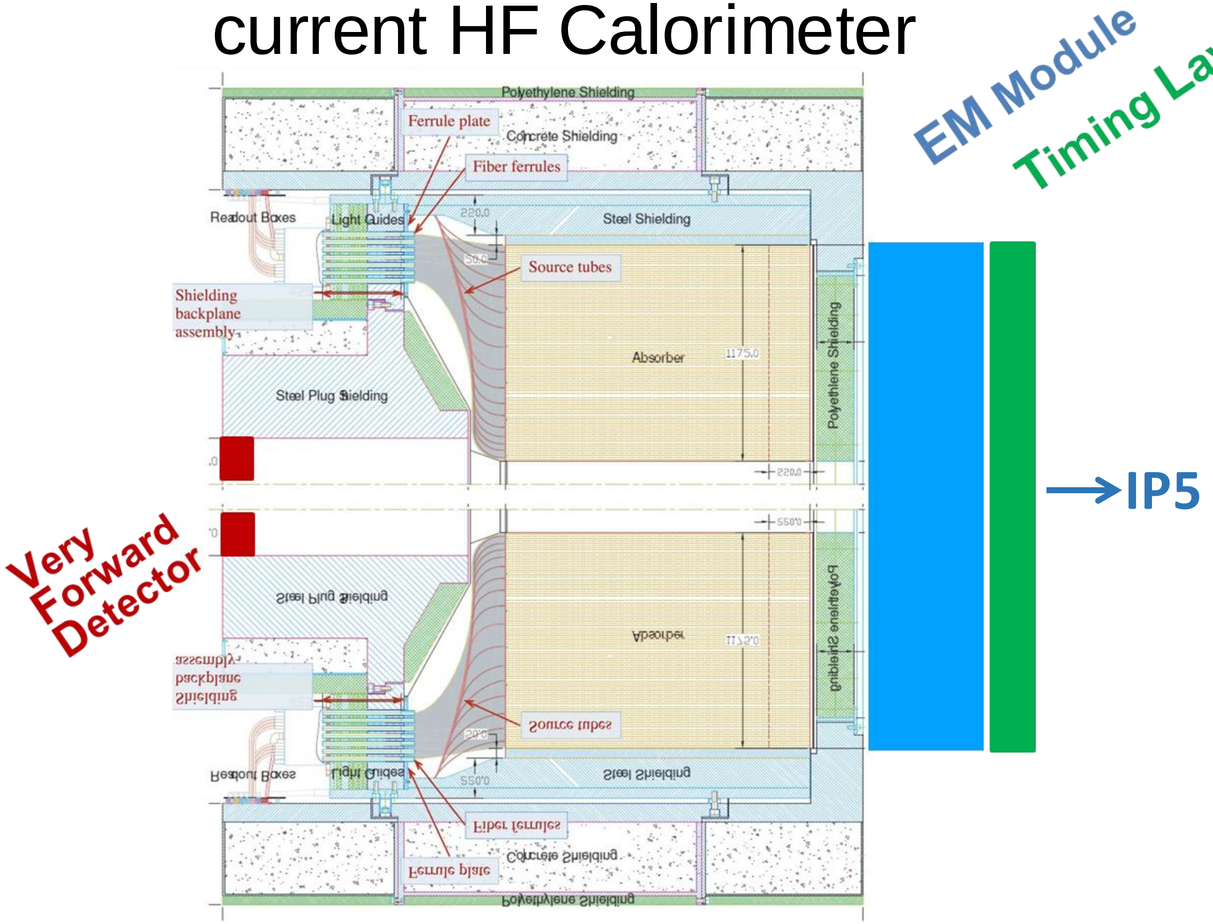
Düşünceden Sonuca Bir Deney

S. Ozkorucuklu

13.02.2025

HCAL Forward Region Task Force

Proposed additions to current HF Calorimeter



Scheme of principle
(not technical design!)

1. Timing Layer:
Quartz bar arrays to achieve high precision timing (IHEP)

2. EM Module:
Sampling calorimeter with high-Z absorbers and active layers either:

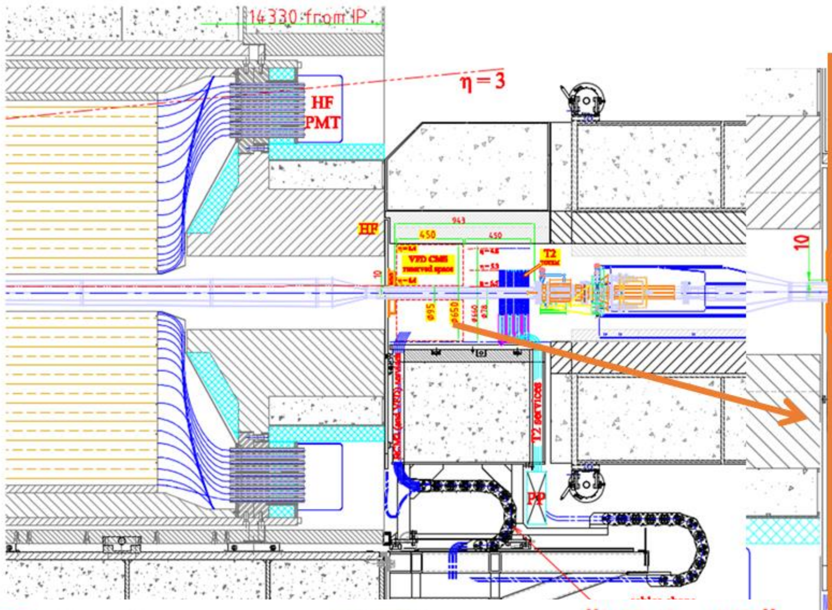
2.1 HF-nose :
Si Calorimeter (like HGCal) for region [$3 < \eta < 4.5$] (MIT)

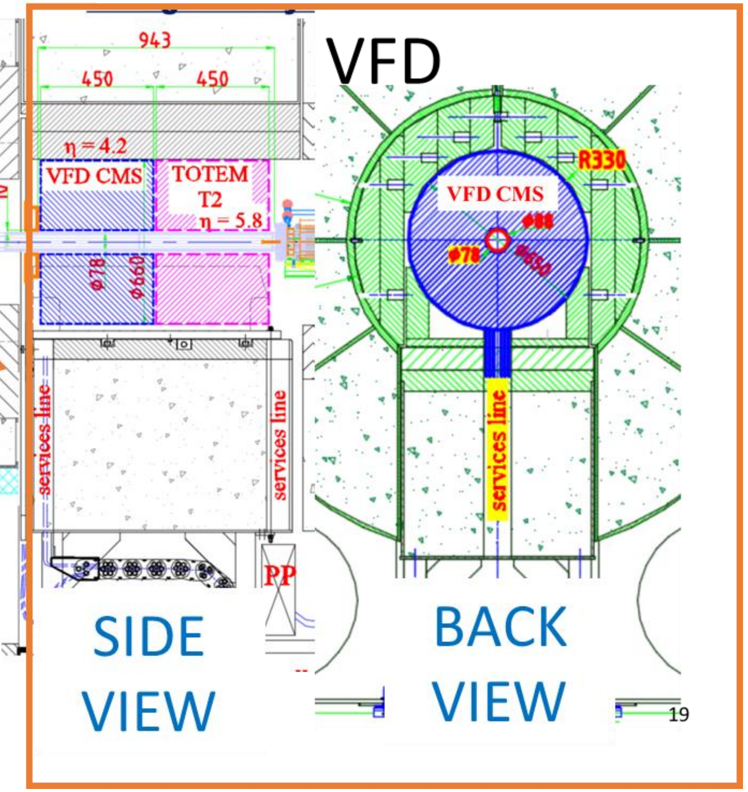
2.2 Quartz Wall :
Quartz tile+PMT arrays (Iowa).

3. VFD :
Quartz Fiber bundle device above eta of 5 (Istanbul)

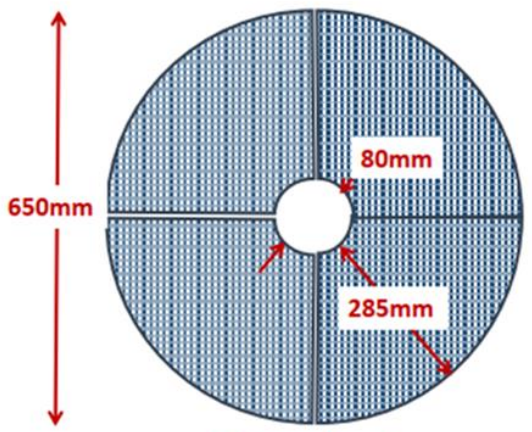
1

VFD: Quartz fiber ribbons + pixelized PMTs/MCP or SiPM (*)



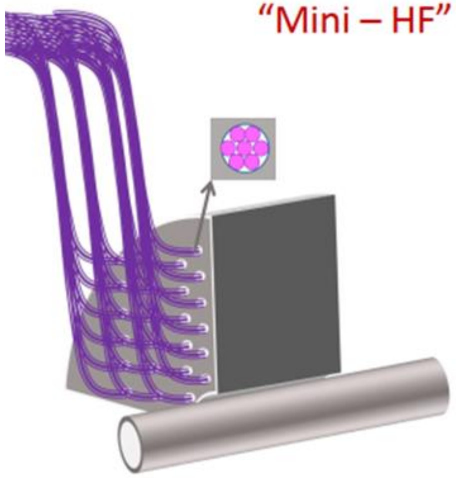


VFD structure



4 Quadrants

“Mini – HF”



ıadrant block, Tungsten (10Xo)

ngitudinal fibers, FF ≈ 10-15%

(*) proposed by S. Ozkorucuklu &C. (Istanbul U.)

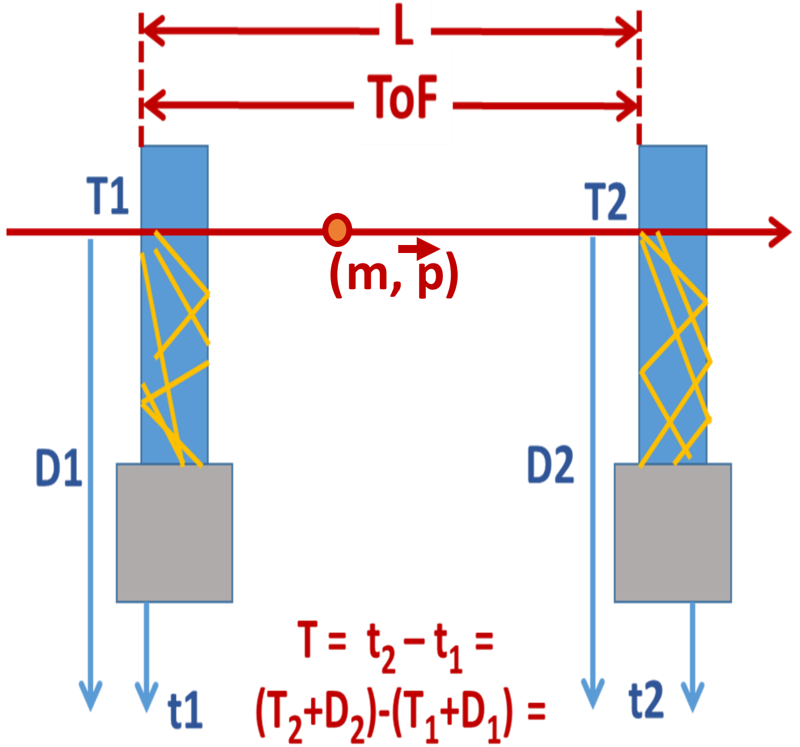
Precision Timing with quartz bars/fibers and segmented photodetectors

S. Ozkorucuklu

13.02.2025

ToF Measurements

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



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

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

For p >> mc (β -> 1):

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

As function of β (->1) and γ (>>1) :

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

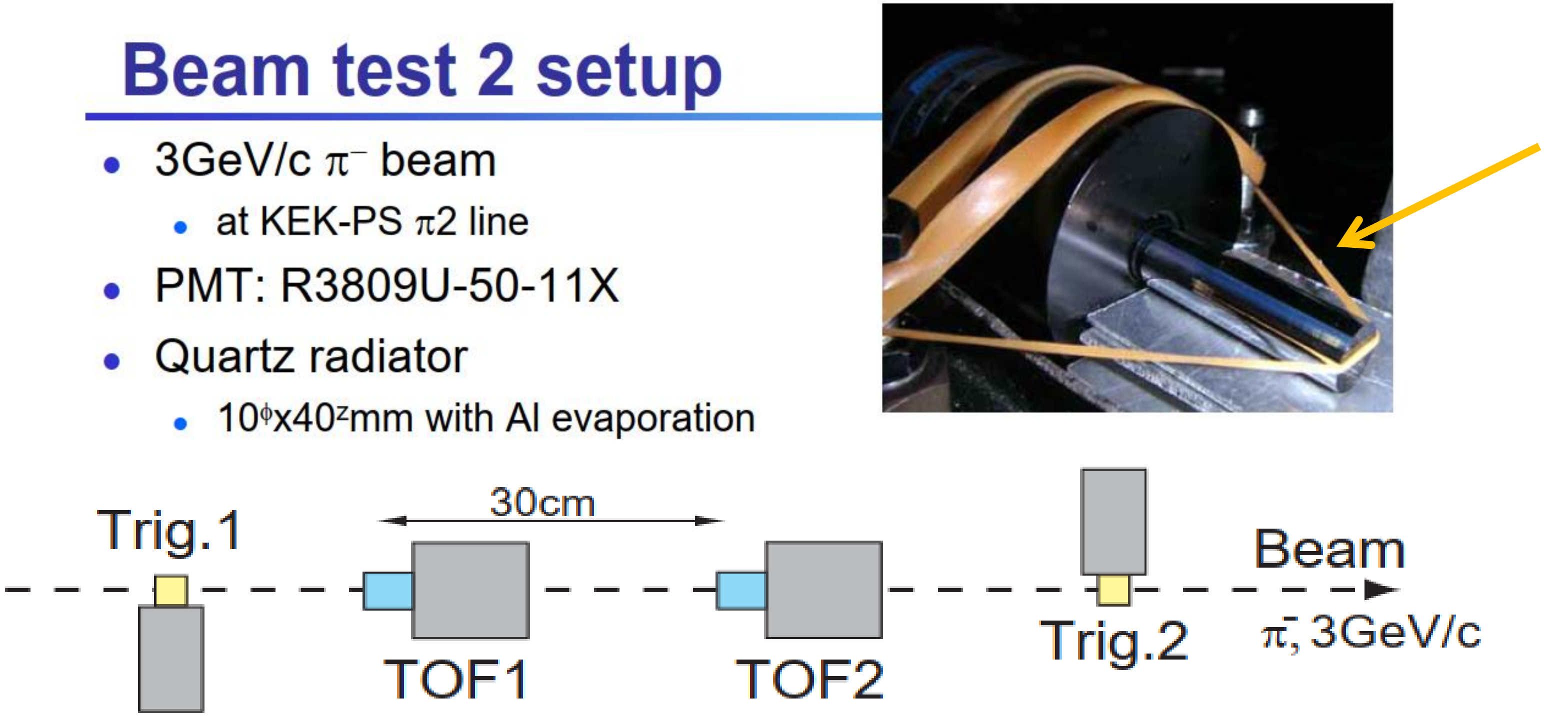
[geometric] [electric – electronic]

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

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

Example: K. Inami - Time of Flight measurements with MCP-PMT

International Symposium on the Development of Detectors, 2006/4 at SLAC



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

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

Non-negligible material budget:

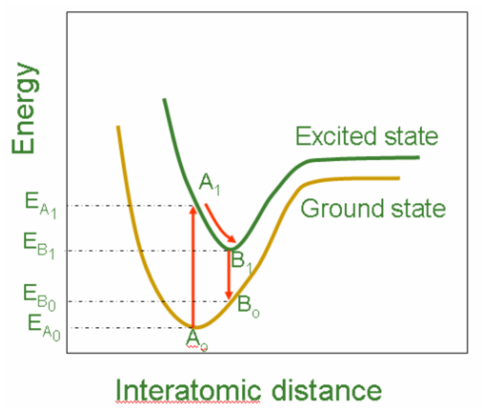
- Quartz block
- MCP-PMT

Multiple (independent) measurements problematic; showering produce correlations

Example: Optical detectors

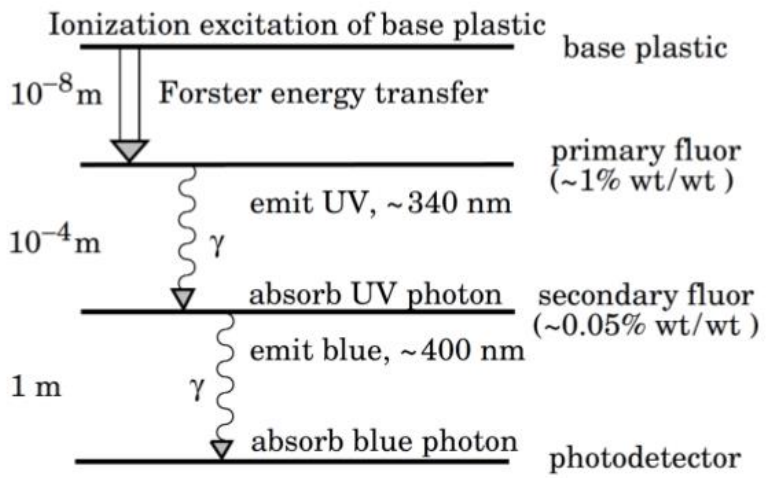
TOF precision depends on intrinsic time spread of light emission

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)

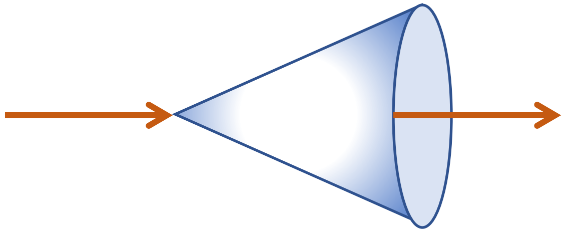
Photons’ distribution isotropic; for 1” sized scintillator typ. $\Delta t \approx$ 130ps

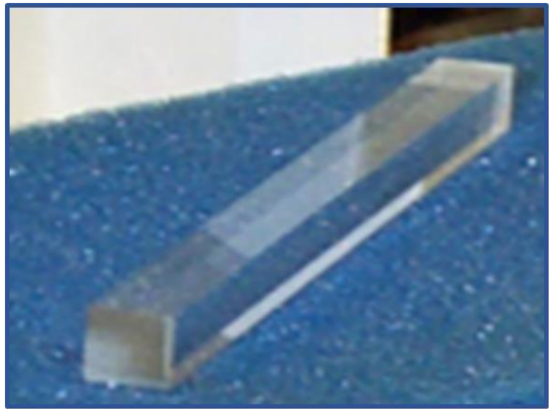
Quartz + MCP-PMT

- Quartz (Fused Silica) Cherenkov Timing Detectors
  - 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]

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





Speciality Glass Products (USA)

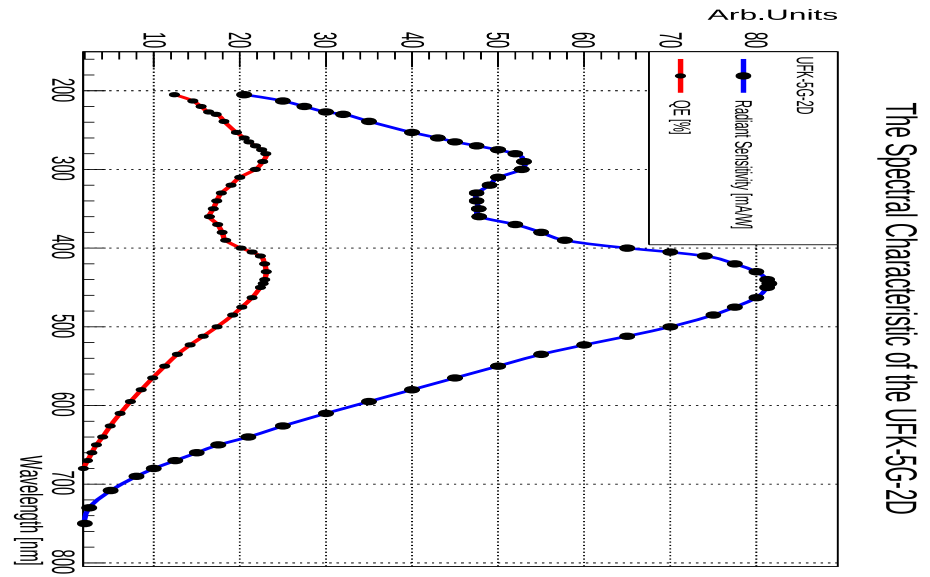
KU-1 (Russian Standard)

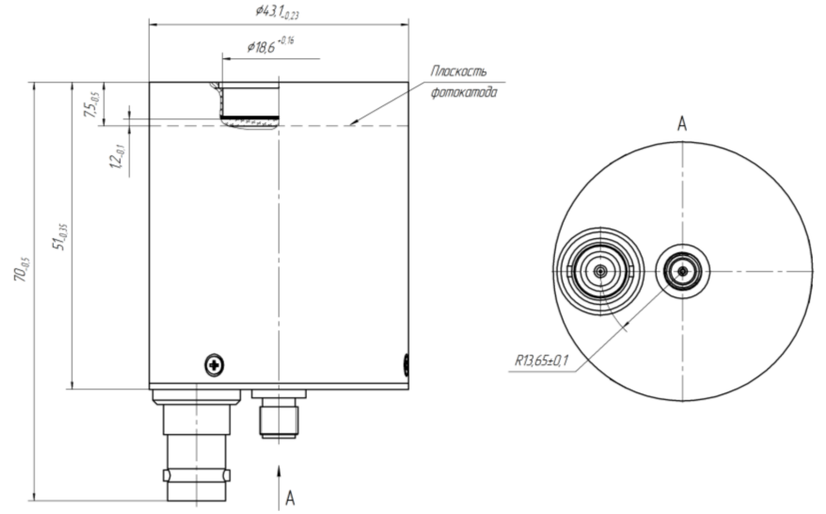
- MCP-PMT are photodetectors with
- negligible transit time spread (TTS < 50 ps)
- and high gain ($G \approx 10^6$)

