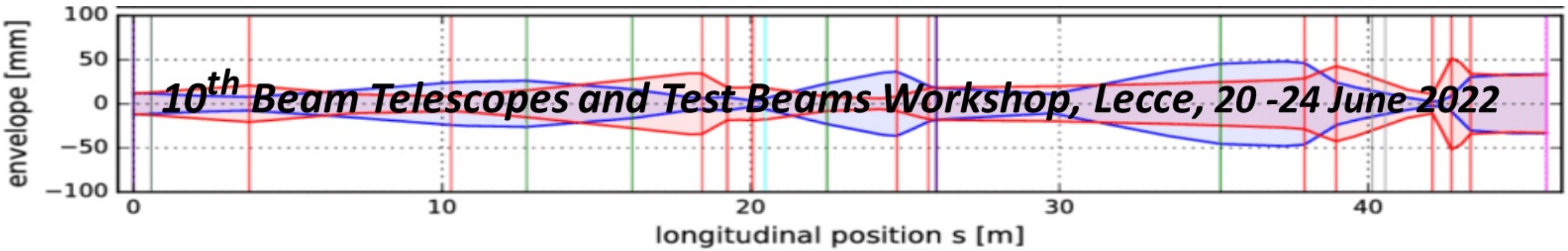


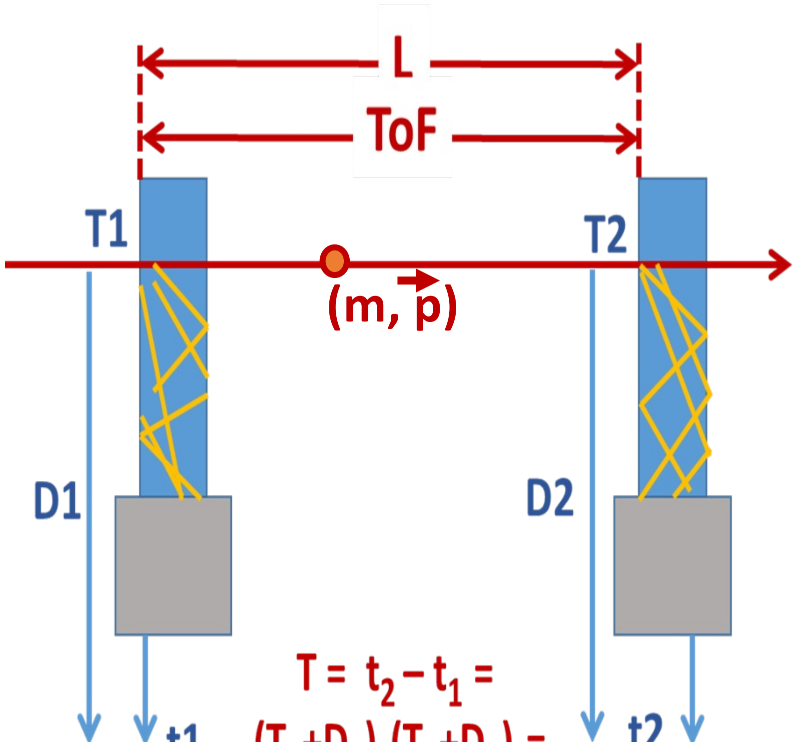
A Beam ToF Reference System with 10 ps Resolution

- Test beams are used for developing high resolution Time-of-Flight (ToF)
- ToF detectors are calibrated only occasionally
- no guarantee that calibration is maintained for the whole period of measurement.
- Need reliable and reproducible Time Reference System (TRS)
- permanently monitoring the calibration of the reference counter itself
- scheme with 3 timing counters based on Cherenkov radiation from quartz bars and a quartz block readout with MCP-PMT photodetectors, which insure excellent timing properties.
- By combining the 3 time measurements it is possible to extract the resolution (better than 10 ps) of the TRC counter (with quartz block), and use it as reference for any other device installed on the beam.

Berkan Kaynak, CERN and Istanbul University

ToF Measurements

$$\mathrm{ToF} = L/v = L/(\beta c) \text{ with } \beta = pc/E = pc/[(mc^2)^2+(pc)^2]^{1/2}$$



$$T = t_2 - t_1 =$$
$$(T_2+D_2)-(T_1+D_1) =$$
$$(T_1+\mathrm{ToF}+D_2)-(T_1+D_1) =$$
$$= \mathrm{ToF} + (D_2-D_1)$$
$$(D = d_{tr}+d_{pd}+d_{ca})$$

[tr = transit; pd = photodetector; ca = cables]

$$\mathrm{ToF} = (L/pc)\,[(mc)^2+p^2]^{1/2}$$

$$\mathrm{ToF} = (L/c)\,[1+(mc/p)^2]^{1/2}$$

For $p \gg mc$ ($\beta \to 1$):

$$\mathrm{ToF} \approx (L/c)\,[1+(1/2)(mc/p)^2]$$

As function of β (->1) and γ (>>1) :

$$\mathrm{ToF} = (L/c)\,[1+(1/\beta\gamma)^2]^{1/2}$$
$$\approx (L/c)\,[1+(1/2)(1/\beta\gamma)^2]$$

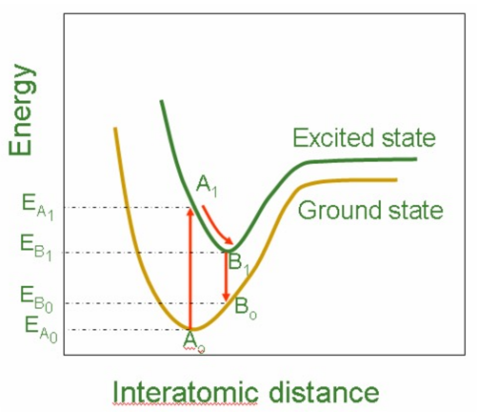
[geometric] [electric – electronic]

$$\sigma^2_{\mathrm{Total}} \approx \sigma^2_{\Delta L} + \ldots + \sigma^2_{\mathrm{T\text{-}Walk}} + \sigma^2_{\mathrm{Jitter}} + \sigma^2_{\mathrm{T\text{-}Dig}} + \ldots$$

Example: Optical detectors

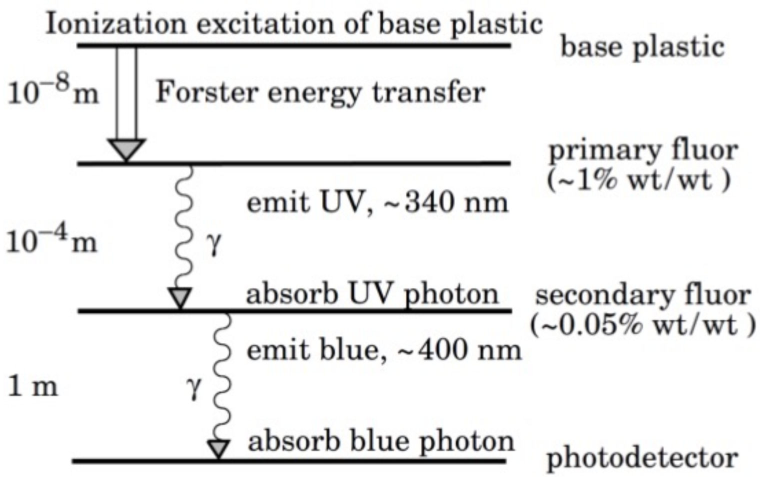
TOF precision depends on intrinsic time spread of light emission

S. E Derenzo, Woon-Seng Choong and W W Moses, Fundamental limits of scintillation detector timing precision; Phys. Med. Biol. 59 (2014) 3261–3286



A) Scintillation:

- absorption of ionization energy,
- electron excitation and return to gound state
- photon emission with decay times of few ns.



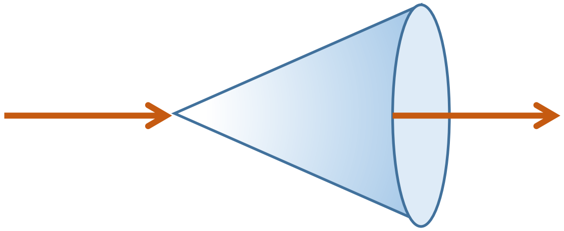
For scintillator – 1MIP produces : $N_{ph} \approx$ 20’000/cm; $\Delta t \approx$ 53ps (n= 1.59)

Photons’ distribution isotropic; for 1” sized scintillator typ. $\Delta t \approx$ 130ps

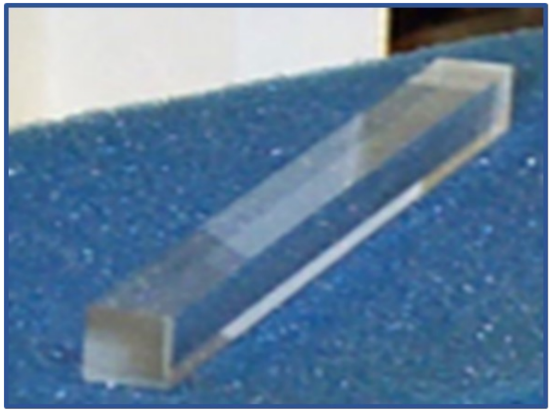
Quartz + MCP-PMT

- Quartz (Fused Silica) Cherenkov Timing Detectors: ([1], [2])
  - instantaneous source of almost isochronous photons
  - transmission by total internal reflection (TIR)
- Fused Silica are radiation-hard (≈ 20 Grad)

[Typ. yield (270 < λ < 680 nm) : 1 MIP - -> Nph ≈ 500/cm]



- MCP-PMT are photodetectors with
- negligible transit time spread (TTS < 50 ps)
- and high gain (G≈ 10^6)

