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

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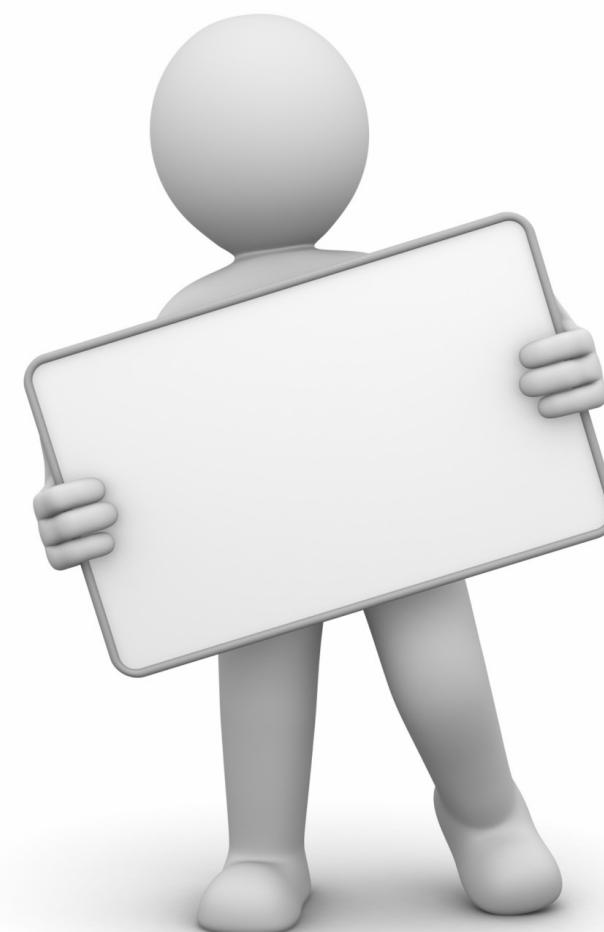


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Outline

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



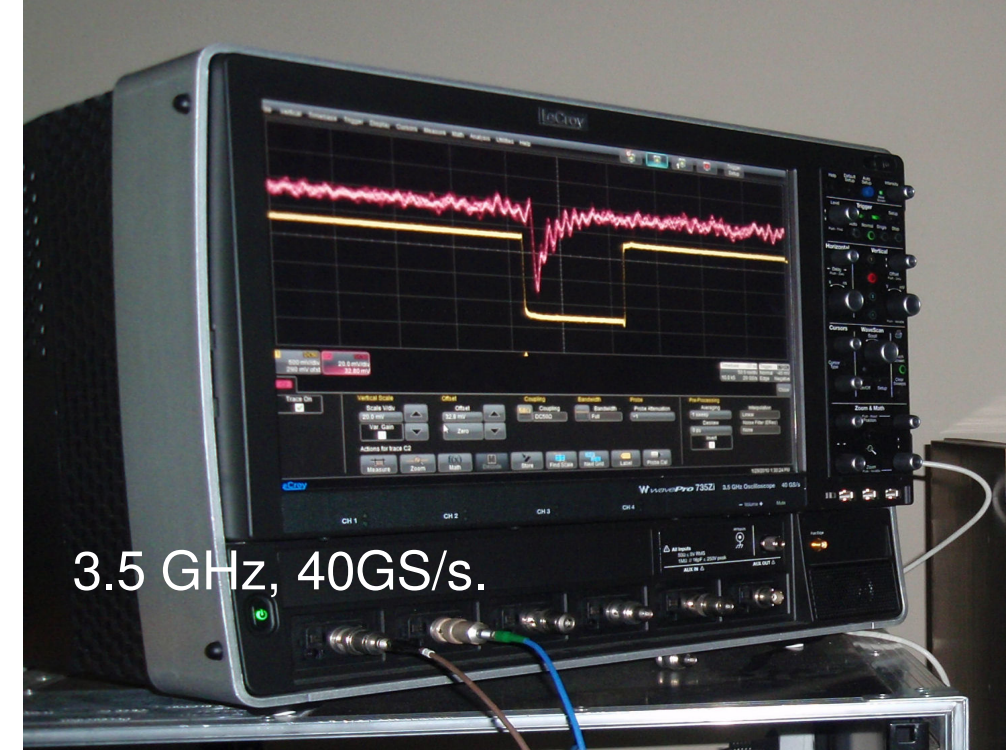
Motivation

- ✦ 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

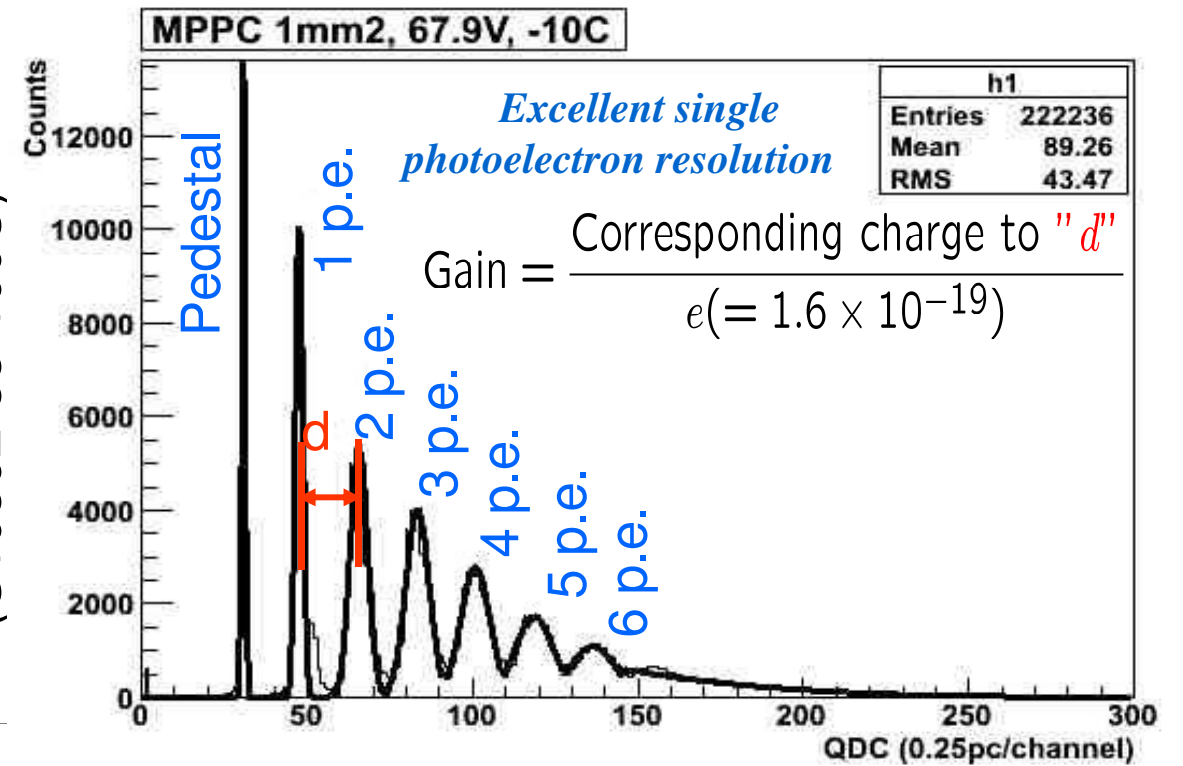
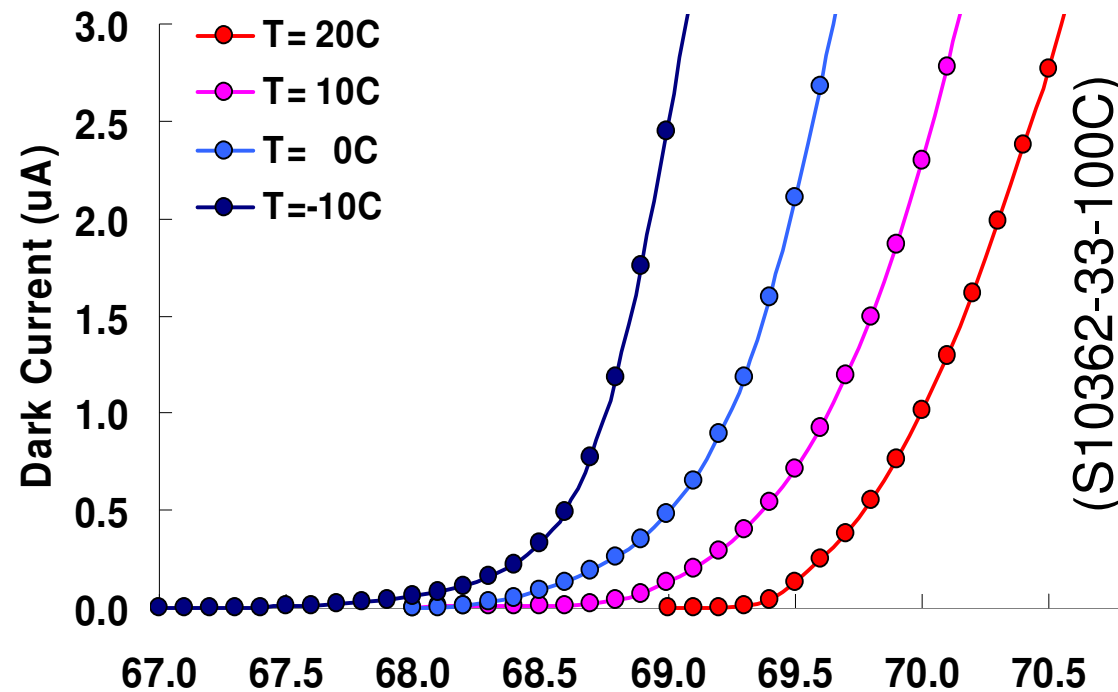
Dark box, Keithley 617 programmable electrometer,
Pico second laser system



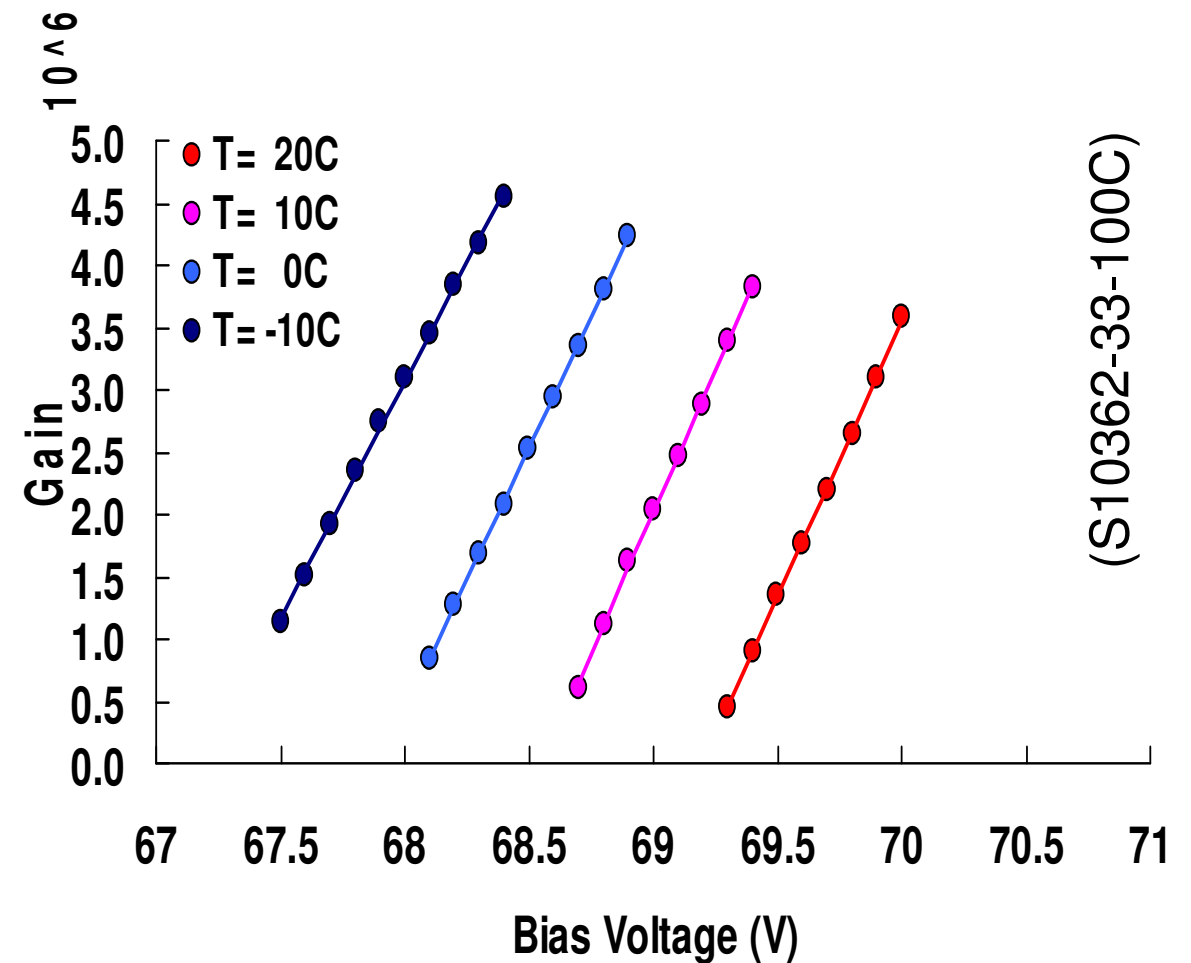
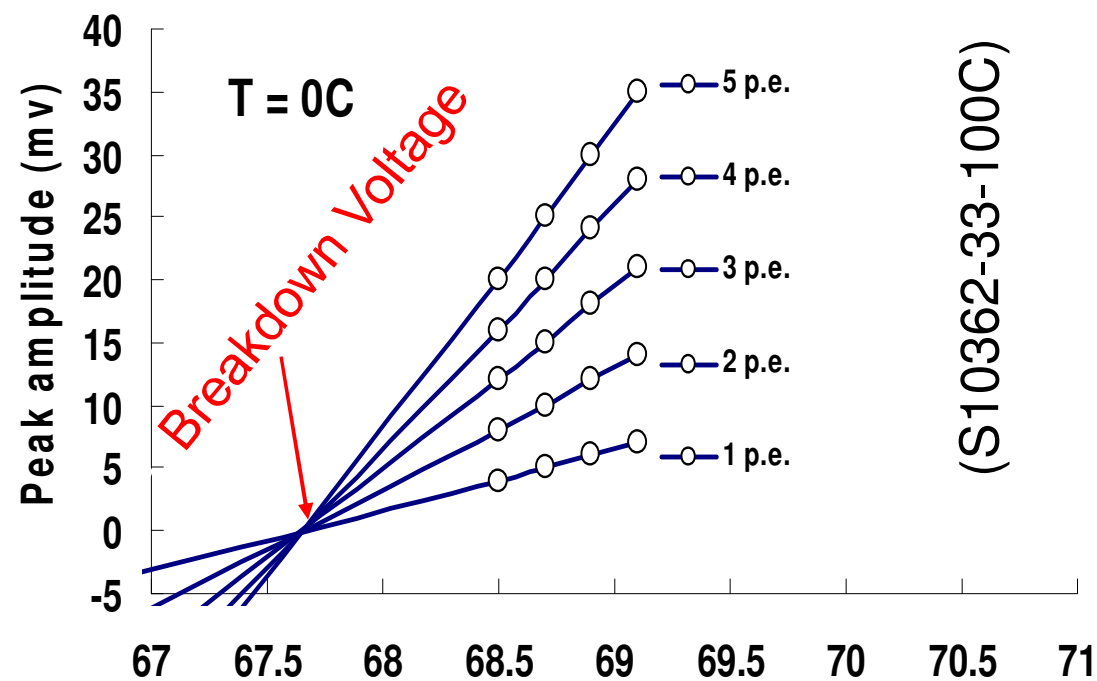
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SiPM parameter measurements