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

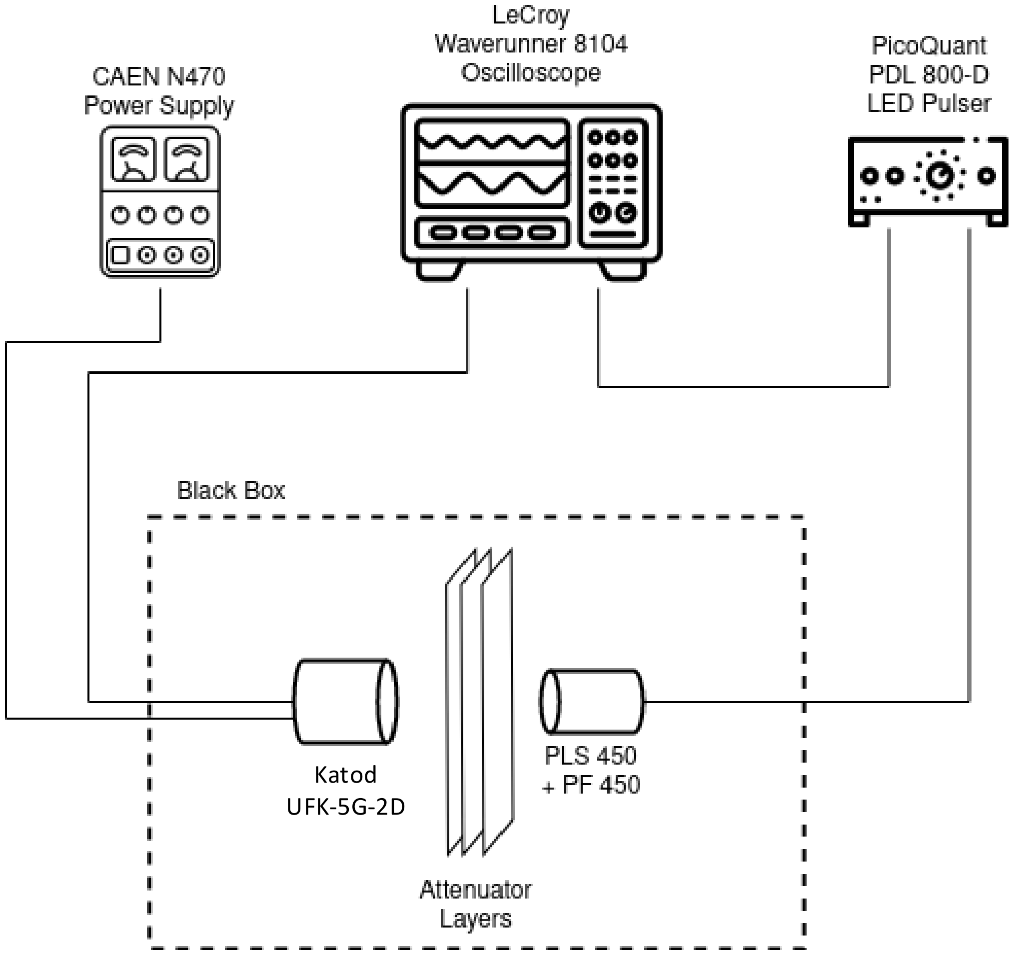
Thanks to V. Samoylenko (IHEP-Protvino) for establishing contact with the KATOD Company (Novosibirsk) and following the UFK-5G-2D custom development

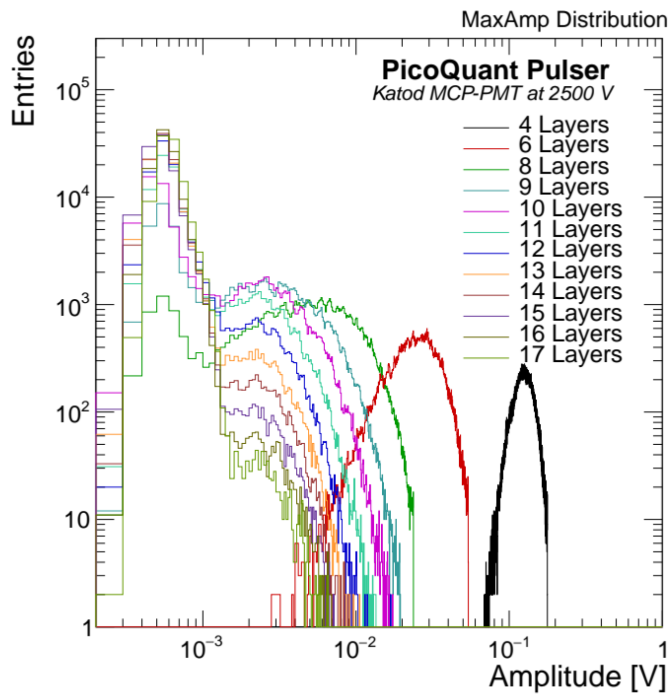


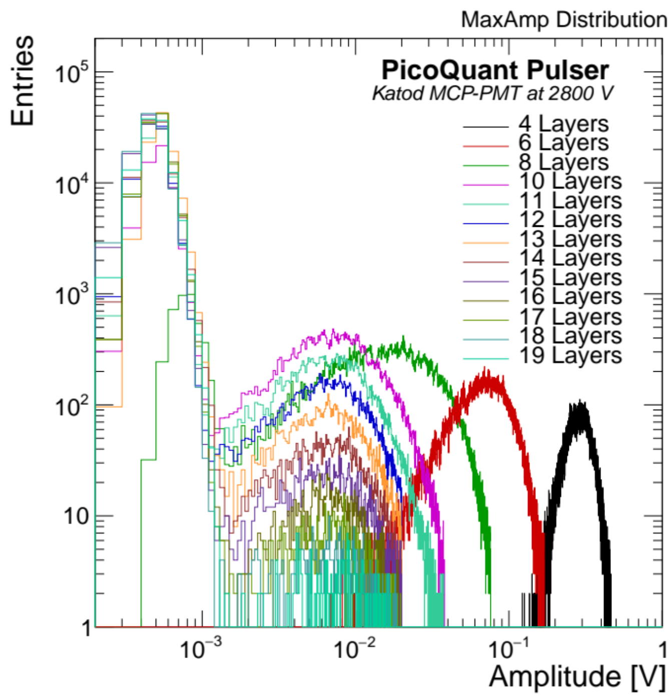


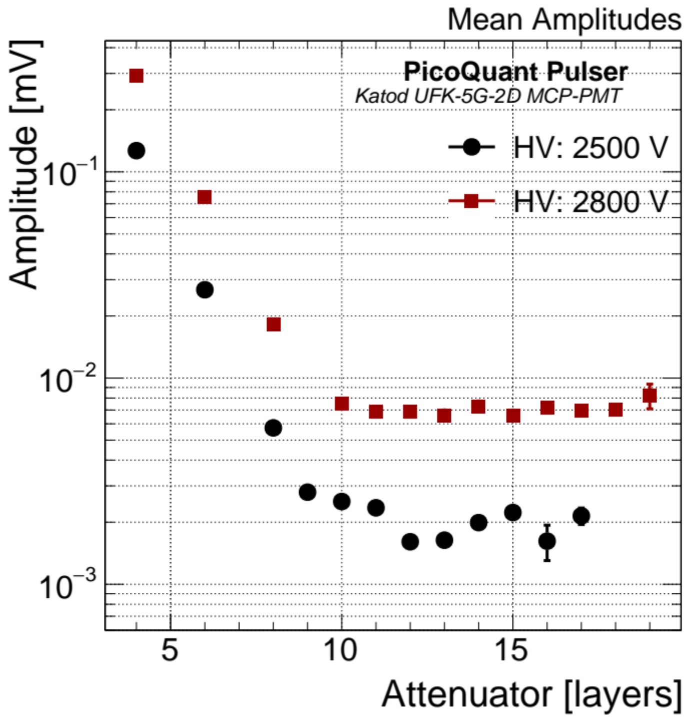
Dimensional Outline

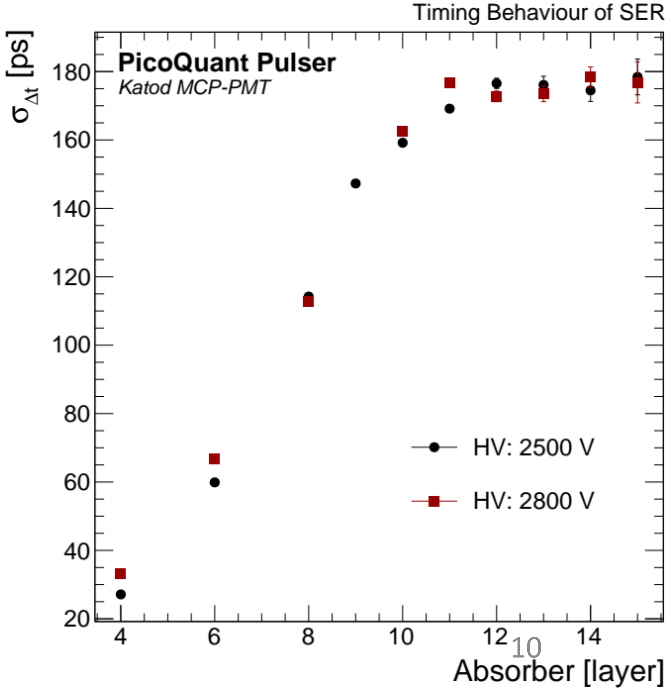
Single Photoelectron Study [Katod UFK-5G-2D MCP-PMT]



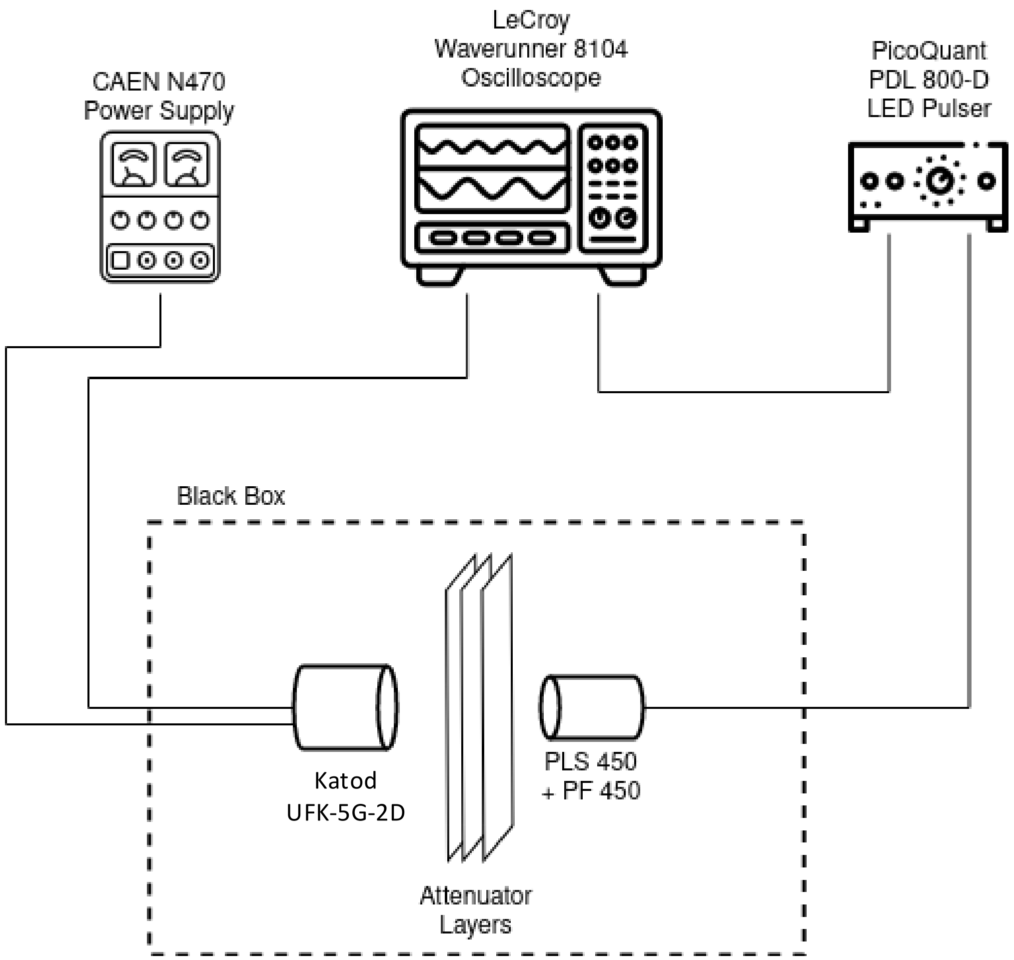


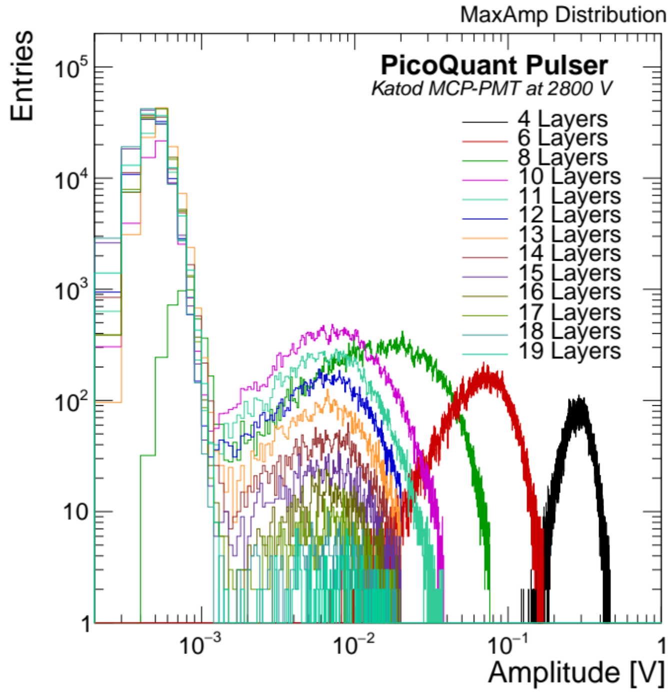


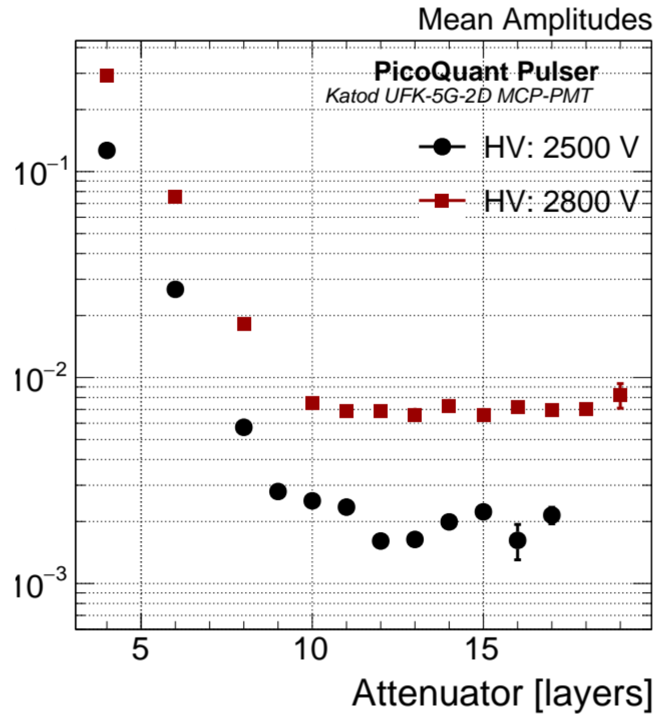


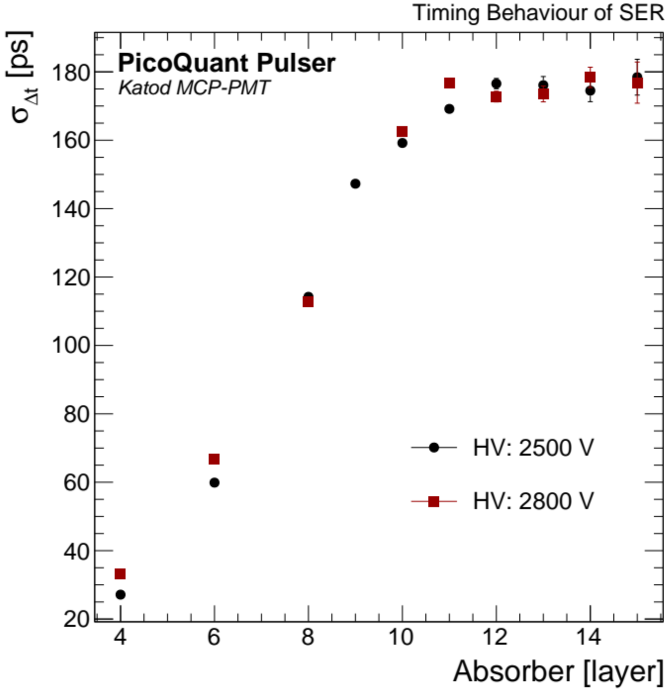


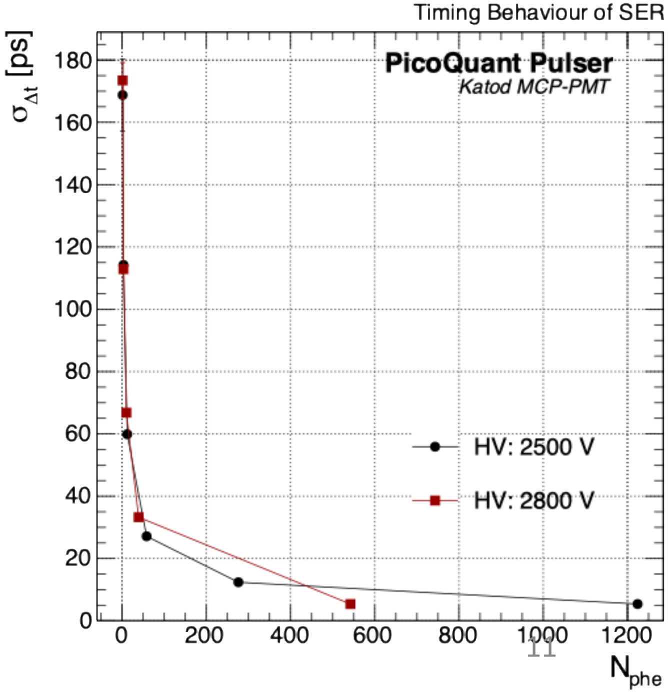
Single Photoelectron Study [Katod UFK-5G-2D MCP-PMT]









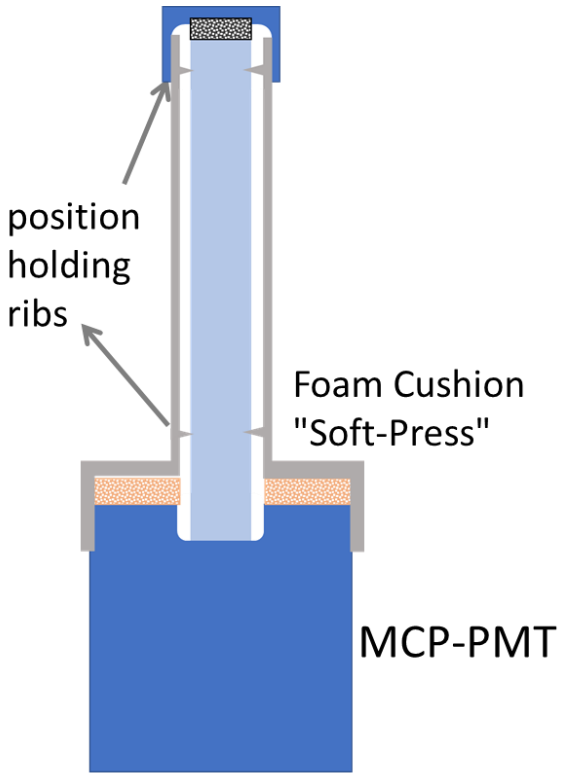


Single photoelectron's
$\sigma_{TTS} \approx 170$ ps

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:

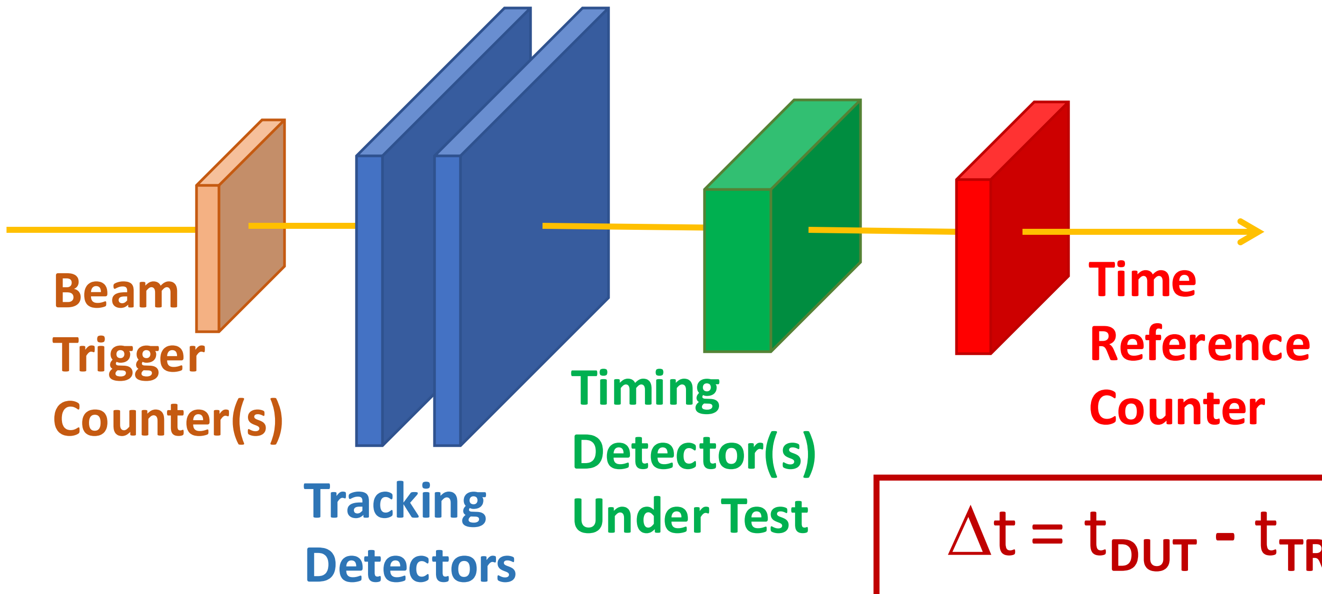
- Correct geometry of bars and MCP-PMs, allowing a reliable installation on the supports at the test-beam area in DESY;
- Good optical contact of the quartz bar ends and the MCP-PMT window; we chose a direct “dry” contact (without optical grease) at low pressure in order to avoid damage of delicate borosilicate 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.

