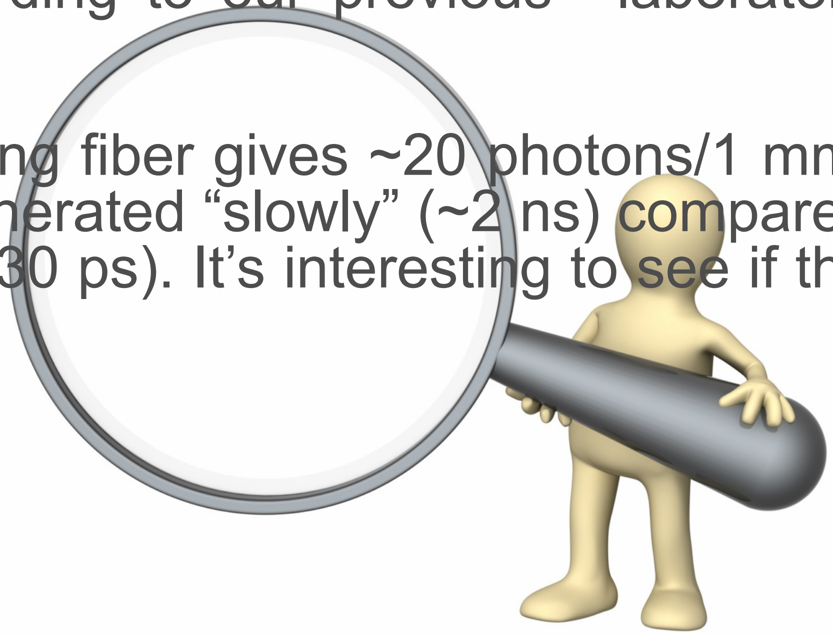
- In order to reduce the losses due to imperfect reflection the radiator is wrapped with an aluminum foil and covered with light-tight black tape.
- MPPC signals are amplified with fast preamp, AMP_0611, while attached directly to the preamp board to minimize electronic noise pick-up.

Cherenkov counter prototype

- We estimate ~20 detectable photo-electrons on each photosensor due to radiator interaction with 500 MeV electron beam, considering light losses due to transmission, absorption and photosensor efficiency.

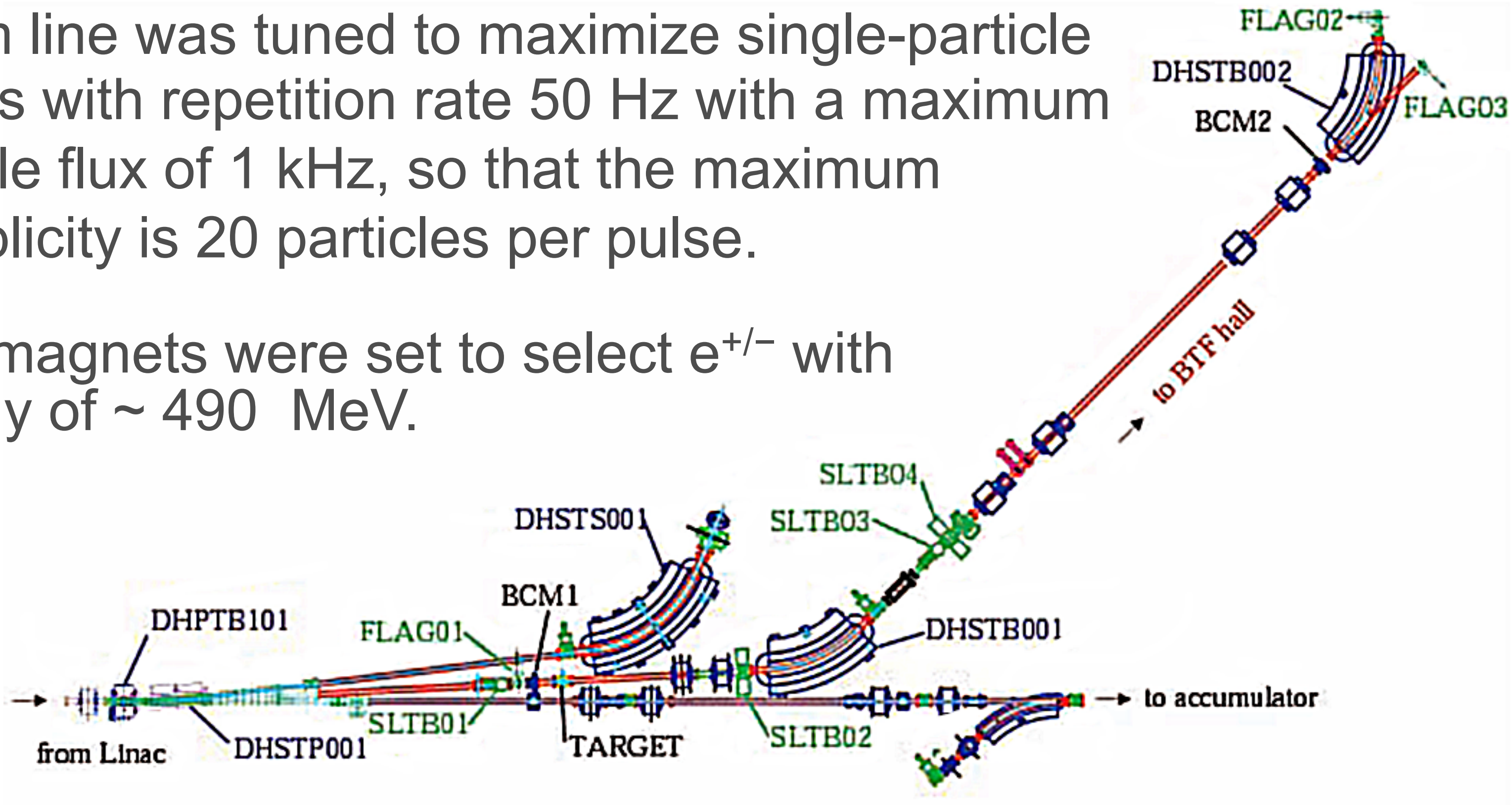
- Based on the number of photons, the expected time resolution is ~200 ps, according to our previous laboratory measurements.

- For a comparison, scintillating fiber gives ~20 photons/1 mm^2 but presumably photon is generated “slowly” (~2 ns) compared to the Cherenkov process (~30 ps). It’s interesting to see if the SiPM can exploit that.



The Beam Test Facility (BTF)

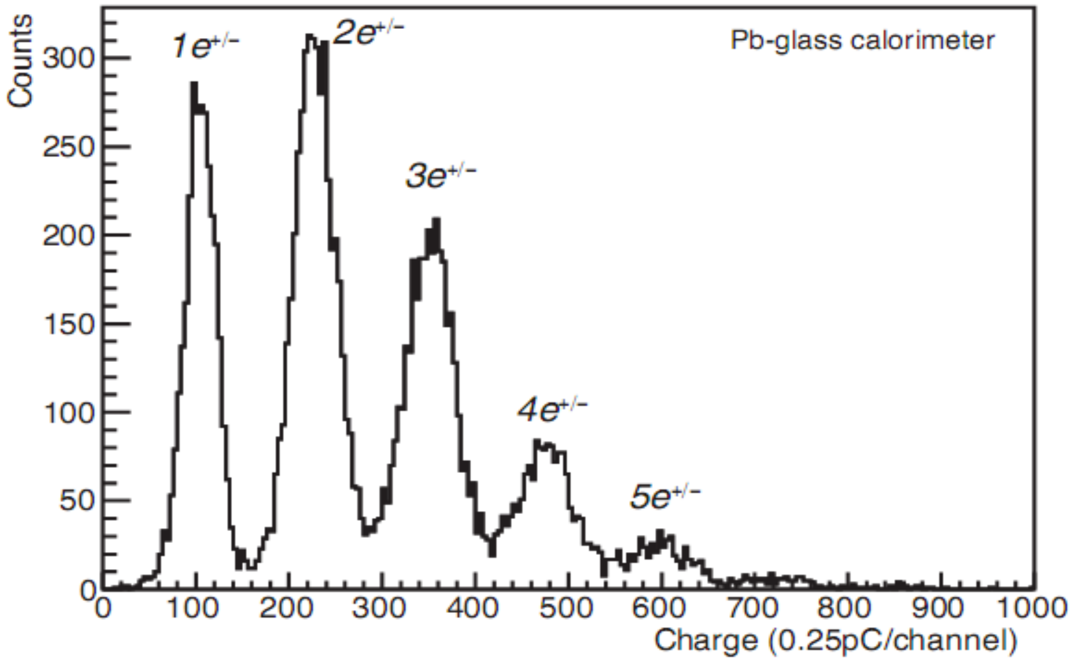
- The DAFNE Beam Test Facility (BTF) initially optimized to produce single electrons and positrons in 25 – 750 MeV energy.
- Beam line was tuned to maximize single-particle events with repetition rate 50 Hz with a maximum particle flux of 1 kHz, so that the maximum multiplicity is 20 particles per pulse.
- BTF magnets were set to select $e^{+/-}$ with energy of ~ 490 MeV.



Layout of the BTF transfer line and its main components.