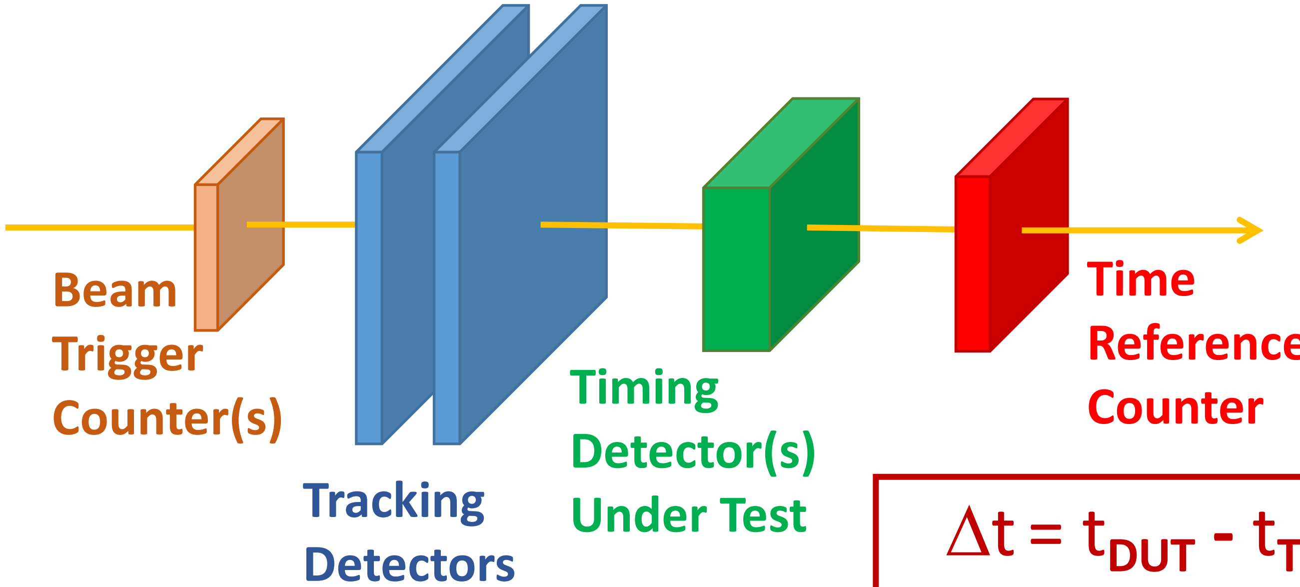


Speciality Glass Products (USA)

KU-1 (Russian Standard)

KATOD UFK-5G-2D (Russian MCP-PMT)

Typical Test Beam Configuration for Timing Detectors



- Time Reference Counter (TRC) [can be] *calibrated occasionally*
- Calibration can be done *«in situ» or elsewhere*
- Between calibrations TRC properties *may drift in time*

$$\Delta t = t_{DUT} - t_{TRC}$$

$$\sigma_{\Delta t}^2 = \sigma_{DUT}^2 + \sigma_{TRC}^2$$

$$\sigma_{DUT}^2 = \sigma_{\Delta t}^2 - \sigma_{TRC}^2$$

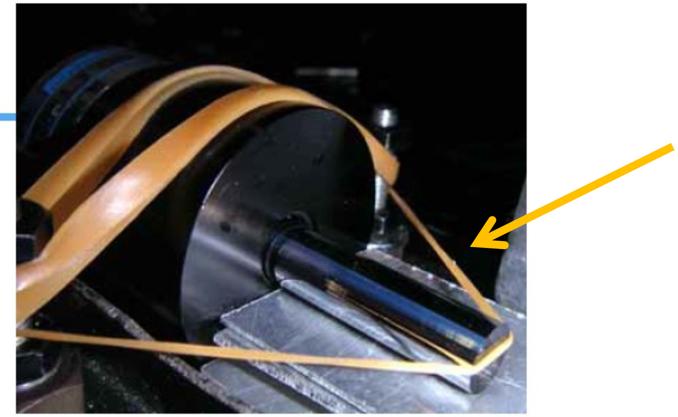
$$\sigma_{DUT} = \sqrt{\sigma_{\Delta t}^2 - \sigma_{TRC}^2}$$

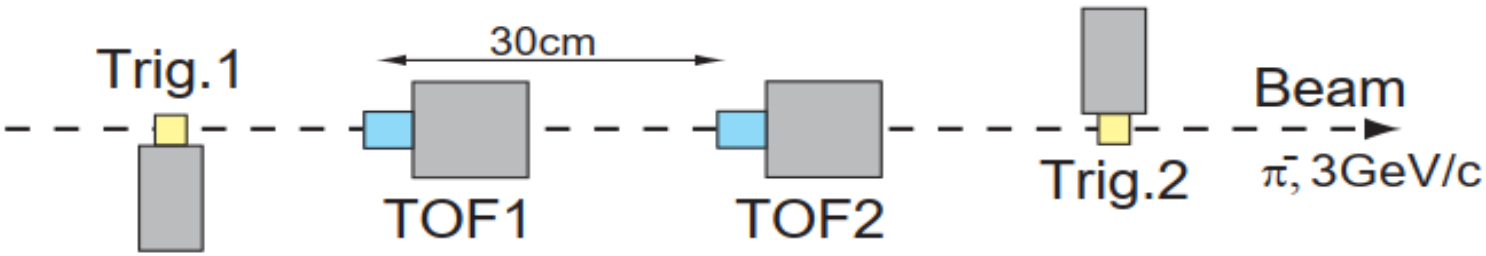
Set up a Time Reference System (TRS) that is *continuously calibrated*

Example: K. Inami - Time of Flight measurements with MCP-PMT
International Symposium on the Development of Detectors, 2006/4 at SLAC

Beam test 2 setup

- 3GeV/c π^- beam
  - at KEK-PS π2 line
- PMT: R3809U-50-11X
- Quartz radiator
  - 10^{ϕ}x40^{z}mm with Al evaporation





Quartz radiator block + MCP-PMT $\sigma_t \approx 5$ps ([3])

Get resolutions by $\sigma_{\Delta t}/\sqrt{2}$

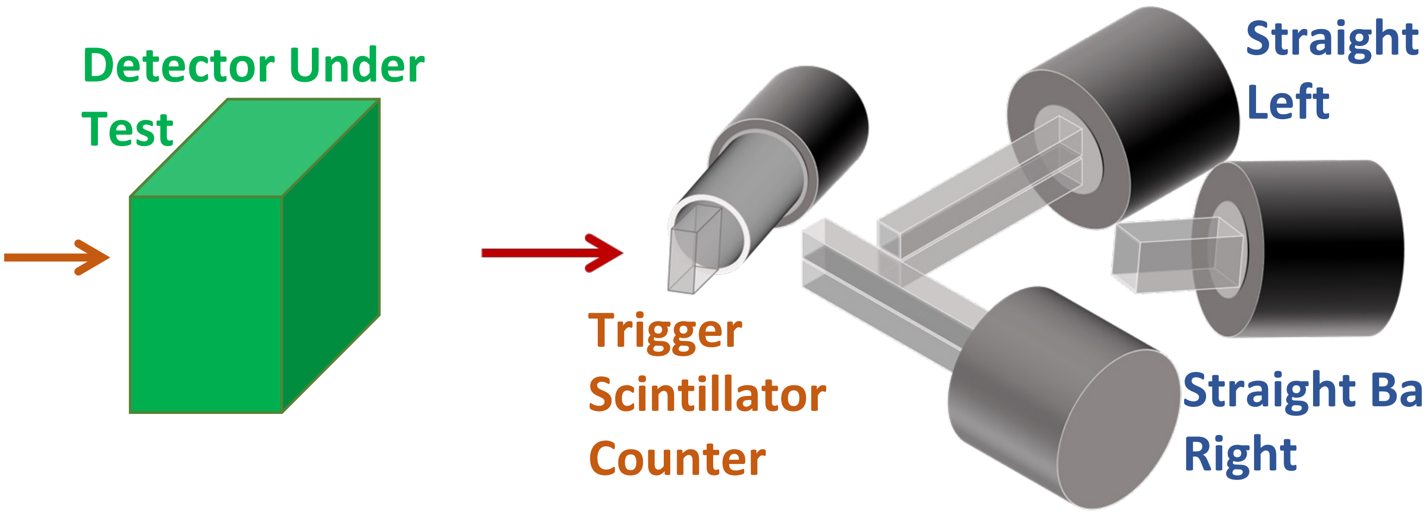
Non-negligible material budget:

- Quartz block
- MCP-PMT

Multiple (independent) measurements problematic; showering produce correlations

Time Reference System (TRS)

TRS consist of three quartz Cherenkov counters



Apparatus: Quartz Bars and Block + MCP (KATOD)

- 2 (identical) Slant (45°) Bars (SBL-R)
- 1 Head-on Block (0°) Time Reference Counter (TRC)

Measuring simultaneously ToF between each pair of the 3 counters, in hypothesis of independent measurements (no covariance):

$$\sigma_{12}^2 = (\sigma_1^2 + \sigma_2^2) \quad ; \quad \sigma_{13}^2 = (\sigma_1^2 + \sigma_3^2) \quad ; \quad \sigma_{23}^2 = (\sigma_2^2 + \sigma_3^2)$$

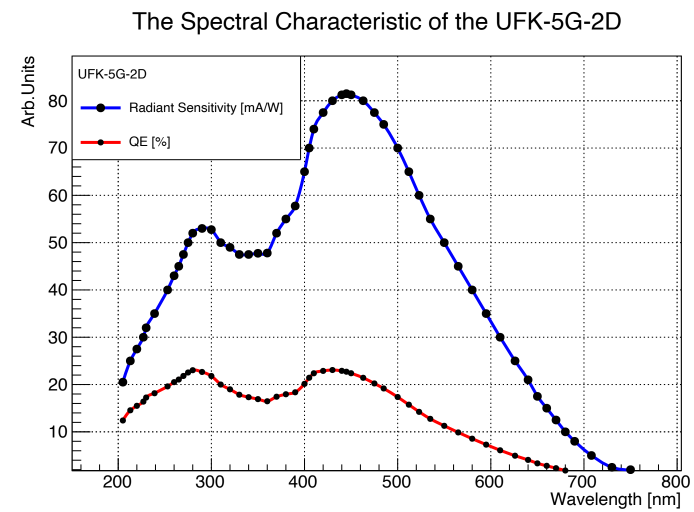
time resolution for each counter can be obtained.