Typical Test Beam Configuration for Timing Detectors



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

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

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

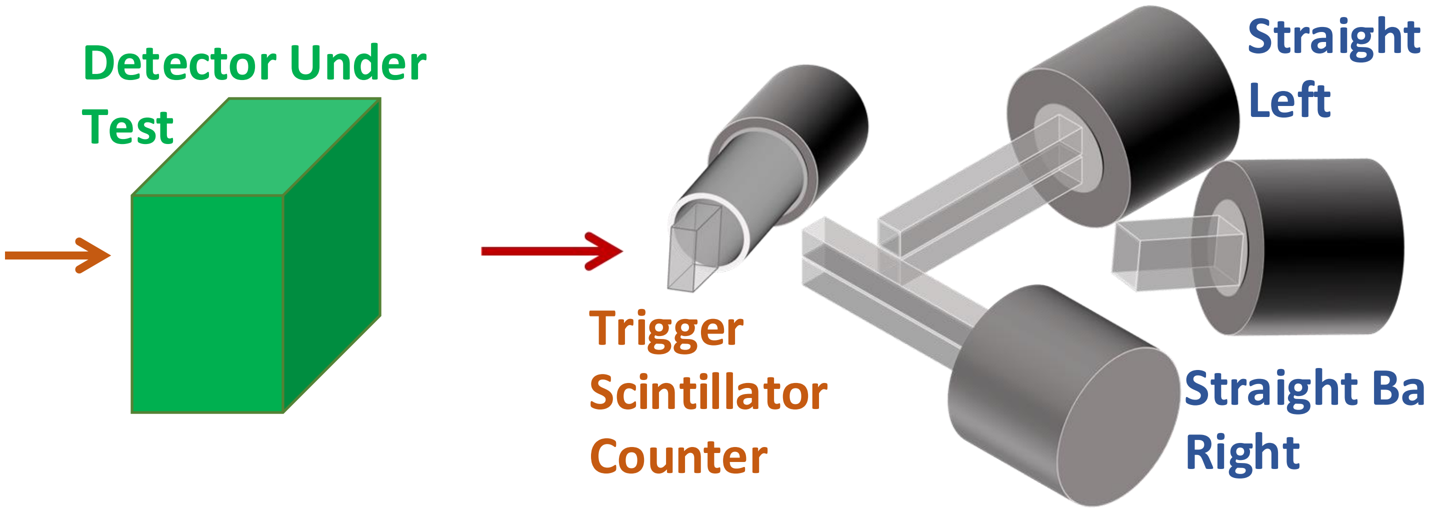
$$\sigma_{DUT} = \sqrt{\sigma^2_{\Delta t} - \sigma^2_{TRC}}$$

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

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

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):

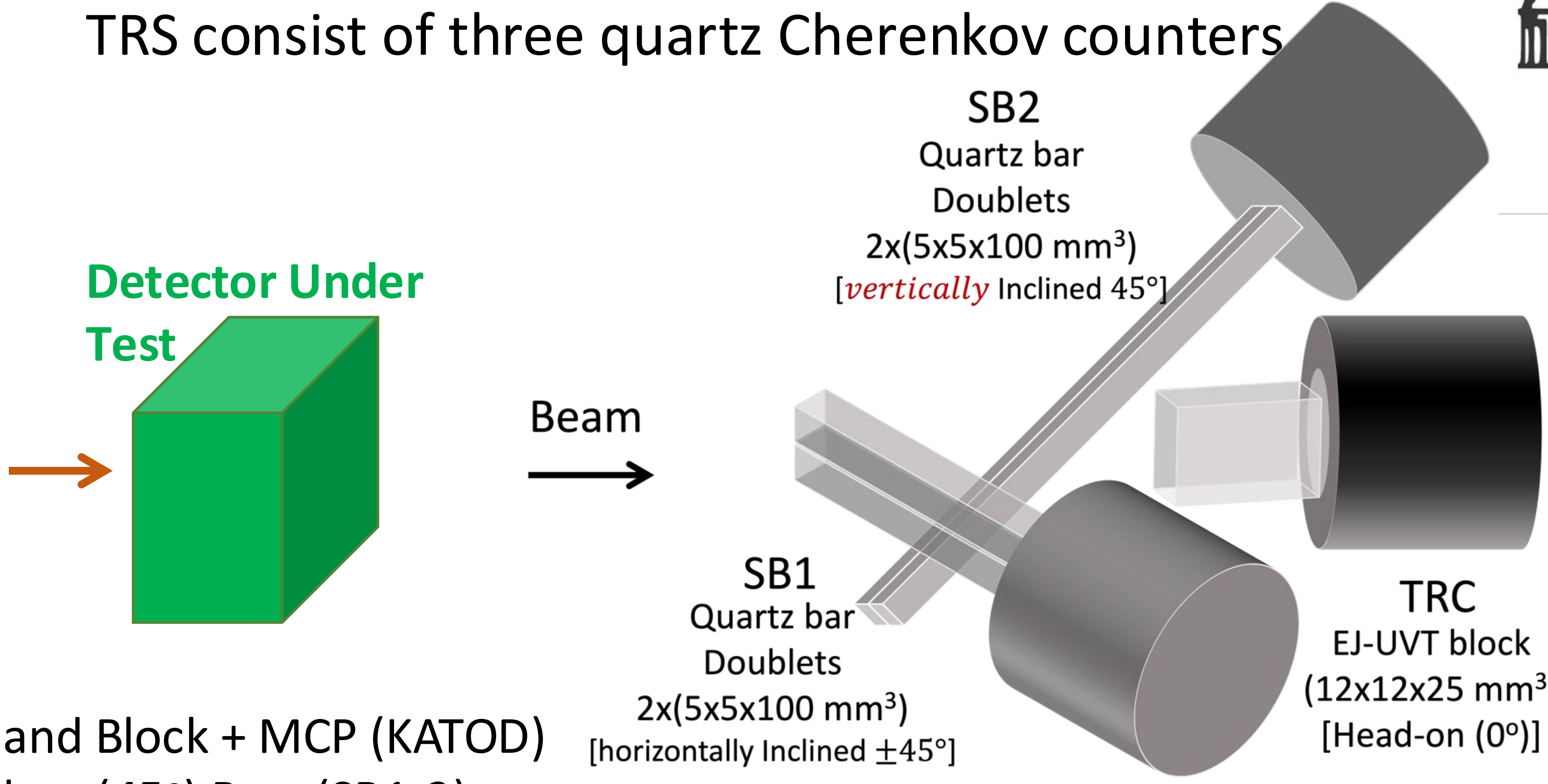
$$\sigma_{12}^2 = (\sigma_1^2 + \sigma_2^2) \quad ; \quad \sigma_{13}^2 = (\sigma_1^2 + \sigma_3^2) \quad ; \quad \sigma_{23}^2 = (\sigma_2^2 + \sigma_3^2)$$

time resolution for each counter can be obtained.

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

3D Time Reference System (3D-TRS)

TRS consist of three quartz Cherenkov counters



Apparatus: Quartz Bars and Block + MCP (KATOD)

- 2 (identical) Slant (45°) Bars (SB1-2)
- 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 can be used with DUTs

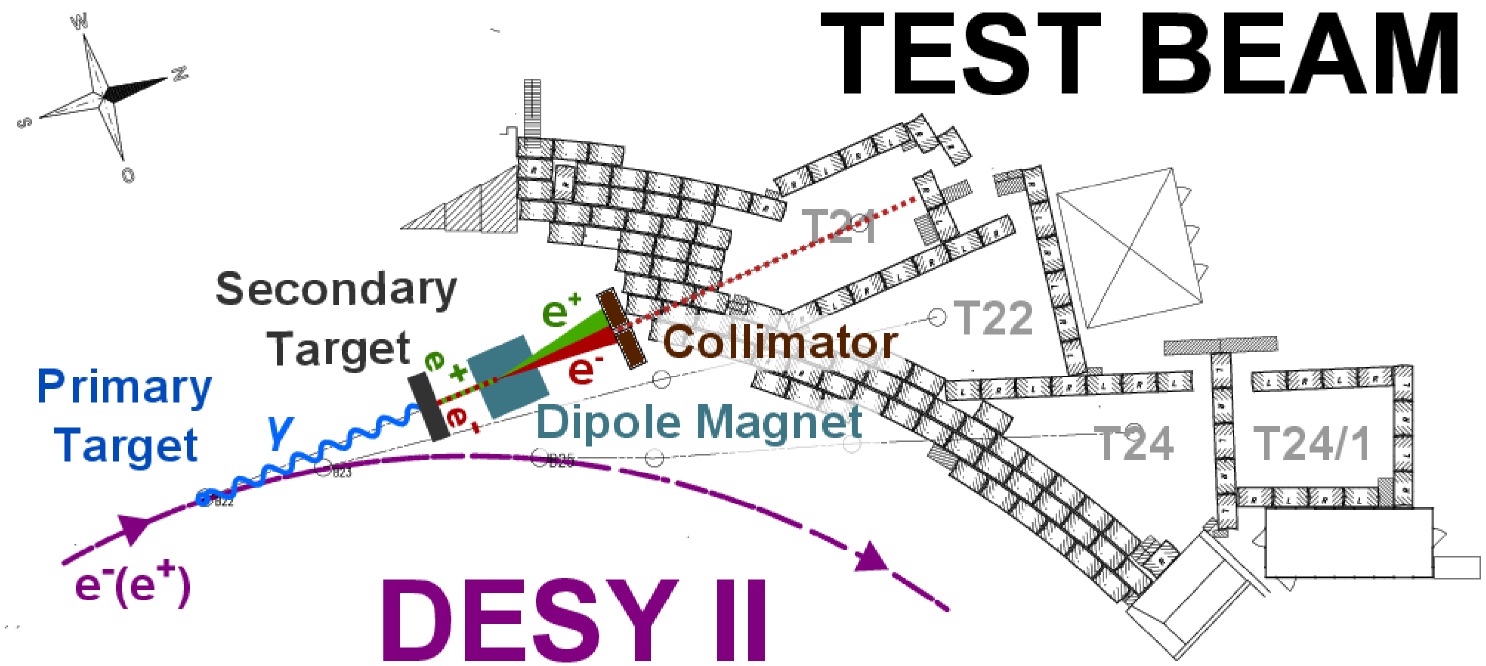
$$\Delta t = t_{DUT} - t_{TRC}$$

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

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

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

DESY II Test Beam Facility



Bremsstrahlung γ beams

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

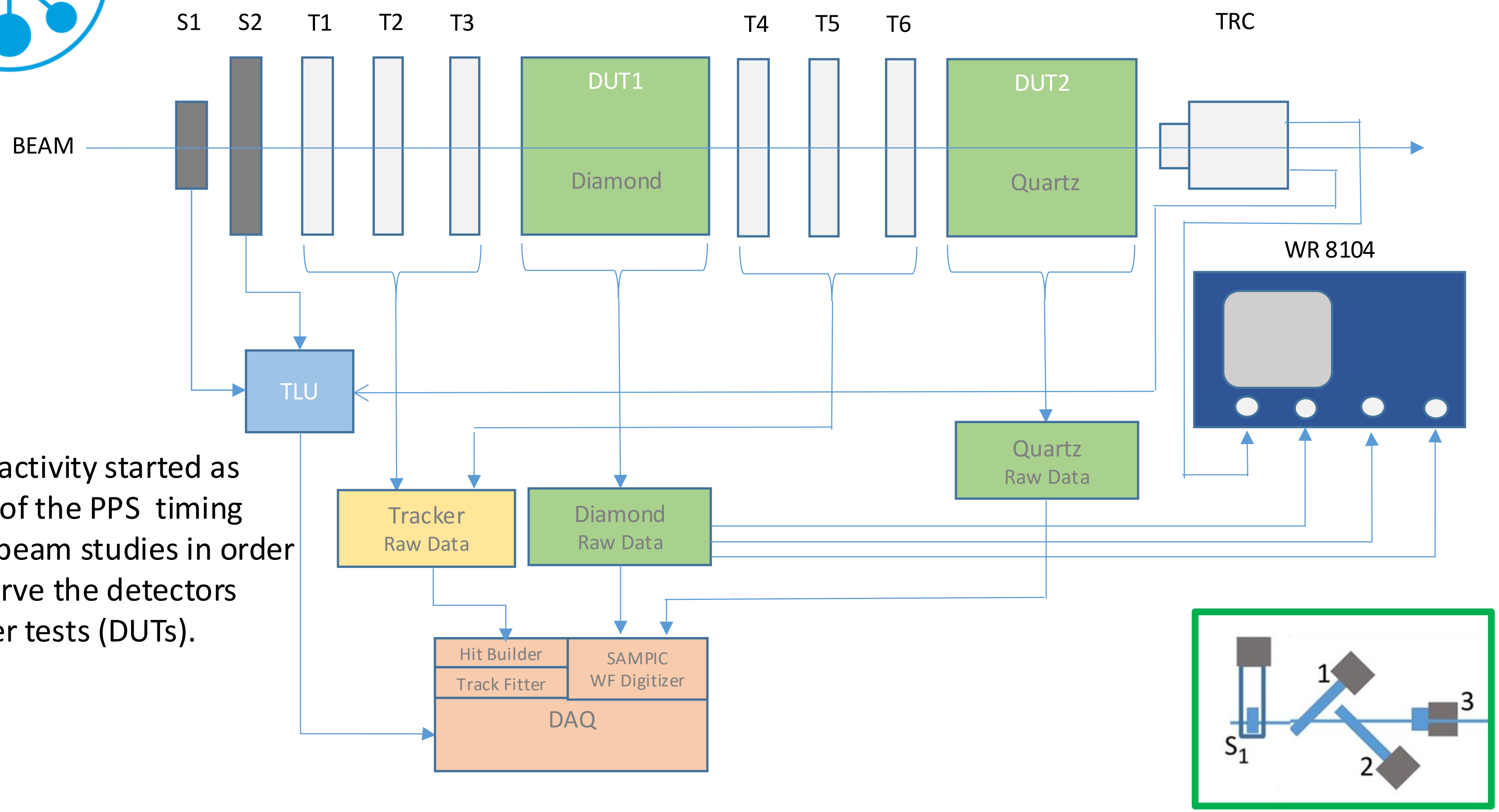
3 beam lines : T21, T22, T24

- 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

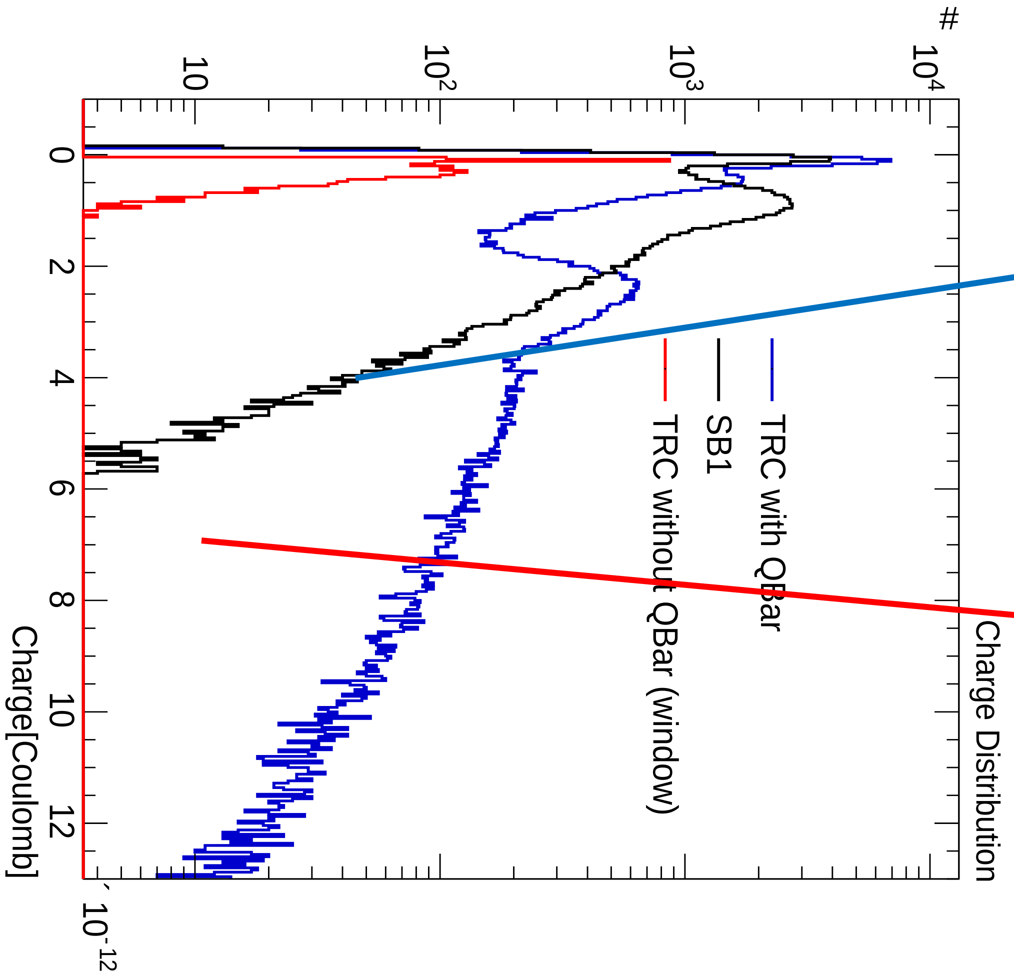


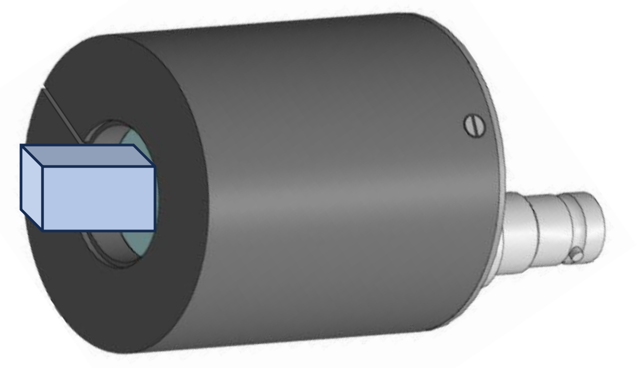
This activity started as part of the PPS timing test beam studies in order to serve the detectors under tests (DUTs).

DUT1 : Diamond timing detectors

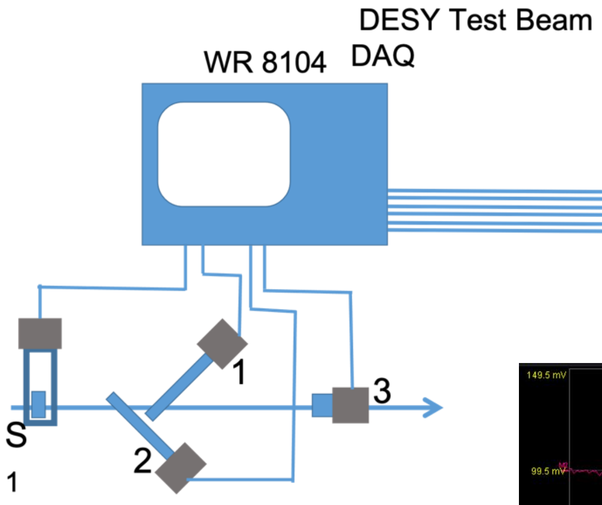
DUT2 : Quartz bars+MCP-PMT

TRC was also investigated without quartz block.
Window effect clearly visible





Data Acquisition (DAQ)

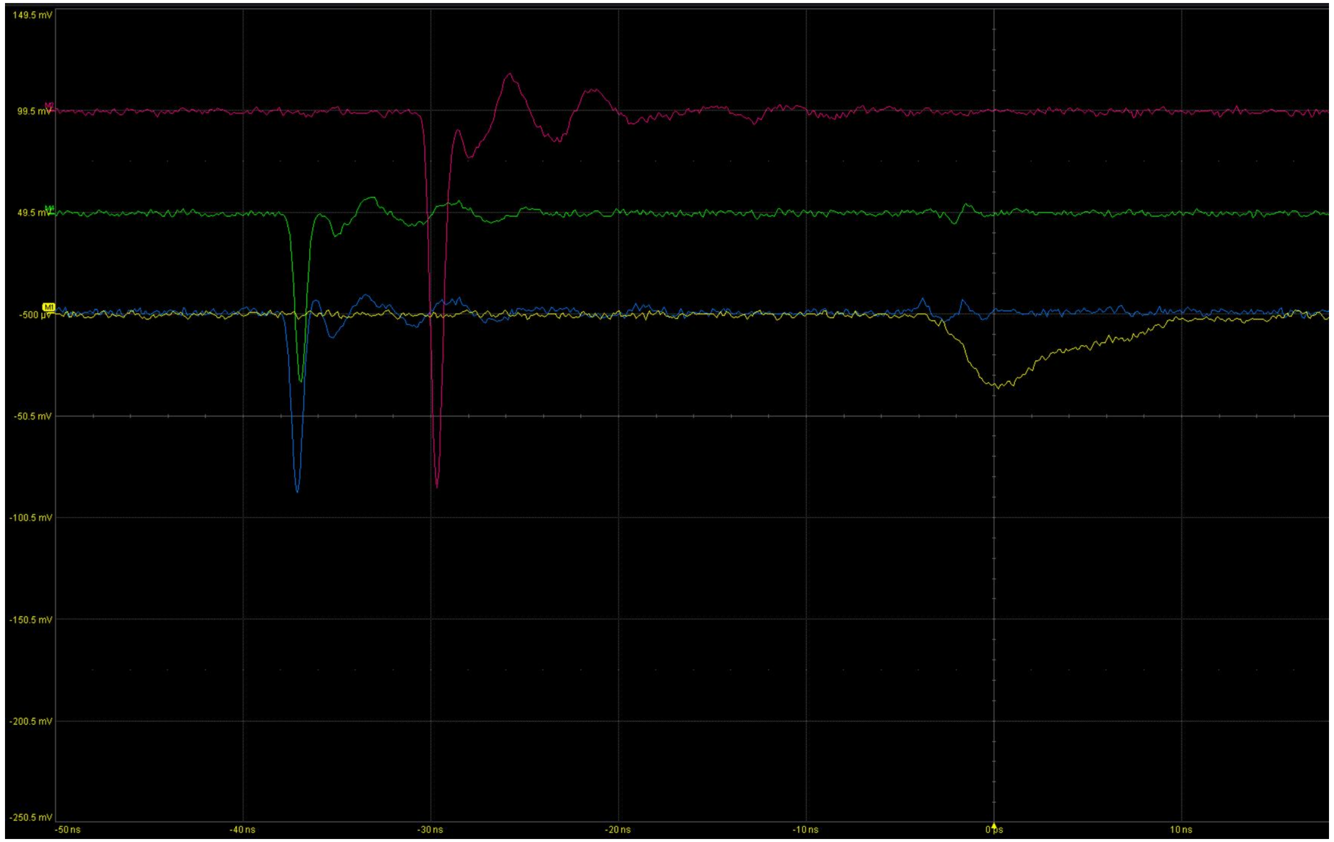


Four channel LeCroy 8104 DSO used for measurement of MCP signals

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

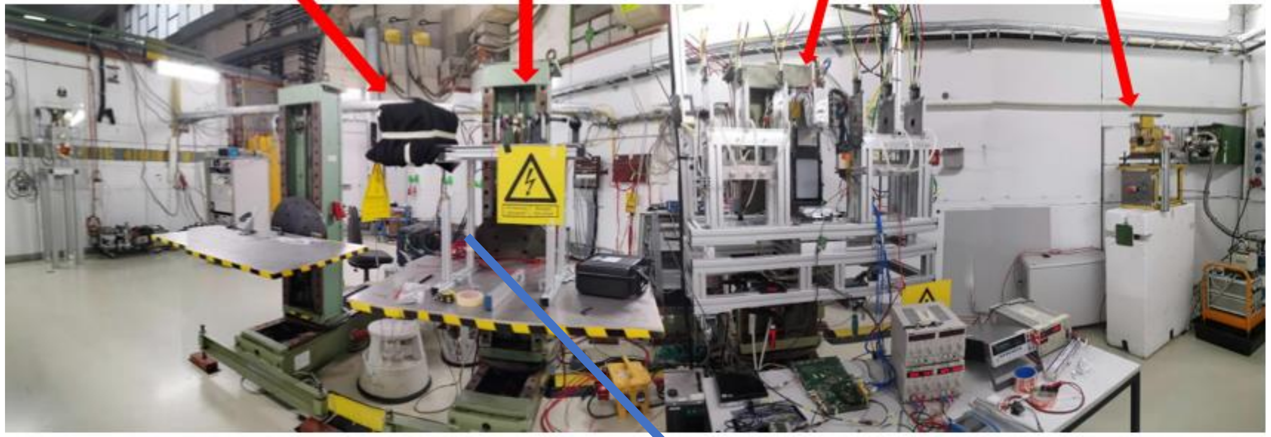
Fast segmented aqusition was used for data taking.