Test at the BTF

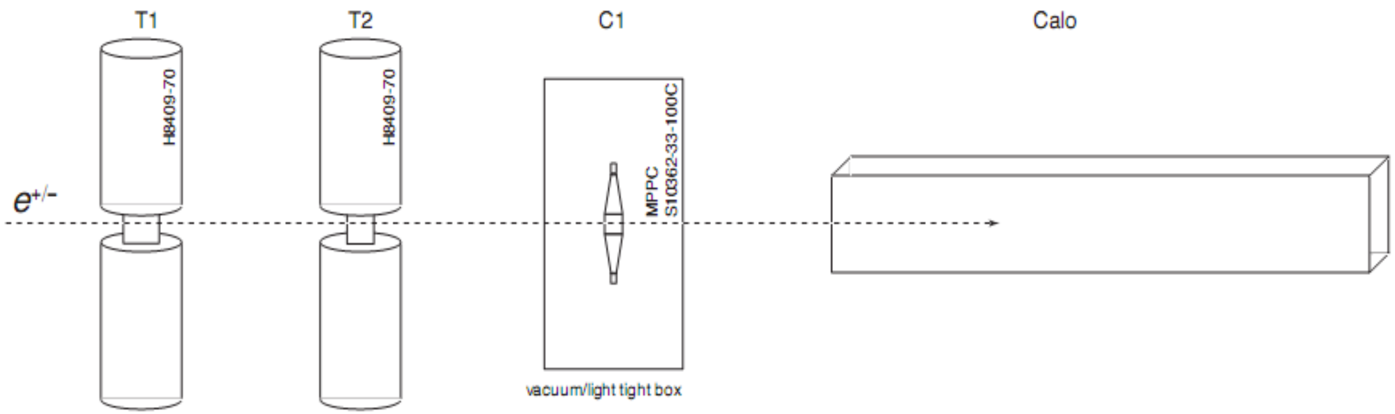
- The beam diagnostics elements at BTF include a Pb-glass calorimeter. The beam particles are totally absorbed in the calorimeter so that the integrated signal from detector provides a measure of the beam particle multiplicity.



- The separate peaks correspond to beam pulses of 1, 2, 3, and more beam particles. This information allows to select beam pulses of a specific multiplicity by software in later analysis.

Detector setup

- Four detectors were installed for the measurements.
- T1 & T2 are the reference counters for the TOF measurements, consist of scintillators (BC-408: 2, 1 cm) and read out on both ends by PMTs (Hama- H8409-70).
- The Cherenkov counter C1 is placed between T2 and the Calo.

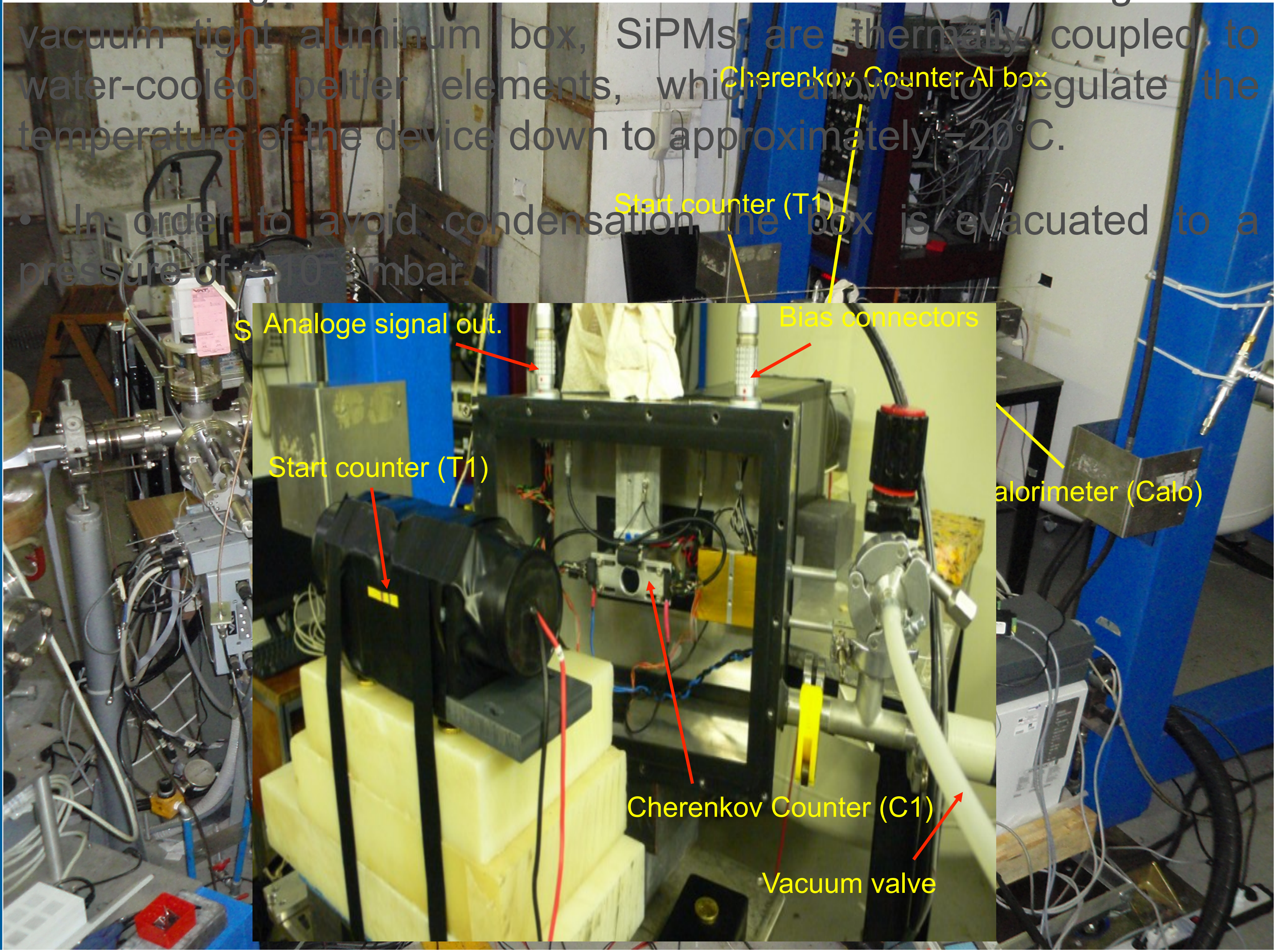


- Data taking was triggered by a coincidence between T1, T2 and extraction signal provided by the accelerator.

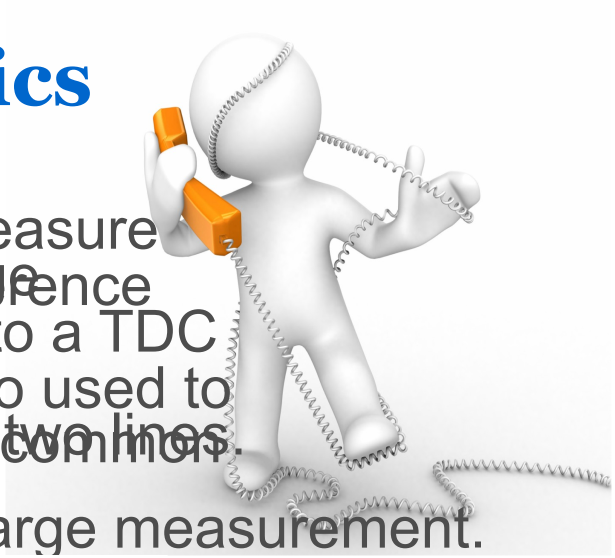
Test at the BTF

Detector setup (BTF-hall)

- For testing the Cherenkov counter is mounted in a light and vacuum tight aluminum box, SiPMs are thermally coupled to water-cooled peltier elements, which allows to regulate the temperature of the device down to approximately -20°C.
- In order to avoid condensation the box is evacuated to a pressure of $\sim 10^{-3}$ mbar.