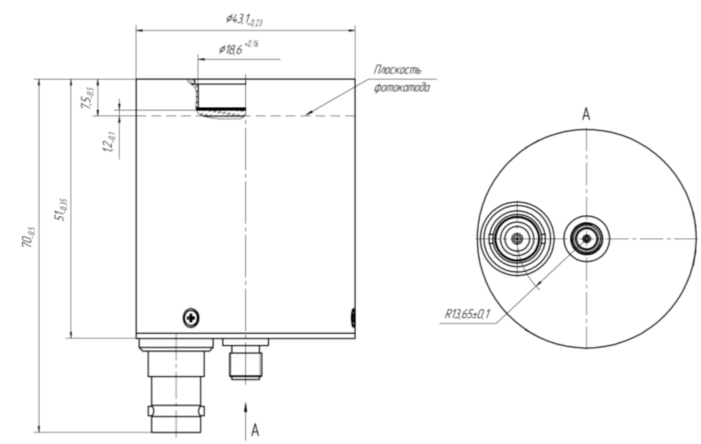
After calibration the TRC (was/can be) used with DUTs

KATOD MCP-PMT UFK-5G-2D

KATOD UFK-5G-2D MCP-PMT	
Window	Glass US-49
Photocathode Material	$(Na_2KSb)Cs$
Effective Photocathode Diameter, mm	18
Spectral response range, nm	200 - 750
Radiant photocathoe sensivity at $\lambda = 450\ nm$	>70
Gain	$1.x10^6$
Dark Current at gain $1x10^6$, A	$< 1x10^{-9}$
Max anode current, nA	300
Supply Voltage, kV	<3.1, negative

Thanks to V. Samoylenko (IHEP-Protvino) for establishing contact with the KATOD Company (Novosibirsk) and following the UFK-5G-2D custom development



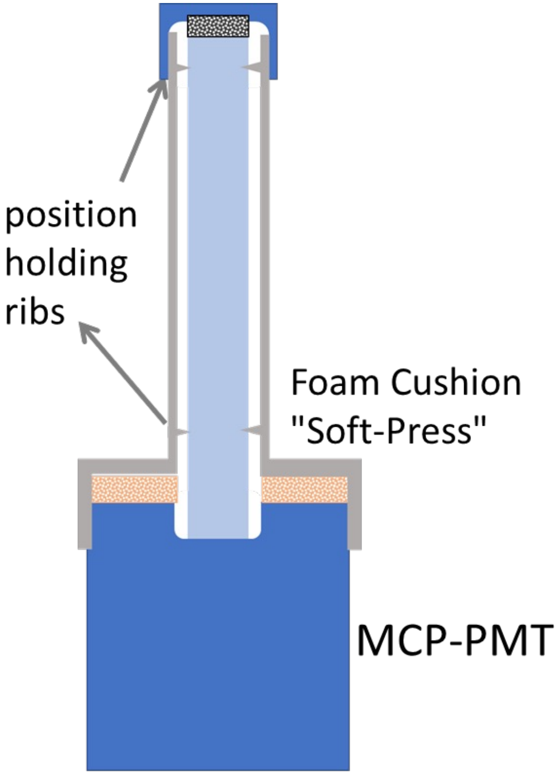


Dimensional Outline

Counter's assembly in the Laboratory

KATOD recommend ≤ 1N on UFK-5G – 2D window (1.2mm thick): quartz bars were coupled to MCP-PMT windows following a rigorous procedure to insure:

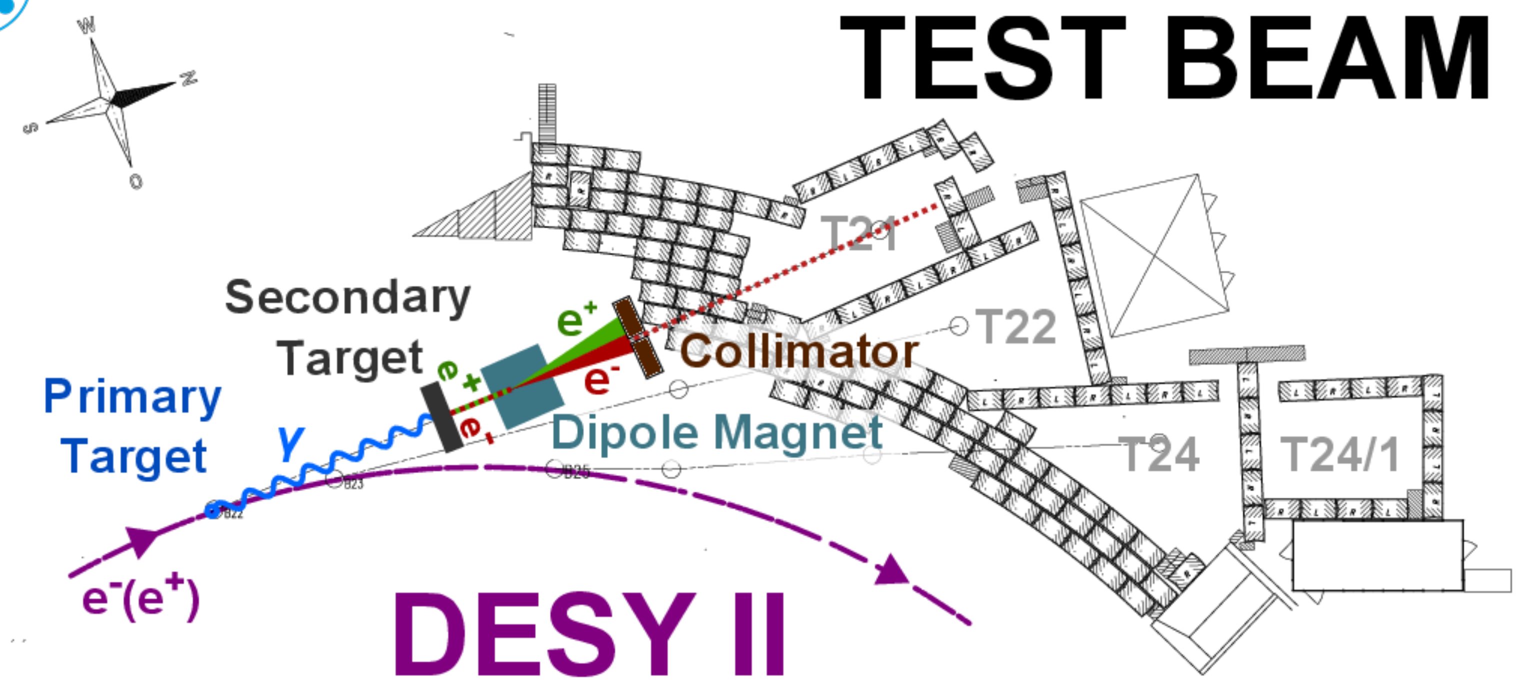
- Correct geometry of bars and MCP-PMs, allowing a reliable installation on the supports at the test-beam area in DESY;
- Good optical contact of the quartz bar ends and the MCP-PMT window; we chose a direct "dry" contact (without optical grease) at low pressure in order to avoid damage of delicate borosilicate glass windows
- Complete light tightness of the assembly, with no contact of the envelope walls with the faces of the bars, except with ends opposite the MCP-PMT window, which were covered with black absorbing pads to suppress reflected rays and gently press the bars against the photocathode window.



Assembled Counter

The quality and stability of the bar end – photocathode window contacts, and light tightness were checked for the assembled counters at nominal HVs and irradiating the quartz bars with a radioactive Sr90 source, observing the typical beta ray signals.

DESY II Test Beam Facility



Bremsstrahlung γ beams

- Converted to $e^+ e^-$ pairs,
- Momentum/Charge selected in magnet – colimator setup