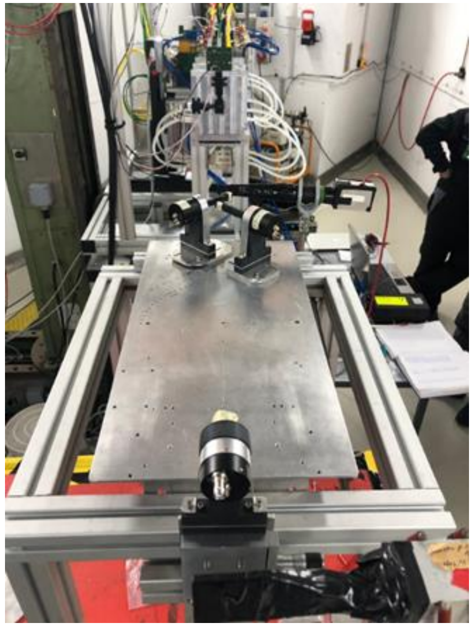
Event display



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

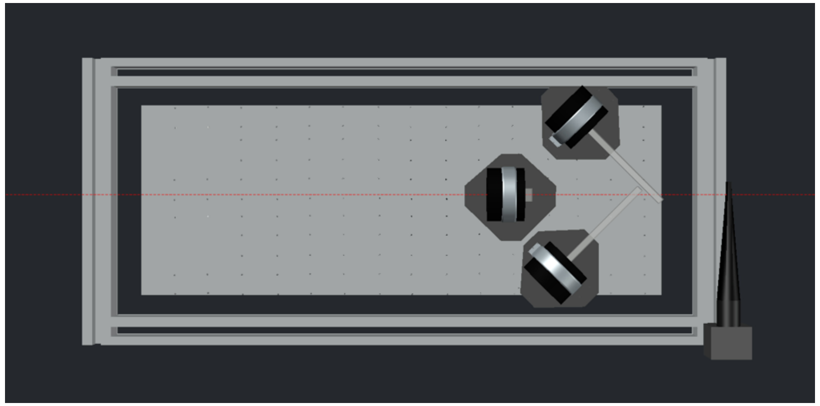
@DESY Test Beam Setup



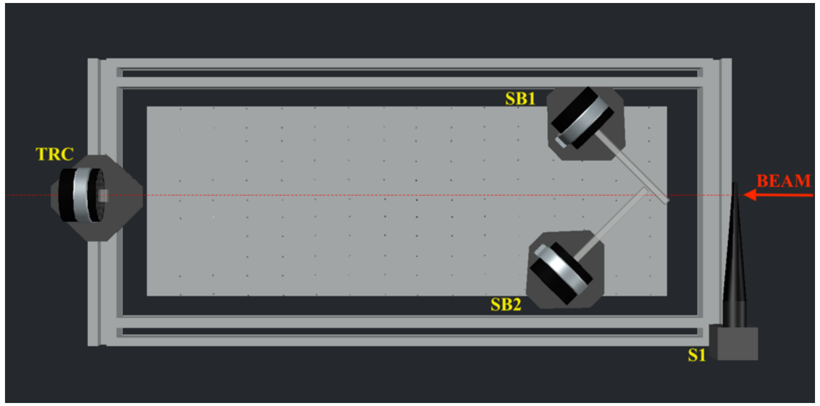


Calibration and test Runs

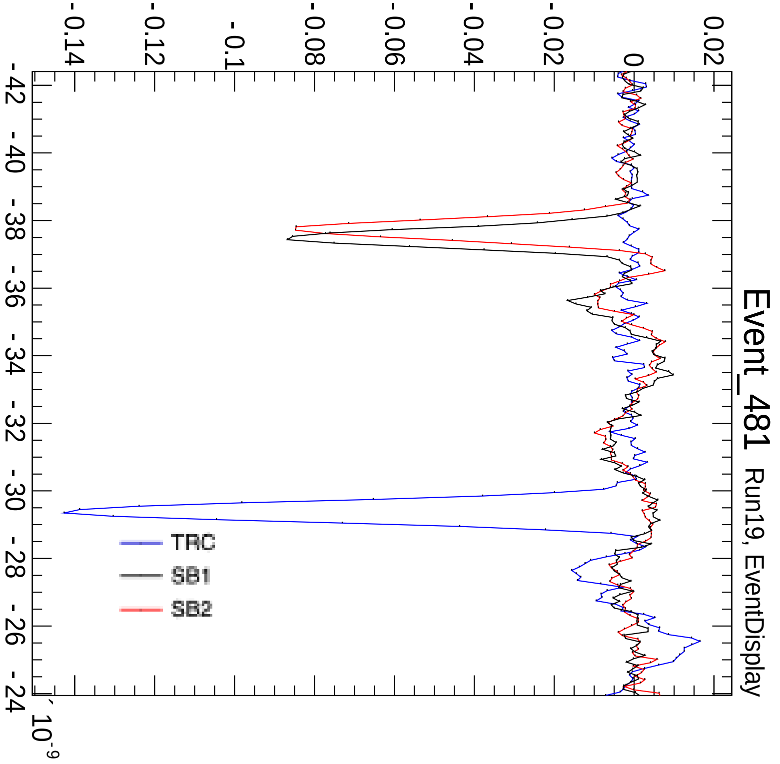
Phase 2 : more compact configuration

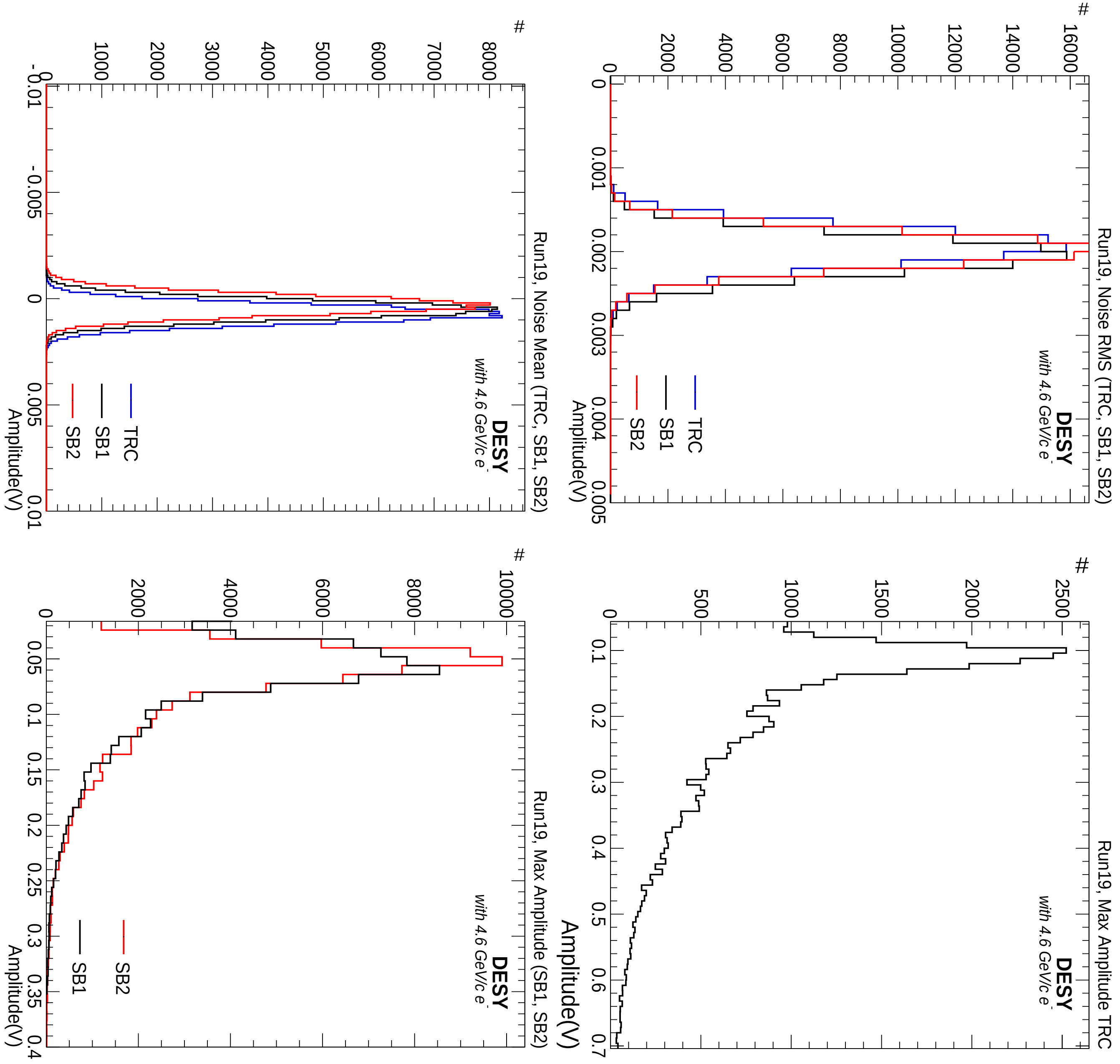


Phase 1: Initial setup



Characterization of the Counters





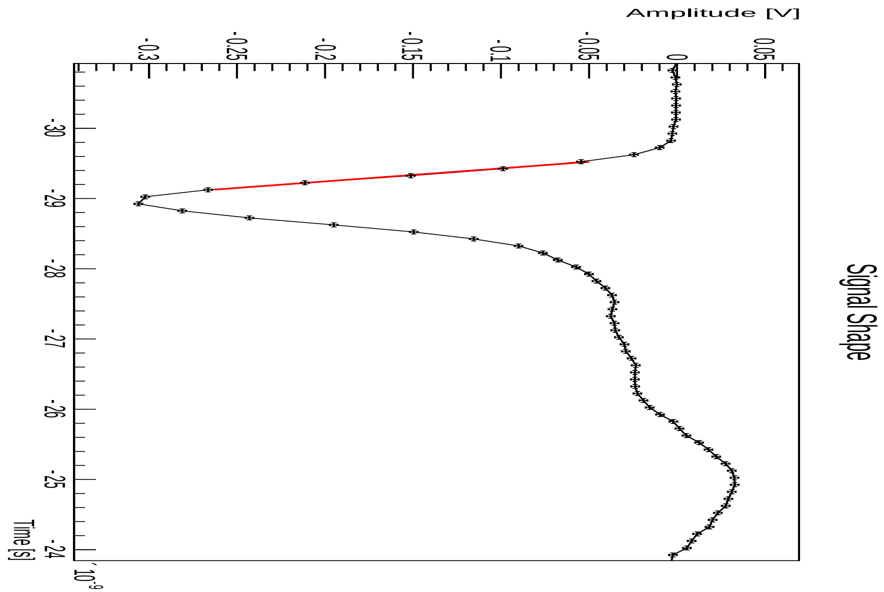
Timing Measurement

4 Signals in LeCroy DSO WR8104 :

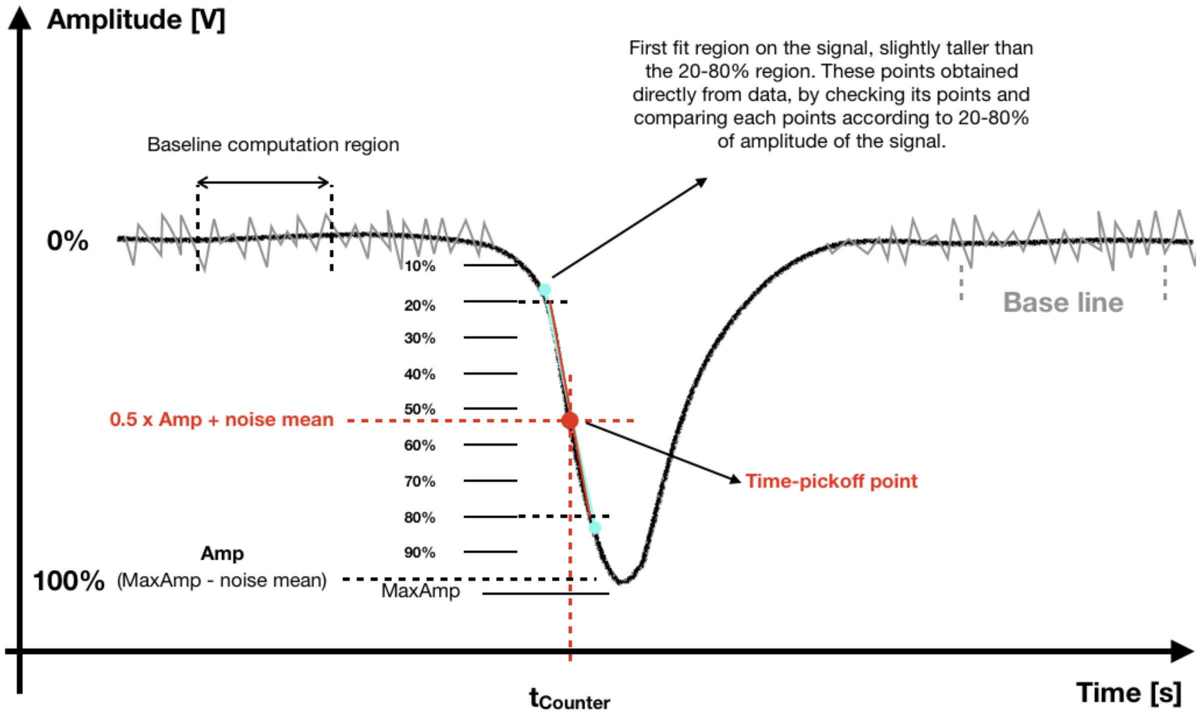
- Ch1 = S1(trigger), Ch2 = TRC , Ch3 = SB1, Ch4 = SB2
- ToF1 = Ch3 – Ch4, ToF2= Ch2-Ch3, ToF3 = Ch2-Ch4
- $\sigma_1^2 = (\sigma_{SB2}^2 + \sigma_{SB1}^2)$, $\sigma_2^2 = (\sigma_{TRC}^2 + \sigma_{SB1}^2)$, $\sigma_3^2 = (\sigma_{TRC}^2 + s_{SB2}^2)$

Then the time resolutions for each counter can be obtained:

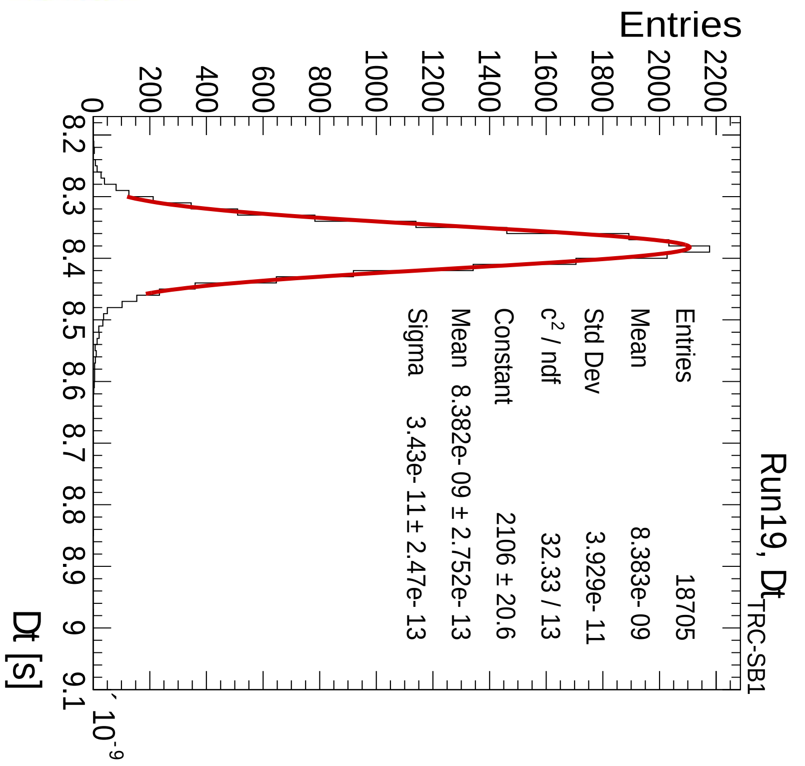
- $\sigma_{TRC} = \text{sqrt}\ \{[\sigma_2^2 + \sigma_3^2 - \sigma_1^2]\ /2\}$
- $\sigma_{SB1} = \text{sqrt}\ \{[\sigma_2^2 - \sigma_3^2 + \sigma_1^2]\ /2\}$
- $\sigma_{SB2} = \text{sqrt}\ \{[\sigma_3^2 - \sigma_2^2 + \sigma_1^2]\ /2\}$

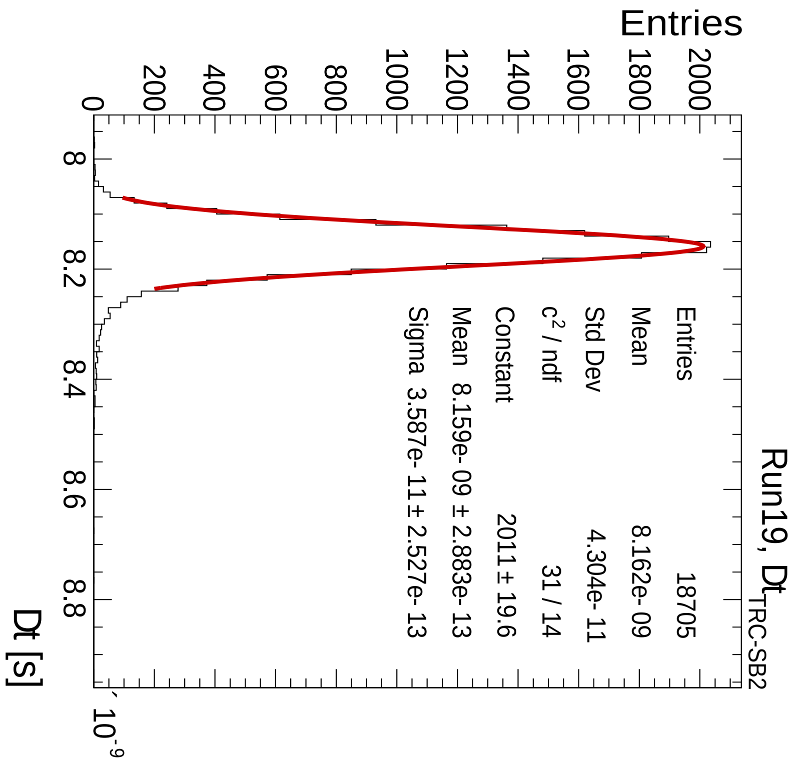


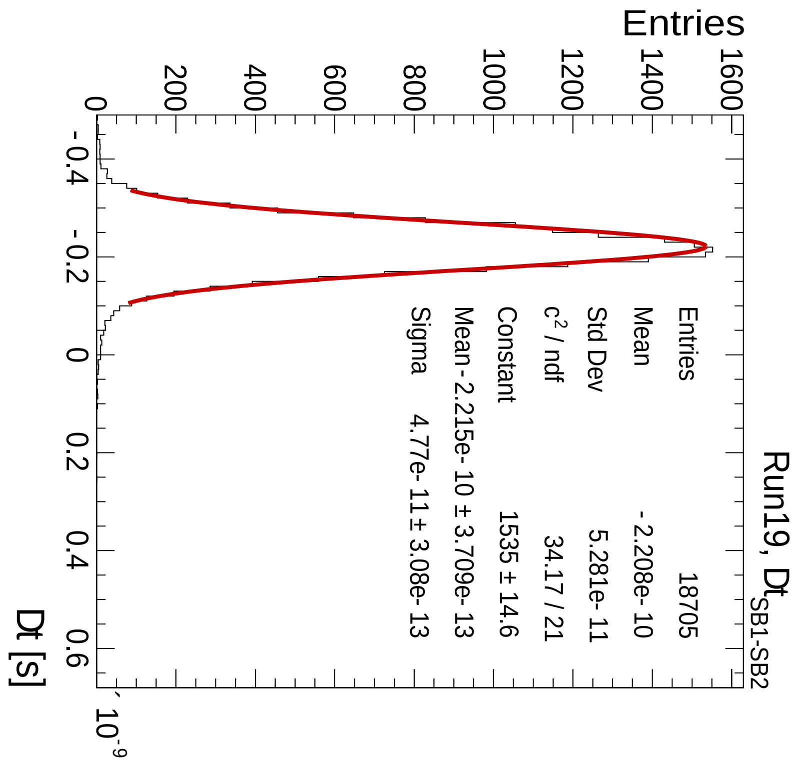
Using offline CFD method, time-pickoff points were extracted for each counter at 50%



Timing Measurement







σ_{TRC}=9.7 $\pm$ 0.99 ps

σ_{SB1}=32.9 $\pm$ 0.3 ps

σ_{SB2}=34.5 $\pm$ 0.28 ps

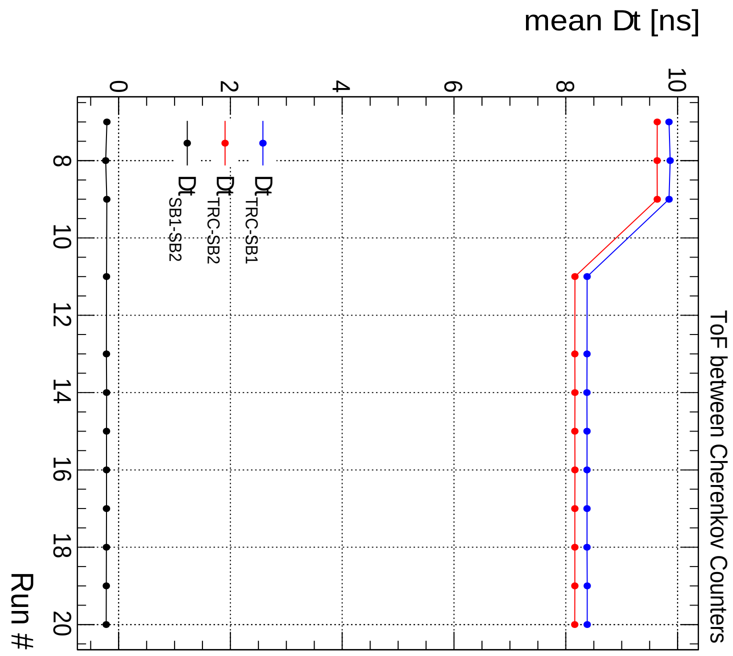
- $0.071mV < Amp_{TRC} < 0.25$ mV
- $0.031mV < Amp_{SB1} < 0.20$ mV
- $0.0235mV < Amp_{SB2} < 0.25$ mV