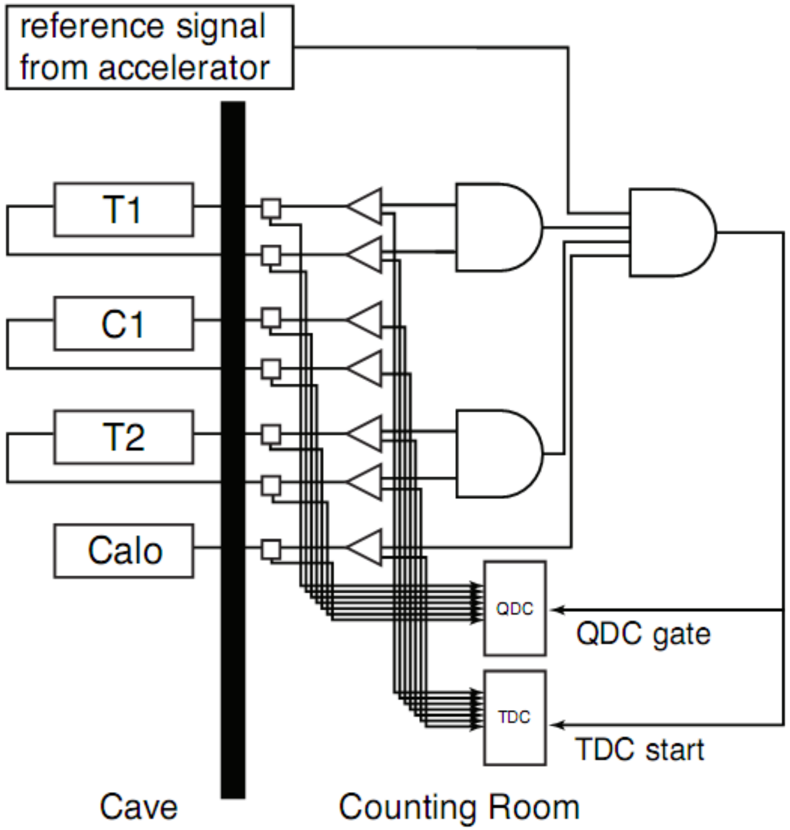


Readout electronics

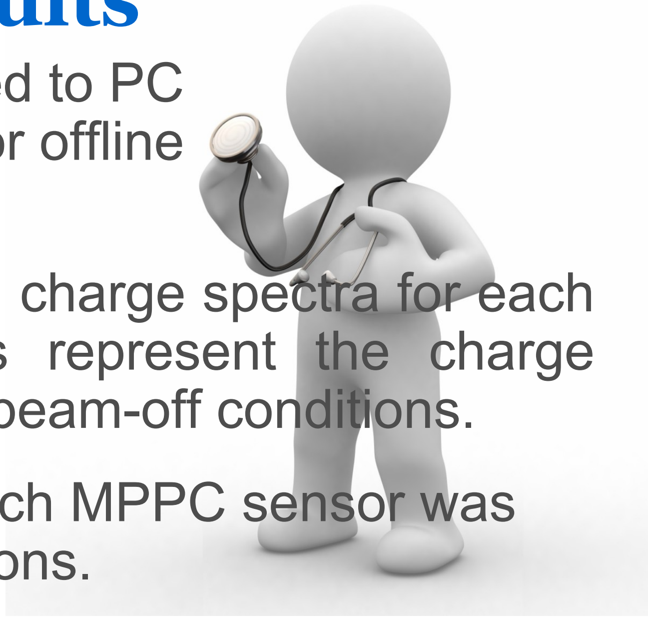


- The readout electronics was set up to measure charge spectra and TOF between the reference and Cherenkov counters.
- Each counter signal output was split into two lines.
- One was connected to a QDC for the charge measurement.

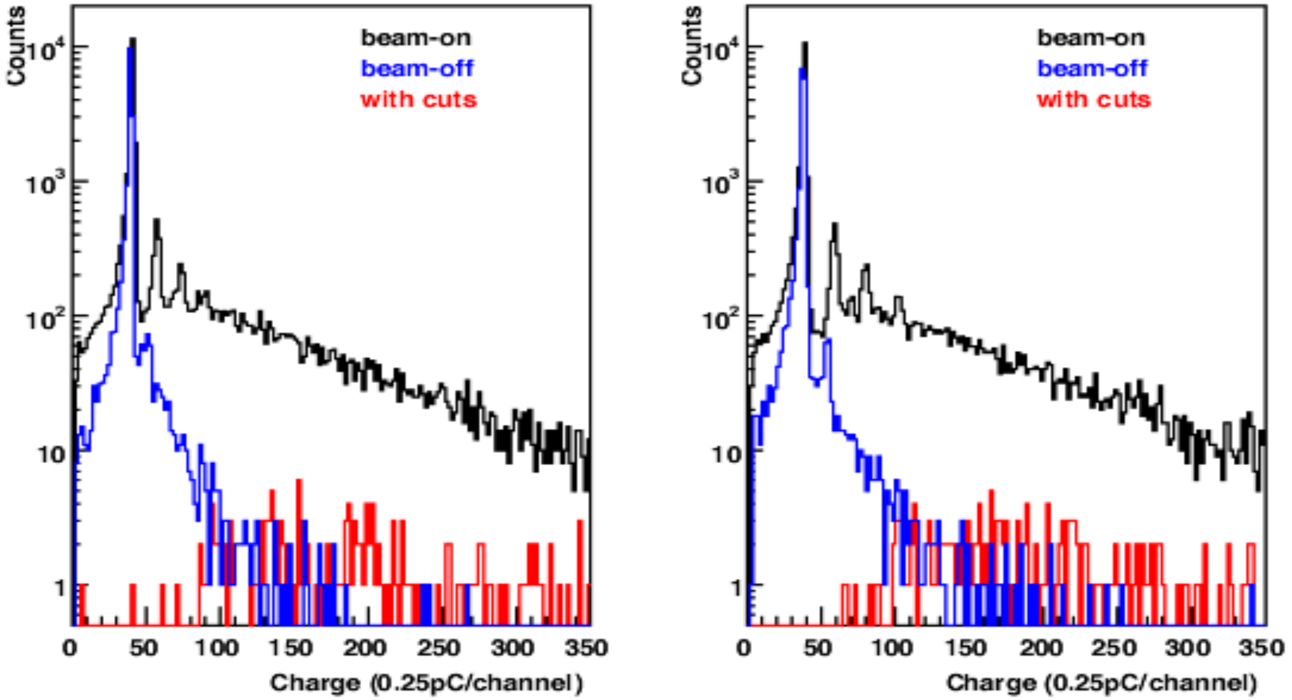
- The other line was fed into a leading edge discriminator and the outputs were fed into a TDC for the time measurements, and were also used to produce a gate signal for the QDC and a common start signal for the TDC.



Beam test and results

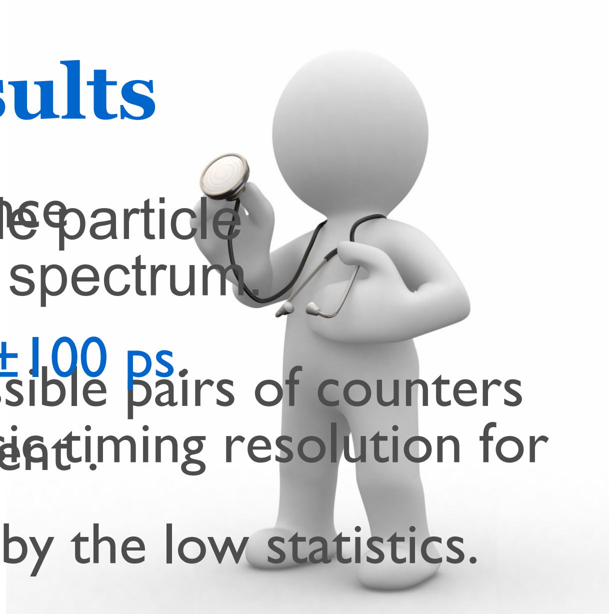


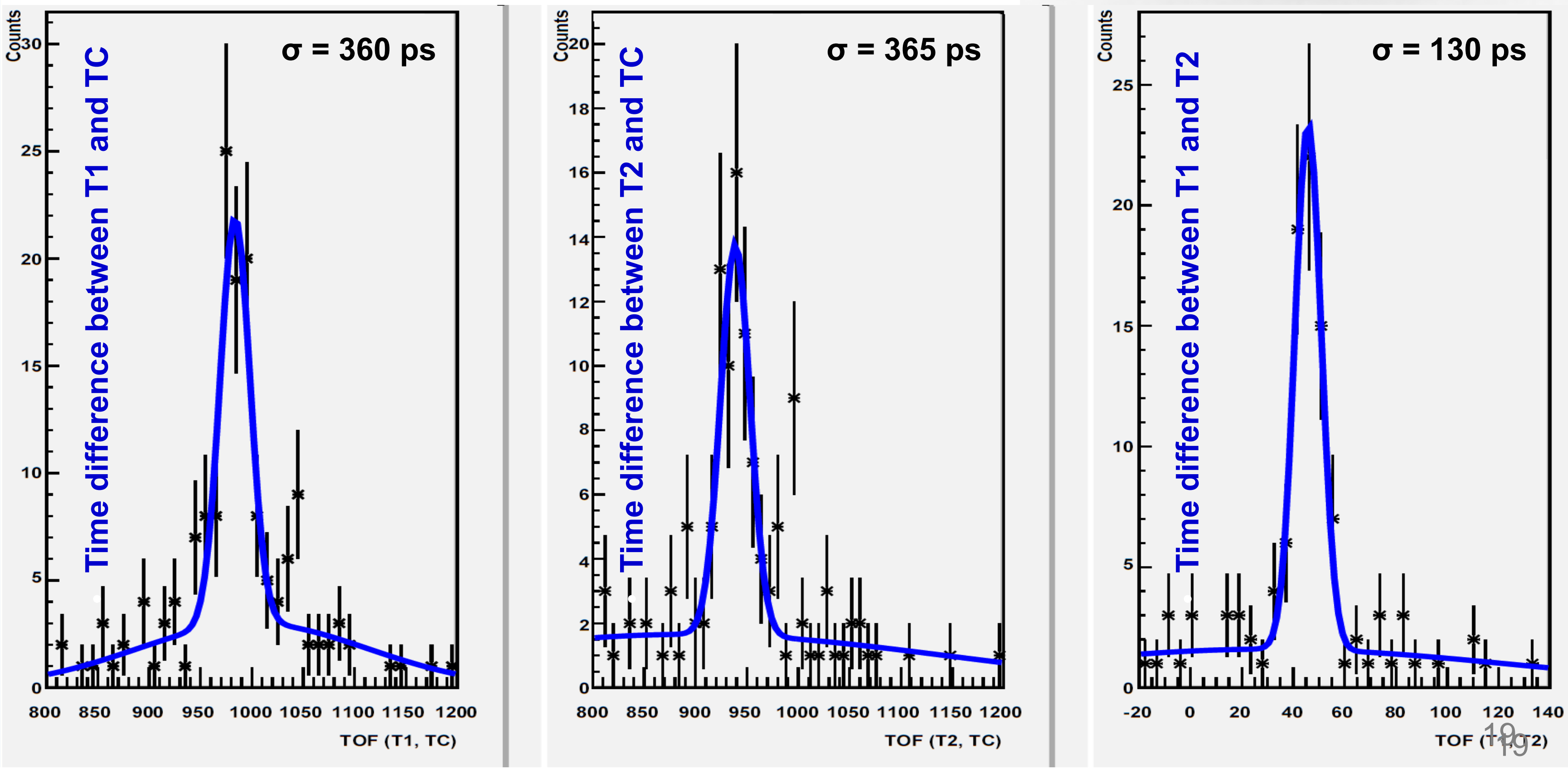
- All the QDC and TDC signals were recorded to PC via CAMAC PCI bus interface and stored for offline analysis.
- Figure shows Cherenkov counter recorded charge spectra for each MPPC side, while black and blue lines represent the charge distributions measured while beam-on and beam-off conditions.
- In response to the penetrating particles, each MPPC sensor was able to detect an average number of 8 photons.