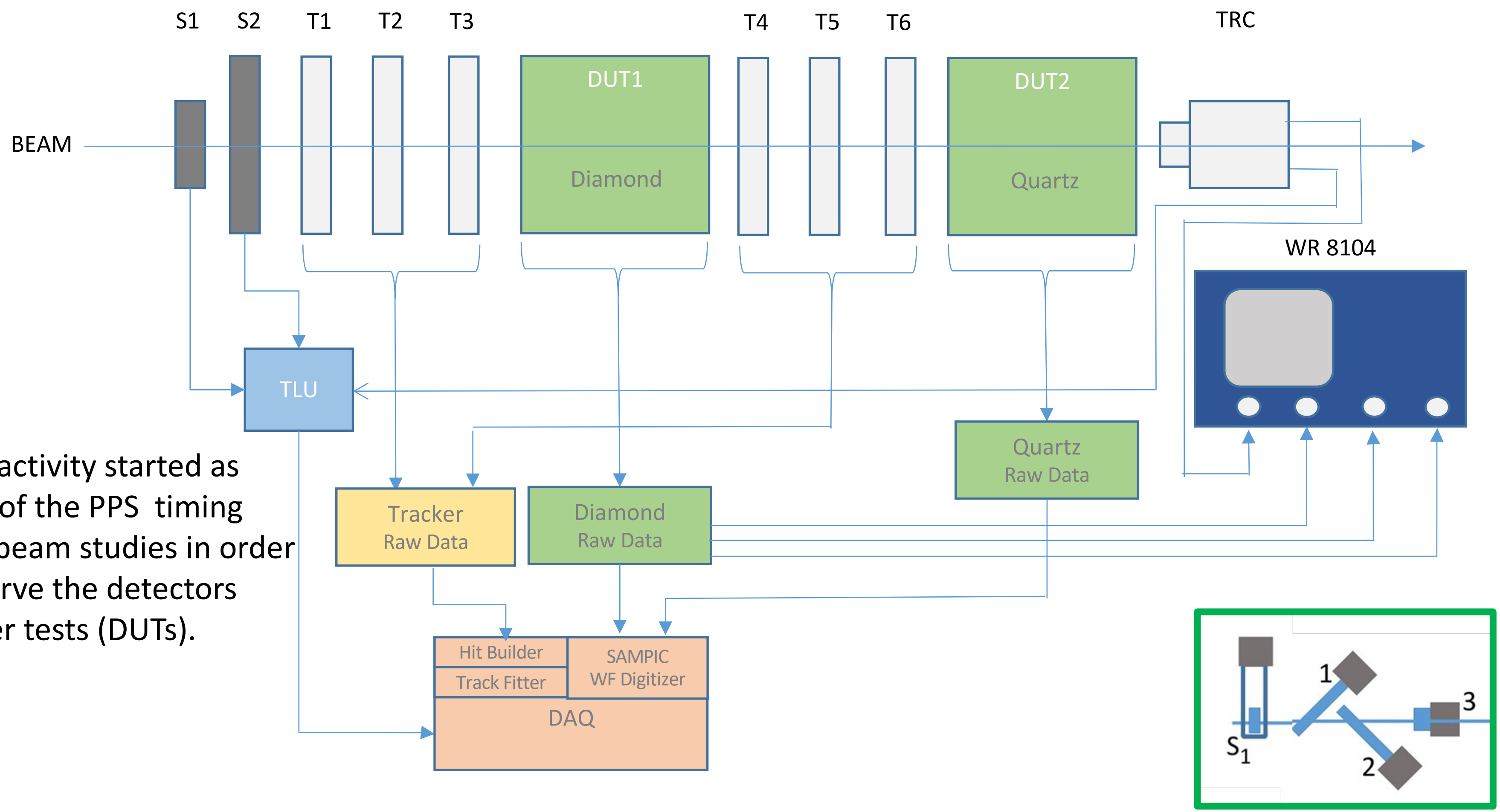
3 beam lines : T21, T22, T24

- TRS measurements were conducted at the **T24** line

Energy : 1 – 6 GeV
Energy spread : 5%
Divergence : 2mrads
Flux : 0.3 – 1kHz/cm^2

"The DESY II test beam facility" (https://doi.org/10.1016/j.nima.2018.11.133)
NIMA, Volume 922, 1 April 2019, Pages 265-28

Block Diagram of Test-Beam Setup and Acquisition System

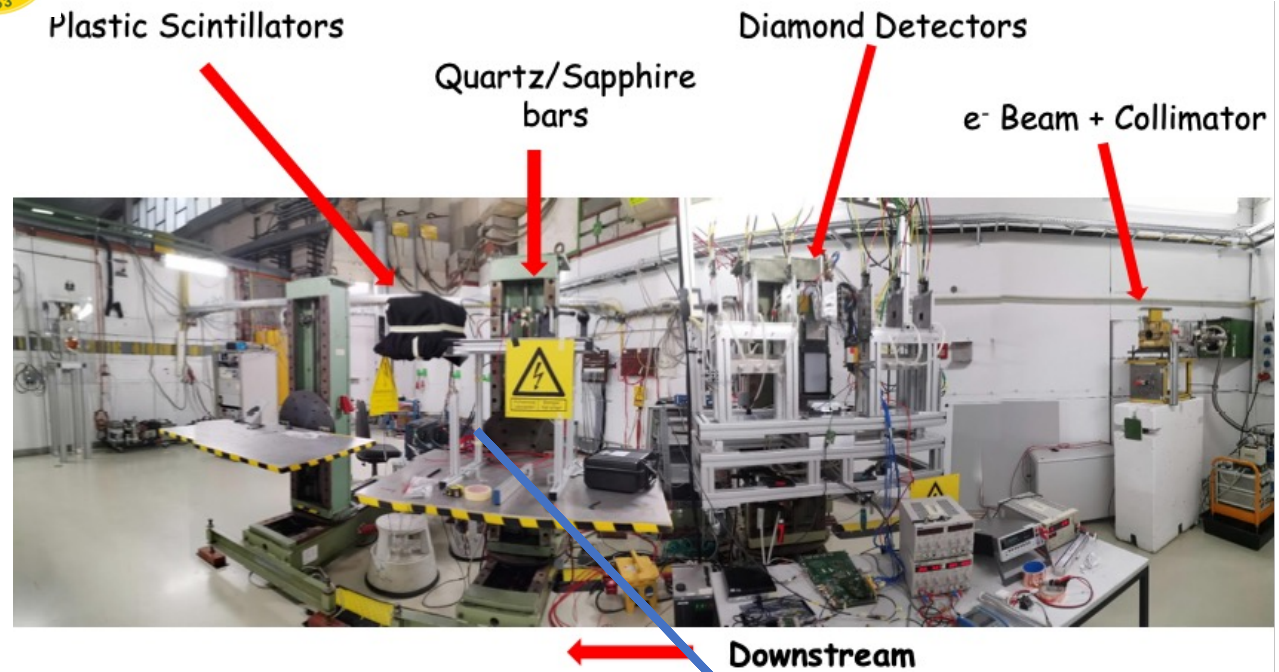


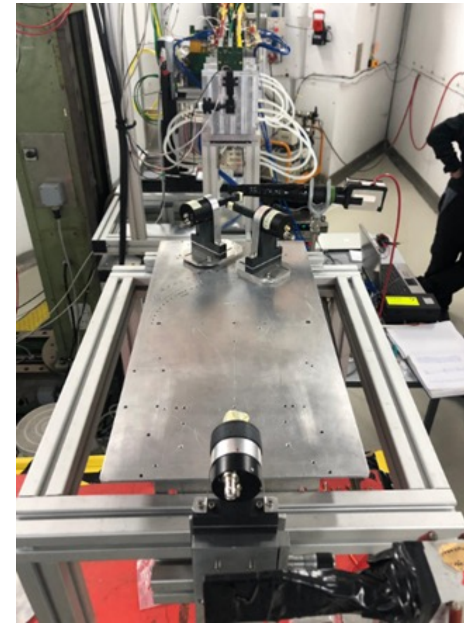
This activity started as part of the PPS timing test beam studies in order to serve the detectors under tests (DUTs).

DUT1 : Diamond timing detectors

DUT2 : Quartz bars+MCP-PMT

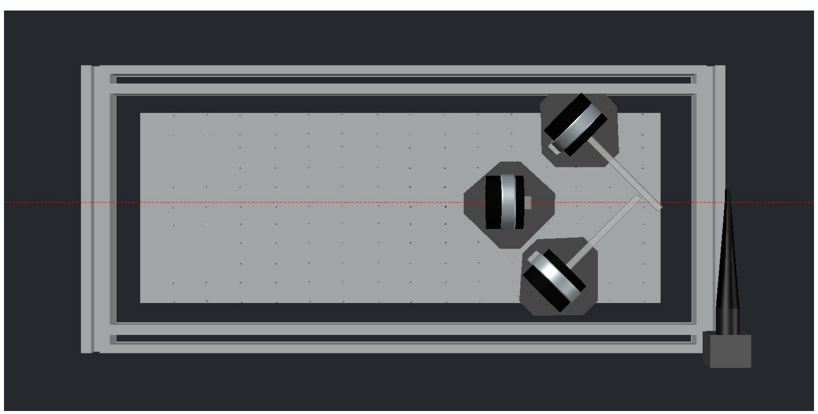
@DESY Test Beam Setup



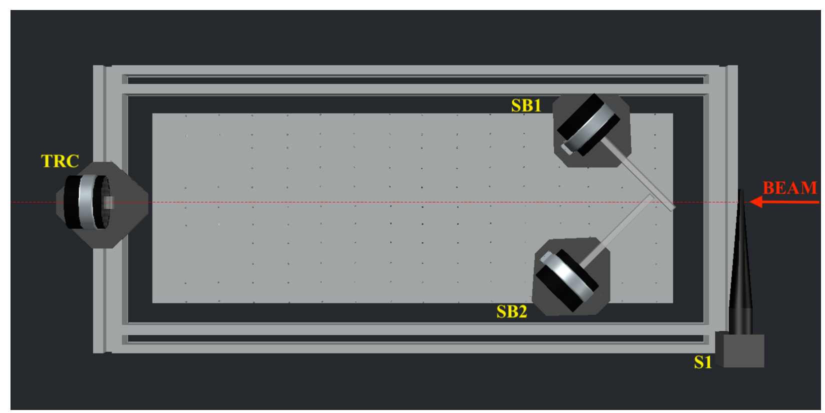


Calibration and test Runs

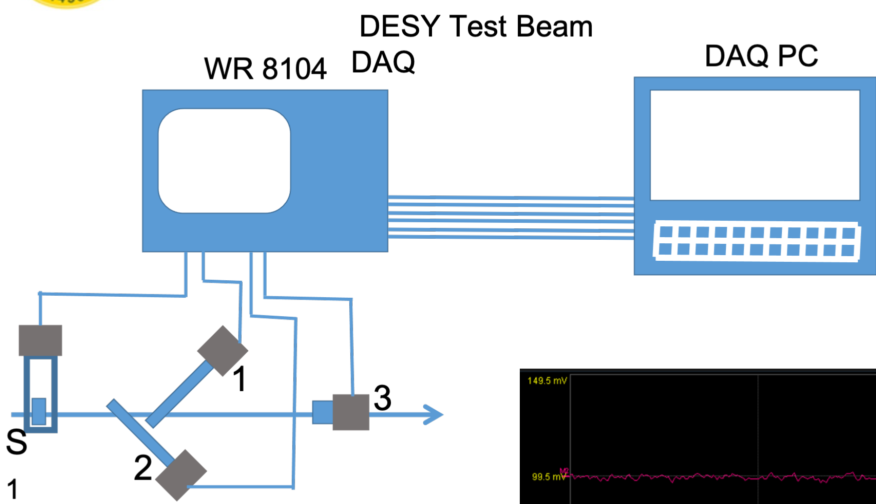
Phase 2 : more compact configuration



Phase 1: Initial setup



Data Acquisition (DAQ)