Dark current vs Bias Voltage



Breakdown Voltage

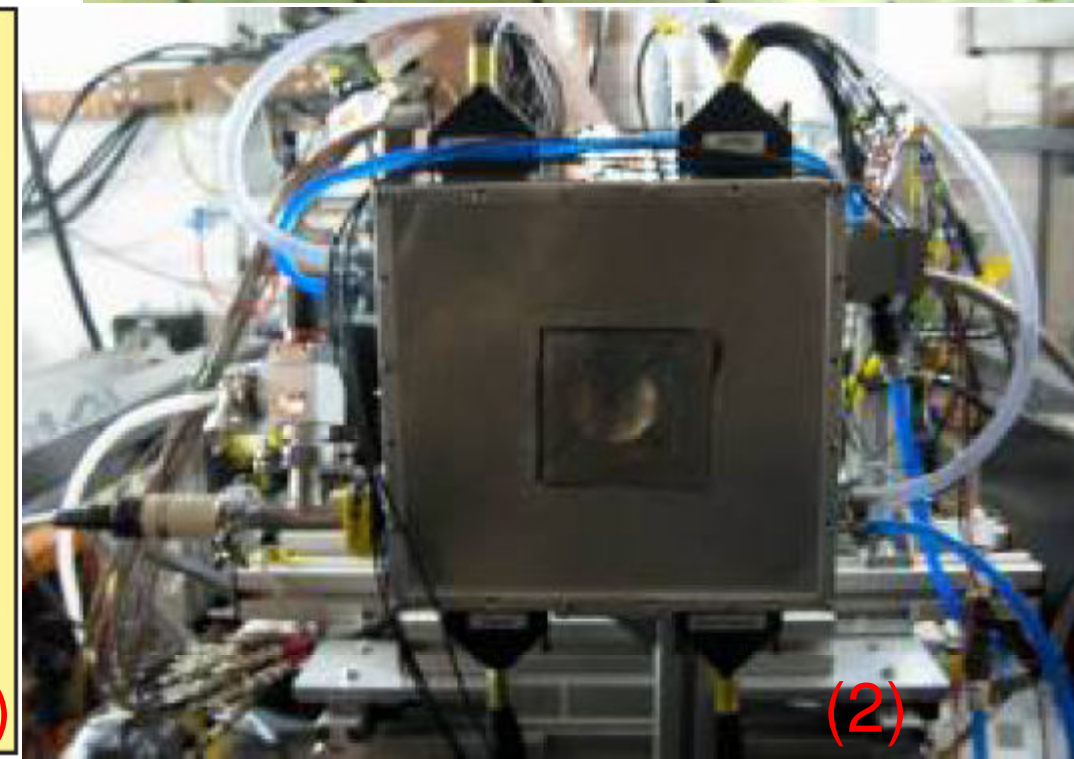
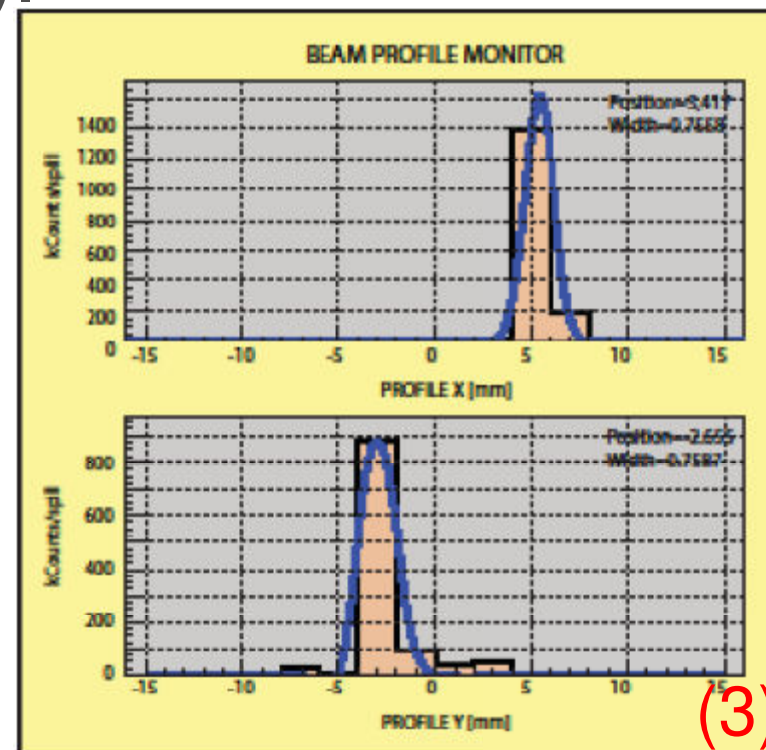
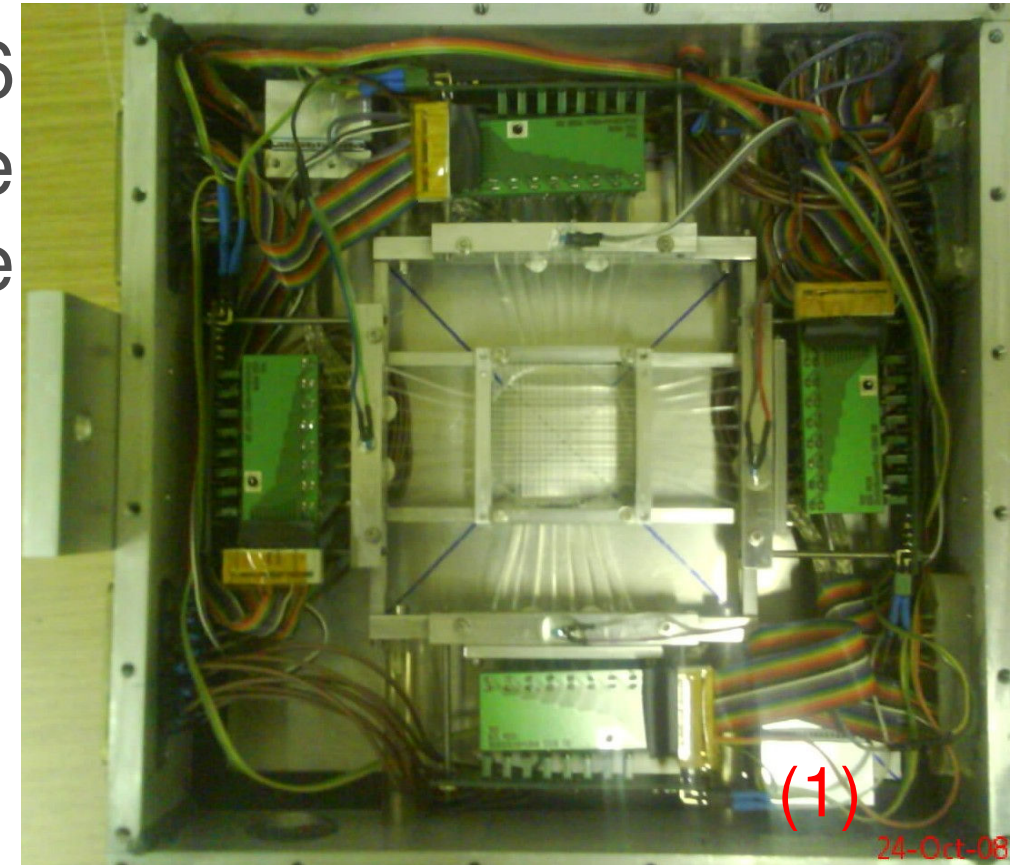


Beam profile monitor

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).

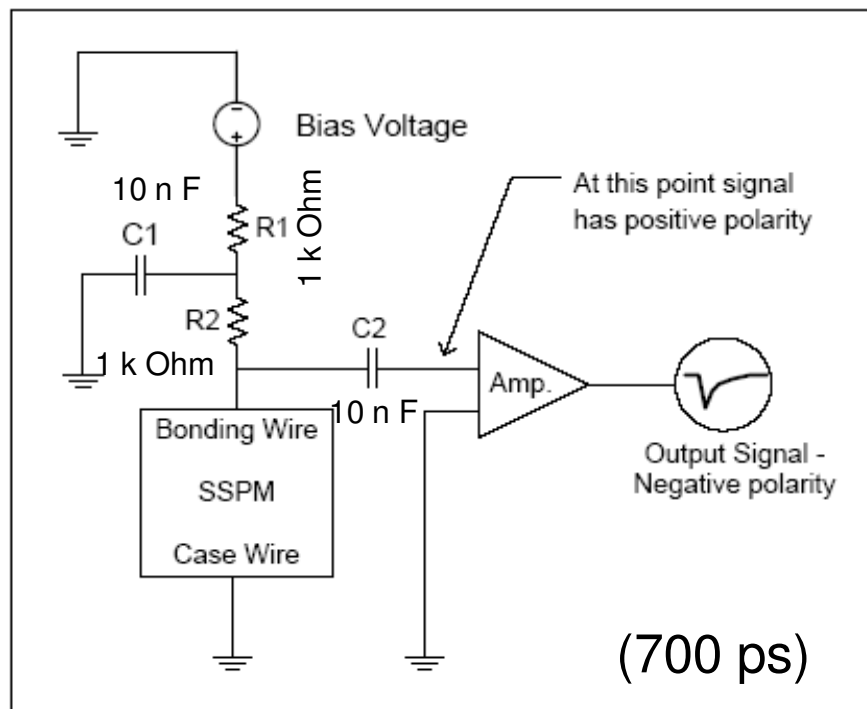
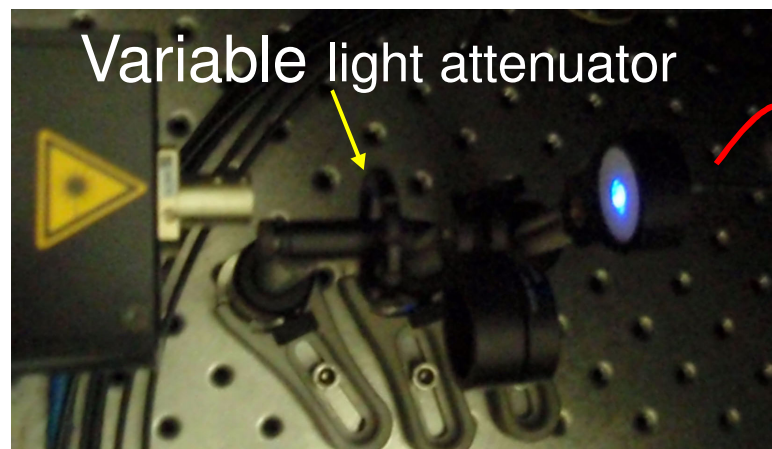
Beam profile monitor mounted at FOPI/GSI (2).

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

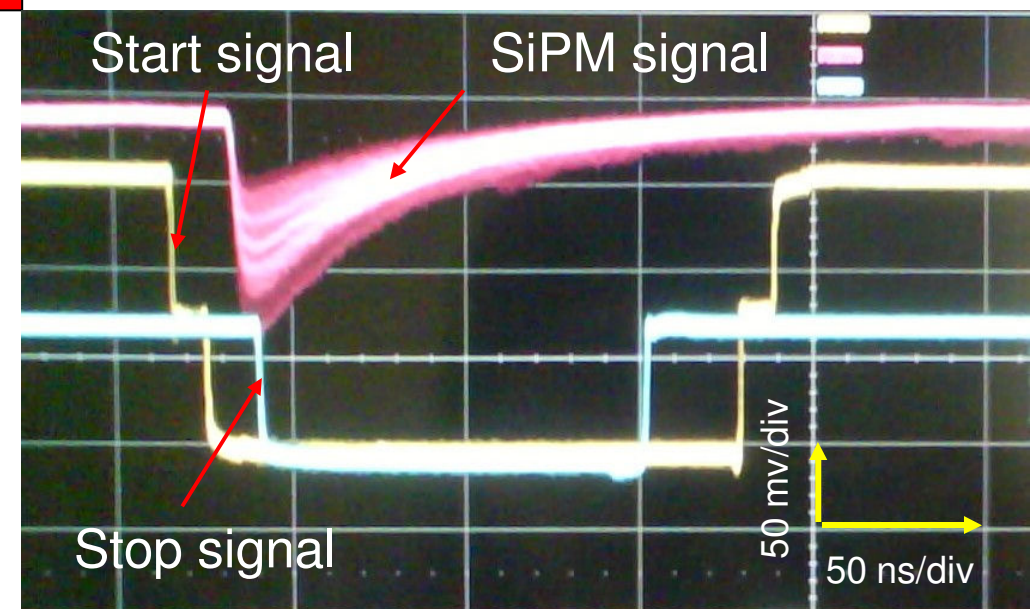
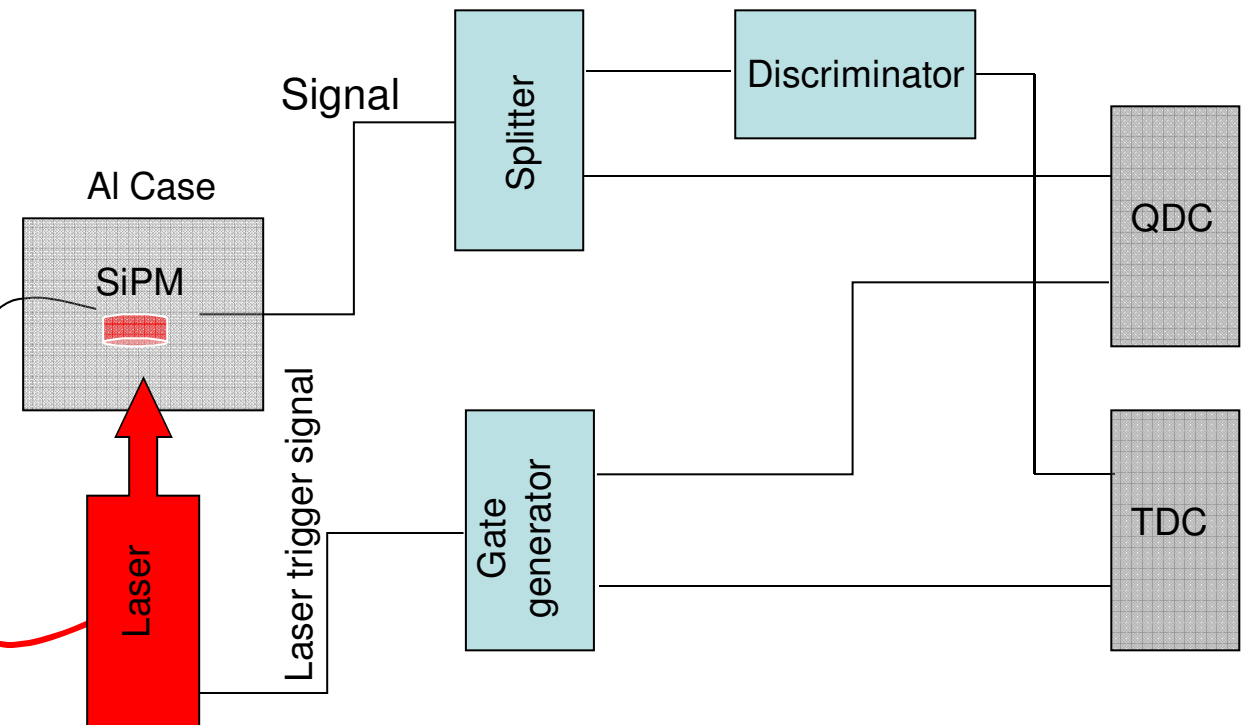