Beam test and results

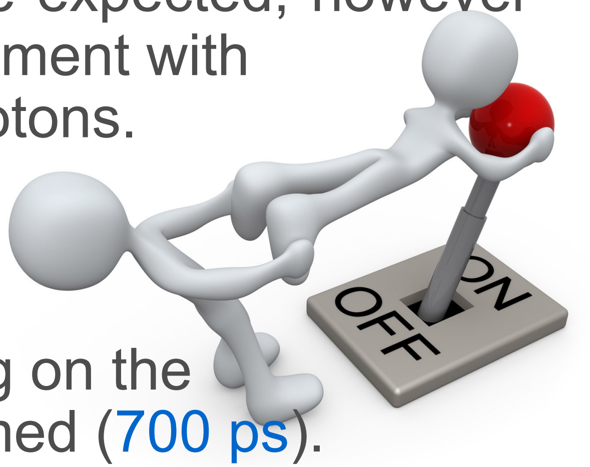
- For data analysis, we selected only single particle ($e^{+/-}$) events using the calorimeter energy spectrum.
- TOF(T1,T2) = 130 ps T1 and T2 performance good enough (~100 ps) to evaluate CI
- Cherenkov counter time resolution is 350 ± 100 ps.
- We measured TOFs between the three possible pairs of counters T1, T2 and CI in order to disentangle intrinsic timing resolution for each counter.
- The result not overwhelming but is agreement.
- Accuracy of the measurements was limited by the low statistics.





Summary

- Cherenkov counter was able to detect 8 photons in comparison with ~20 photons expected.
- The achieved time resolution is 350 ± 100 ps in comparison with 280 ps measured in the lab.
- The detected photons are lower than the expected, however the achieved time resolution is in an agreement with the expectation at the given number of photons.
- Signal rise time turned out to be slow.
- AMP_0611 has 2-3 ns risetime depending on the input pulse height, instead of what is claimed (700 ps).
- Risetime measurement of raw SiPM output on the way.



Conclusion

- We are evaluating SiPM in terms of timing measurement.

- According to our measurement time resolution is not great, though there’s inconsistency with Hamamatsu catalog.

- Simple Cherenkov counter with SiPM was constructed and tested using $e^{+/-}$ beam. The aim was to make a proof of principle and to obtain a first measure of the timing resolution of this device with a TOF measurement in a real accelerator environment.

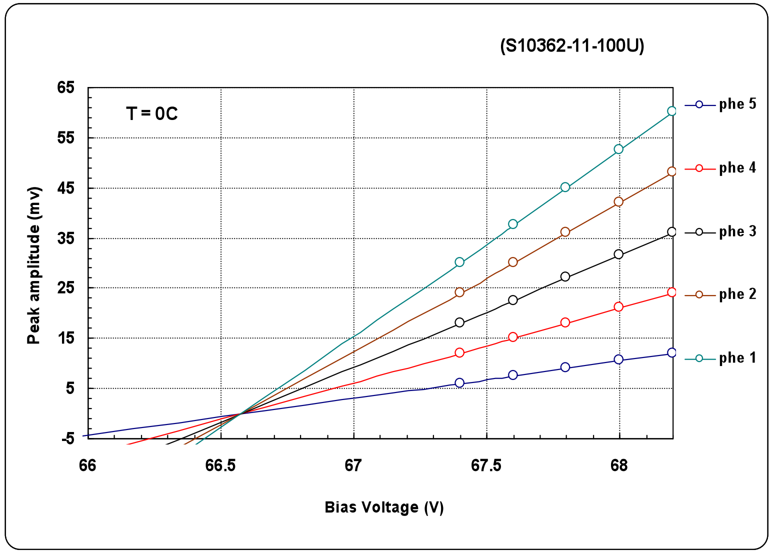
- Sub-nanosecond (~350 ps) time resolution has been achieved.

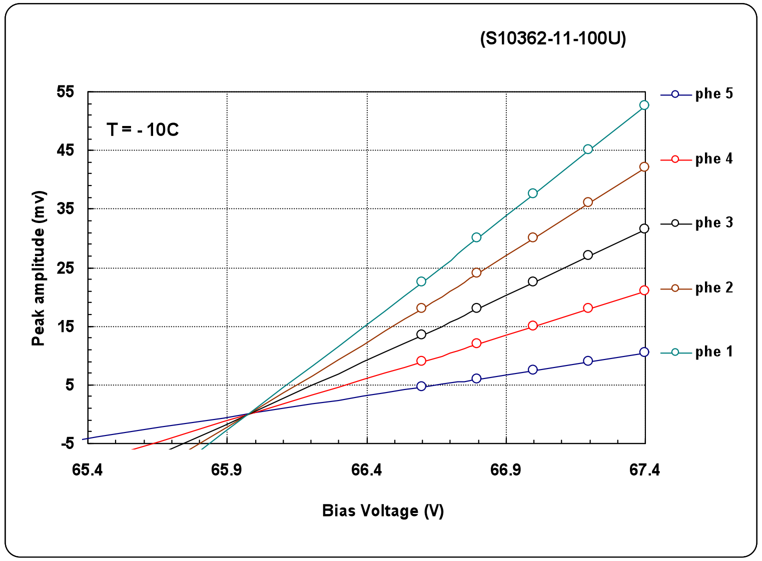
- Current limitation seems to come from the detector performance itself, though there is a room for improvement (preamp, more carefully designed radiator and light guide).

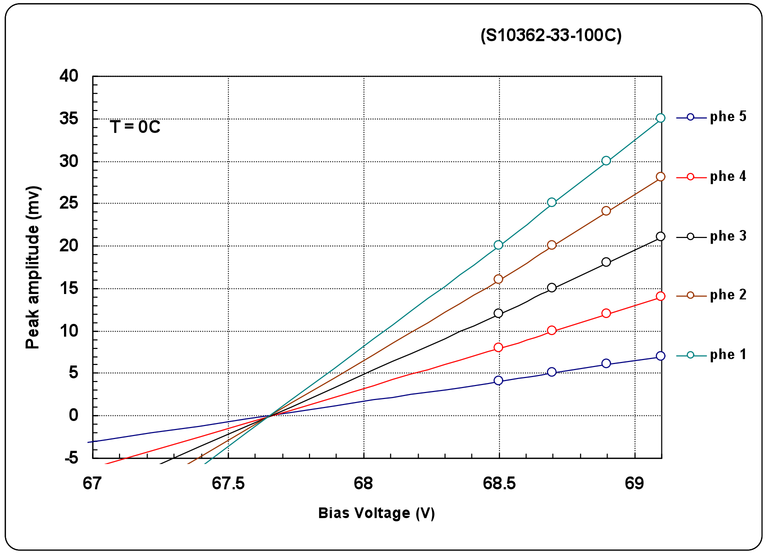
Thank You for your attention !