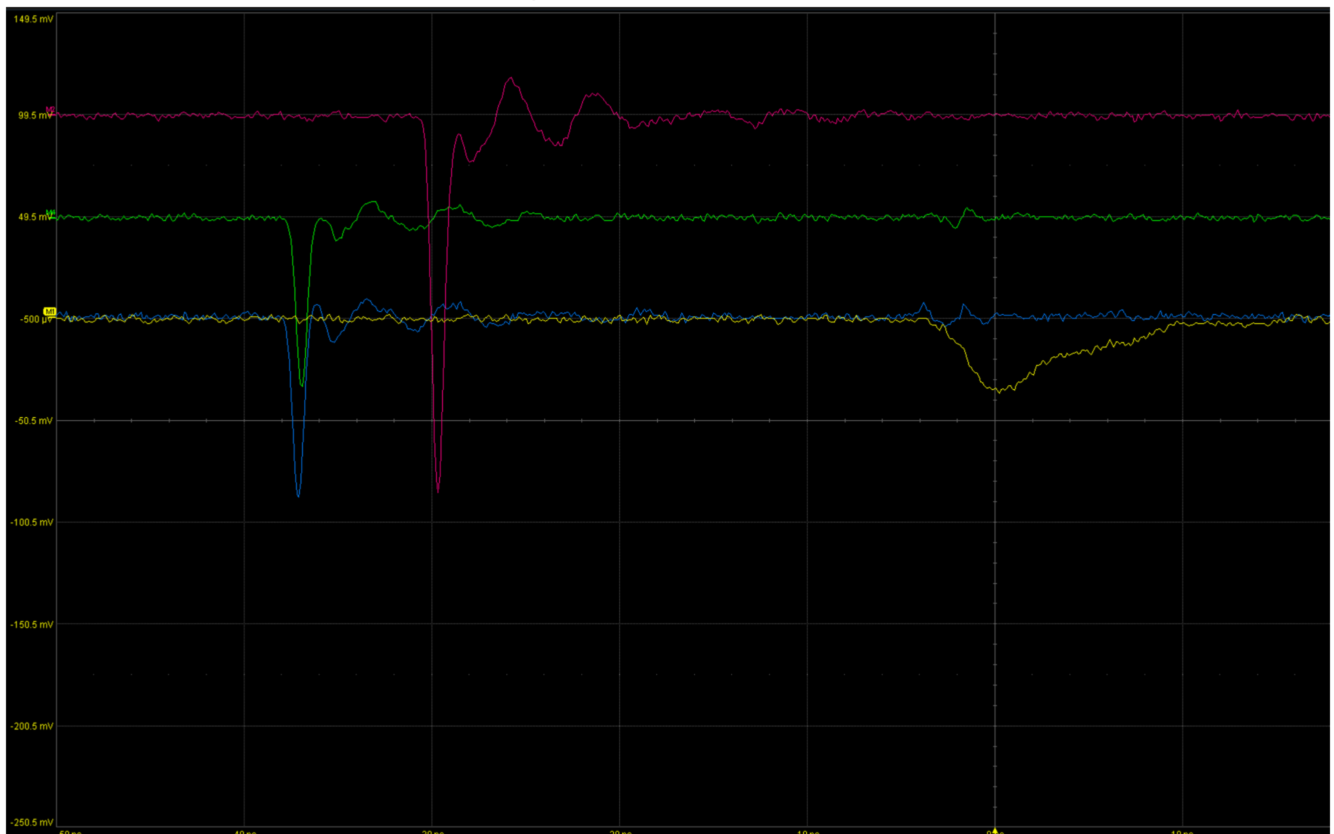
Four channel LeCroy 8104 DSO used for measurement of MCP signals

- Bandwidth 1GHz
- Sampling period 10 GS/s (for 4 Channels)

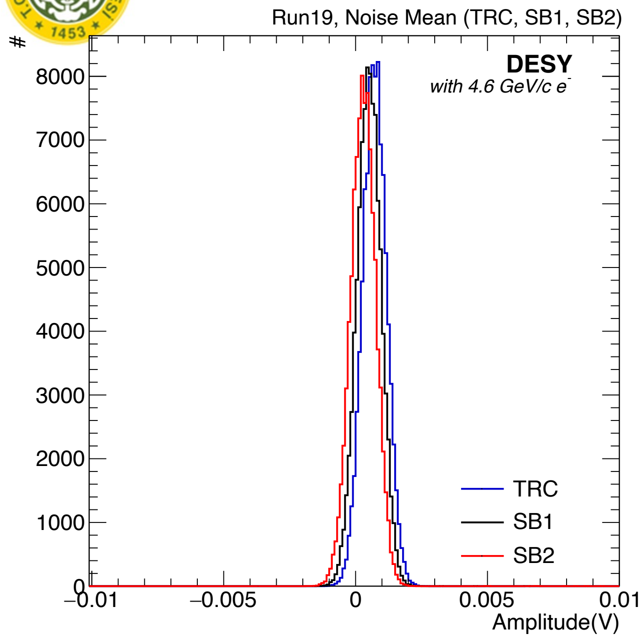
Fast segmented aqusition was used for data taking.

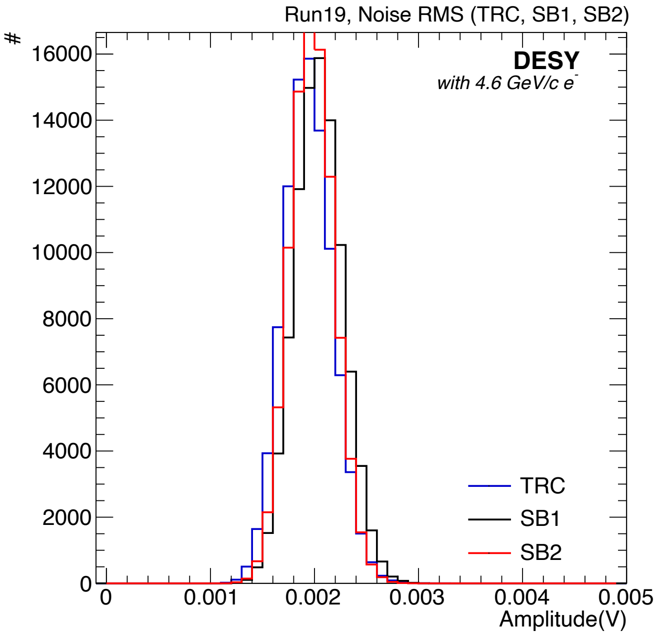
Event display

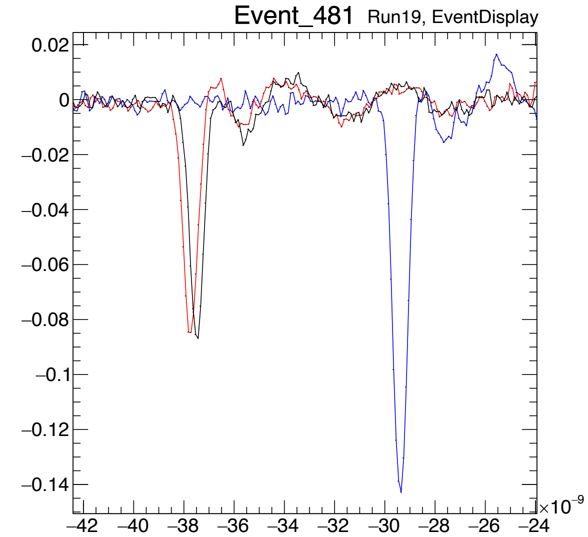
Blue : SB1
Green : SB2
Yellow : SB1
Red : TRC