SiPM time resolution measurements

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



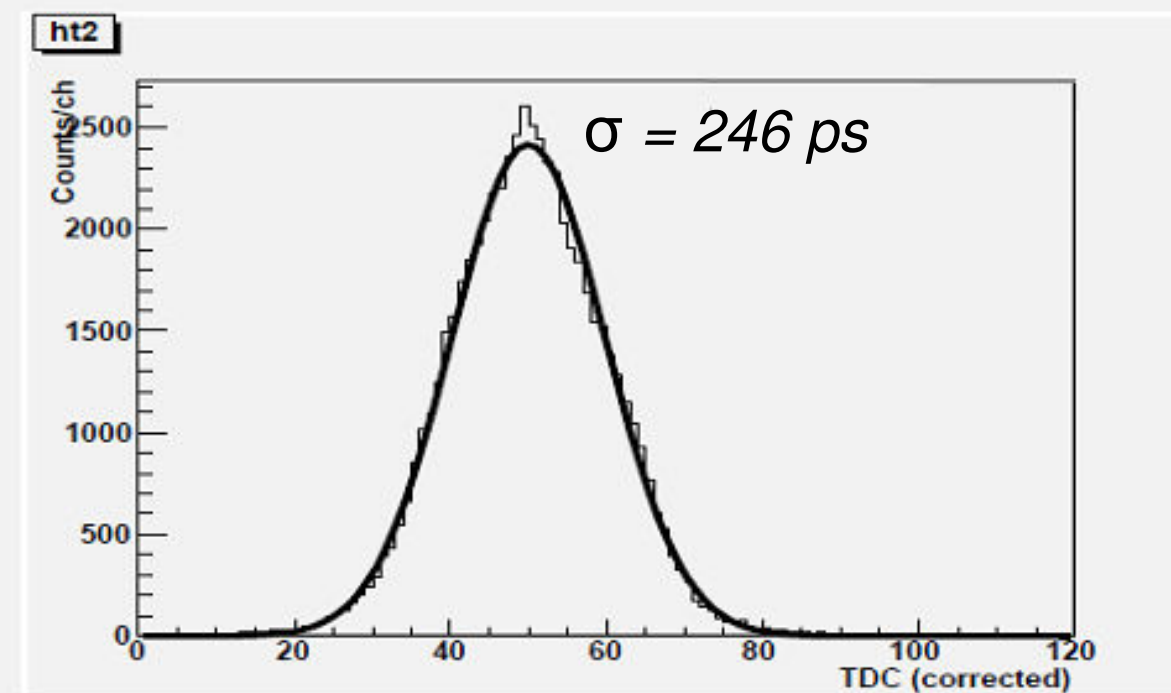
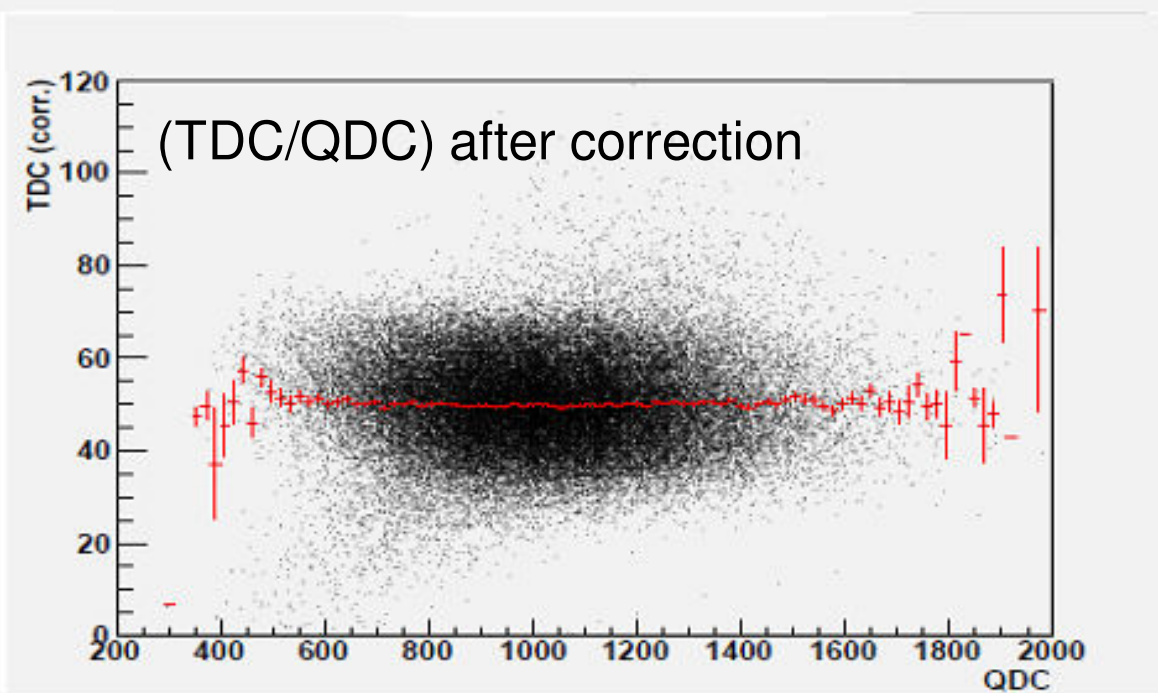
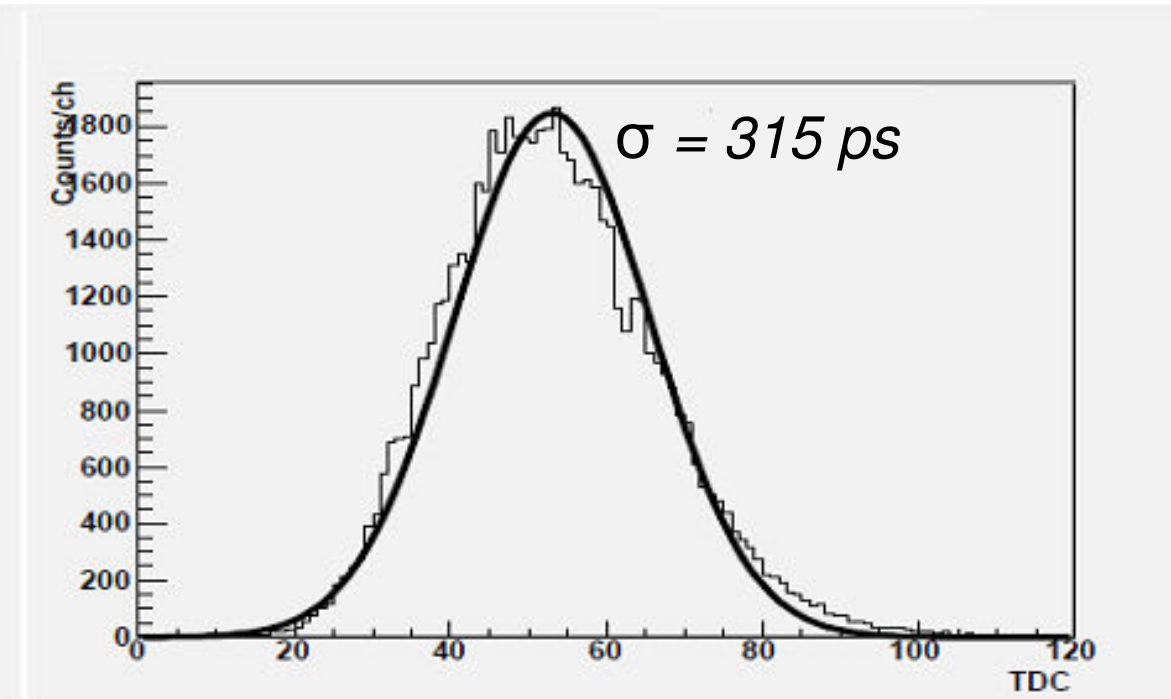
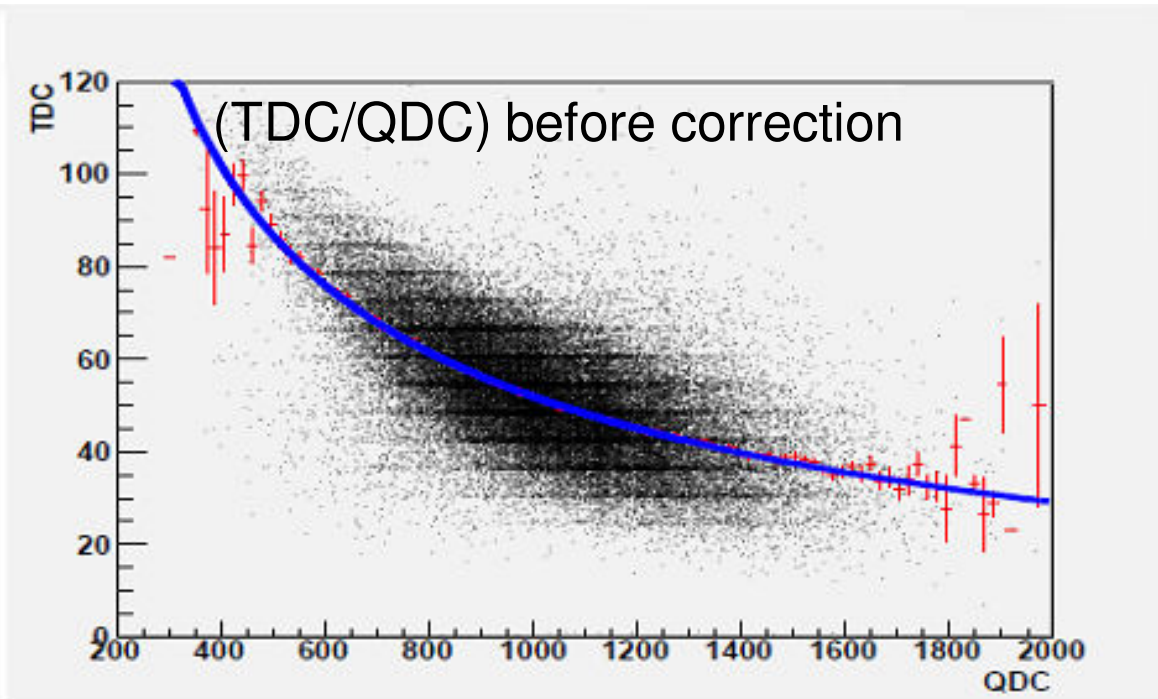
Photonique preamplifier (AMP-0611)