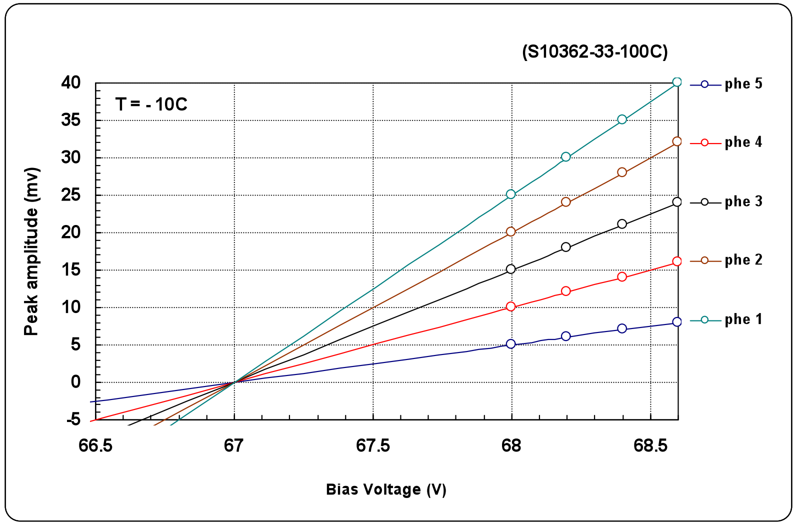
Spare

MPPC - High sensitivity of the Operating voltage to T and bias variations

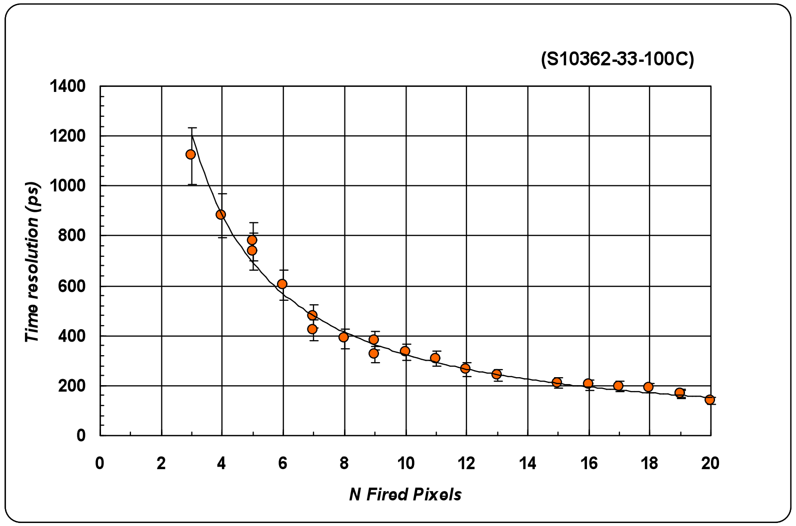


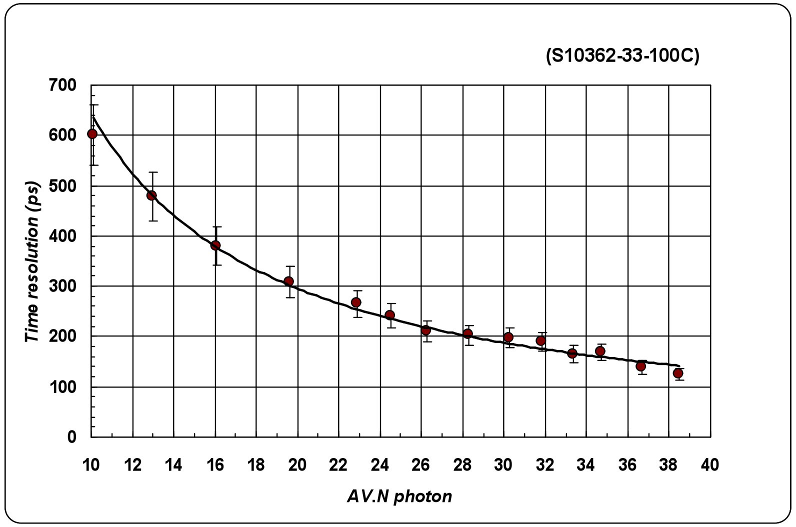


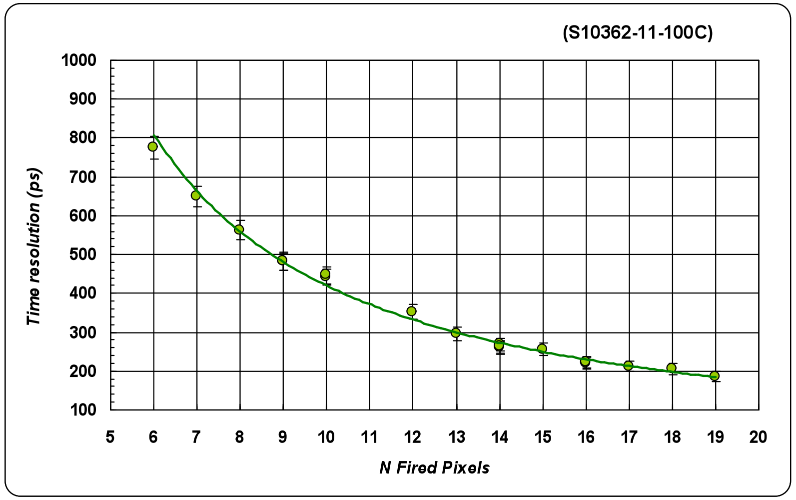


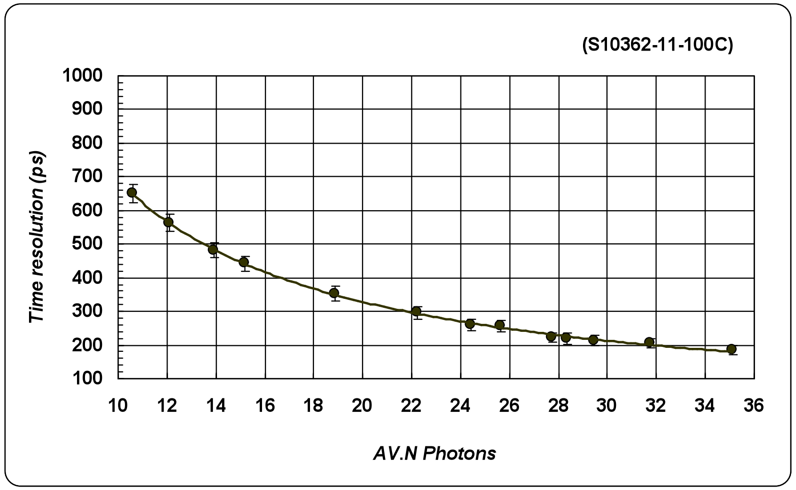


MPPC-time resolution



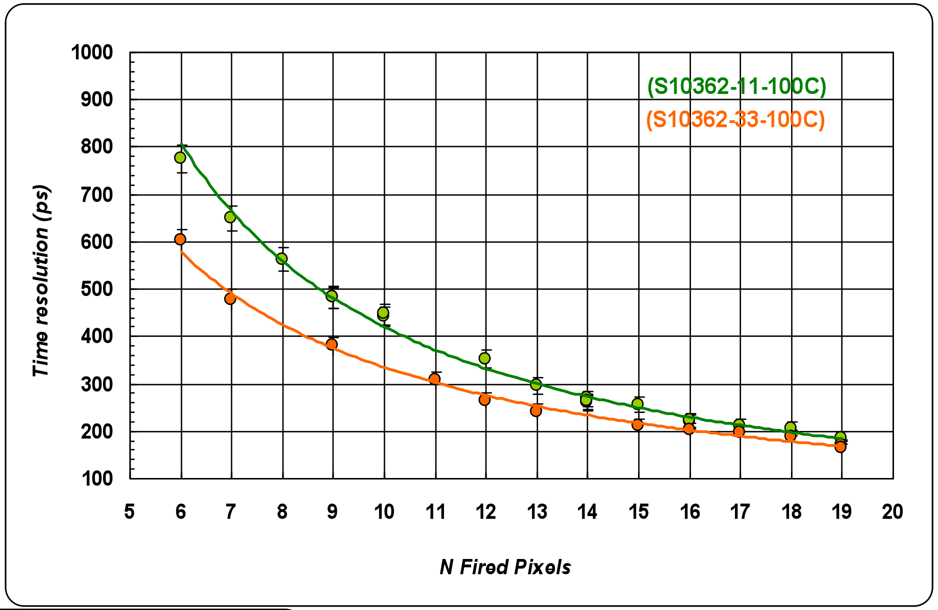


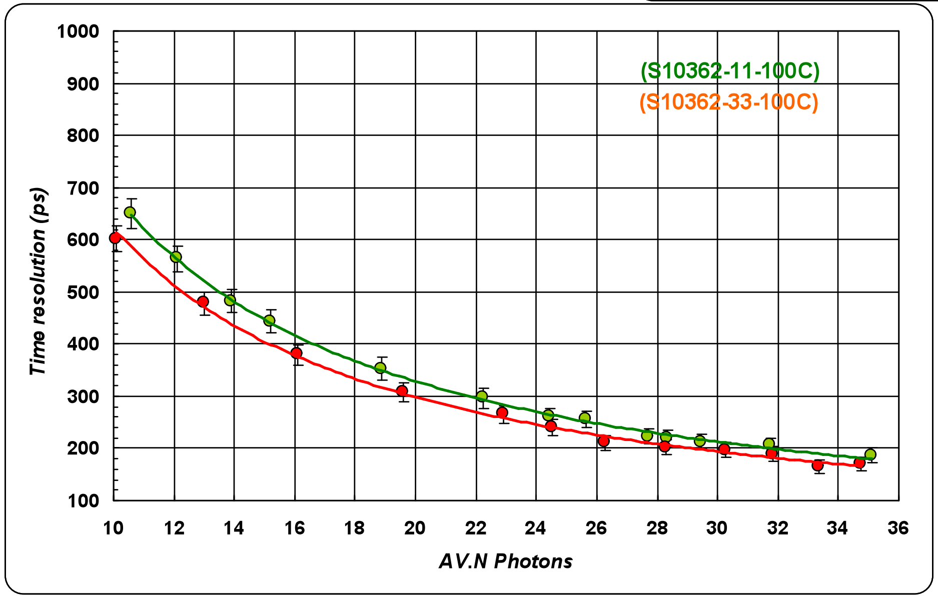




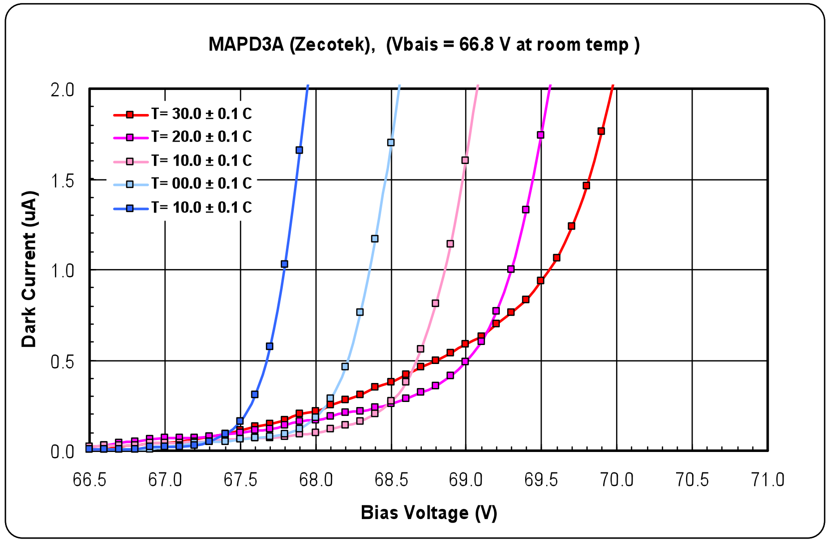
Time resolution improves with number of fired pixels