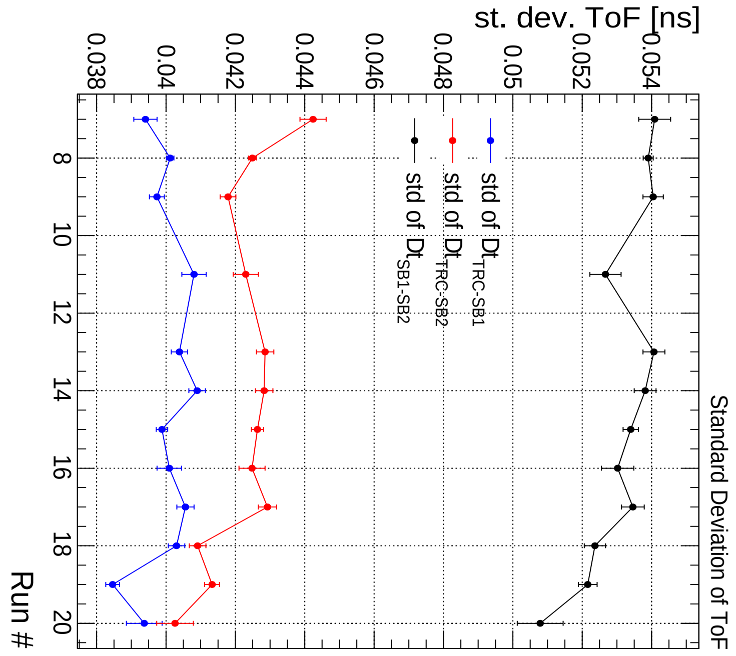
Timing Measurement

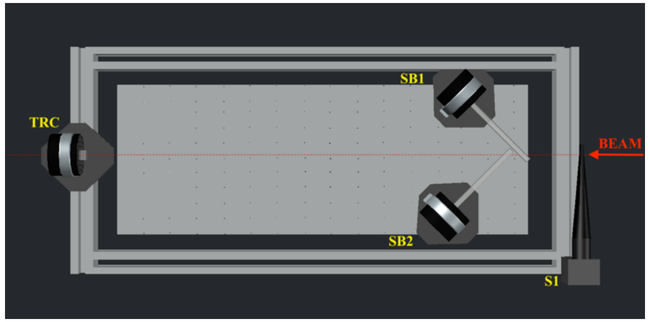
Runs can be grouped according to MCP+QB setup:

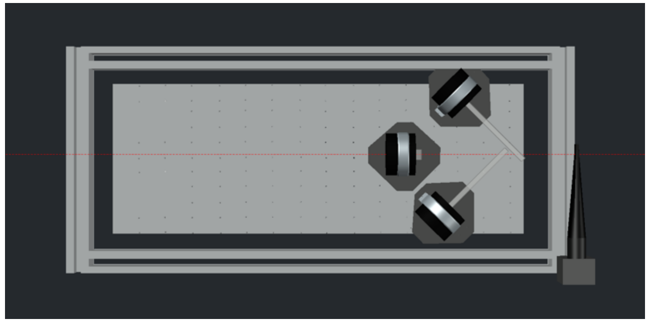
- TRC far from SB1/2 **(Run7-10)**
- TRC near SB1/2 (the displacement 438mm) **(run11-18)**
- Diamond removed from beam line **(Run19-20)**

displacement of TRC is clearly visible





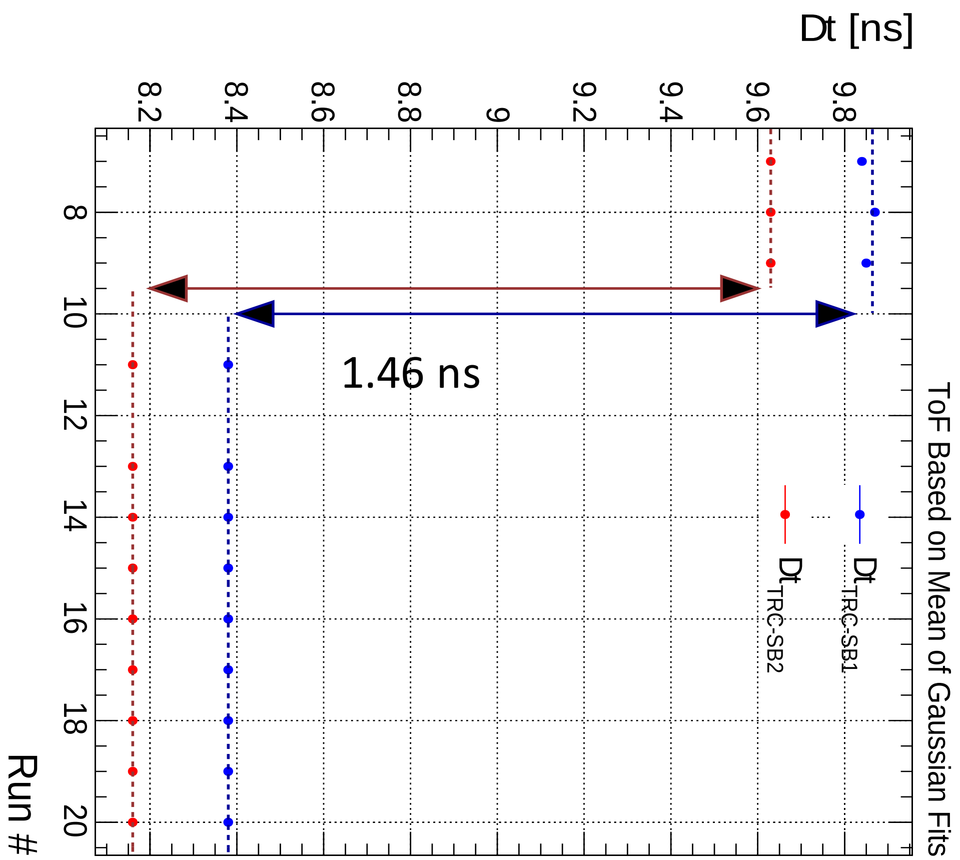




Timing Measurement

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

Runs can be grouped according to MCP+QB setup:

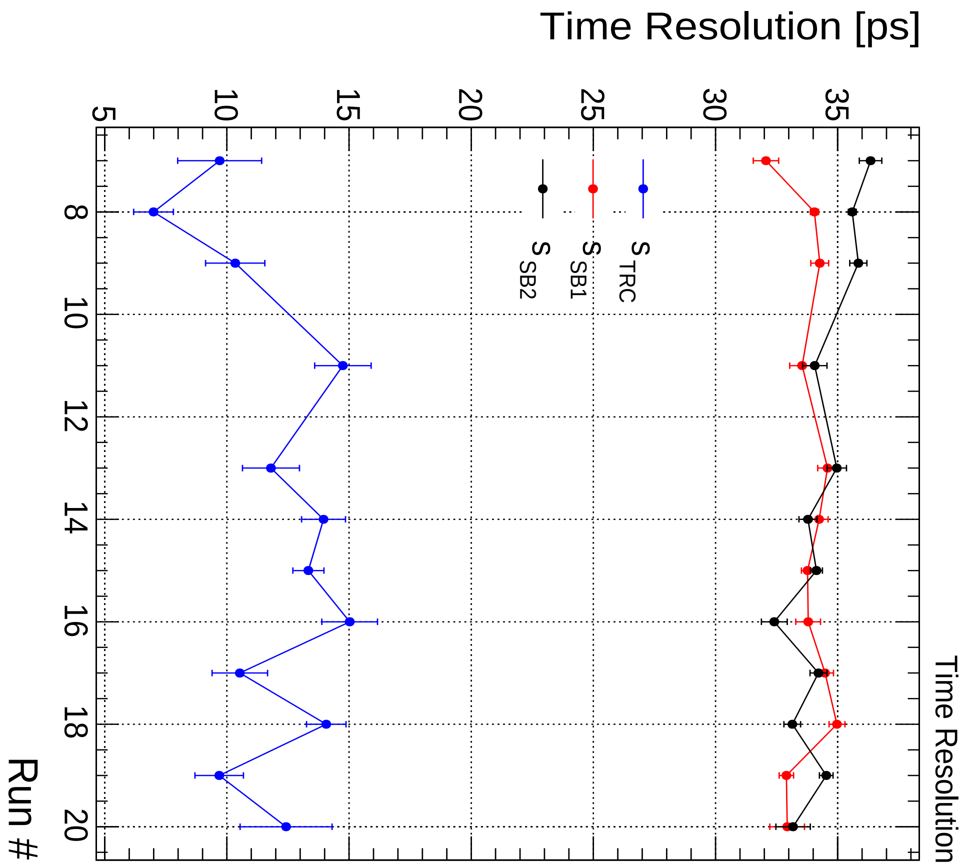


displacement of TRC is clearly visible

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

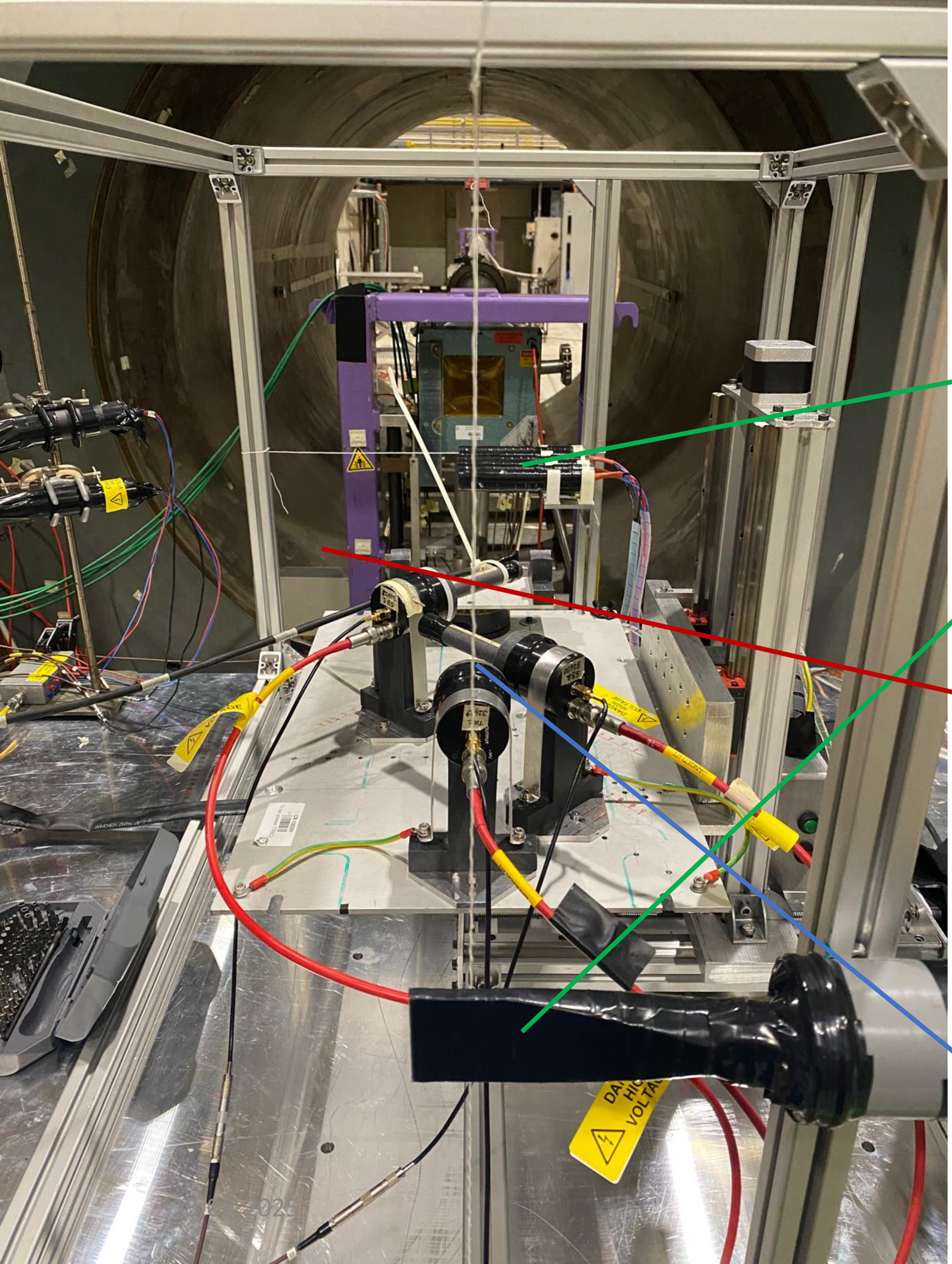
Timing Measurement



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

The results are approximately **33ps** resolution for the 2 straight bar counters, inclined at 45^{o}, and close to **10ps** for the TRC counter.

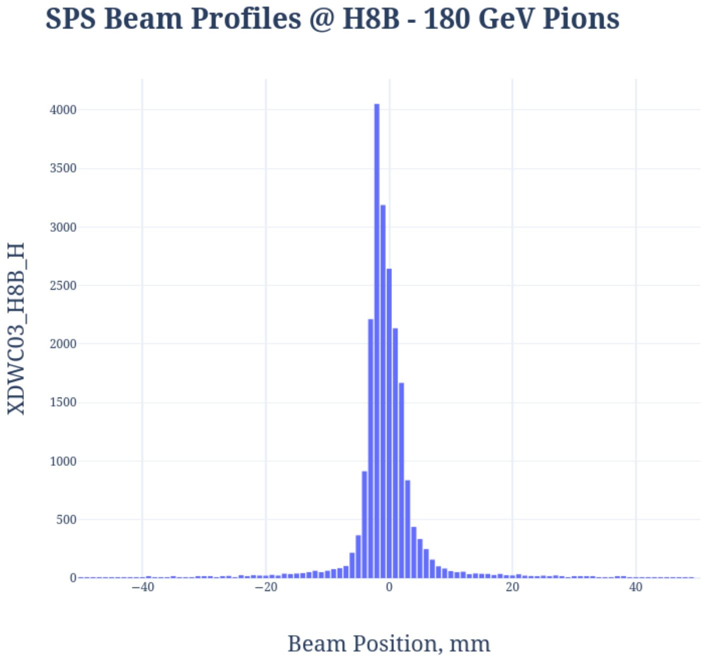
QFib Test Beam Setup

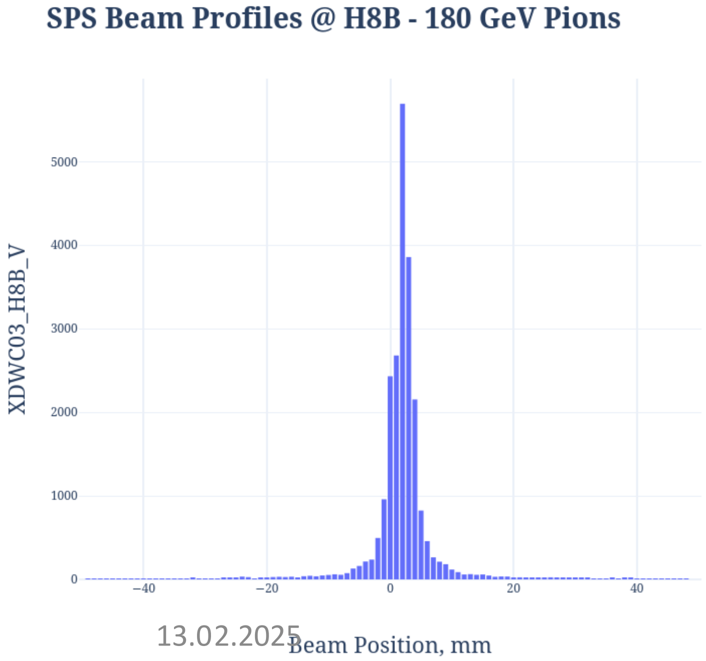


Beam defining counters
Beam defined as 5mm diameter or $10x10mm^2$ according to combination of coincidence of beam counters

DUT: Detector Under Test
- 1.5m long HF-PPP fibers + MCP-PMT/PMT
- 2.5m long HF fiber bundle + MCP-PMT
- 12cm Polymicro fiber bundle + MCP-PMT
- 8cm Polymicro High NA fiber bundle + MCP-PMT
- 12cm Polymicro fiber array(7x7) + MCP-PMT

TRS: Time Reference System
SB1-2: MCP-PMT + Qbar doublets (two $5x5x100mm^3$), 45^o to the beam
TRC: MCP-PMT + Qblock ($12x12x25mm^3$)/UVT Plexi ($12x12x20mm^3$), Head on





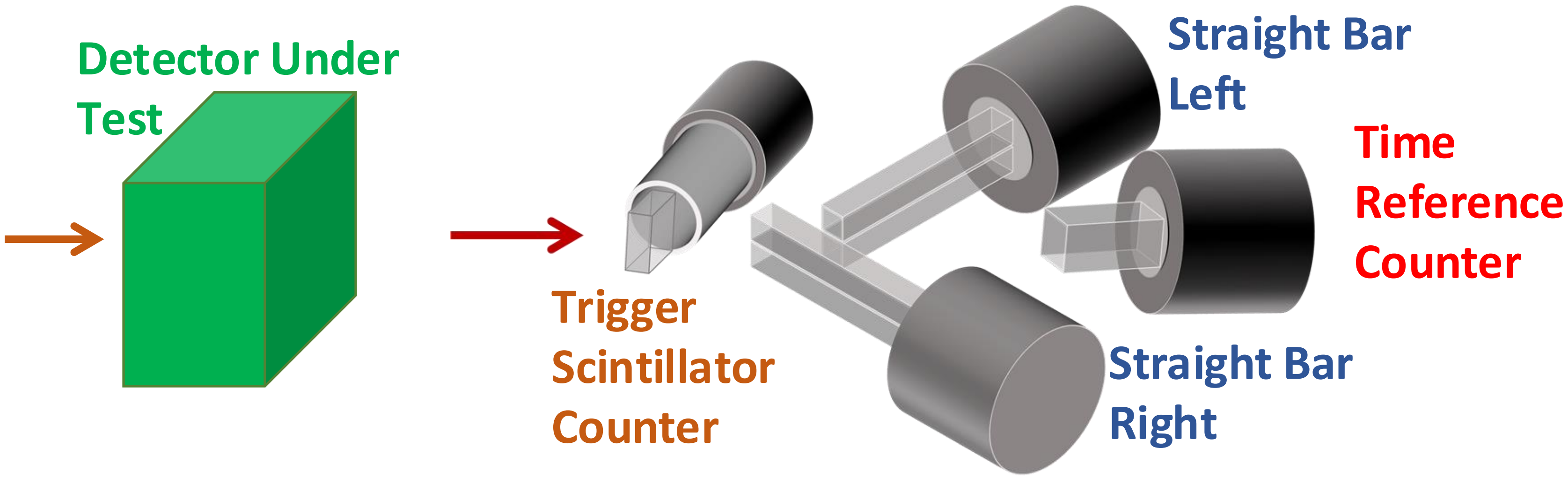
Data Taking Conditions

- 100, 120, 140, and 180 GeV pion beams were available.
- Mainly 180 GeV pion beam was used.
- In total, 57 Runs and 29 Scans were taken.
- More than 61.5 Million events were taken.

- TRS calibrated with the scans.
- Attenuation and time resolution in the different fibres were investigated

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

List of available fibers and dimensions

Module	Type	Core	(µm)	Clad	(µm)	Buffer	(µm)	OH−(ppm)
PPP-HF	FSHA	Silica	(300)	Polymer	(320)	Acrylate	(345)	~700
" "	FIA	Silica	(200)	F-Silica	(240)	Acrylate	(500)	<1
" "	IN	Silica	(300)	F-Silica	(316)	Polyimide	(345)	~1200
HF	FSHA	Silica	(600)	Polymer(?)	(630)	Acrylate	(800)	~500
200m roll	JTFLH	Silica	(600)	Polymer(?)	(630)	Acrylate	(950)	~???
High NA	FSU	Silica	(330)	AF(Teflon)	(350)	???	(400)	~???