Time resolution measurements

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

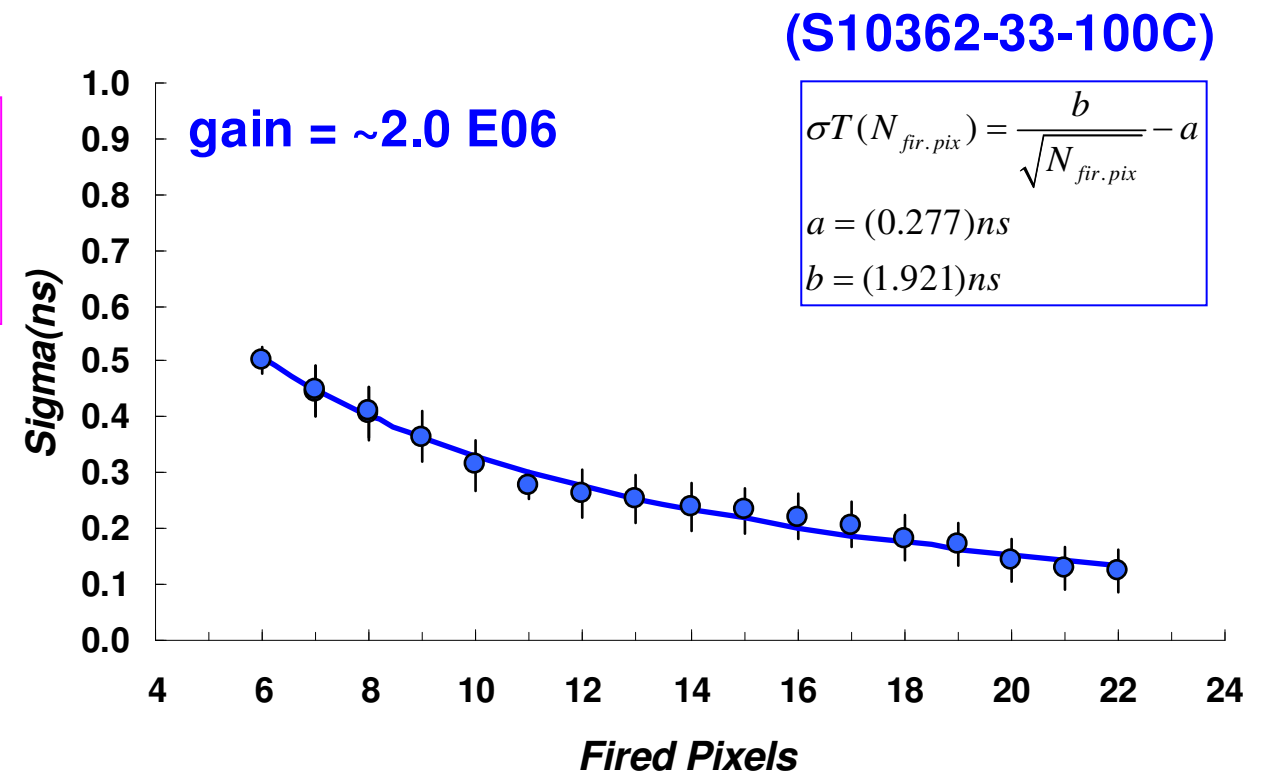
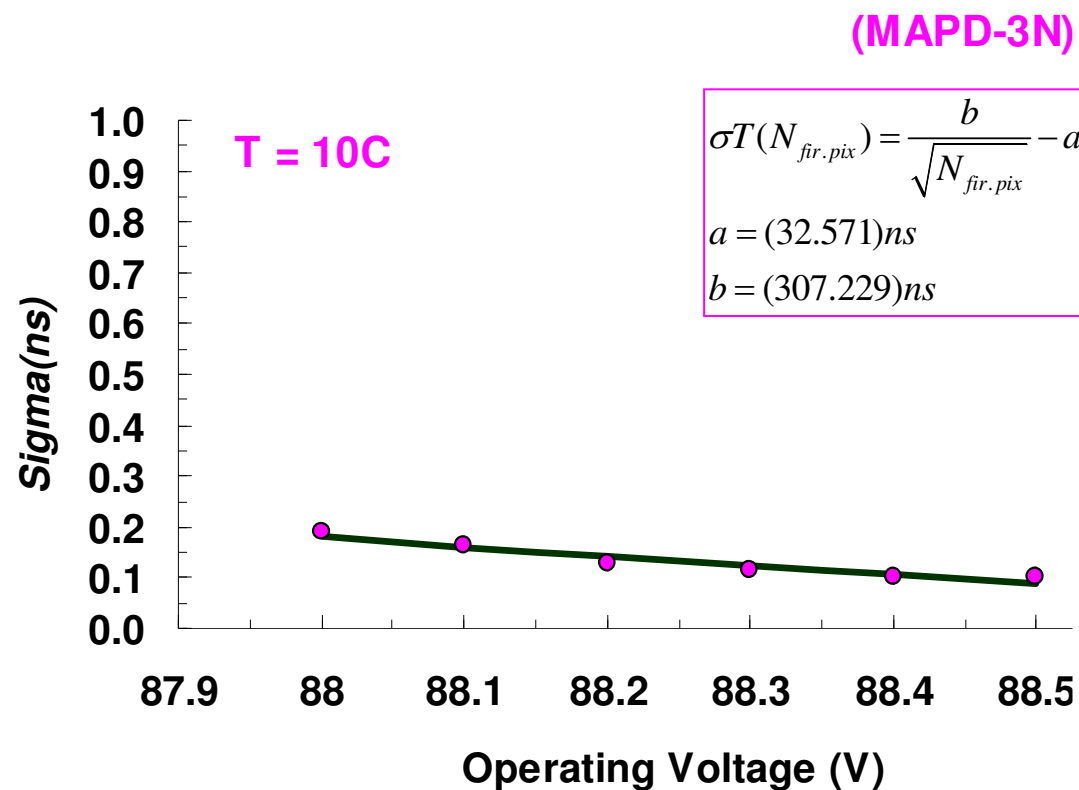
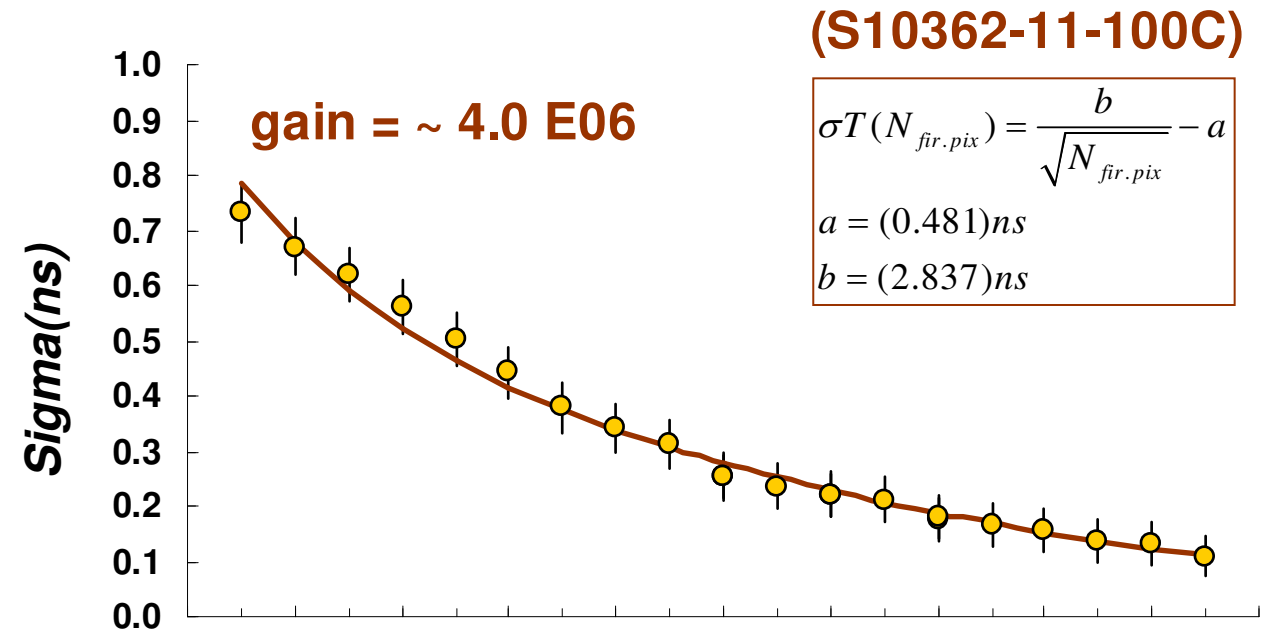




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Time resolution measurements

- ⊕ MPPC (1, 3 mm²)
Hamamatsu.
- ⊕ MAPD-3N, Zecotek.

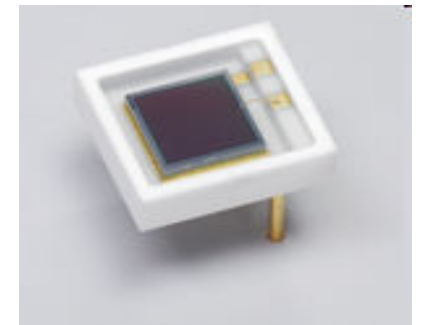
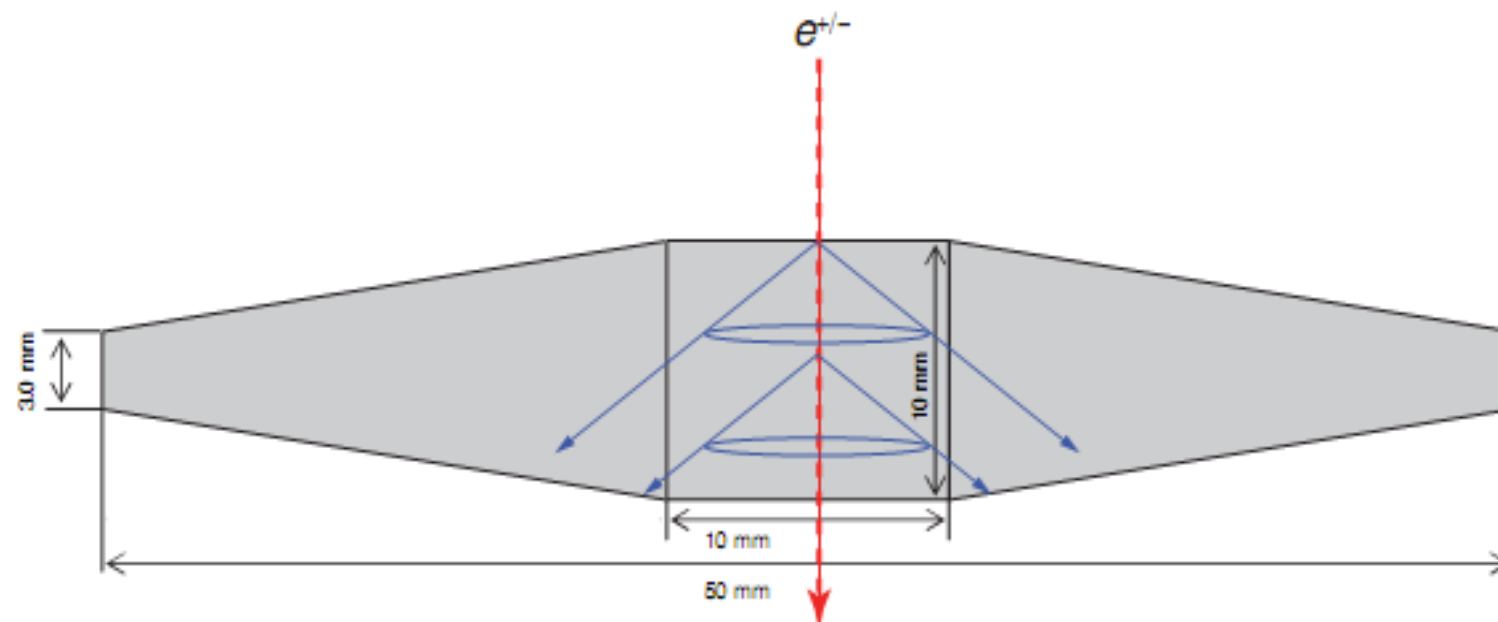


⊕ Time resolution improves with increasing the number of photons and/or operating voltage.

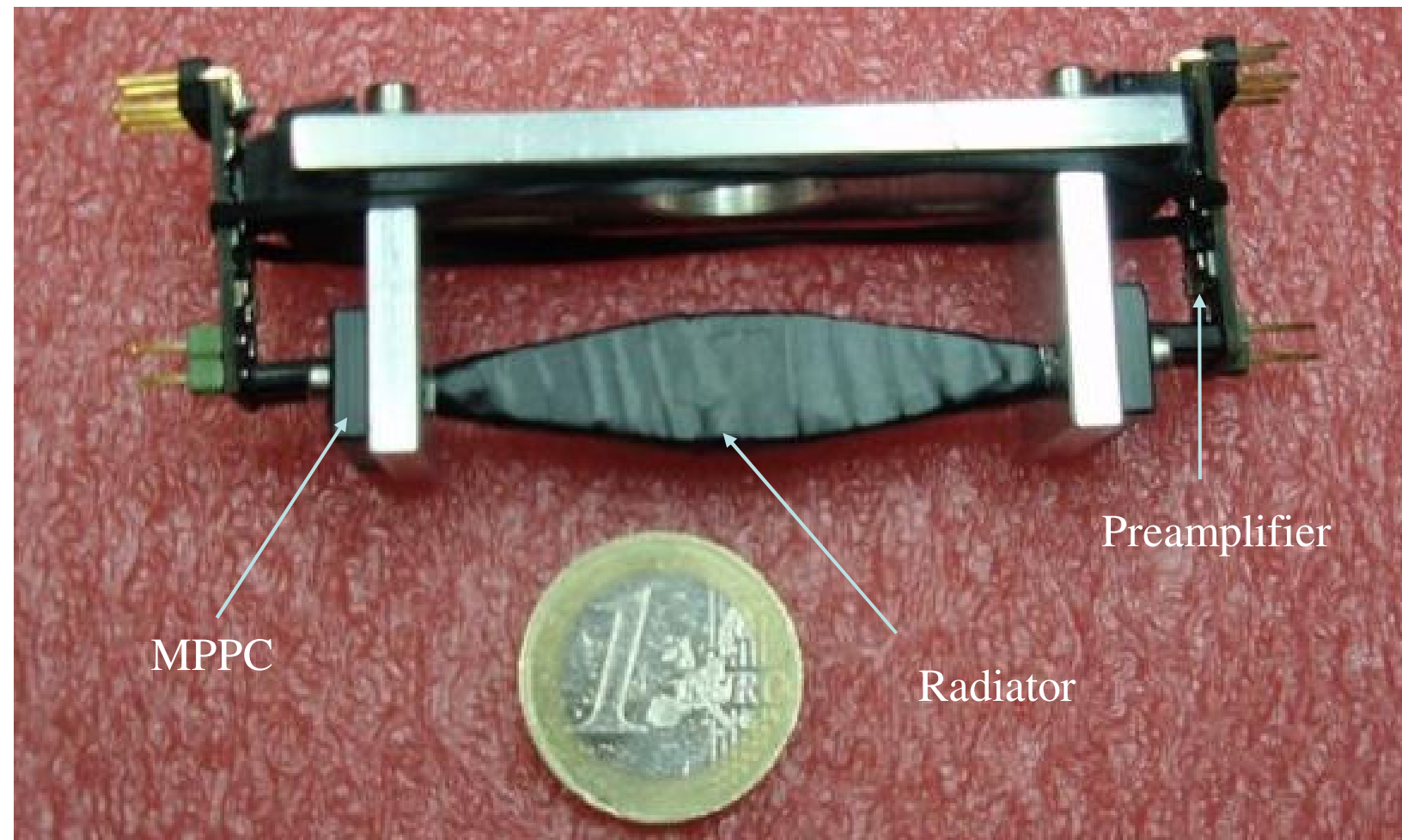


Cherenkov counter prototype

A radiator made of quartz, 1 cm thick and 5 cm long, optically coupled on both sides to 3 mm² MPPCs (S10362-33-100C) (Hamamatsu, this device 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 mm²), the reduction of photon collection will have a negative impact on the overall timing performance.