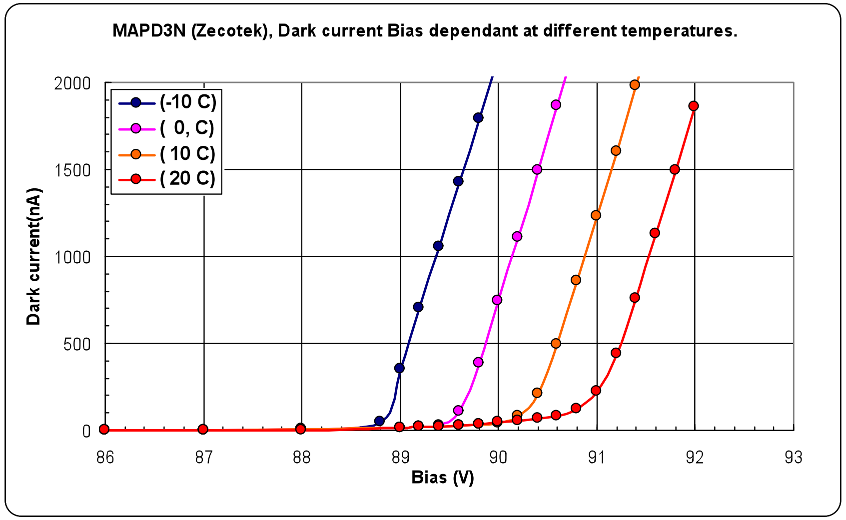
$$\Delta t \propto \frac{1}{\sqrt{\text{number of fired pixels}}}$$





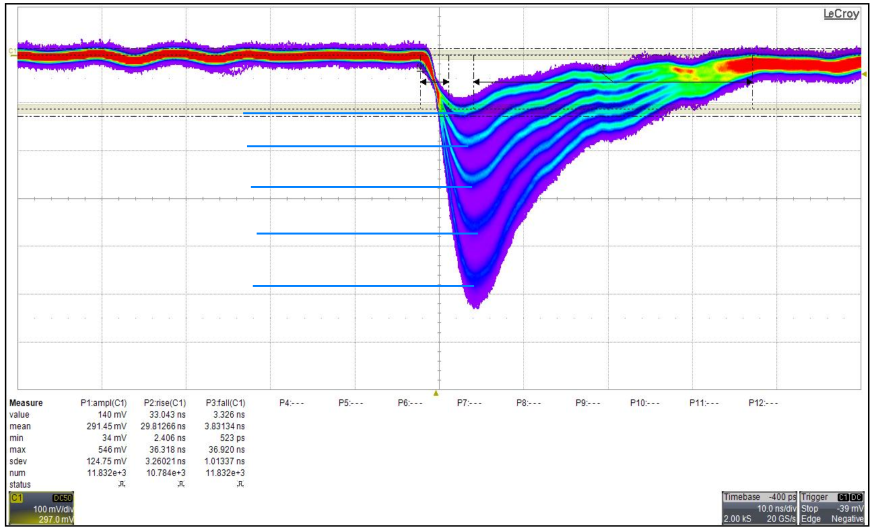
MAPD-High sensitivity of the dark current to T and Vbias variations

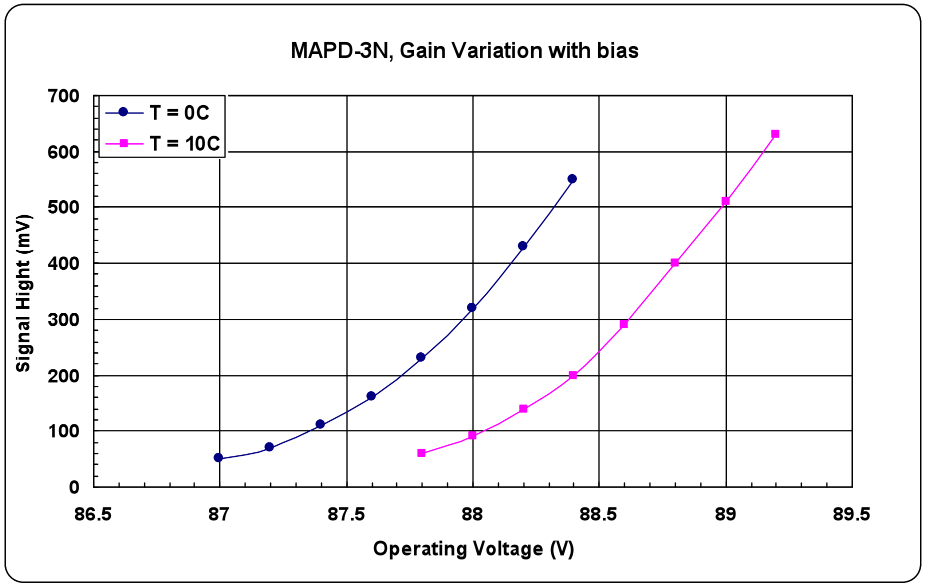




MAPD-High sensitivity of the gain to T and Vbias variations

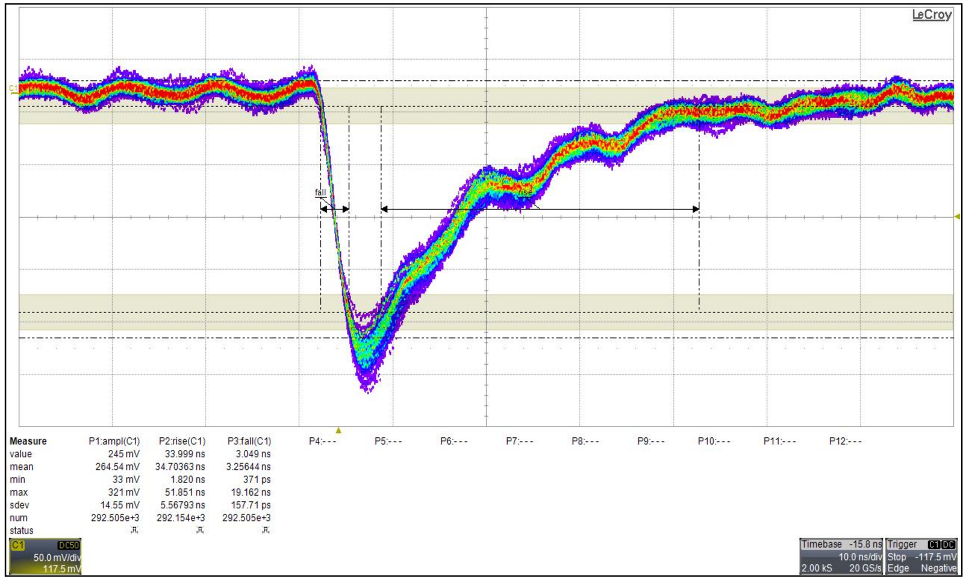
- MAPD pulse height variations with different bias voltage
- Variations is not linear

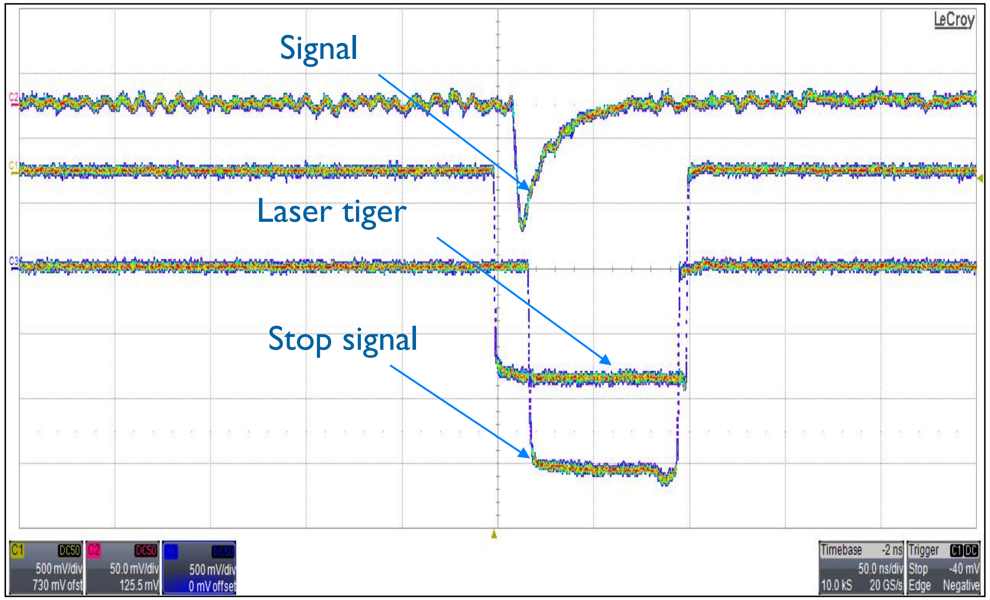




MAPD-time resolution Setup.