For PPP-HF module:

FSHA- and FIA-type manufactured by Polymicro Inc. (USA)

IN-type fibers manufactured by INFOS (Russia)

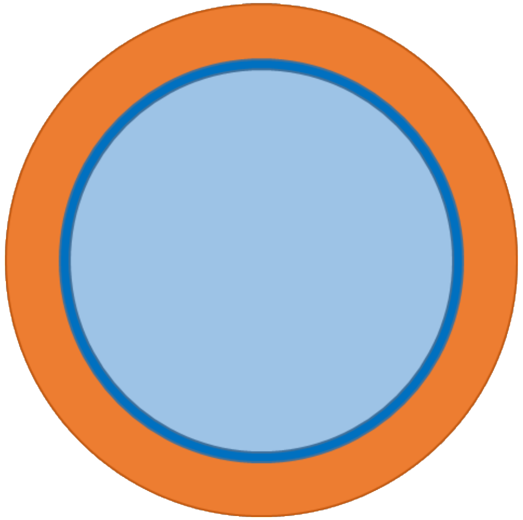
For HF modules:

FSHA-type manufactured by Polymicro Inc. (USA)

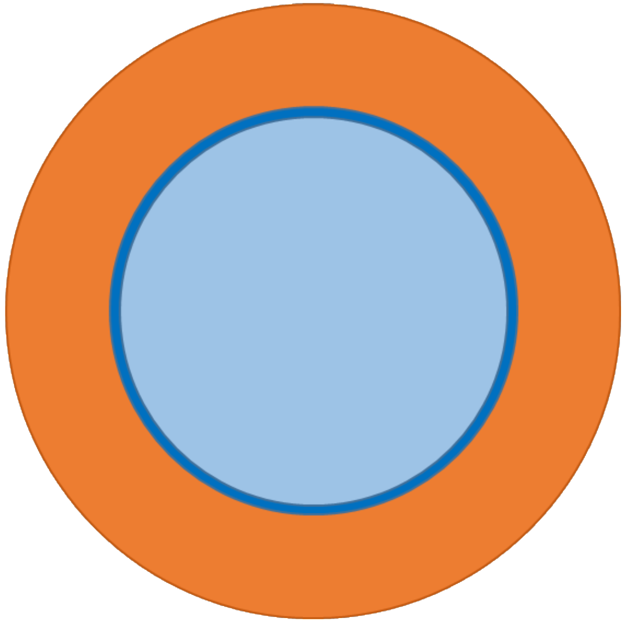
We are also testing plastic clear fibers' bundles (from Kuraray)

Assemblies of fused silica bars and rods (from HERAEUS) will be tested soon

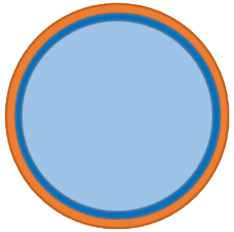
Polymicro (MOLEX) Fibers tested



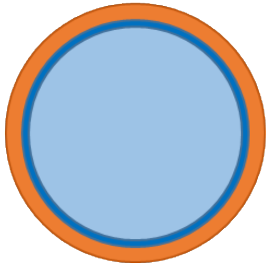
HF : FSHA600630800 (OH- 500ppm)



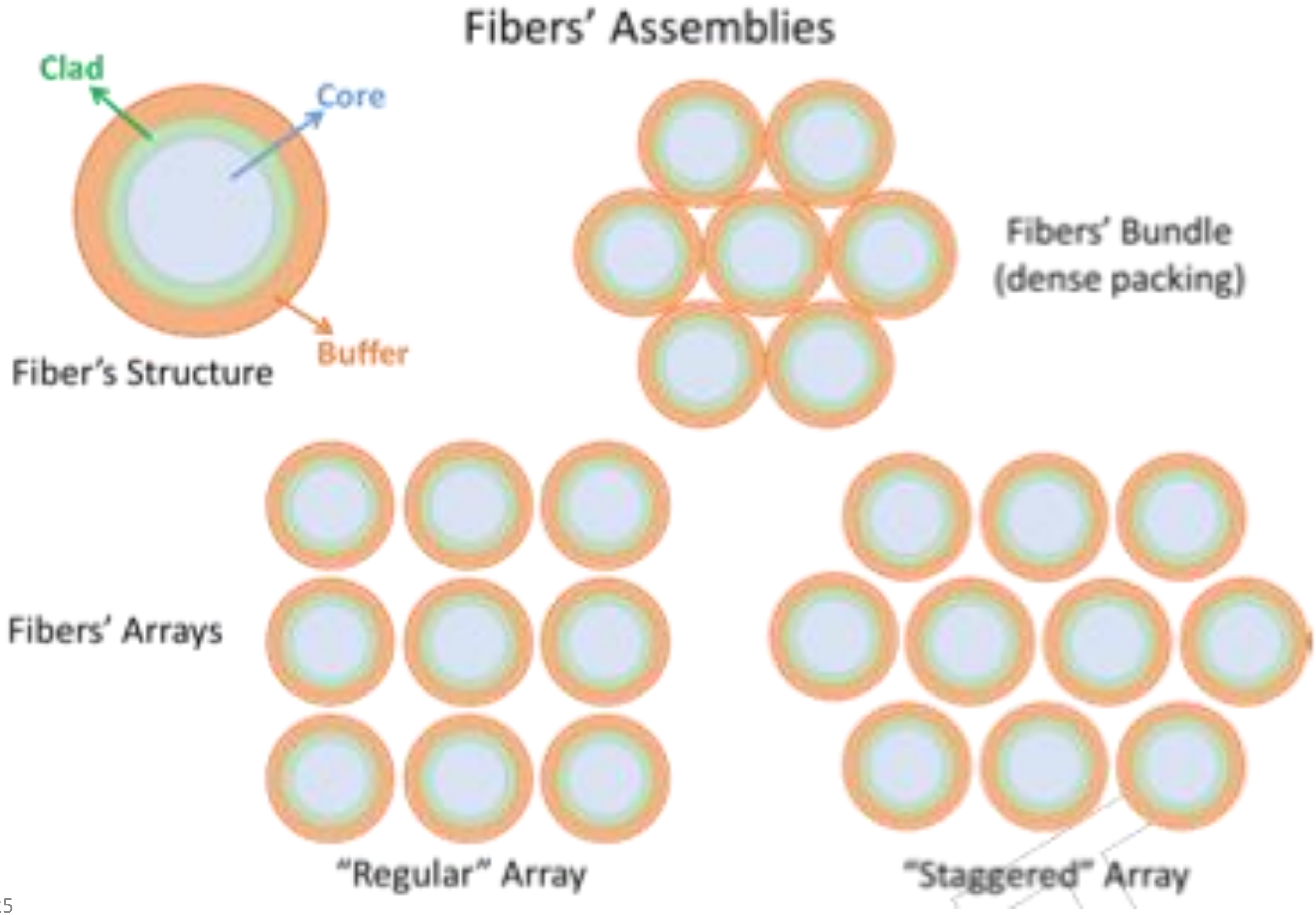
JTFLH600630950 (OH- ??? ppm)
(≈ 200m spool)



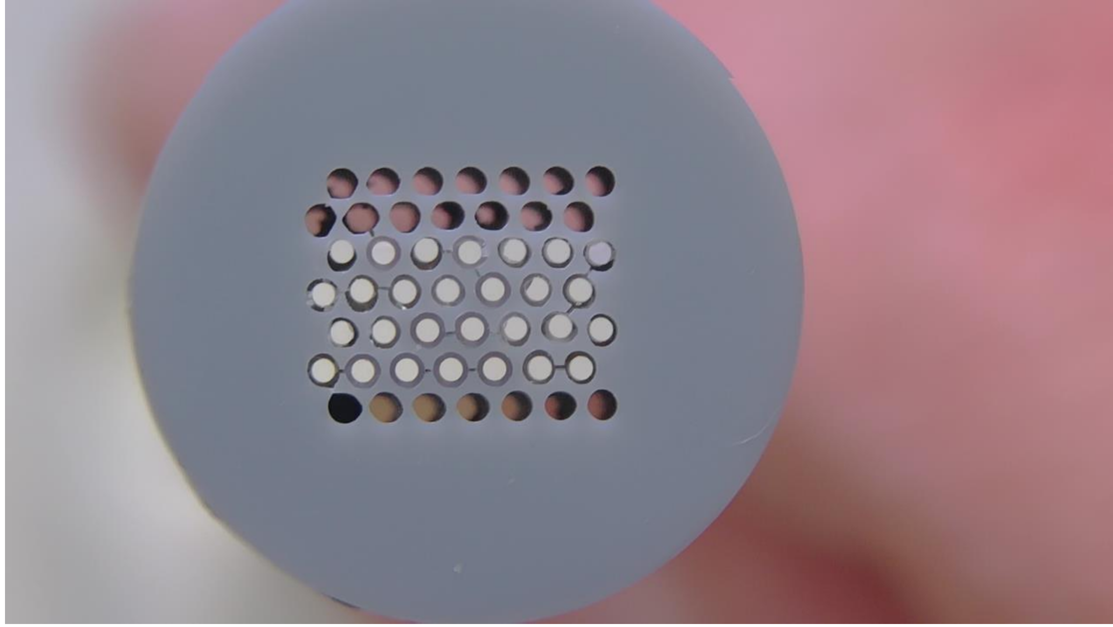
PPP-HF : FSHA300320345 (OH- 700ppm)



High N-A : FSU330350400 (OH- ???ppm)
(≈3m)

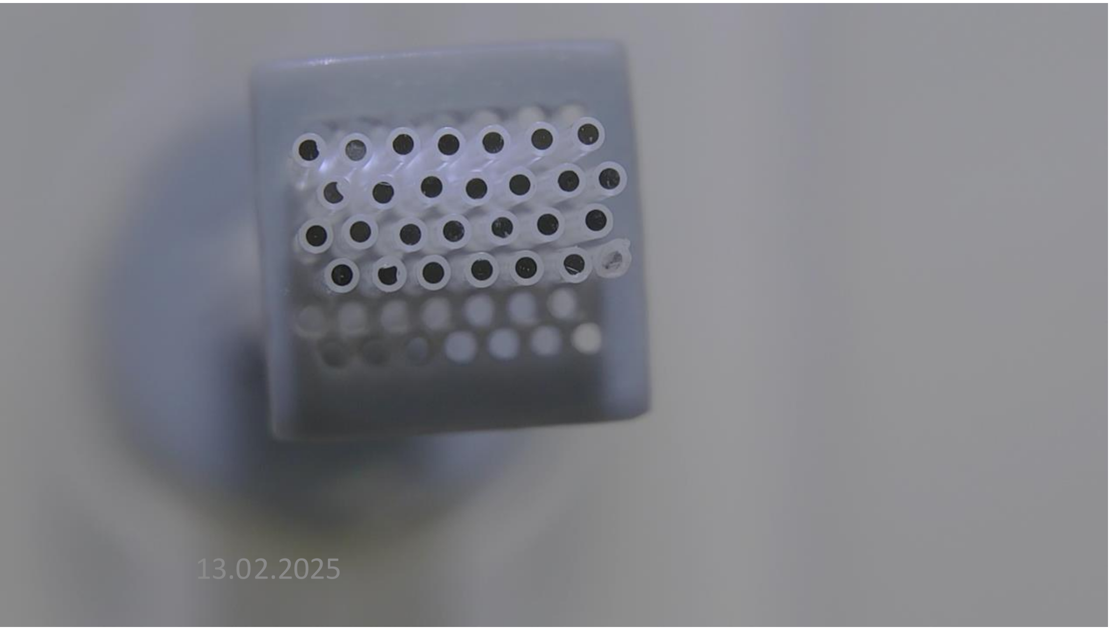

Fibers' Assemblies
Clad
Core
Buffer
Fiber's Structure
Fibers' Bundle
(dense packing)
Fibers' Arrays
"Regular" Array
"Staggered" Array

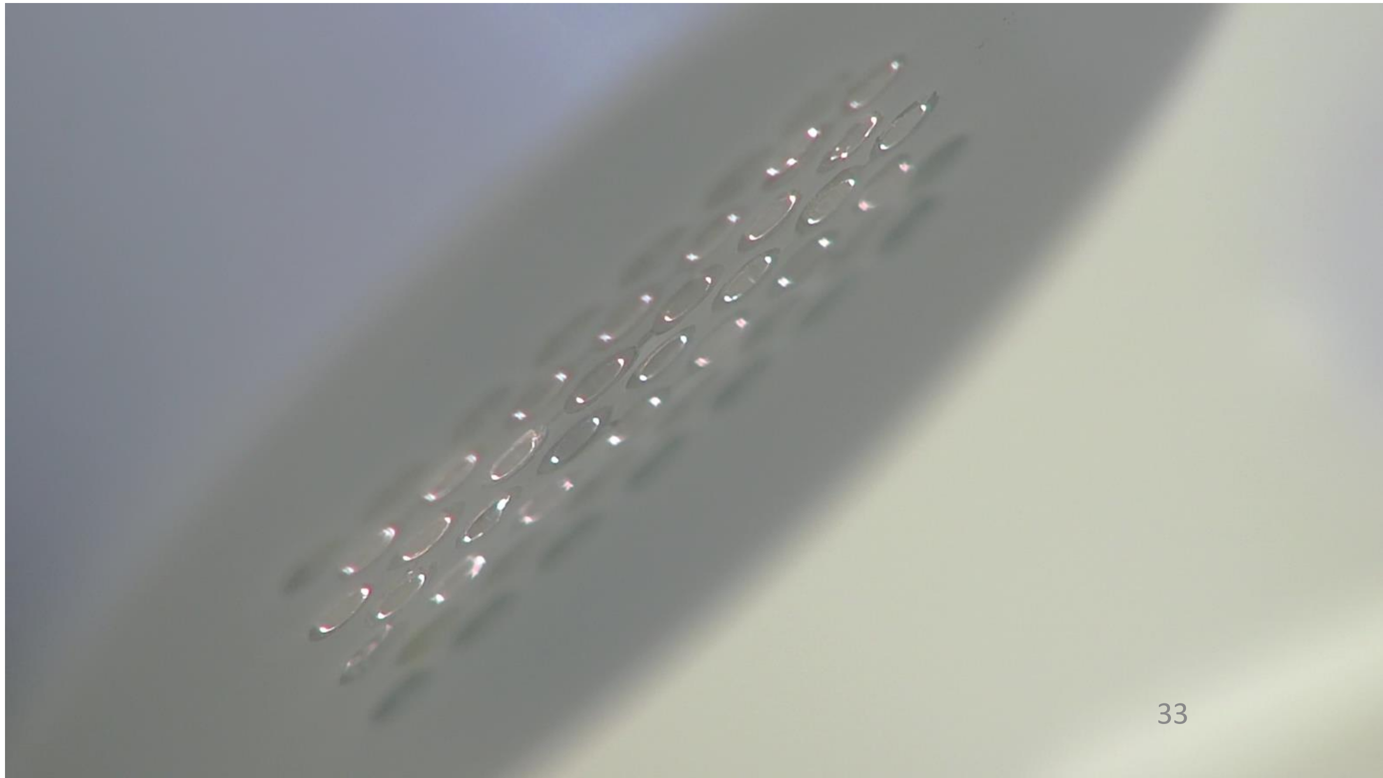
Optical Inspection

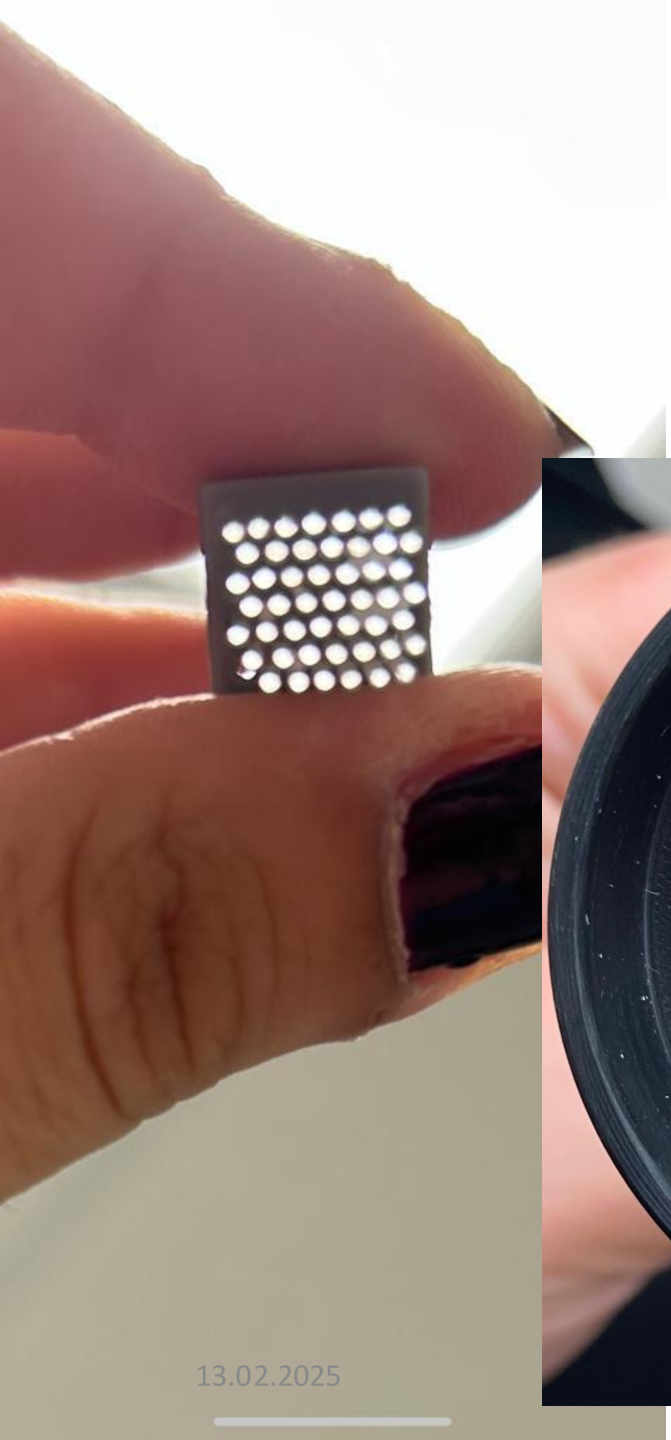


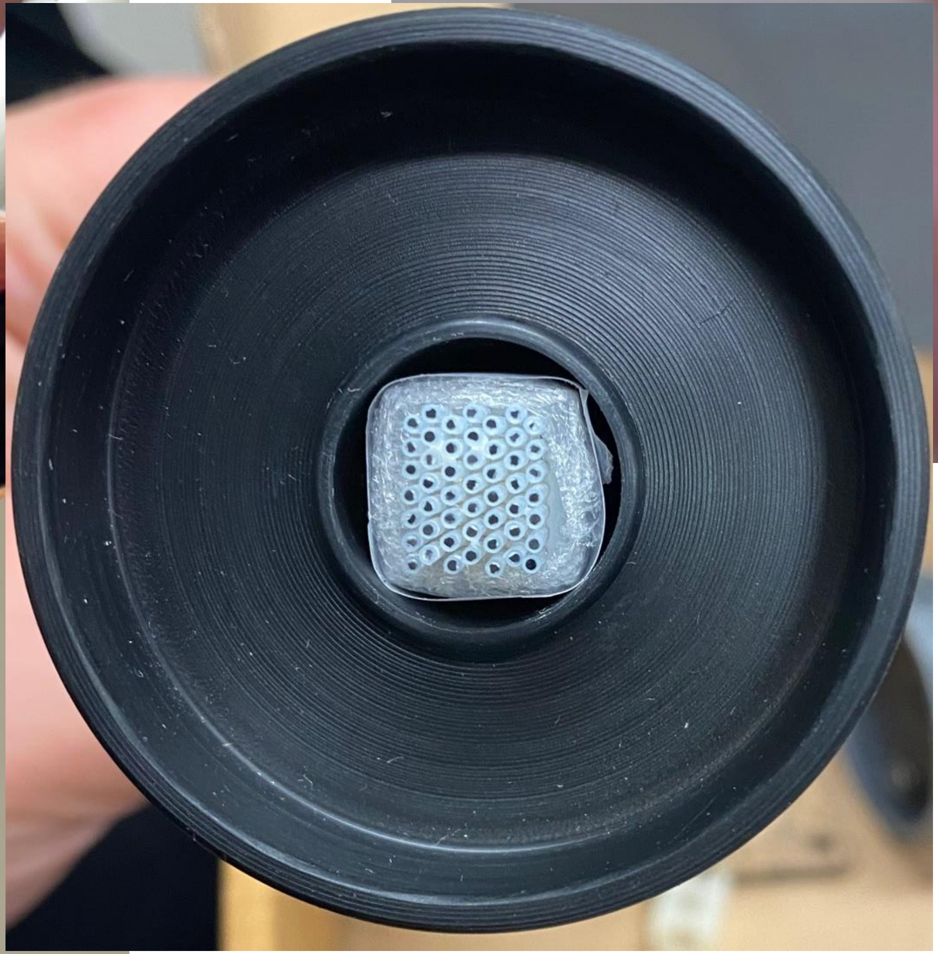
Polymicro JTFLH600630950

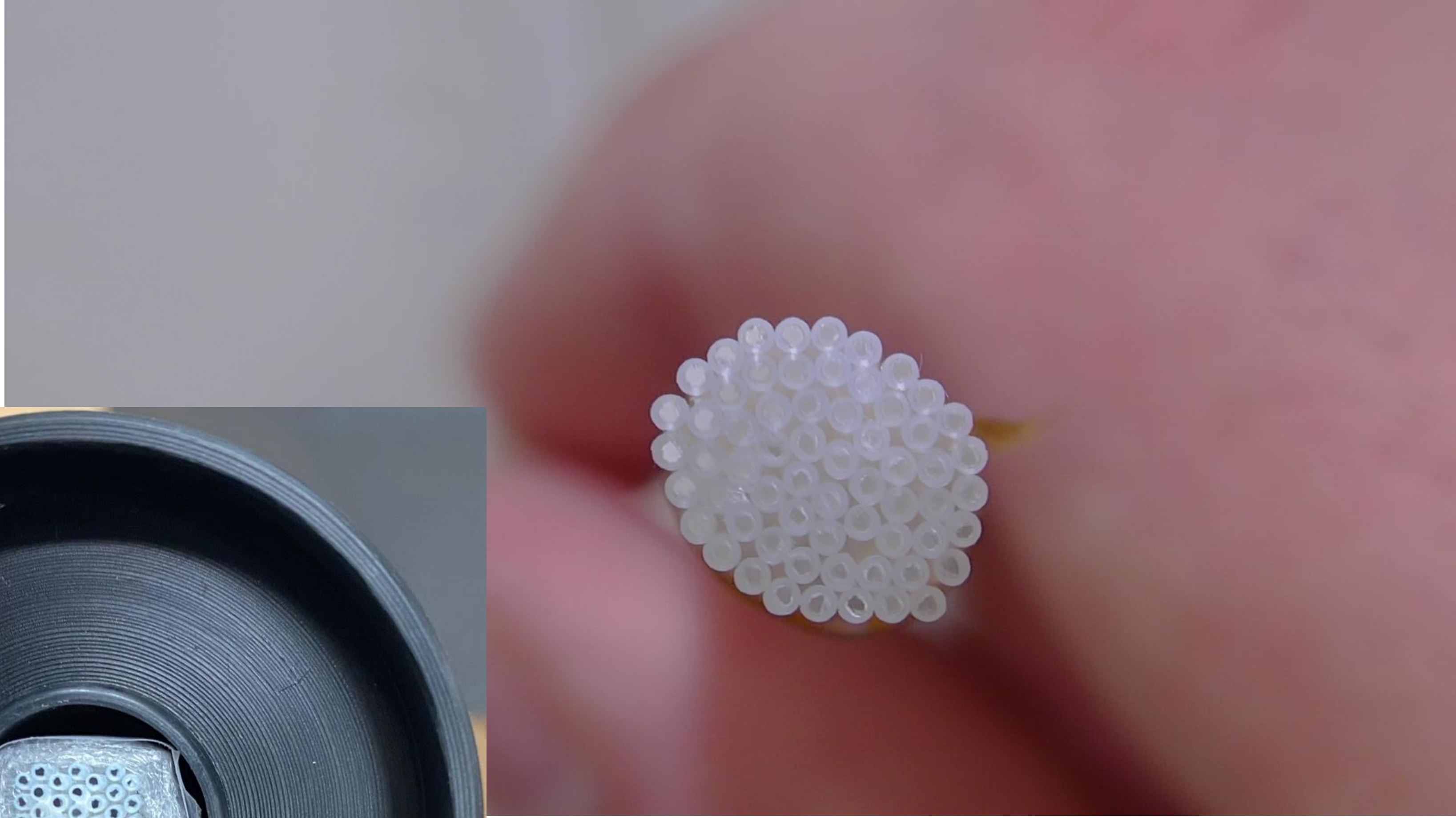
- Thanks to **R. Stefanovitch**, fibers were cut by 12 cm
- Thanks to **Buse Duran**, all fibers were ***polished by hand***
- brought together in different configurations
- Array or Bundle