Cherenkov counter prototype



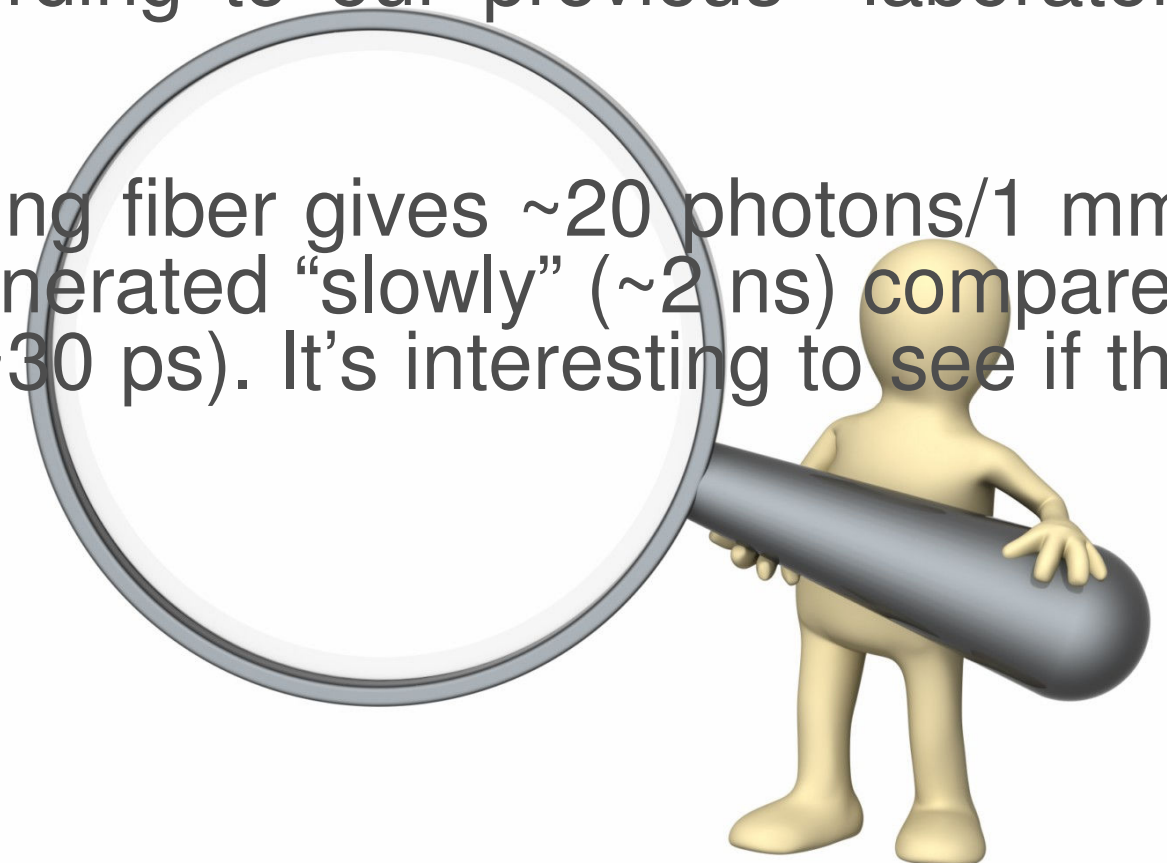
Photograph of the prototype Cherenkov counter

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



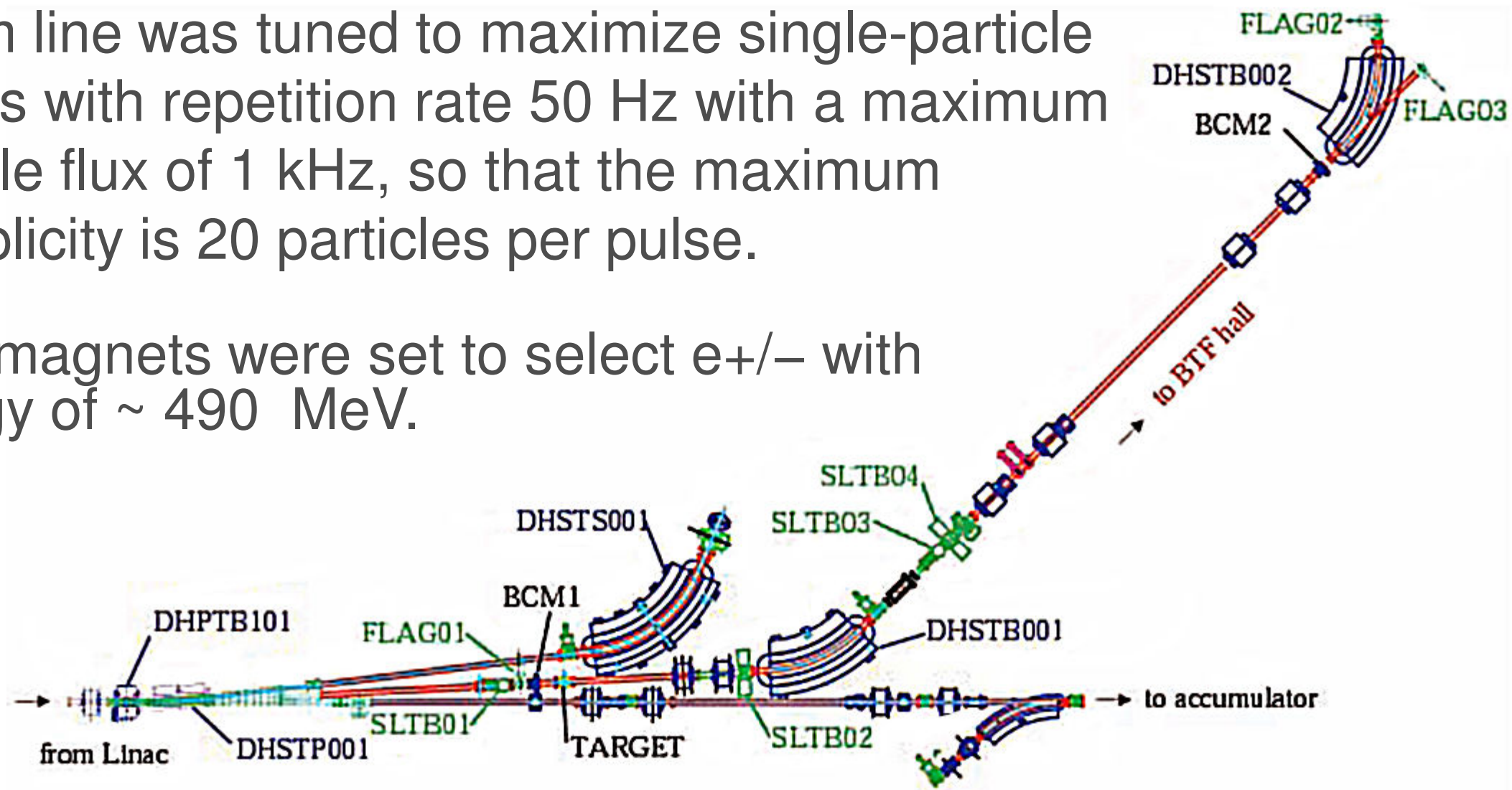
Cherenkov counter prototype

- ✦ 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” ($\sim 2 \text{ ns}$) 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.

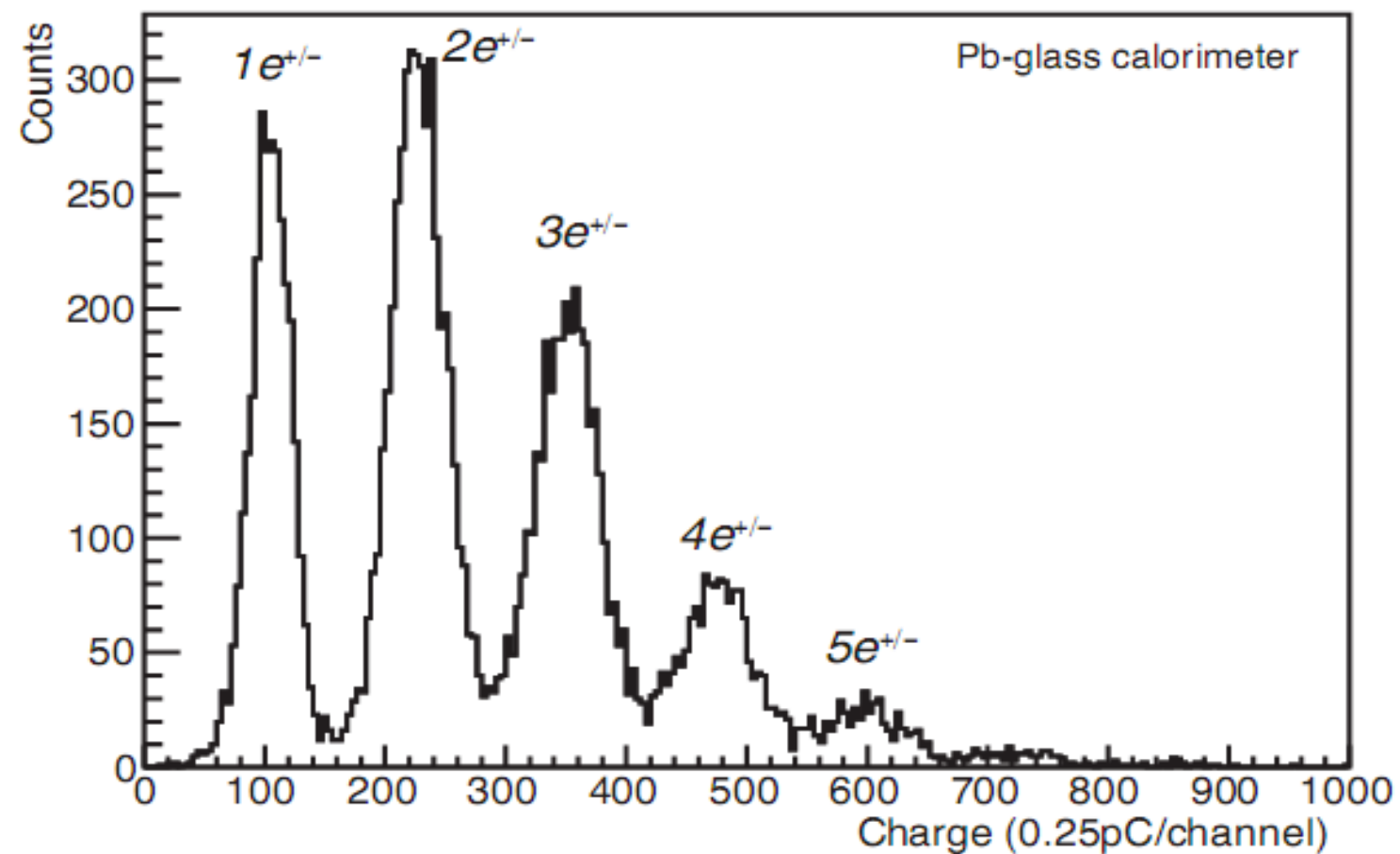


Layout of the BTF transfer line and its main components.



Test at the BTF

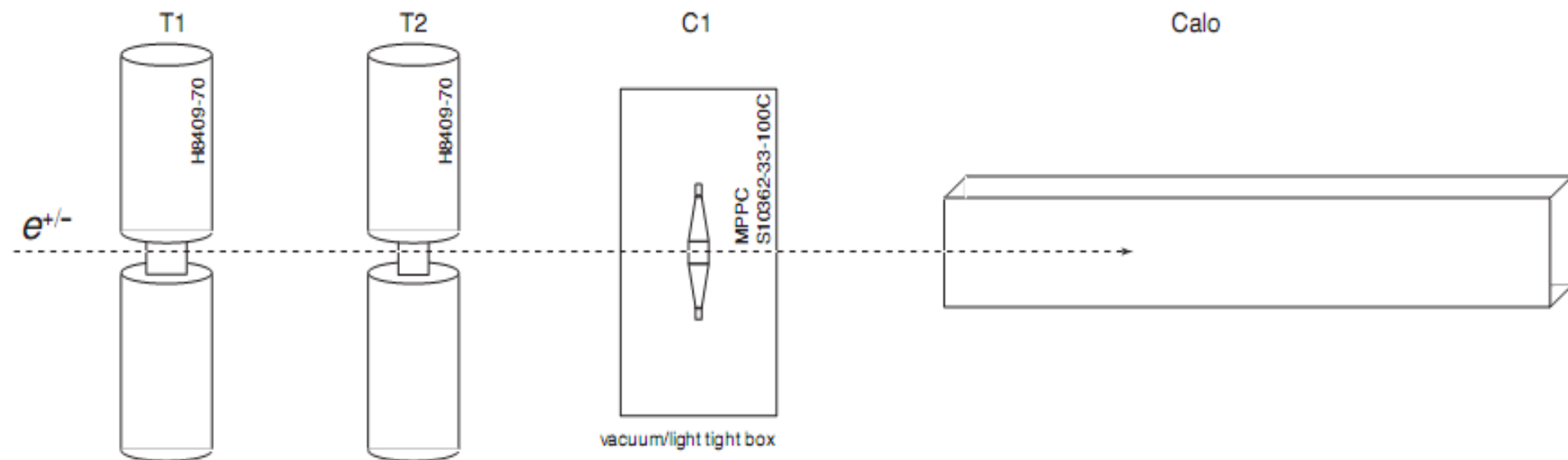
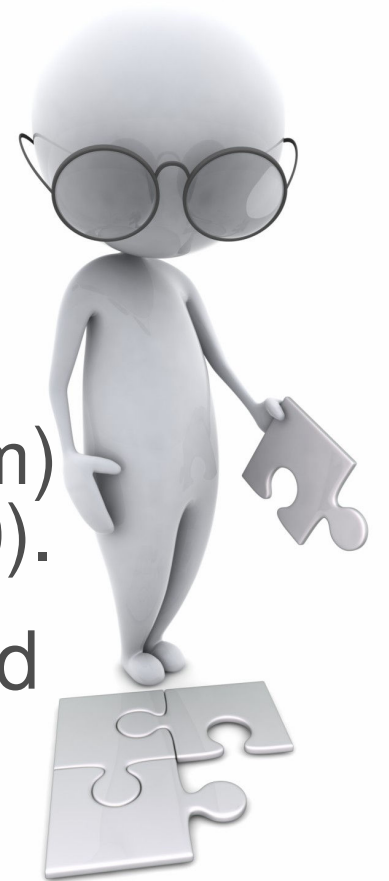
- The beam diagnostics elements at BTF include a Pb-glass calorimeter.
- The separate peaks correspond to beam pulses of 1, 2, 3, and more beam particles. This information allows to select beam pulses of a specific multiplicity by software in later analysis.



- Calo typical energy spectrum of BTF beam at low multiplicity was acquired with charge ADC.

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.