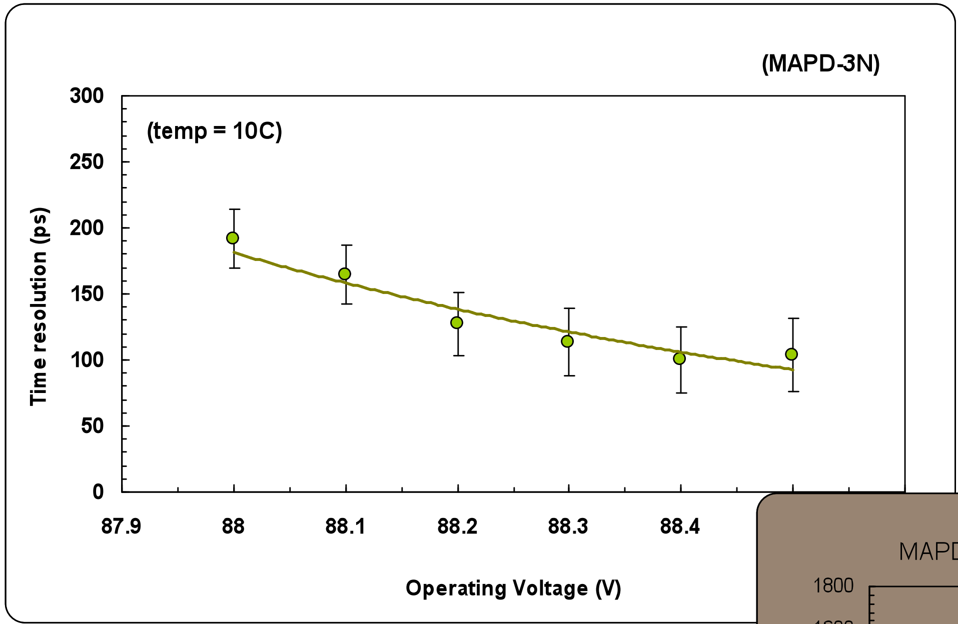
- Rise time ~ 3ns
- Fall time ~ 30 ns

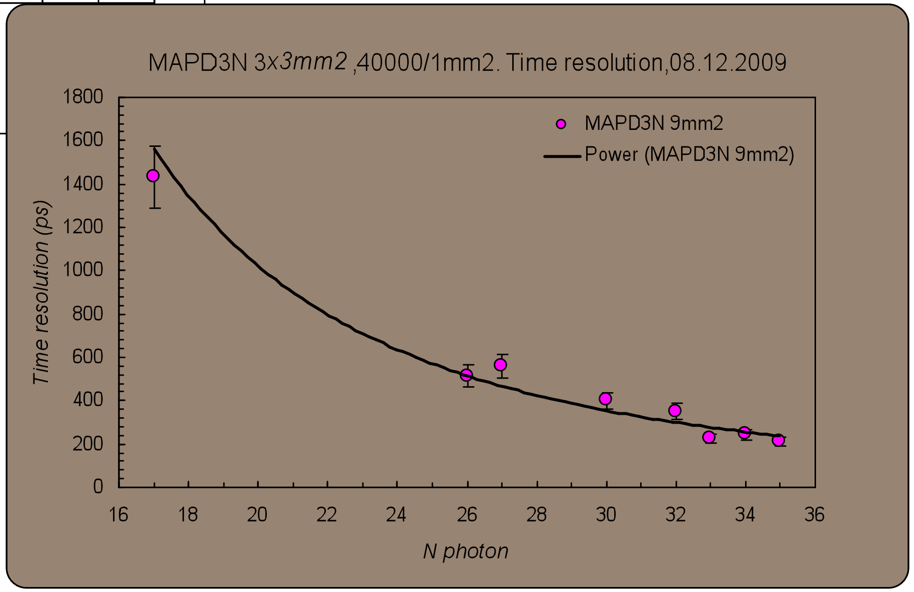




- MAPD-3N
- Fast Laser pulse,
- Bias 88V, temp10C

MAPD-time resolution





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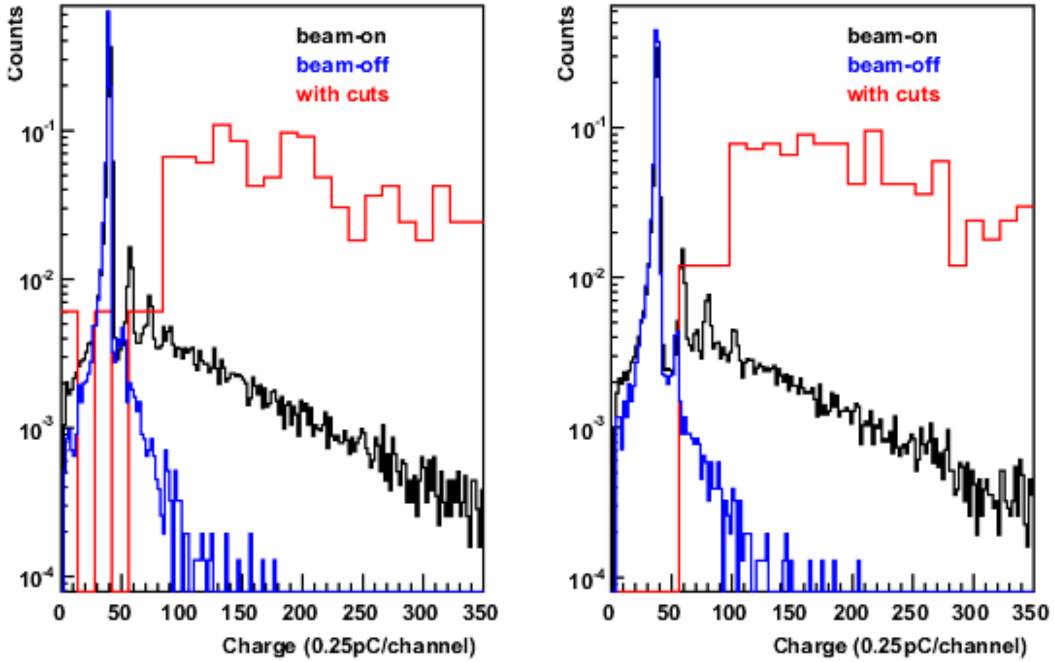

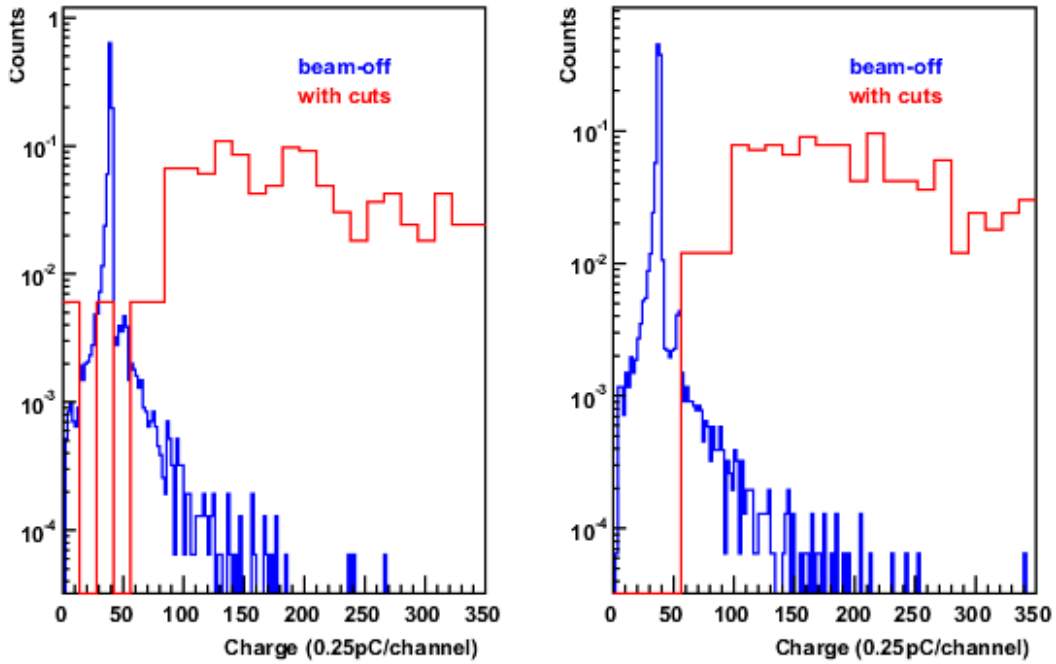
Counts
beam-off
with cuts
Charge (0.25pC/channel)
Counts
beam-off
with cuts
Charge (0.25pC/channel)

Cherenkov Radiation. The angle *θc* of Cherenkov radiation, relative to the particle's direction, for a particle with velocity *βc* in a medium with index of refraction *n* is

$$\begin{aligned} \cos\theta_c &= (1/n\beta) \\ \text{or} \quad \tan\theta_c &= \sqrt{\beta^2 n^2 - 1} \\ &\approx \sqrt{2(1-1/n\beta)} \quad \text{for small } \theta_c, \textit{e.g.} \text{ in gases.} \end{aligned}$$

The number of photons produced per unit path length of a particle with charge *ze* and per unit energy interval of the photons is

$$\begin{aligned} \frac{d^2N}{dEdx} &= \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right) \\ &\approx 370 \sin^2\theta_c(E)\ \text{eV}^{-1}\text{cm}^{-1} \qquad (z=1)\ , \end{aligned}$$

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Calculate the number of emitted Cherenkov radiation if electrons with energy 489 MeV bathing throw 1 cm quartz glass of refractive index (n = 1.46).

According to the relativistic dynamics,

$$E = \frac{m_o c^2}{(1-\beta^2)^{1/2}}$$

$489\ (1\text{-}\beta^2)^{1/2} = 0.511,\ \ \beta = 0.9$

$Cos\,\theta_c = 0.76\ ,\ \ \theta_c = 40$

$Sin^2\theta = (1 - Cos\,2\theta)/2 = (1-(2Cos^2\theta - 1))/2 = \left(1-(2(0.68)^2-1)\right)/2 = 0.42$

N = 205 photons.