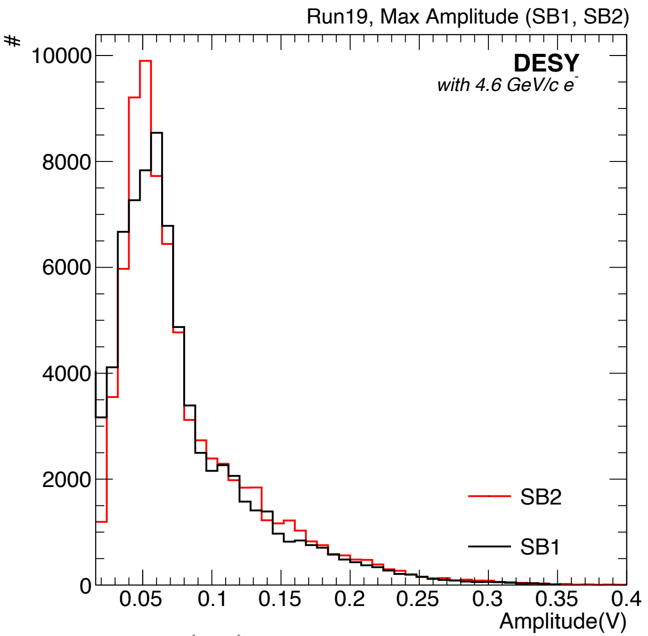


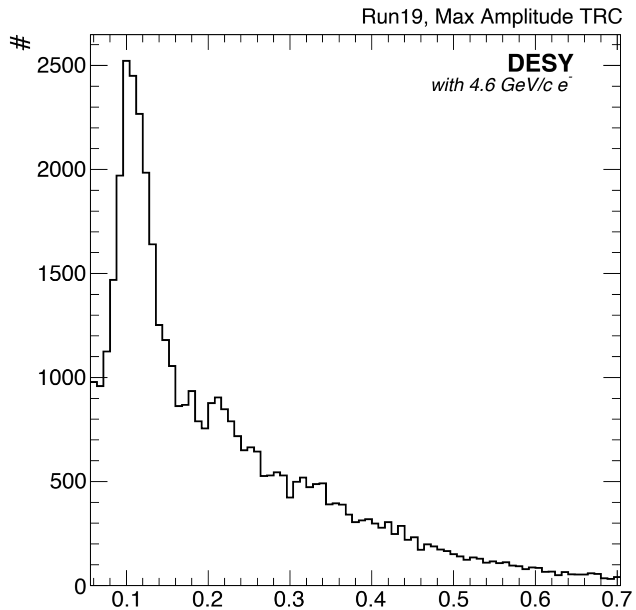
Characterization of the Counters

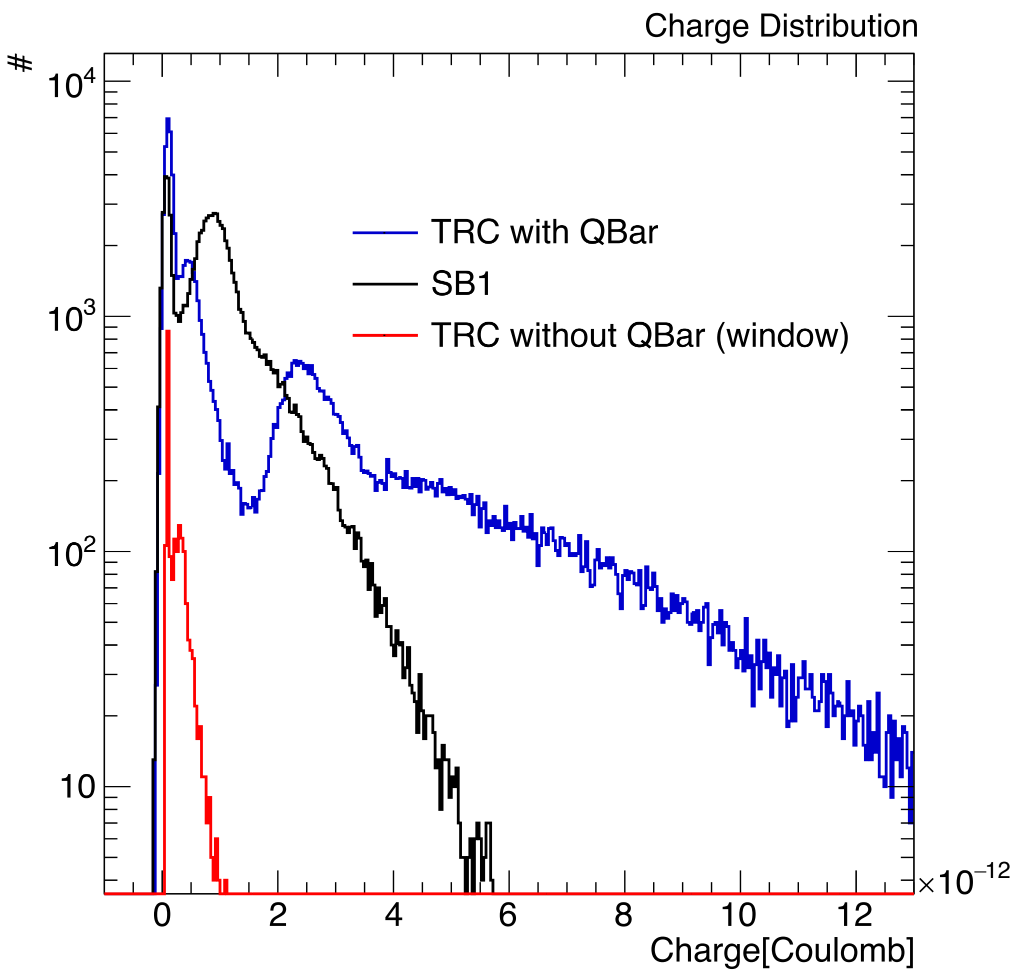












- TRC is also investigated without using quartz block. Window effect clearly visible

TRC is peaking around 2.5x10^-12
SB1 is peaking around 1.0x10^12

Q = gain x Nphe x 1.6x10^-19

For TRC -> Nphe = 15
For SB -> Nphe = 6

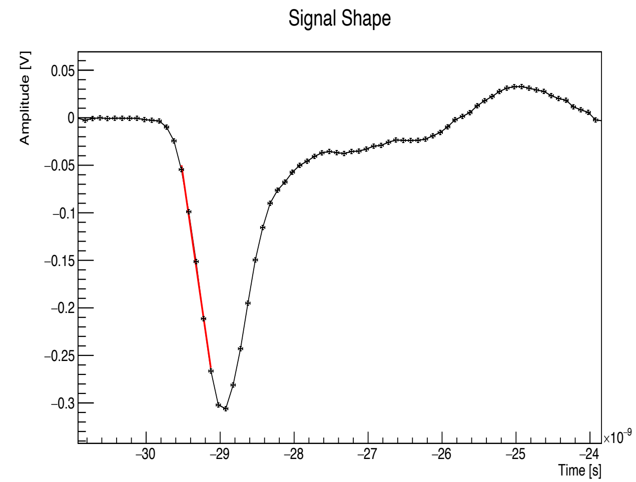
Timing Measurement

4 Signals in LeCroy DSO WR8104 :

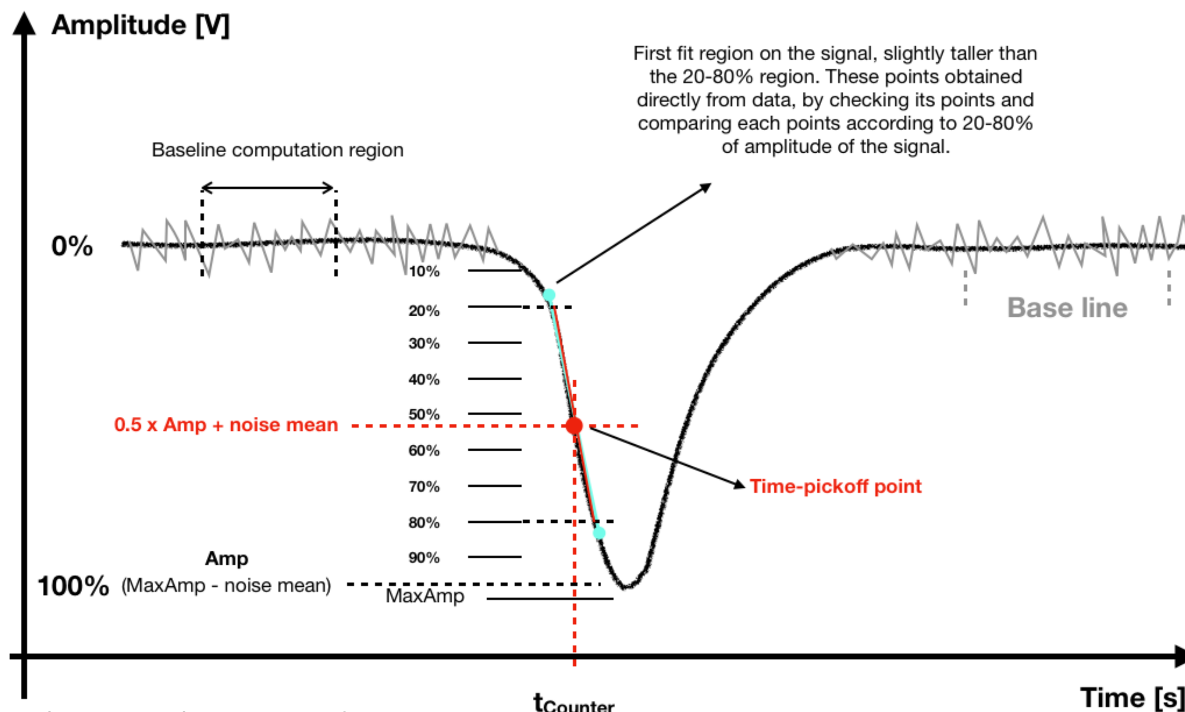
- <u>Ch1 = S1(trigger)</u>, <u>Ch2 = TRC</u> , <u>Ch3 = SB1</u>, <u>Ch4 = SB2</u>
- ToF1 = Ch3 – Ch4, ToF2= Ch2-Ch3, ToF3 = Ch2-Ch4
- $\sigma_1^2 = (\sigma_{SB2}^2 + \sigma_{SB1}^2)$, $\sigma_2^2 = (\sigma_{TRC}^2 + \sigma_{SB1}^2)$, $\sigma_3^2 = (\sigma_{TRC}^2 + s_{SB2}^2)$

Then the time resolutions for each counter can be obtained:

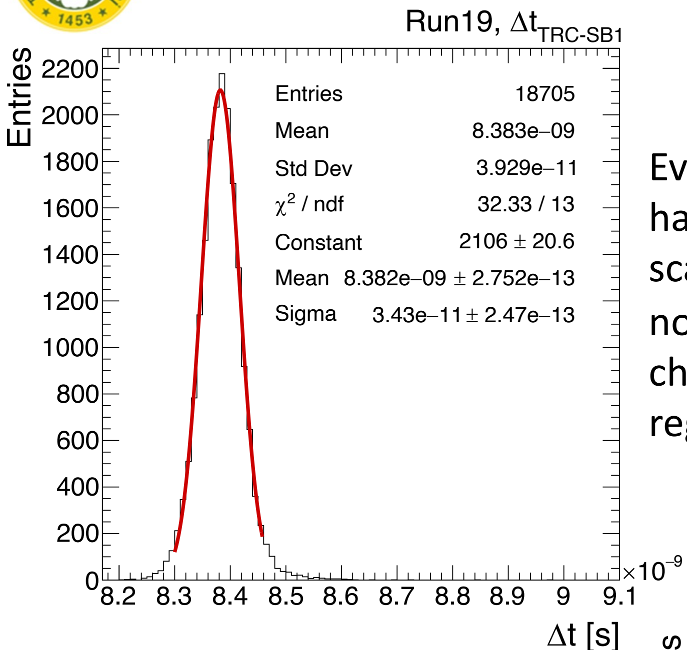
- σ_{TRC} = sqrt $\{[\sigma_2^2 + \sigma_3^2 - \sigma_1^2] /2\}$
- σ_{SB1} = sqrt $\{[\sigma_2^2 - \sigma_3^2 + \sigma_1^2] /2\}$
- σ_{SB2} = sqrt $\{[\sigma_3^2 - \sigma_2^2 + \sigma_1^2] /2\}$



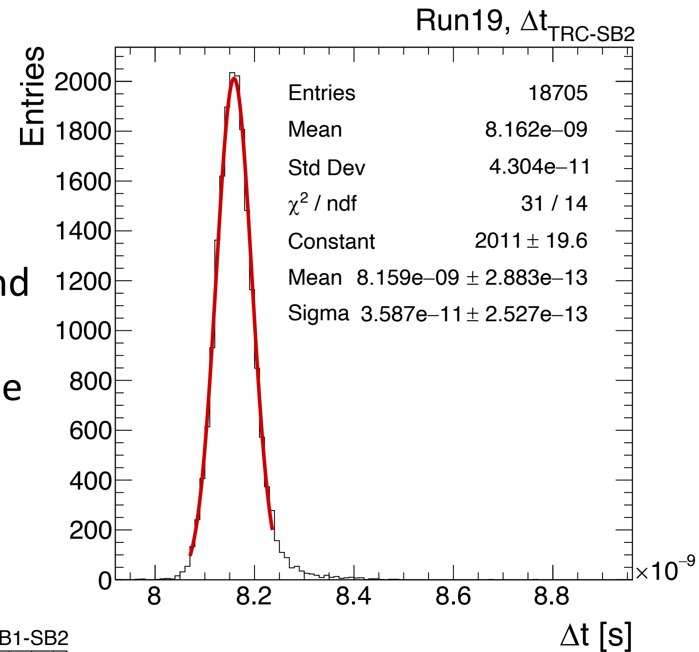
Using offline CFD method, time-pickoff points were extracted for each counter at 50%

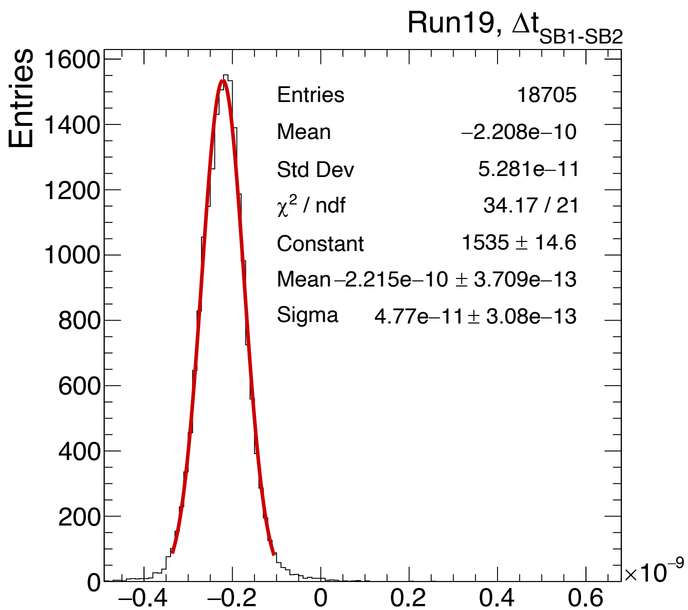


Timing Measurement



Events were selected that didn't have Coulomb scattering. Multiplicity events and noise were eliminated by choosing the following amplitude regions of the counters.





σ_{TRC}=9.7 ± 0.99 ps

σ_{SB2}=34.5 ± 0.28 ps

σ_{SB1}=32.9 ± 0.3 ps

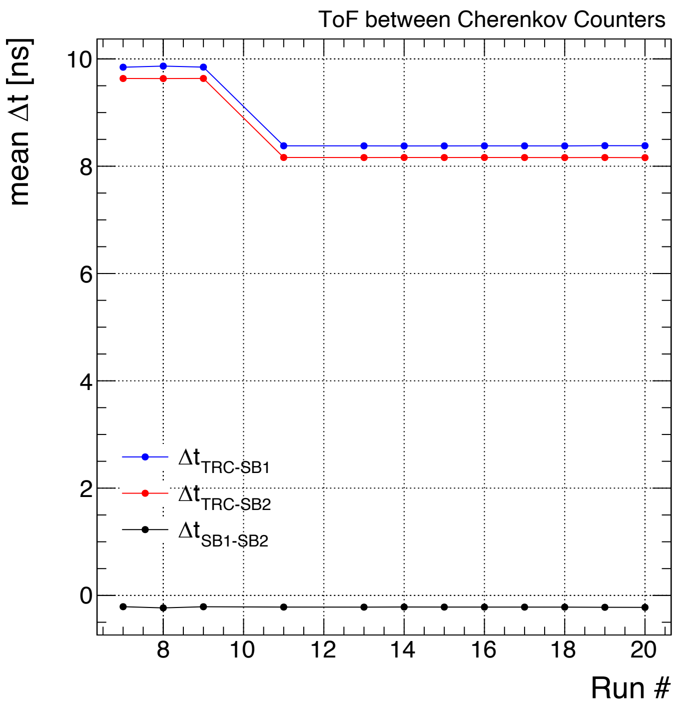
- $0.071mV < Amp_{TRC}$<0.25 mV
- $0.031mV < Amp_{SB1}$<0.20 mV
- $0.0235mV < Amp_{SB2}$<0.25 mV

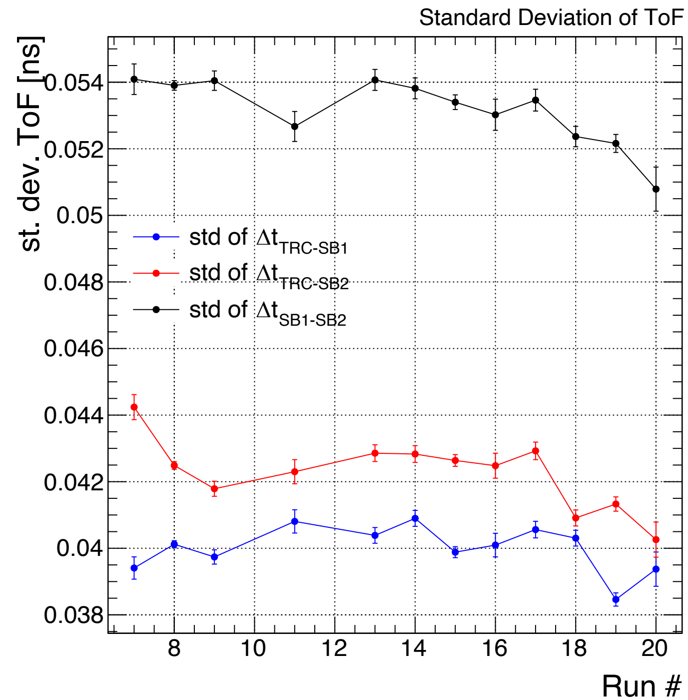
Timing Measurement

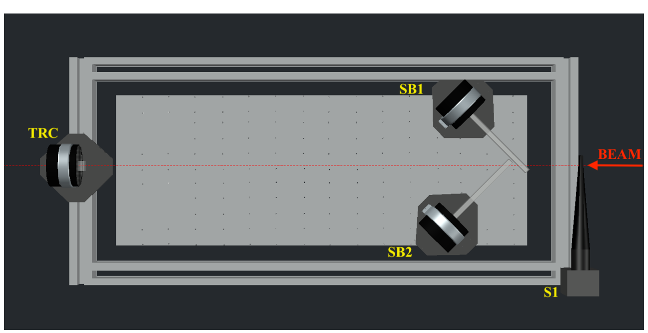
Runs can be grouped according to MCP+QB setup:

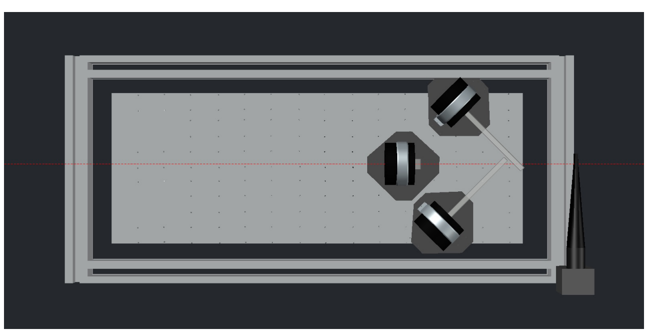
- TRC far from SB1/2 **(Run7-10)**
- TRC near SB1/2 (the displacement 438mm) **(run11-18)**
- Diamond removed from beam line **(Run19-20)**

displacement of TRC is clearly visible









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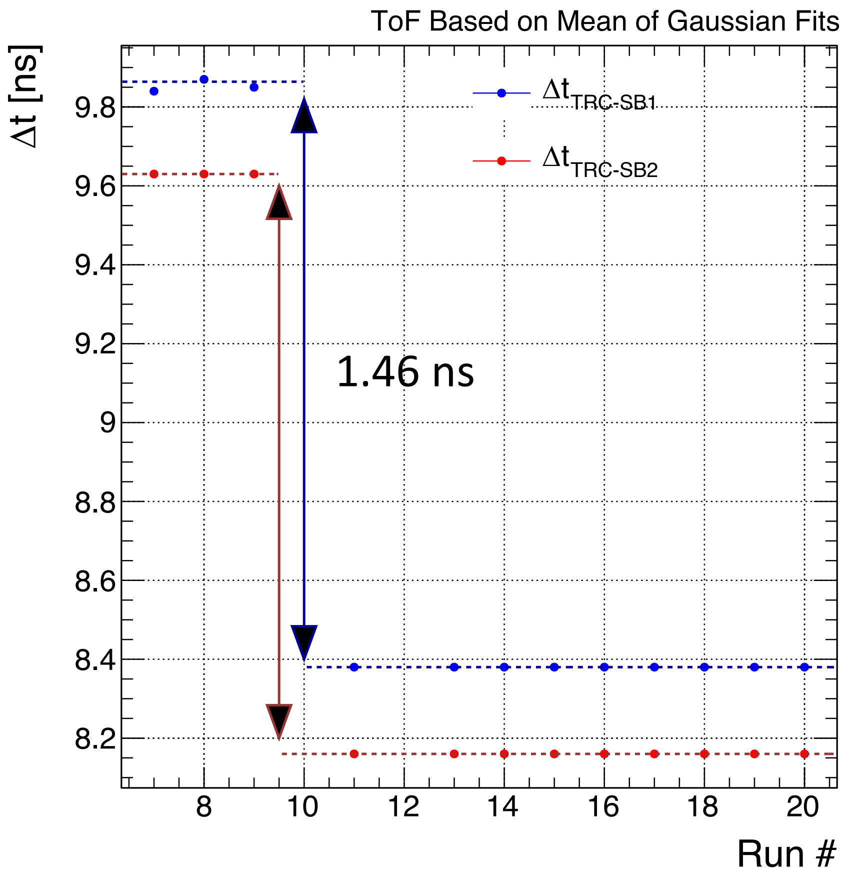
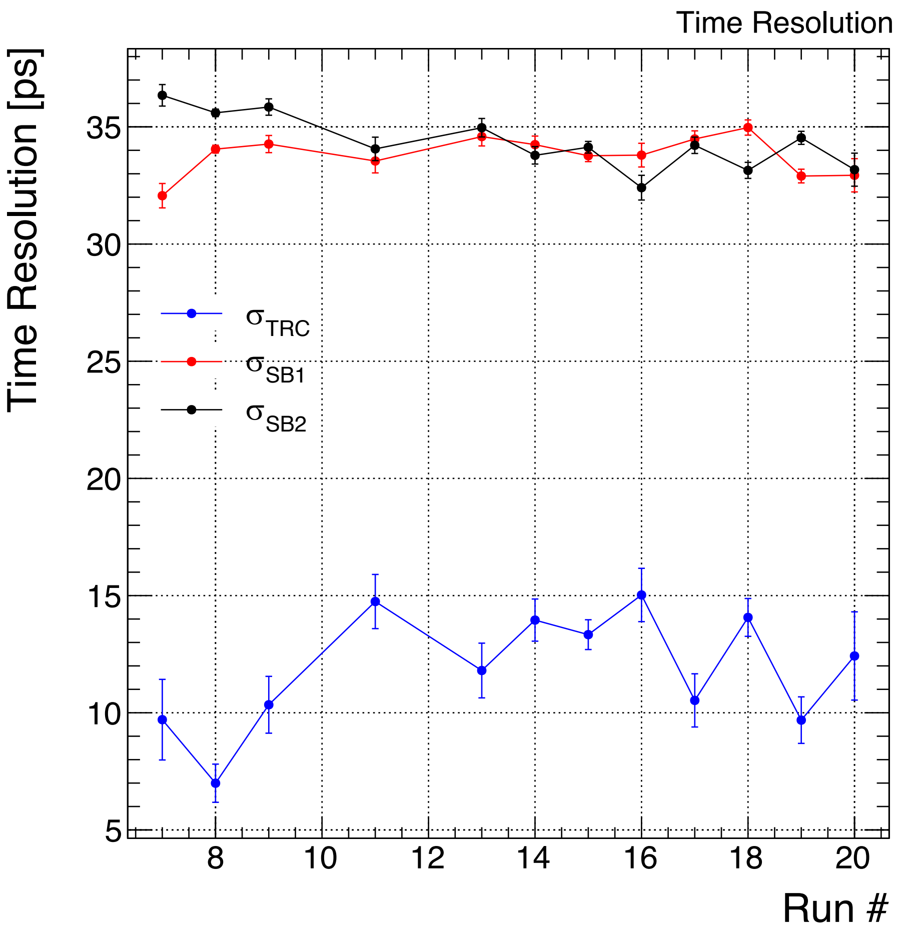


displacement of TRC is clearly visible

The change of ToF between runs # 9 and # 11 corresponds to the displacement of TRC by 438mm (≈ 0.438 x 3.3 ns/m = 1.44 ns); the measured ToF difference is 1.46 ns

1/c =3.3356409519815204957557671447492 ns/m

Timing Measurement



- TRC far from SB1/2 **(Run7-10)**
- TRC near SB1/2 (the displacement 438mm) **(run11-18)**
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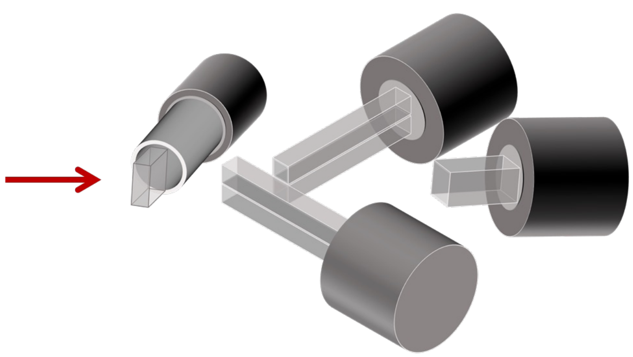
The results are approximately **33ps** resolution for the 2 straight bar counters, inclined at 45o, and close to **10ps** for the TRC counter.

Conclusions

We had developed:

- Continously calibrated TRS using multi channel DAQ system
- With stable TRC's and SB's time resolutions for different configuration
- Where can be easily introduced in the data taking for precise timing reference to DUTs.



Acknowledgements, Credits & References

(Essential contributions by A. Penzo and S. Ozkorucuklu)
(Inspiring discussions with: M. Albrow, A. Mestvirishvili, Y. Onel)

Research described here is part of a technical development R&D work bs teams of CMS, engaged in the Forward Hadron Calorimetry (HF) and in the Proton Precision Spectrometer (PPS) and belonging to CERN, FNAL, IPM – Teheran, Istanbul Universities, the University of Iowa and IHEP – Protvino.

Persons involved: M. G. Albrow, O. Atakisi, J. Baechler, A. Baud, S. Cerci, D. Druzhkin, M. Kaya, B. Kaynak, M. Khakzad, S. Los, F. D. Ingram, A. Mestvirishvili, Y. Onel, S. Ozkorucuklu, A. Penzo, V. Samoylenko, C. Simsek, C. Snyder, R. Stefanovitch, D. Sunar Cerci, M. J. Wagner

Photodetectors : MCP-PMT Hamamatsu, Photek, Photonis, Katod

MCP PM UFK-5G-2D produced by KATOD [4]

Quartz (fused silica) radiators : Specialty Glass Products; Russian company Alpha-TM

Test beams at CERN – North Area H8 and at DESY

[1] J. Vavra et al., Beam test of a time-of-flight detector prototype, NIM-PR 299 A 606 (2009) 404
[2] M. G. Albrow et al., Quartz Cherenkov Counters for Fast Timing: QUARTIC, JINST 7 (2012) P10027
[3] K. Inami et al, A 5-ps TOF-counter with an MCP-PMT, Nucl. Instrum. Meth. A560 (2006) 303–308.
[4]http://katodnv.com; special thanks to :

Backup

Counter's assembly in the Laboratory

KATOD recommend ≤ 1N on UFK-5G – 2D window (1.2mm thick): quartz bars were coupled to MCP-PMT windows following a rigorous procedure to insure:

- Correct geometry of bars and MCP-PMs, allowing reliable installation on the supports at the test-beam area in DESY;
- Good optical contact of the quartz bar ends and the MCP-PMT window; we chose a direct "dry" contact (without optical grease) at low pressure (using soft pads between quartz bar envelope holders and the MCP-PMT housing flange) in order to avoid risks of damaging the delicate borosilicate glass windows (with non-easily controllable stress via mechanical locking systems;
- Complete light tightness of the assembly, with no contact of the envelope walls with the faces of the bars, except with ends opposite the MCP-PMT window, which are not expected to receive directly produced Cherenkov photons, and were therefore covered with black absorbing pads to suppress reflected rays.

The quality and stability of the bar end – photocathode window contacts, and light tightness were checked for the assembled counters at nominal HVs and irradiating the quartz bars with a radioactive Sr90 source, observing the typical beta ray signals.

Counter’s assembly in the Laboratory