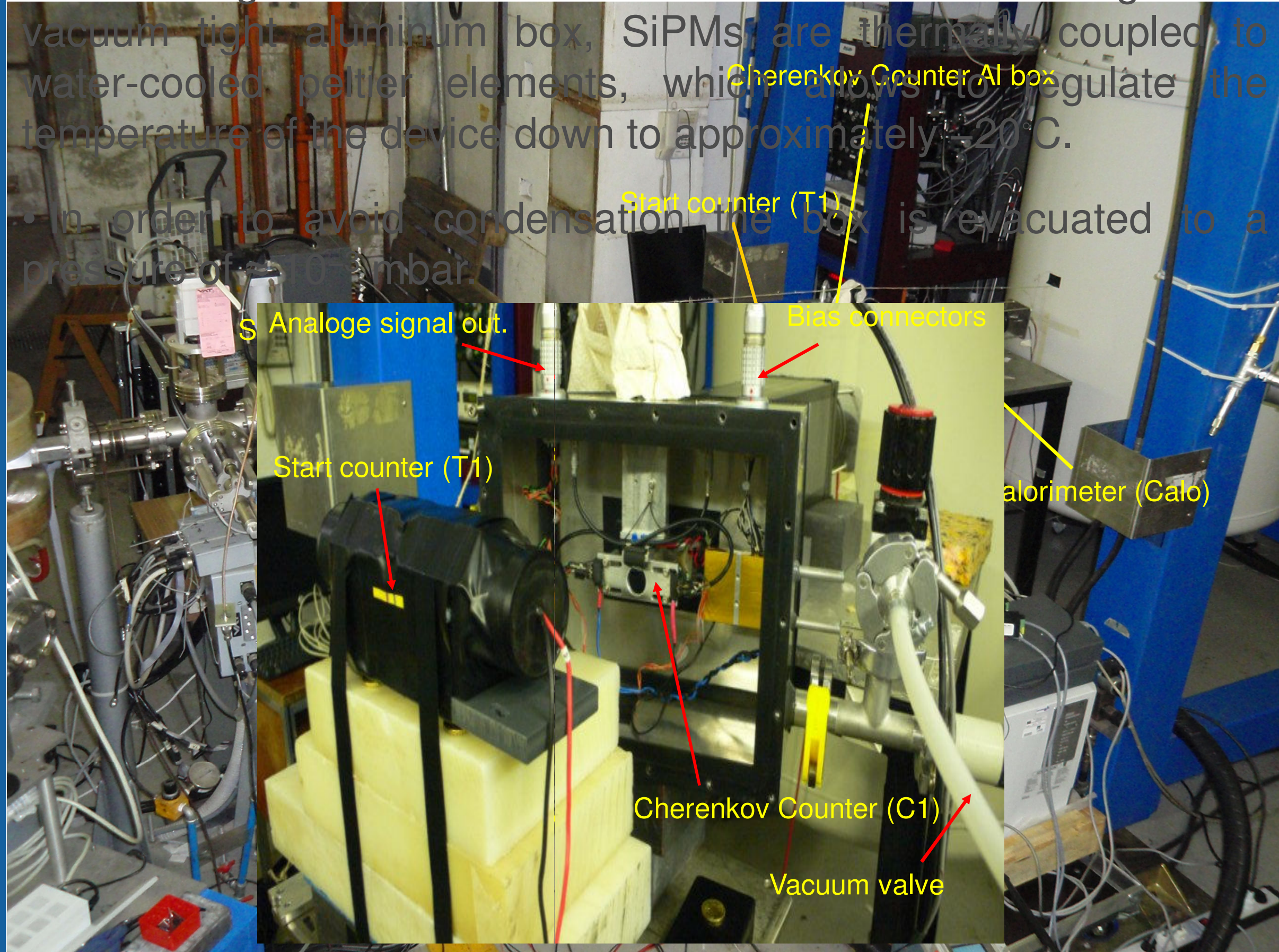




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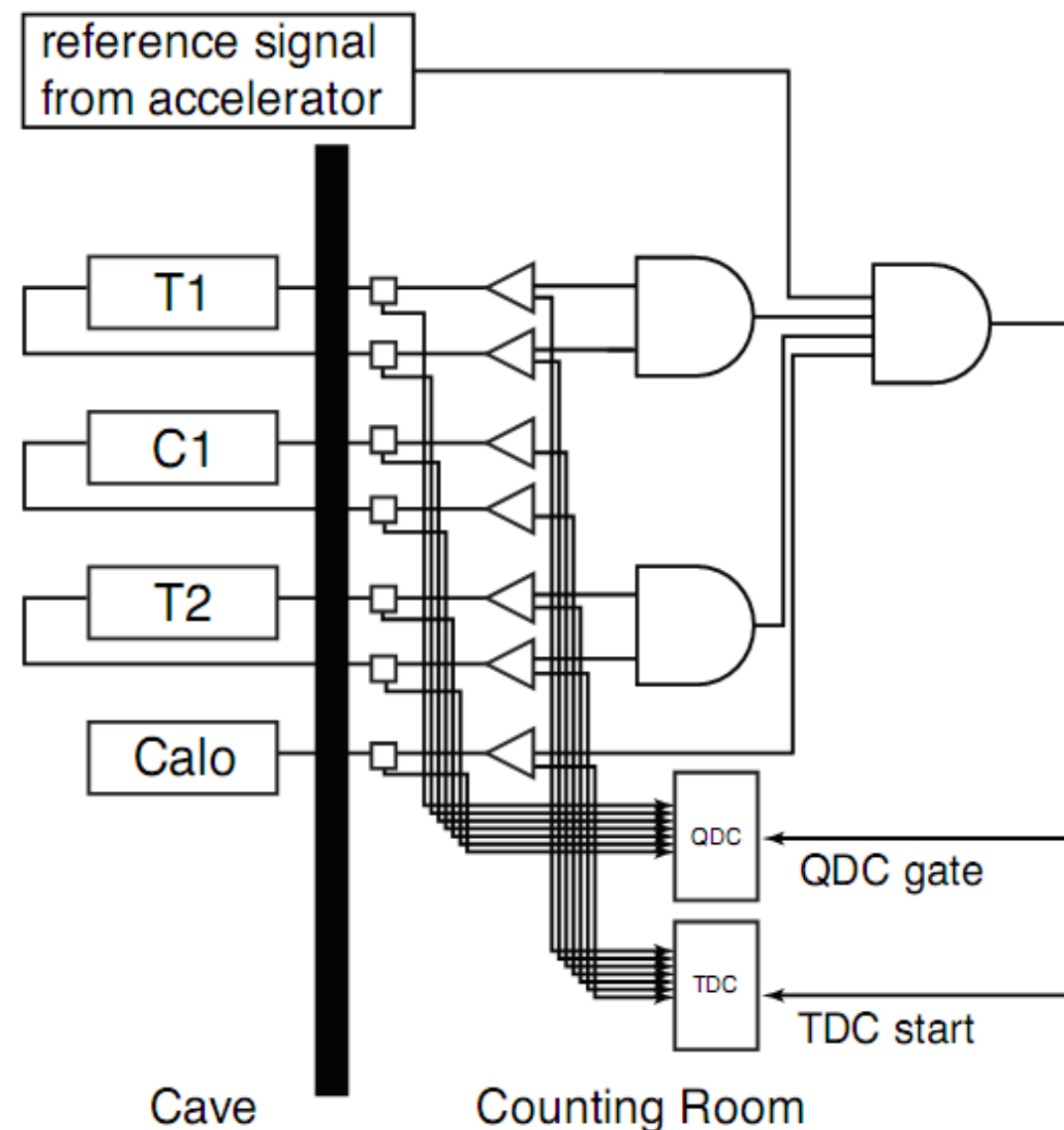
Detector Setup (BTF Hall)

- 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 $\sim 10^{-5}\text{mbar}$.



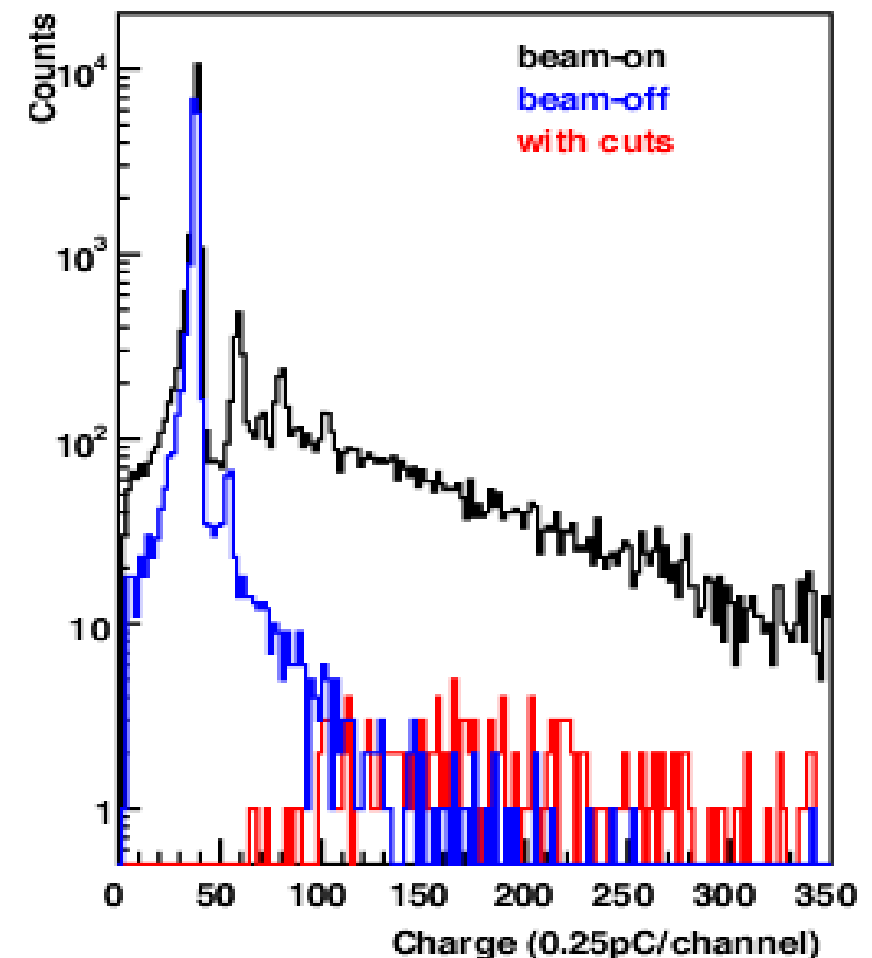
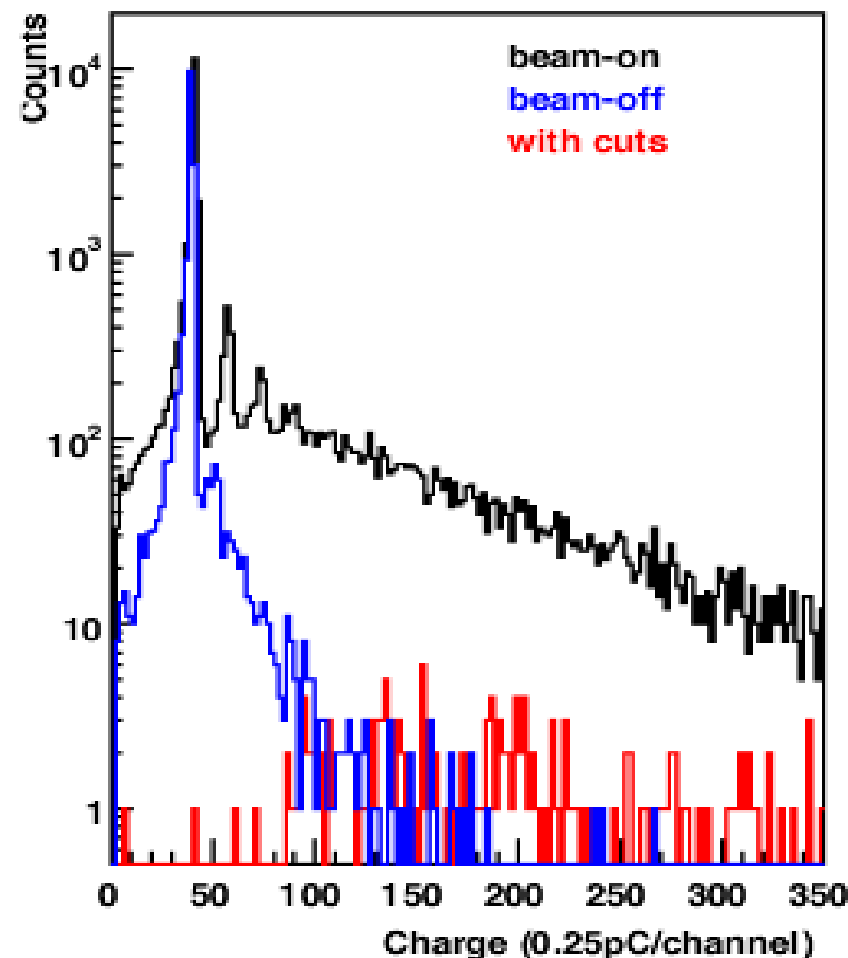
Readout electronics

- The readout electronics was set up to measure charge spectra and TOF between the reference discriminator and the outputs were fed into a TDC and Cherenkov counters.
- Each counter signal output was split into two lines. produce a gate signal for the QDC and a common start signal for the TDC.
- One was connected to a QDC for the charge measurement.



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.