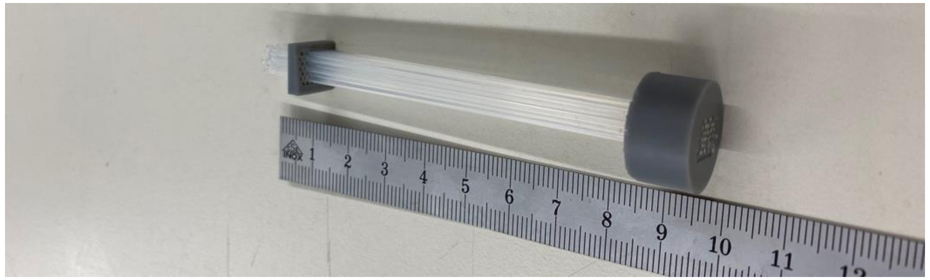


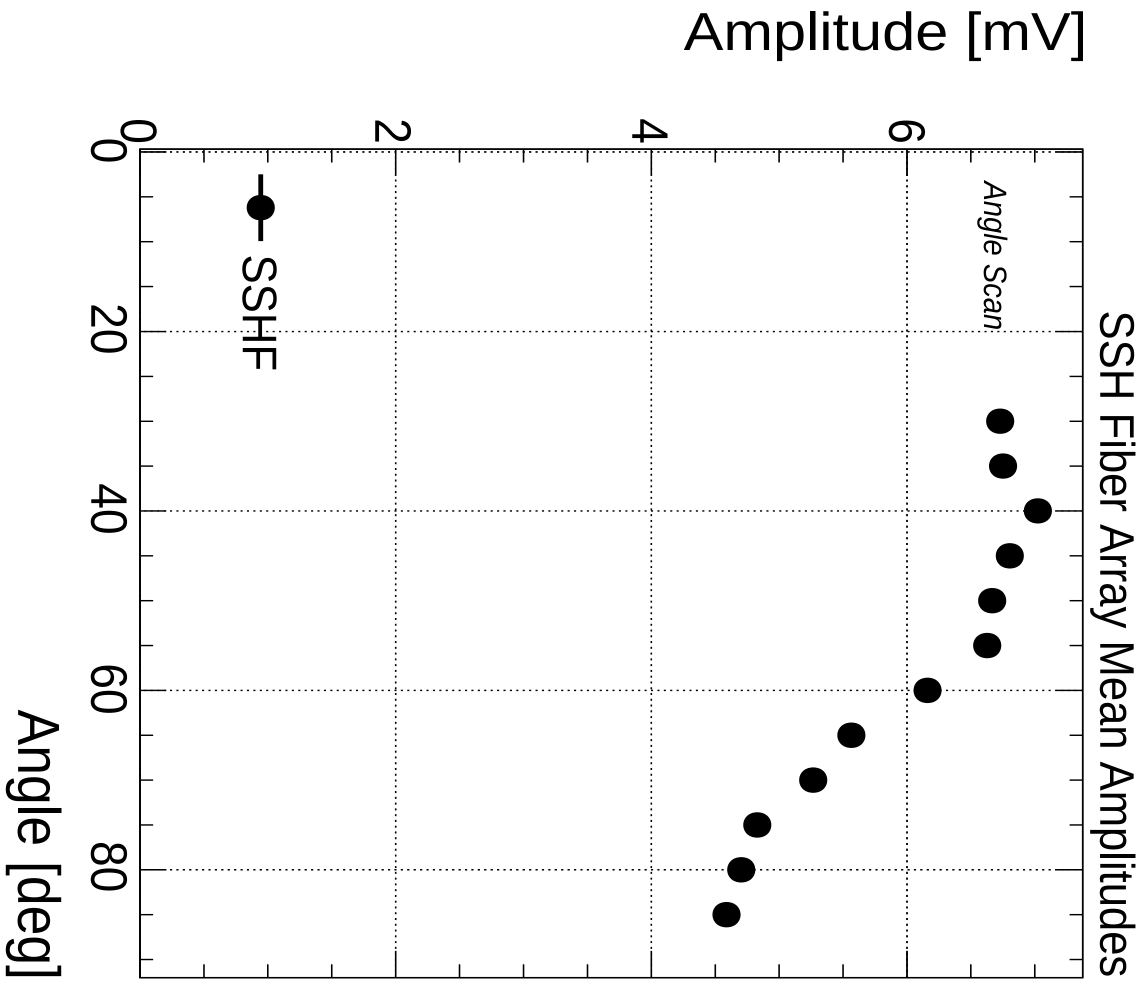
7x7 12cm Polymicro Fiber (SSHF- Array)
JTFLH600630950

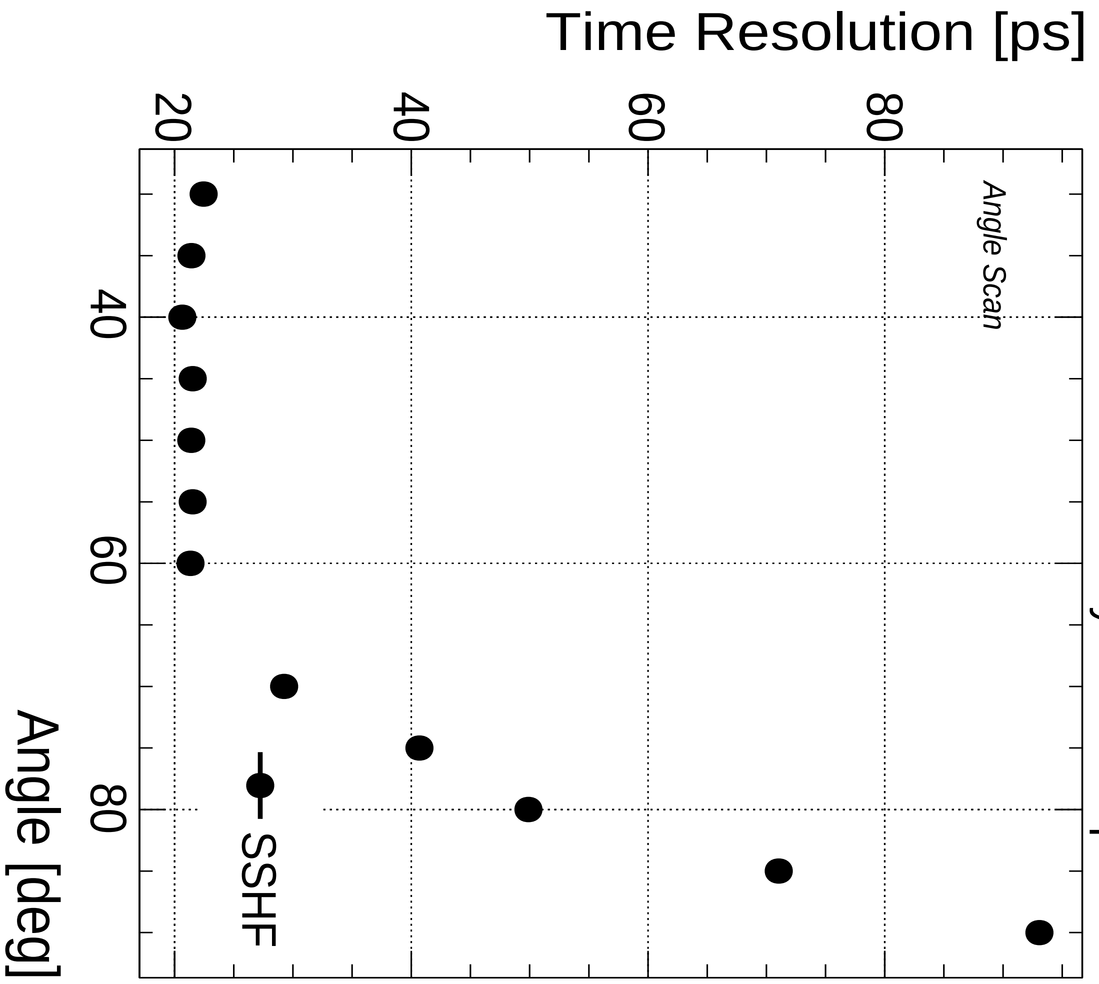
Conditions for 12th Scan;

- 7x7 12cm Poly-Micro Fiber with Si-pad
- SSHF- Array
- Fiber stands 5.5 cm and 7 in a row.

Angle Scan

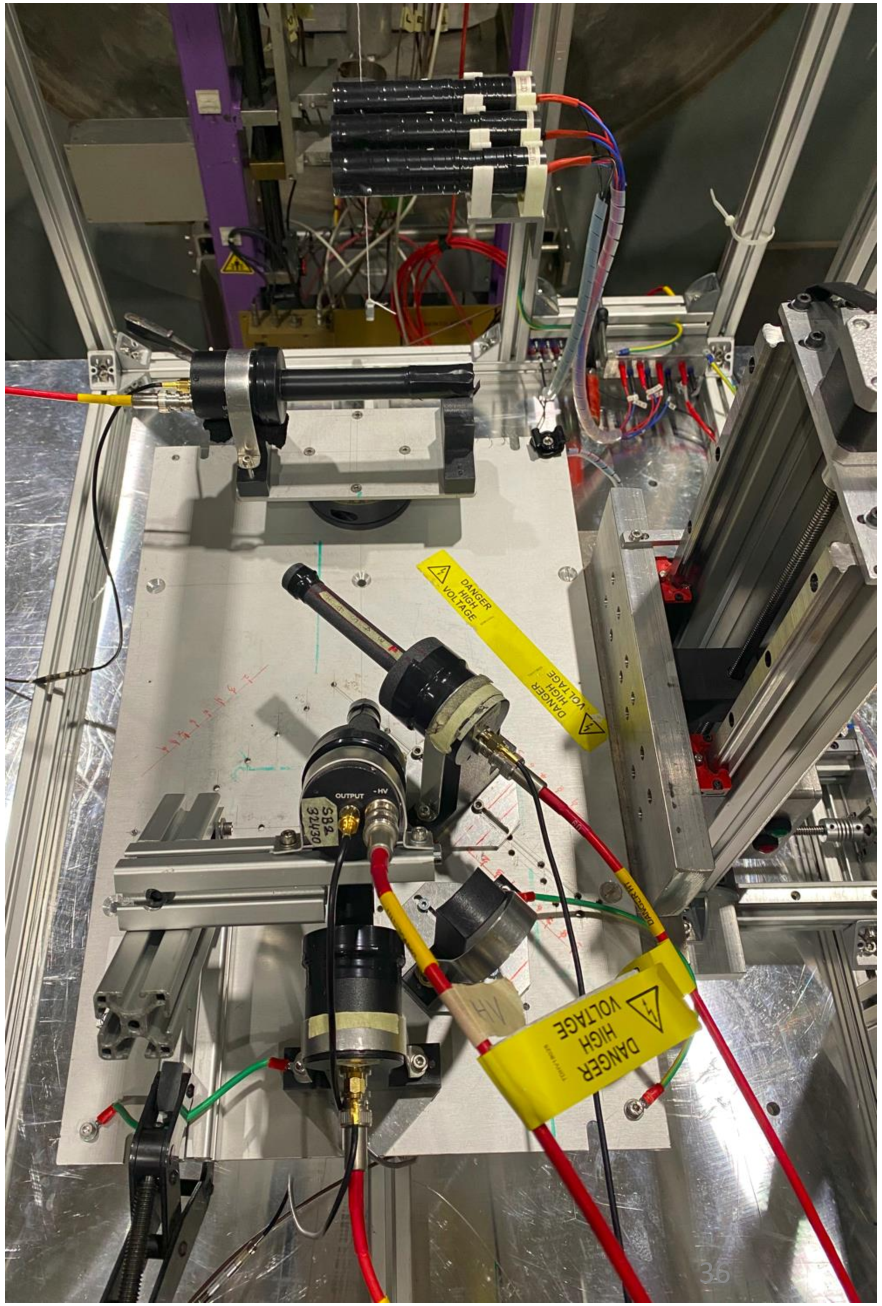






12cm Polymicro Fiber (SSHF- Bundle)

JTFLH600630950

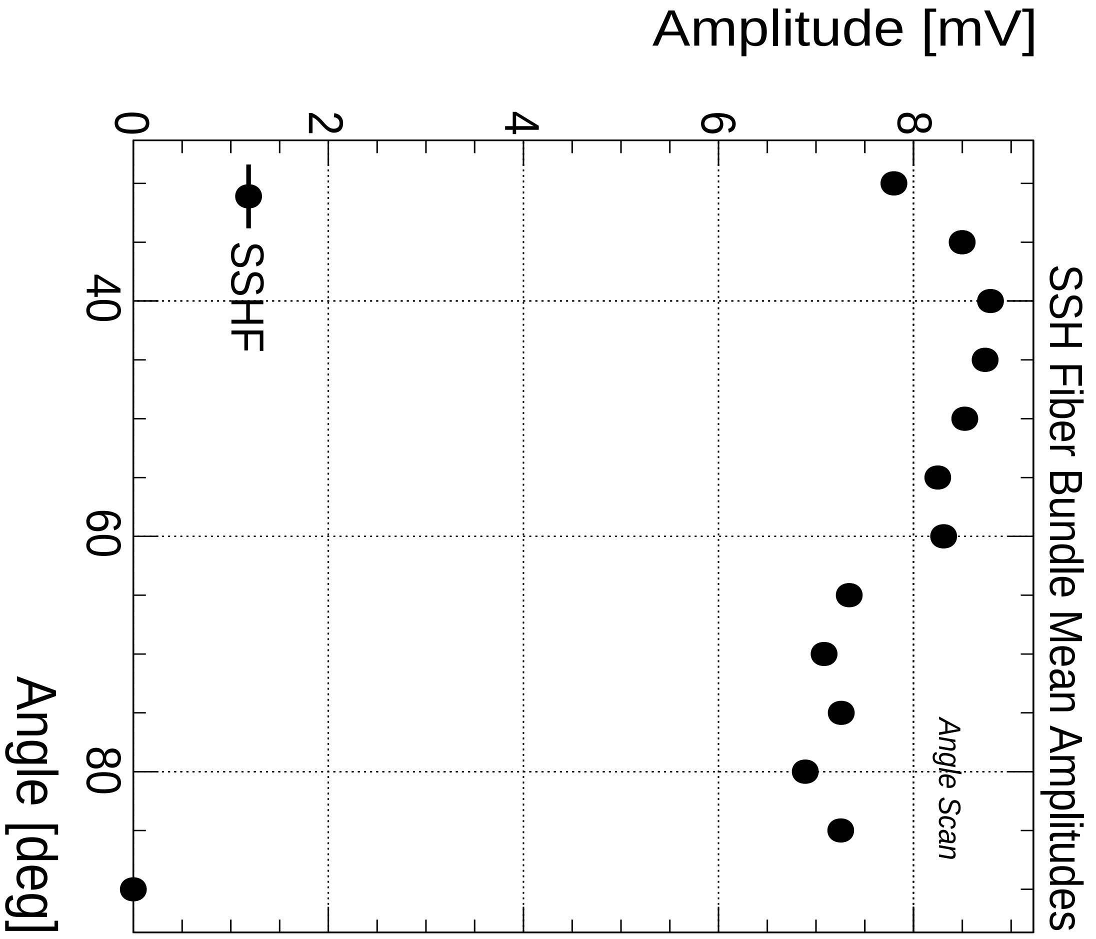


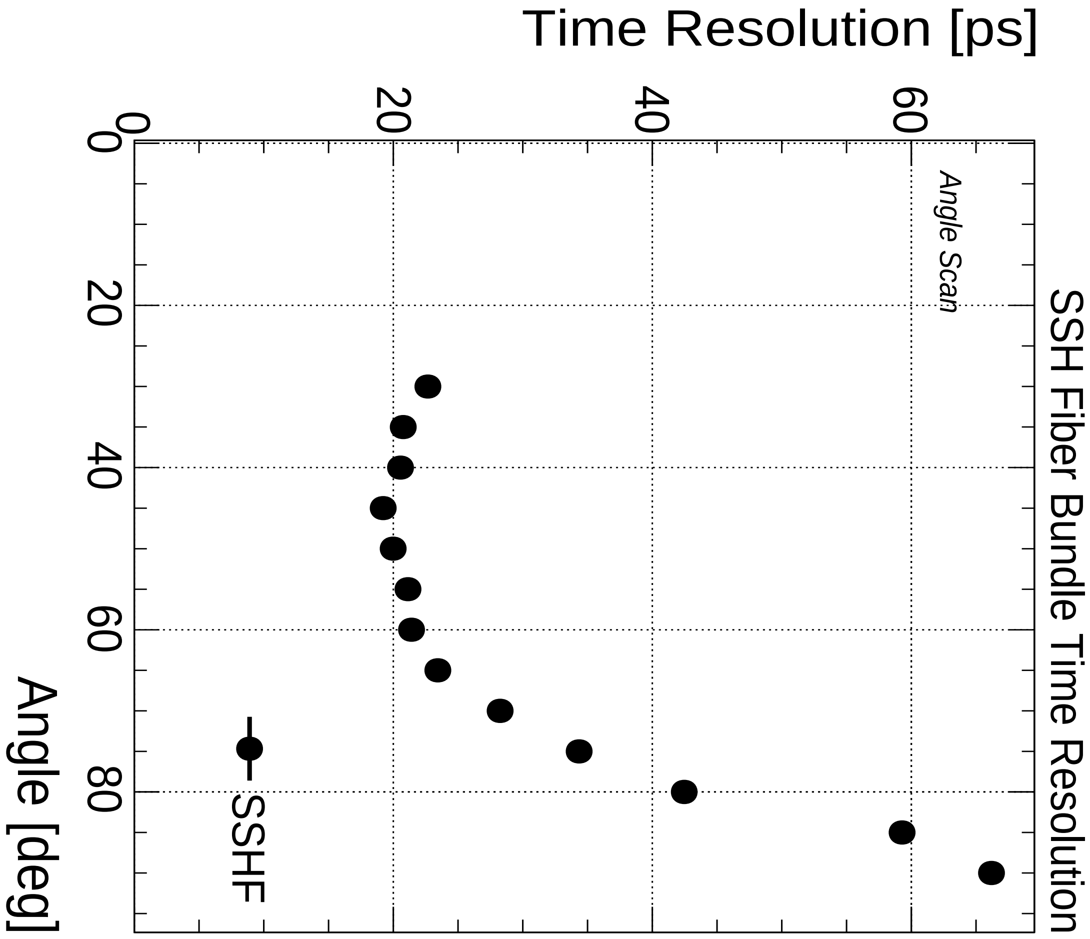
Angle Scan

SSHF- Bundle

- Fibers are more compact and more fibers were broth together, so the amplitude is higher than the fiber array

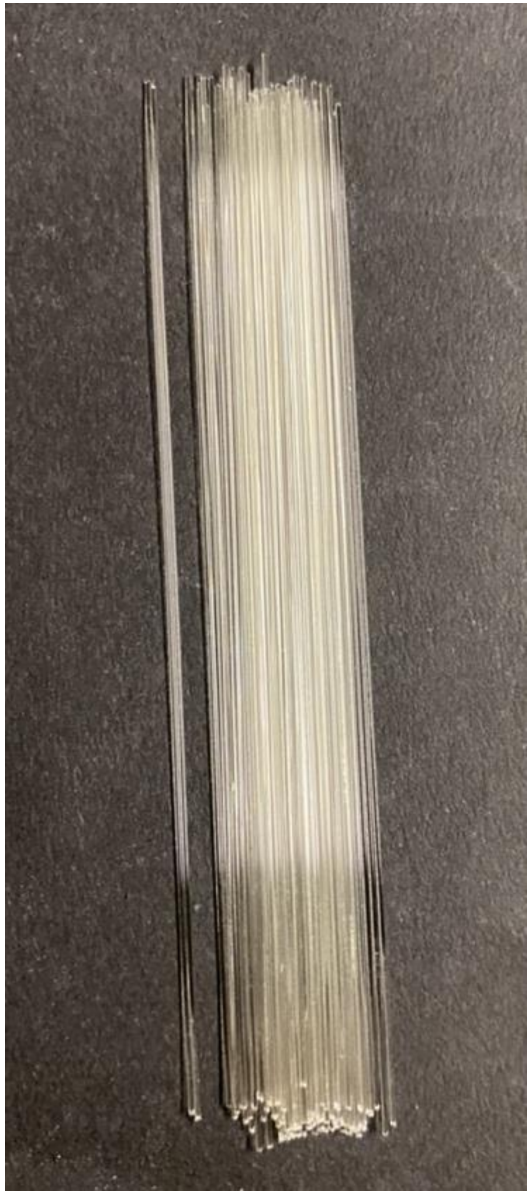
For both cases (fiber array or bundle), 90degree configuration could not be read out because of the critical angle. Created Cherenkov photons go out from the fiber.





High NA- Bundle

- 74 x 8 cm HNA fiber bundle
- Using same HV and MCP, amplitudes are better than other fibers. Even though effective thickness slightly small than the other types!!!