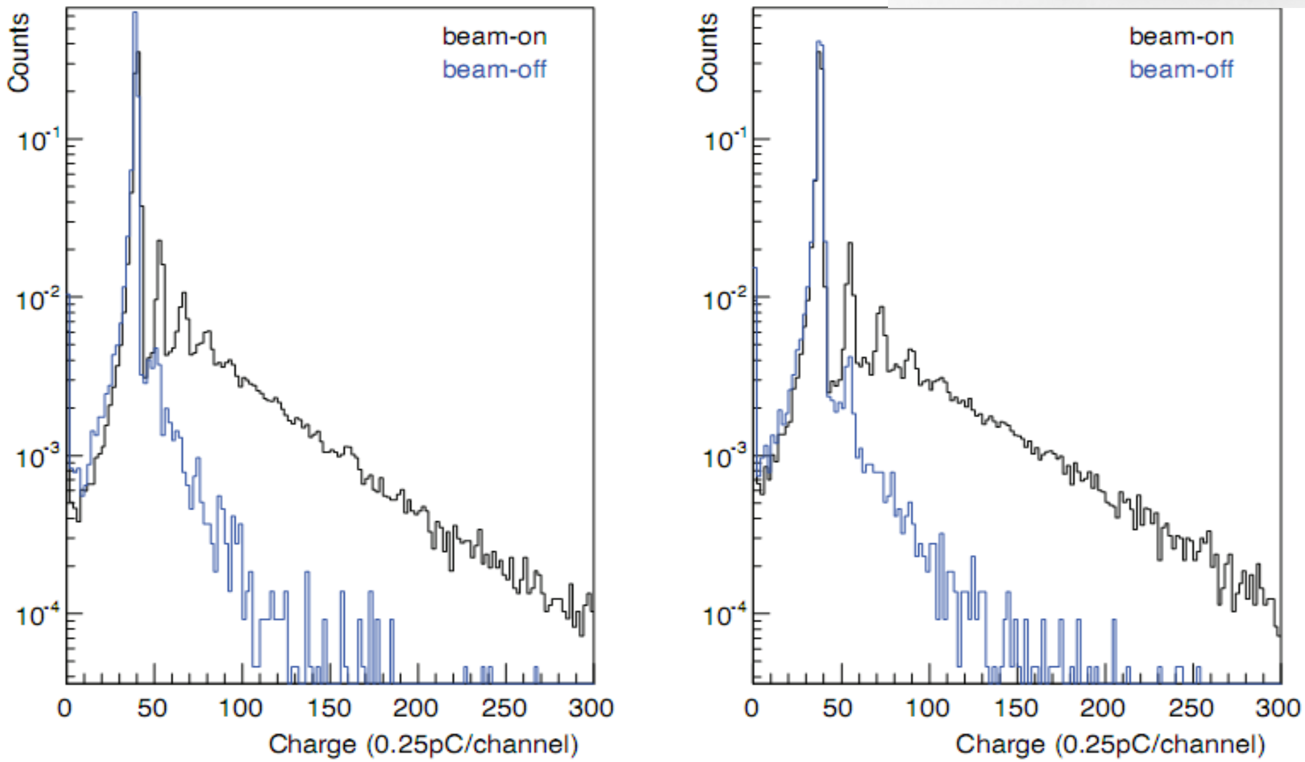
TOF

- Ti = (TiLeft + TiRight)/2 average mean time for each detectors.
- TOF (Tc, T1) = $T_{T1} - T_{C.}$
- The intrinsic timing resolution of each counter is obtained by solving three linear equations of the TOF resolutions among three counters, the Tc, the T1 and the T2

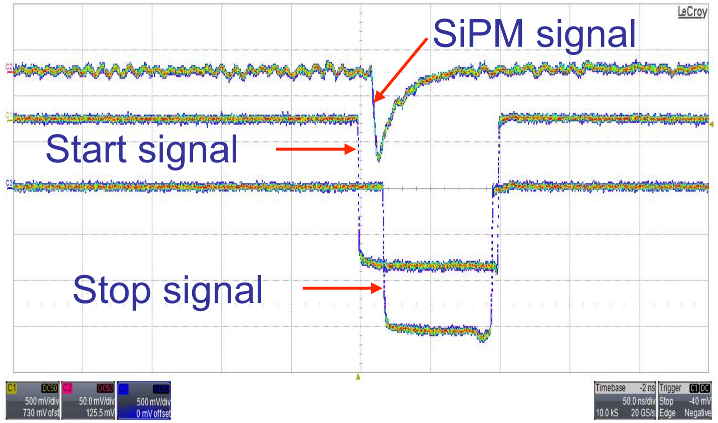
$$\left.\begin{aligned} \sigma^2 TOF\,(T_C,T_1) &= \sigma^2 T_C + \sigma^2 T_{T1} \\ \sigma^2 TOF(T_C,T_2) &= \sigma^2 T_C + \sigma^2 T_{T2} \\ \sigma^2 \mathrm{TOF}(T_1,T_2) &= \sigma^2 T_{T2} + \sigma^2 T_{T1} \end{aligned}\right\} \quad \begin{aligned} \sigma T_C &= \\ \sigma T_{T1} &= \\ \sigma T_{T2} &= \end{aligned}$$

Beam test and results

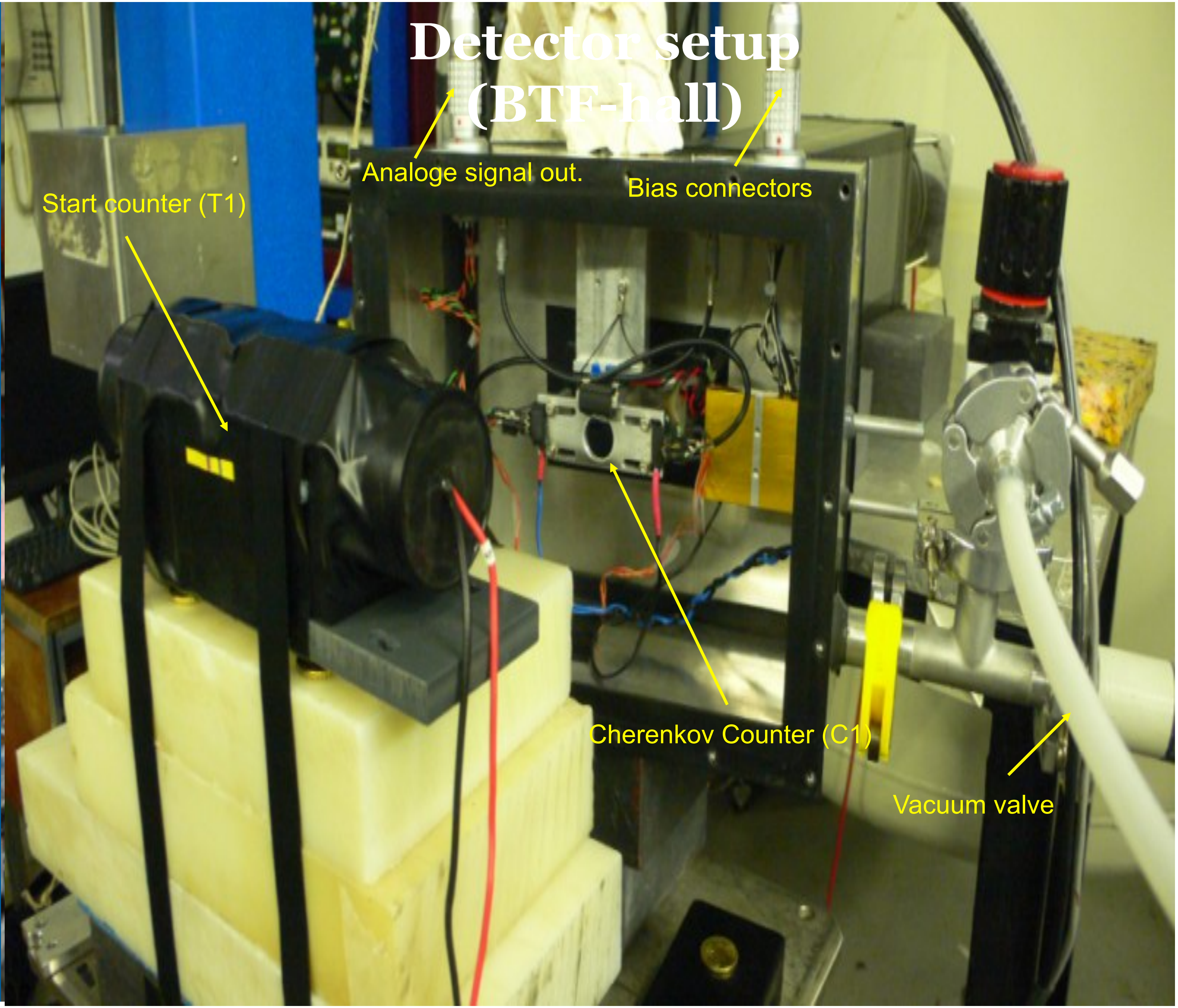
- All the QDC and TDC signals were recorded to PC via CAMAC PCI bus interface and stored for offline analysis.
- Figure shows Cherenkov counter recorded charge spectra for each MPPC side, while black and blue lines represent the charge distributions measured while beam-on and beam-off conditions.
- In response to the penetrating particles, each MPPC sensor was able to detect an average number of 8 photons.



$$\Delta T = \sqrt{\left(\left(\frac{\Delta a}{2}\right)^2 + \left(\frac{\Delta b}{2}\right)^2\right)}$$



Detector setup (BTF-hall)



Detector setup (BTF-hall)