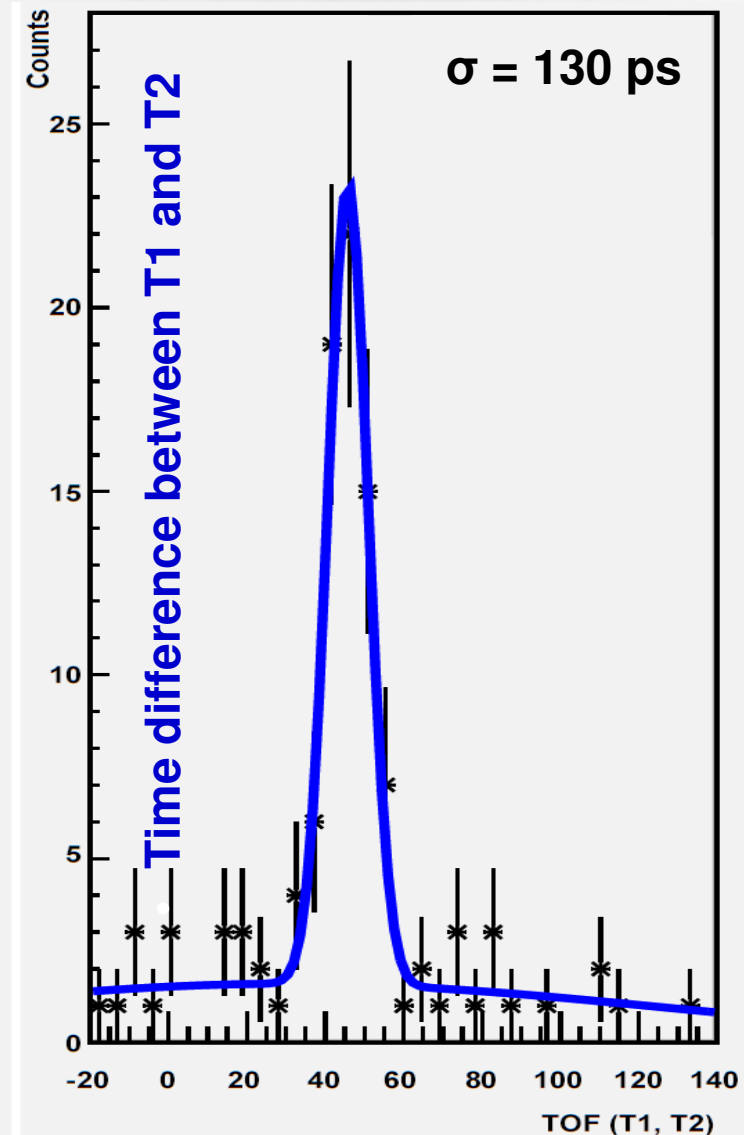
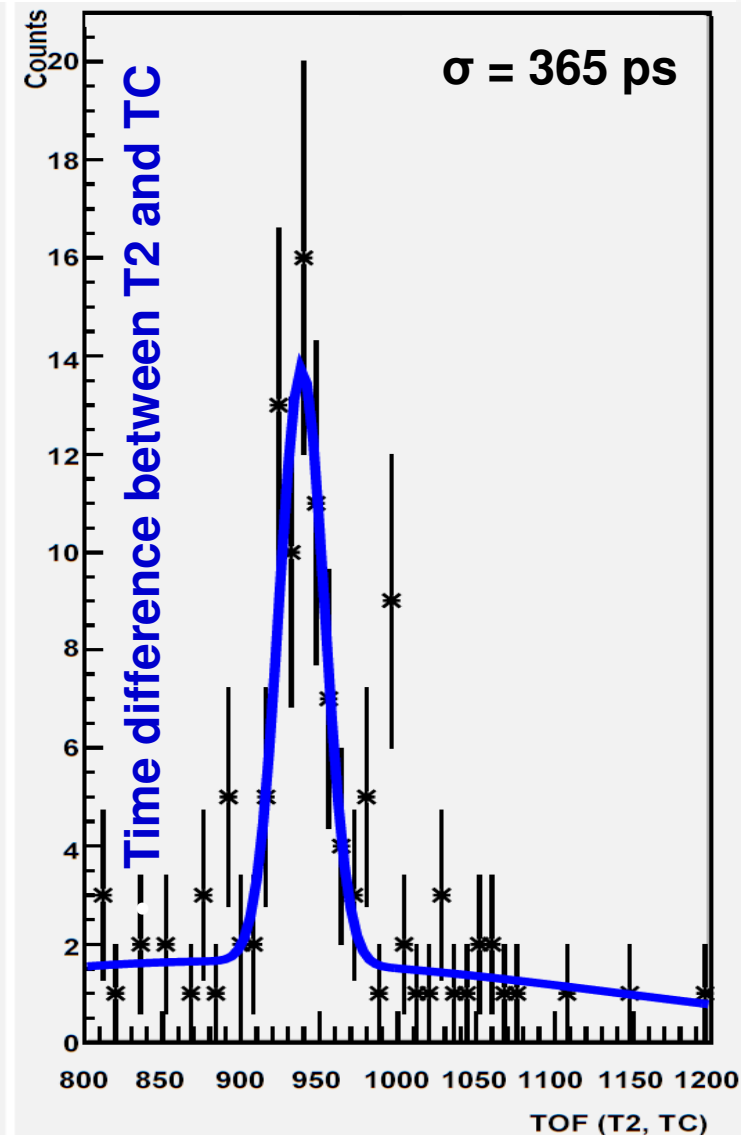
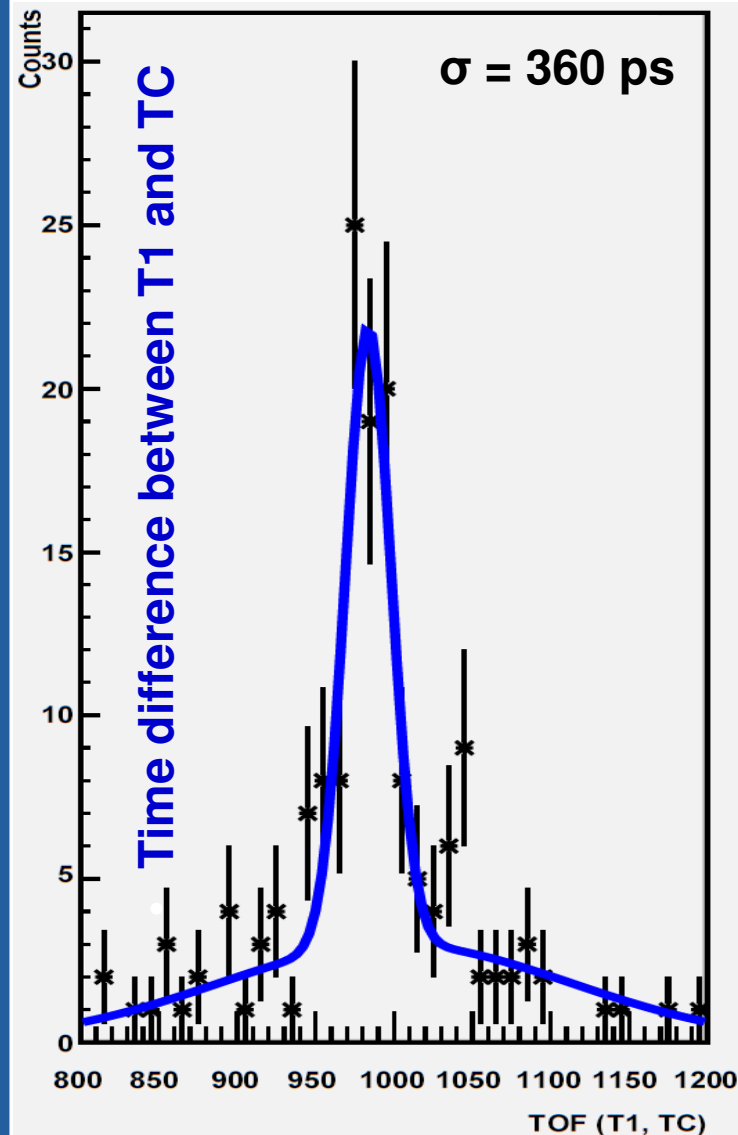




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Beam test and results

- For data analysis, we selected only single particle (good enough) events using the calorimeter energy spectrum.
- Cherenkov counter time resolution is 350 100 ps
- We measured TOFs between the three possible pairs of counters T1, T2 and C1 in order to disentangle intrinsic timing resolution for each counter.
- 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).





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**Thank You for
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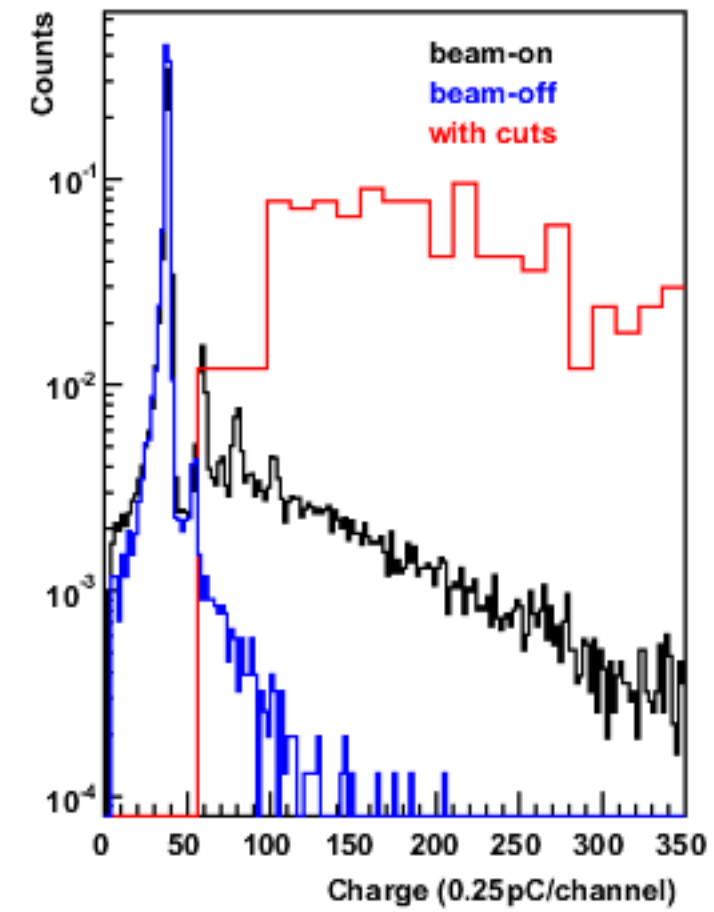
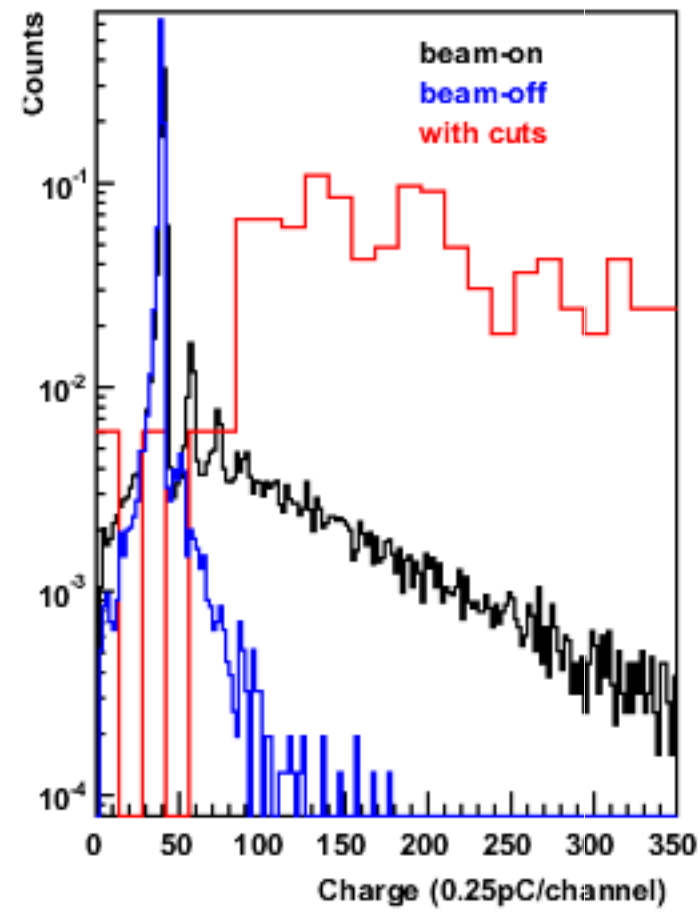


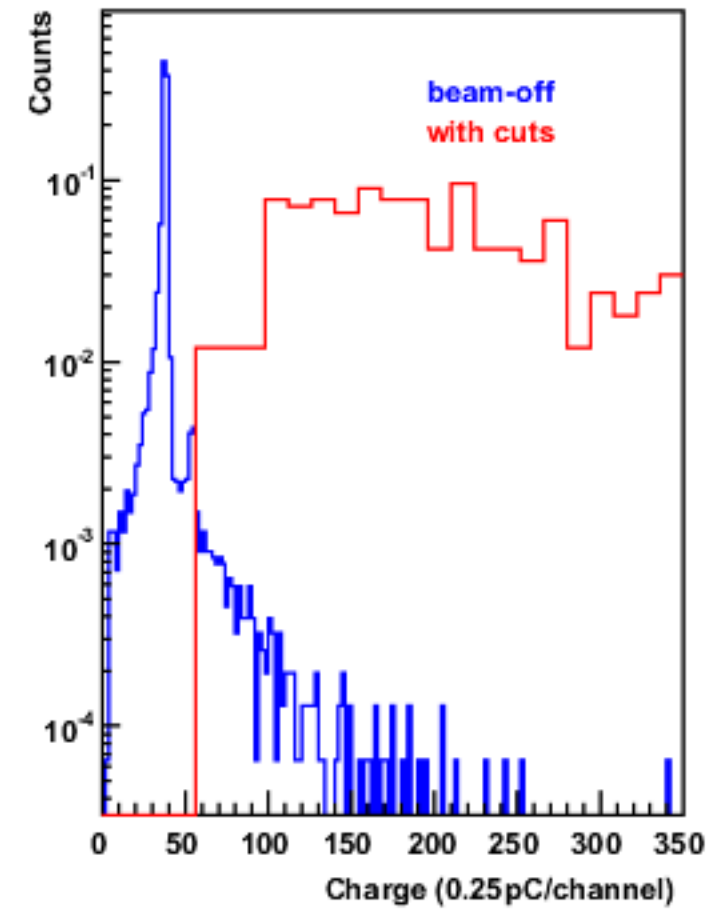
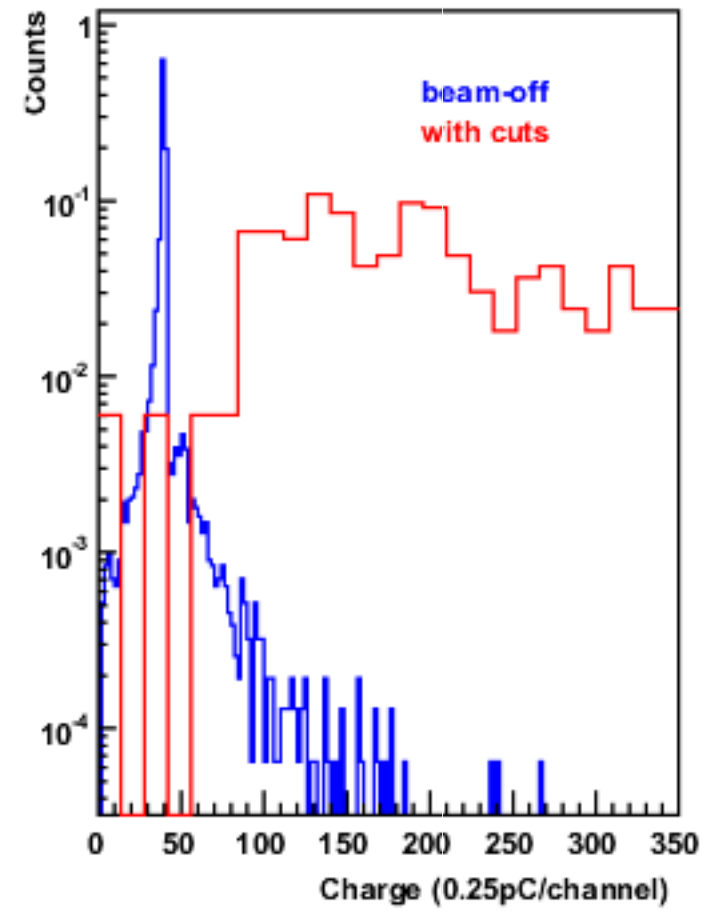
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Cherenkov Radiation. The angle θ_c of Cherenkov radiation, relative to the particle's direction, for a particle with velocity βc in a medium with index of refraction n is

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

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

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



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,

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

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

$$\cos \theta_c = 0.76, \quad \theta_c = 40$$

$$\sin^2 \theta = (1 - \cos 2\theta) / 2 = (1 - (2\cos^2 \theta - 1)) / 2 = (1 - (2(0.68)^2 - 1)) / 2 = 0.42$$

$N = 205$ photons.

TOF

- $T_i = (T_{iLeft} + T_{iRight})/2$ average mean time for each detectors.
- $TOF(T_c, T_1) = T_{T_1} - T_c$.
- The intrinsic timing resolution of each counter is obtained by solving three linear equations of the TOF resolutions among three counters, the T_c , the T_1 and the T_2

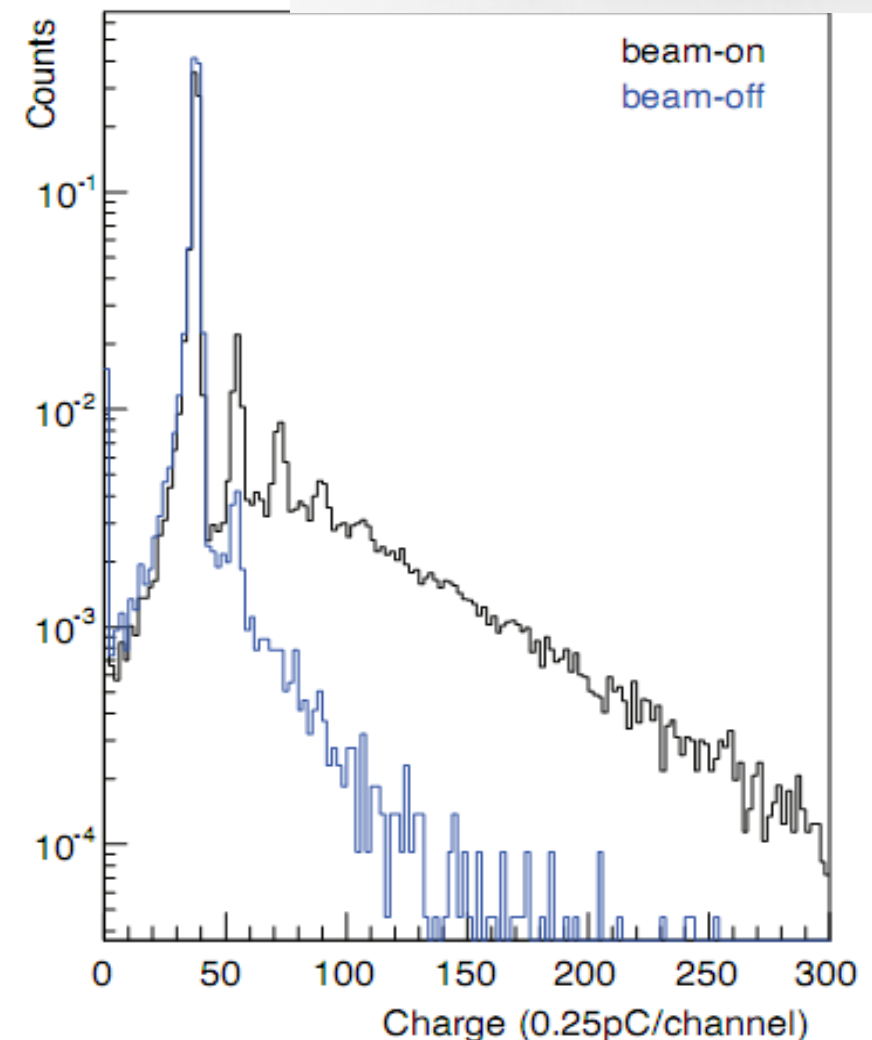
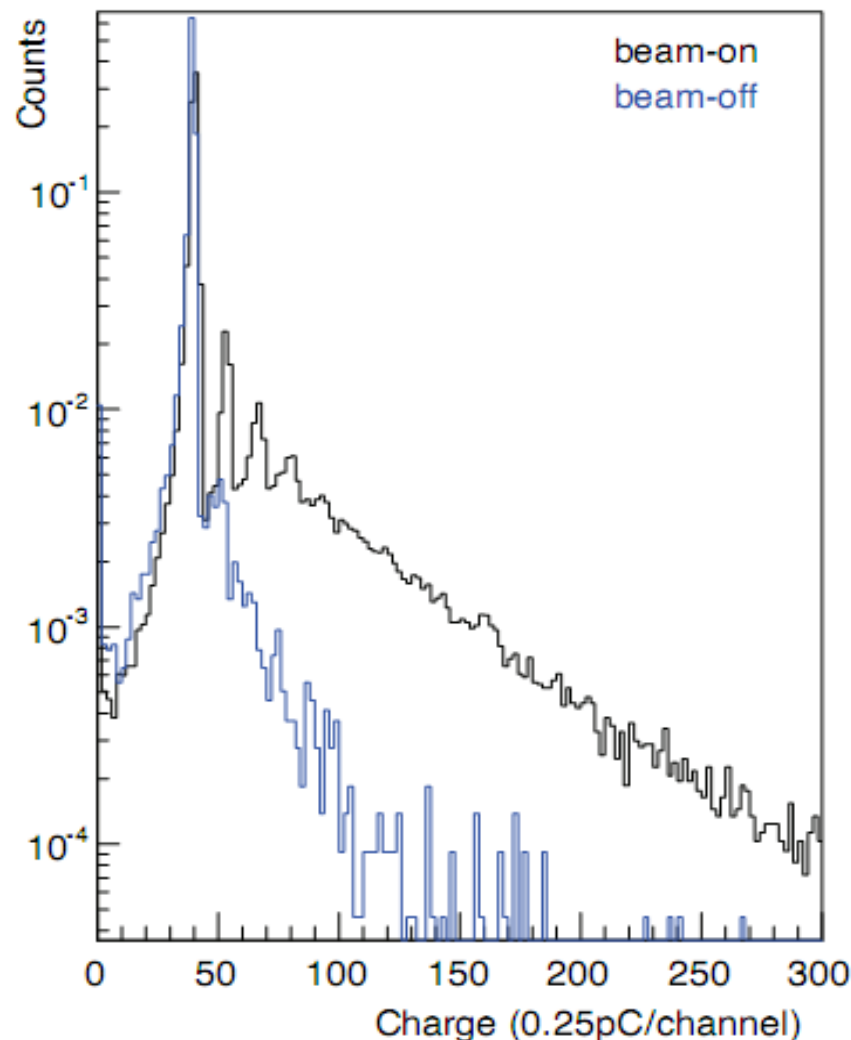
$$\begin{array}{l}
 \sigma^2 TOF(T_c, T_1) = \sigma^2 T_c + \sigma^2 T_{T_1} \\
 \sigma^2 TOF(T_c, T_2) = \sigma^2 T_c + \sigma^2 T_{T_2} \\
 \sigma^2 TOF(T_1, T_2) = \sigma^2 T_{T_2} + \sigma^2 T_{T_1}
 \end{array}
 \left. \vphantom{\begin{array}{l} \sigma^2 TOF(T_c, T_1) = \sigma^2 T_c + \sigma^2 T_{T_1} \\ \sigma^2 TOF(T_c, T_2) = \sigma^2 T_c + \sigma^2 T_{T_2} \\ \sigma^2 TOF(T_1, T_2) = \sigma^2 T_{T_2} + \sigma^2 T_{T_1} \end{array}} \right\}
 \begin{array}{l}
 \sigma T_c = \\
 \sigma T_{T_1} = \\
 \sigma T_{T_2} =
 \end{array}$$



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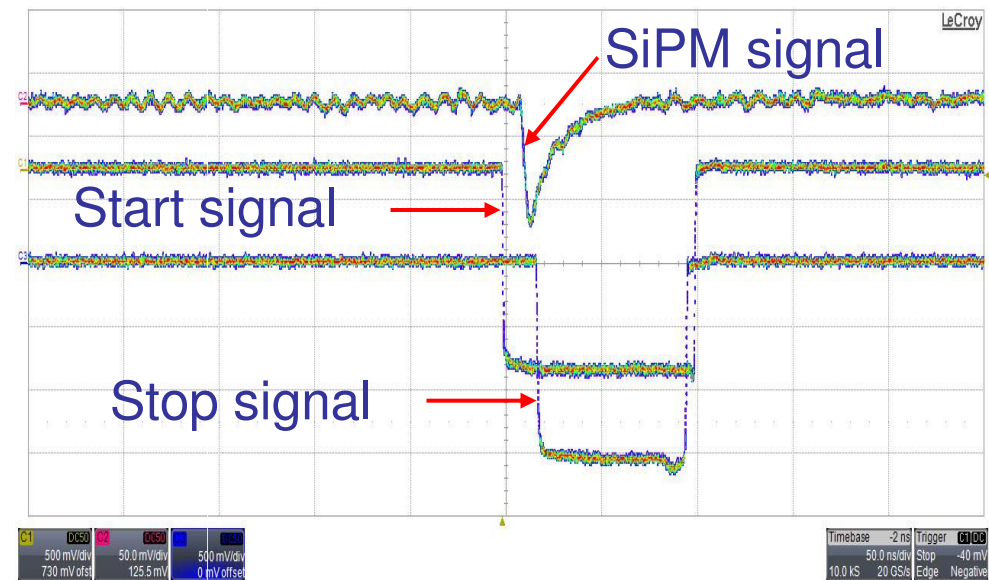
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- ✦ Figure shows Cherenkov counter recorded charge spectra for each MPPC side, while black and blue lines represent the charge distributions measured while beam-on and beam-off conditions.
- ✦ In response to the penetrating particles, each MPPC sensor was able to detect an average number of 8 photons.





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





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Detector setup (BTF-hall)

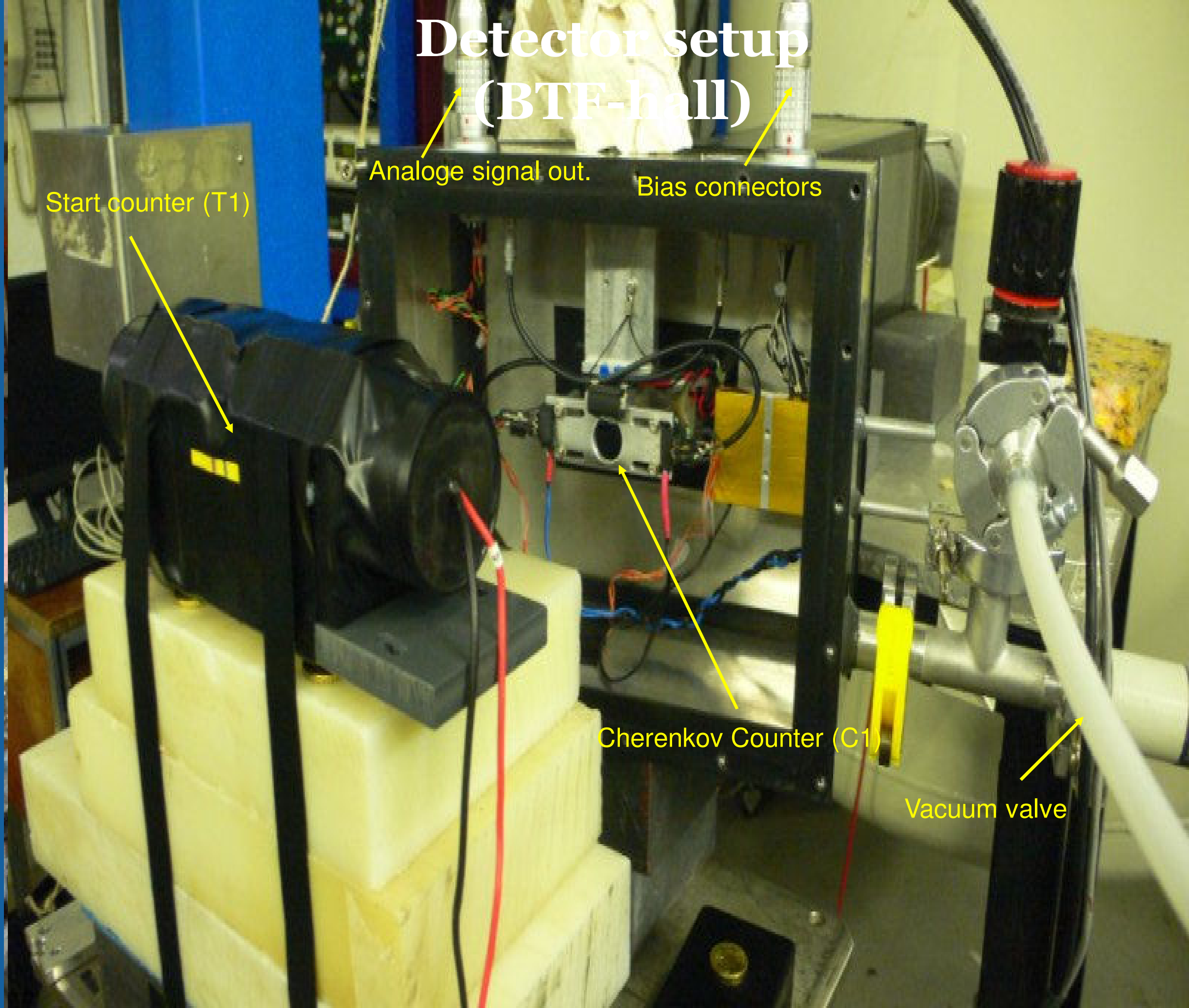
Start counter (T1)

Analoge signal out.

Bias connectors

Cherenkov Counter (C1)

Vacuum valve





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Detector setup (BTF-hall)