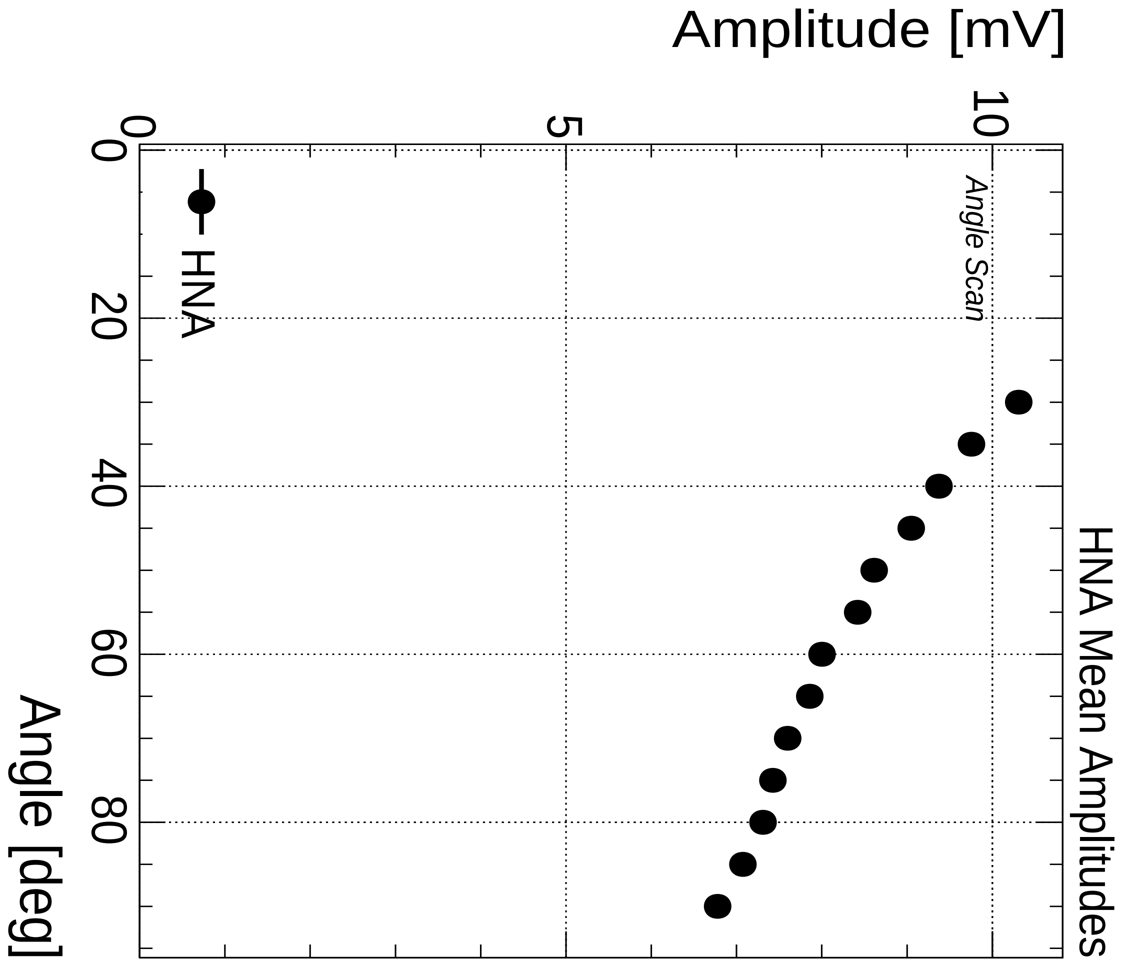


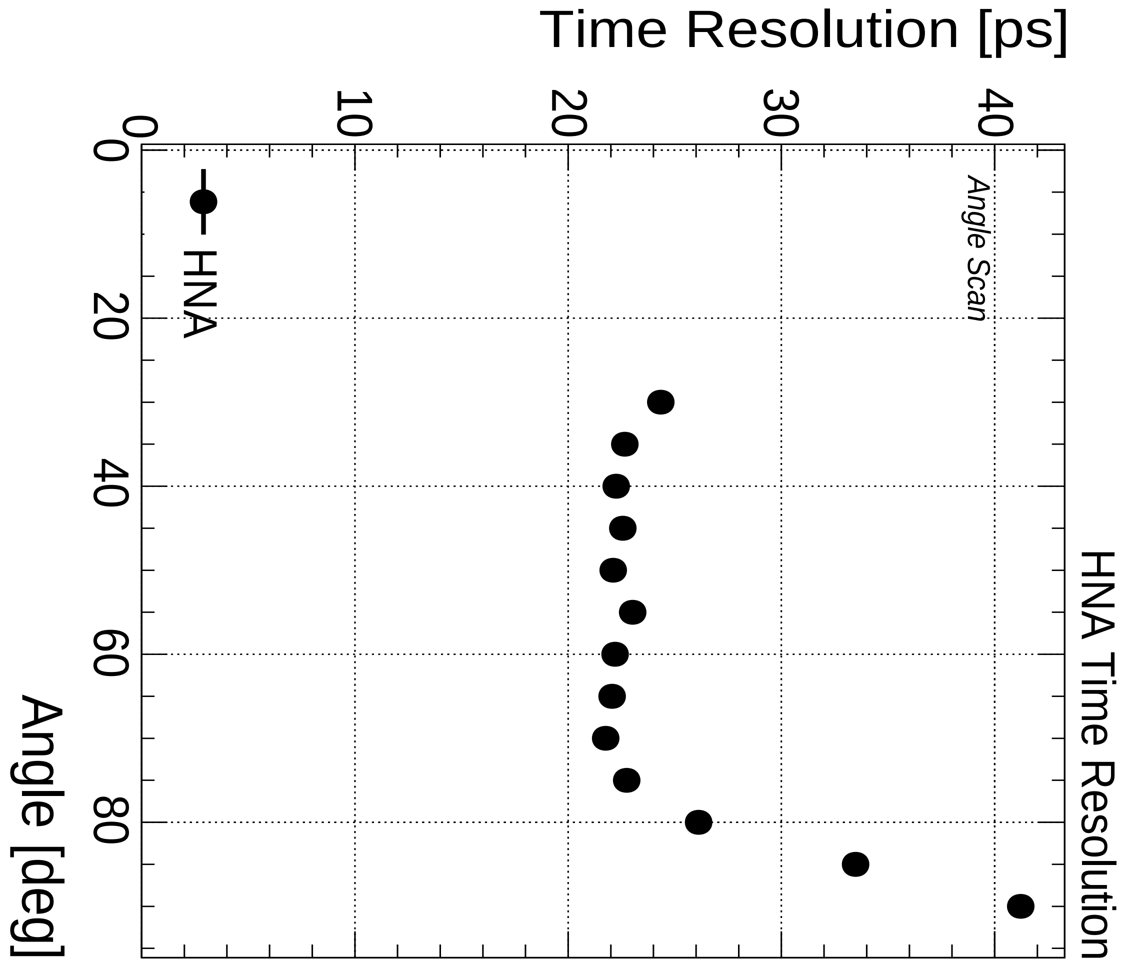
High NA- Bundle

Angle Scan

- 74 x 8 cm HNA fiber bundle
- Using same HV and MCP, amplitudes are better than other fibers. Even though effective thickness slightly small than the other types!!!

Even 90-degree configuration gives very good results!!!!

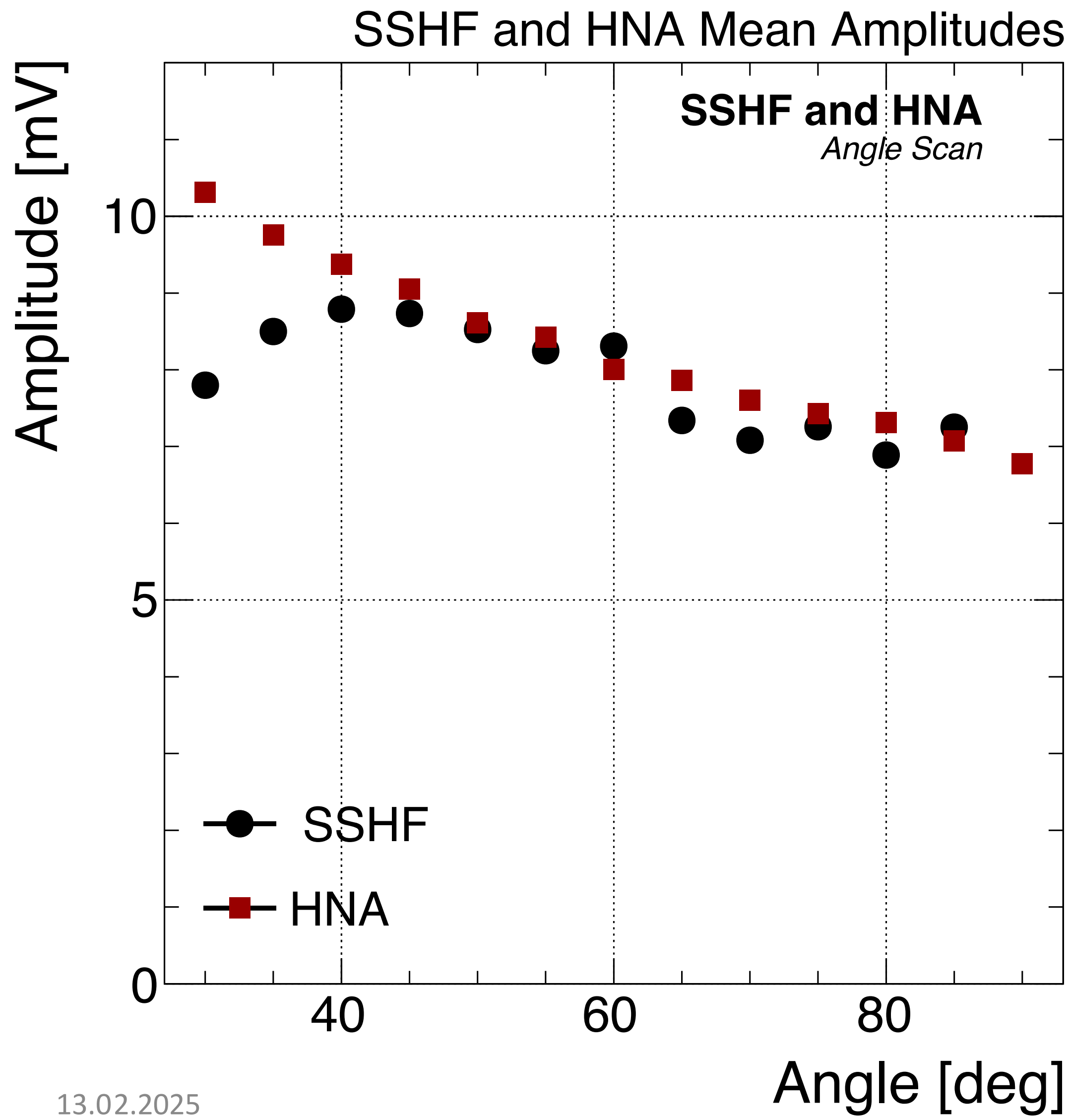


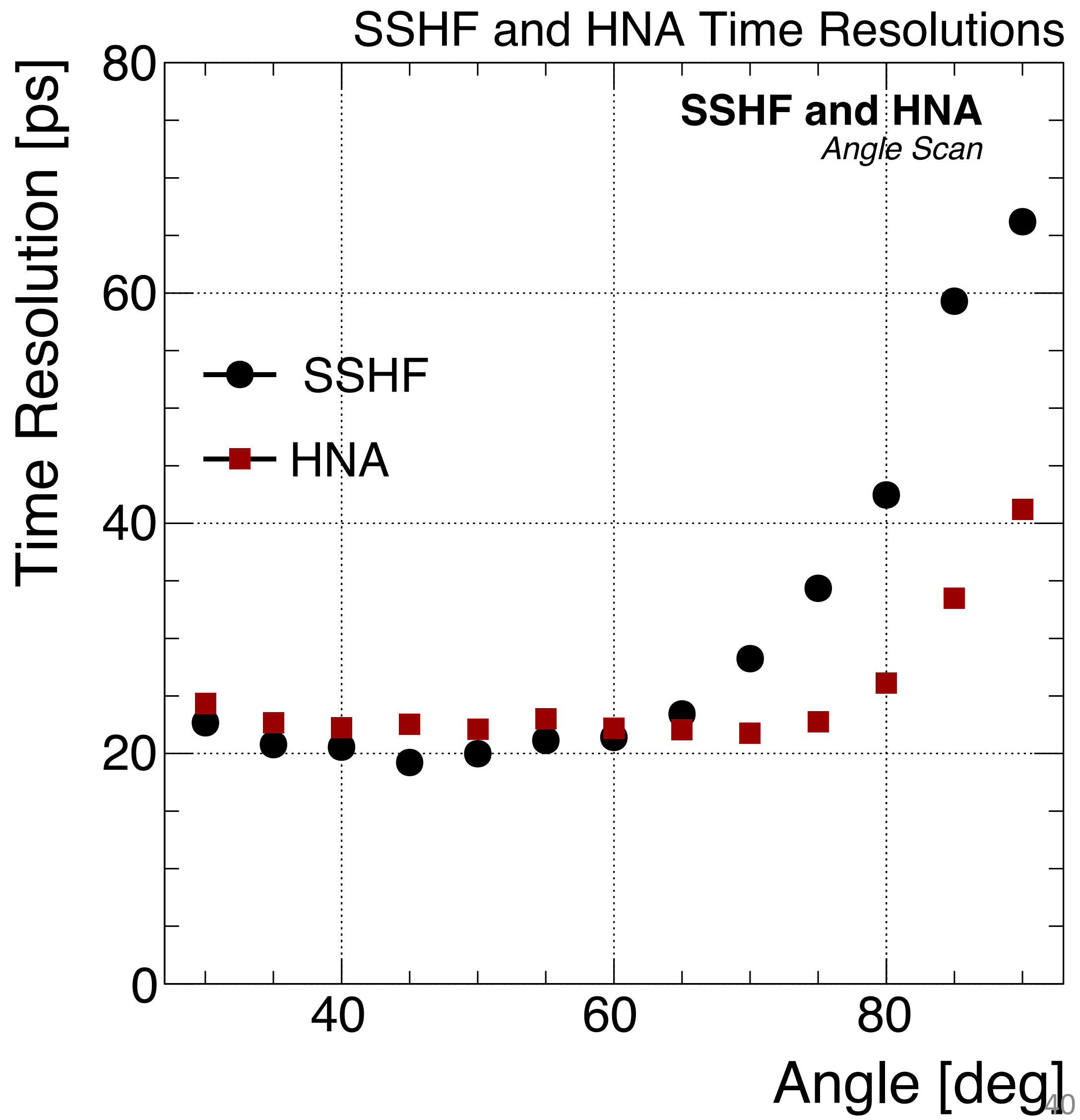


Short Segment HF like Fiber (SSHF) Bundle
JTFLH600630950

vs

High NA Fiber Bundle
FSU330350400

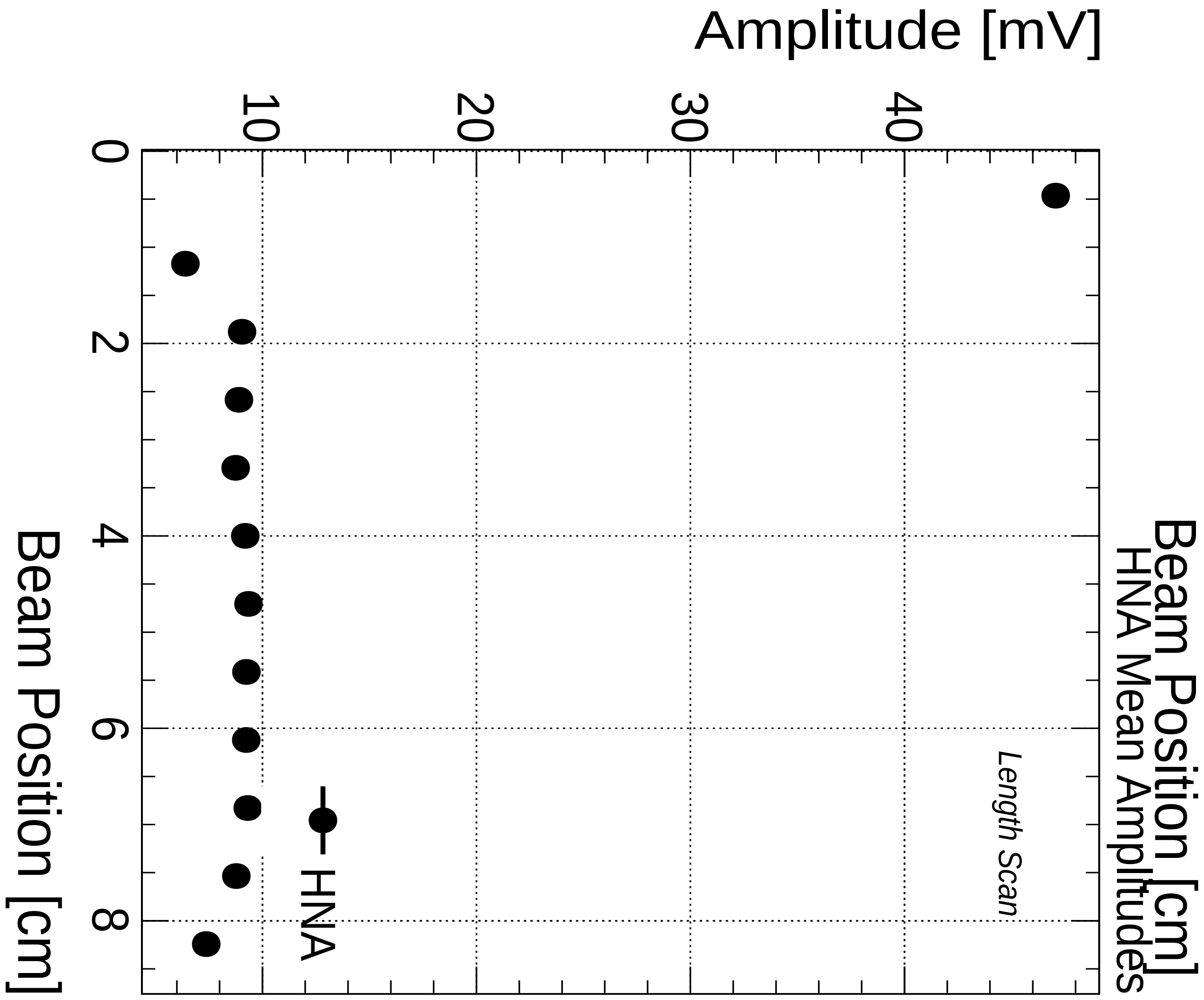


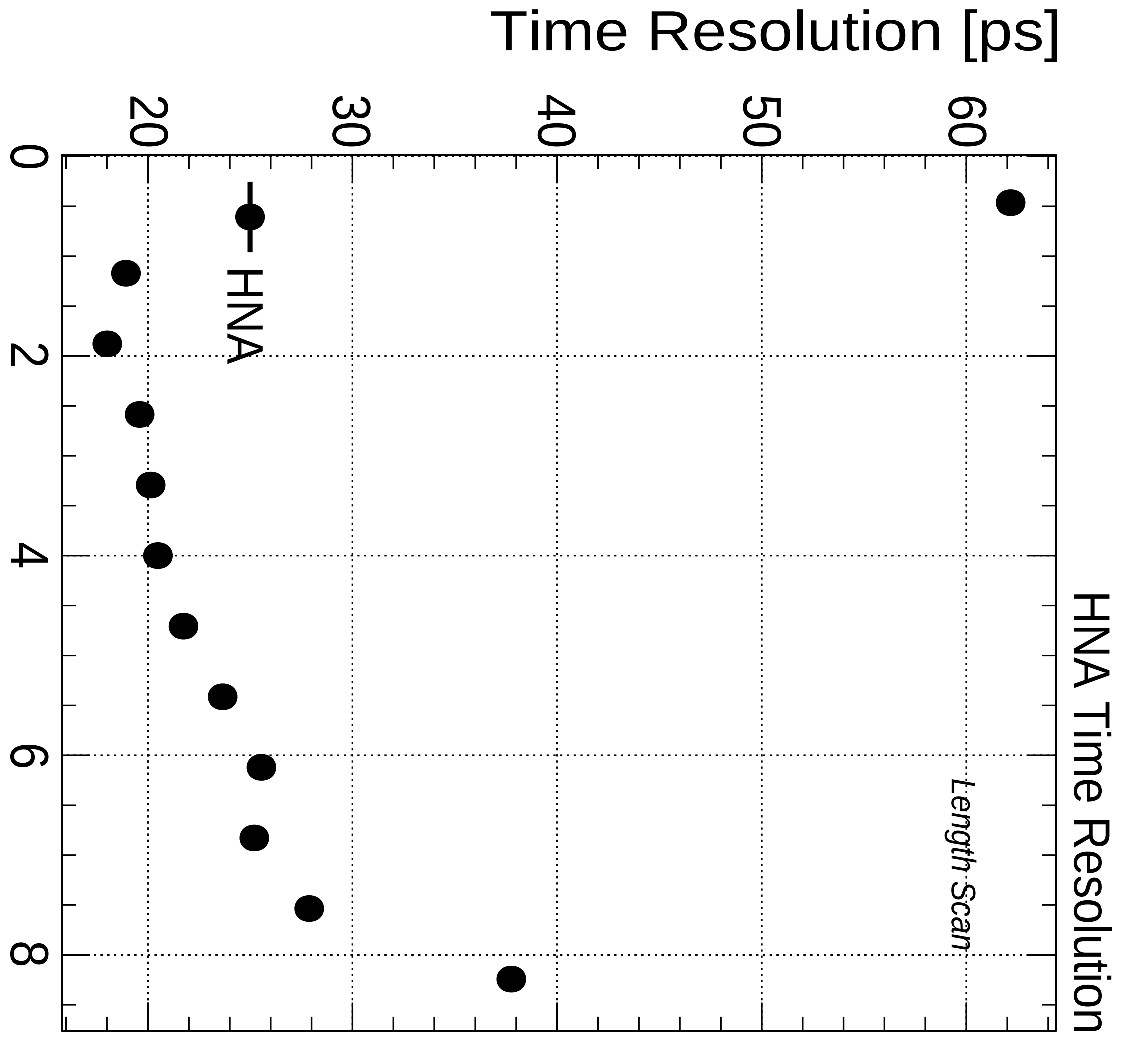


High NA- Bundle

- 74 x 8 cm HNA fiber bundle
- **Length Scan at 45 degree**

Amplitude of the HNA fibres is quite stable along the full-length (8cm)
And time resolution varies between 20 -30 ps



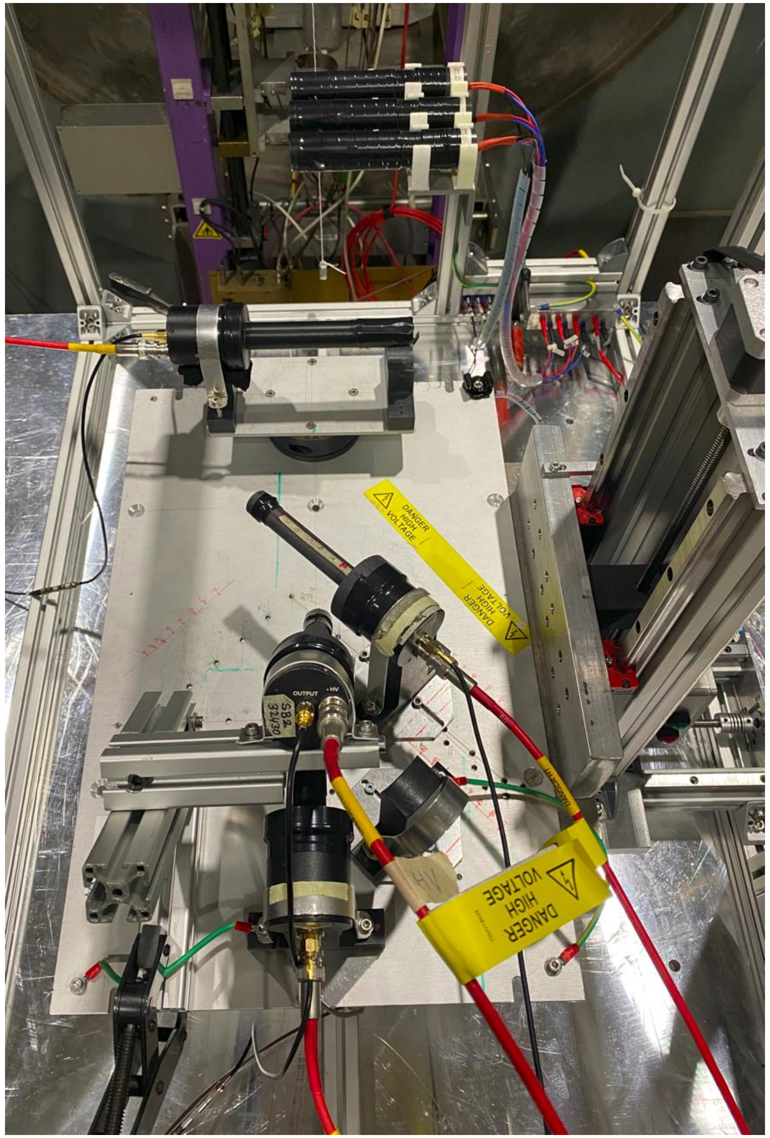


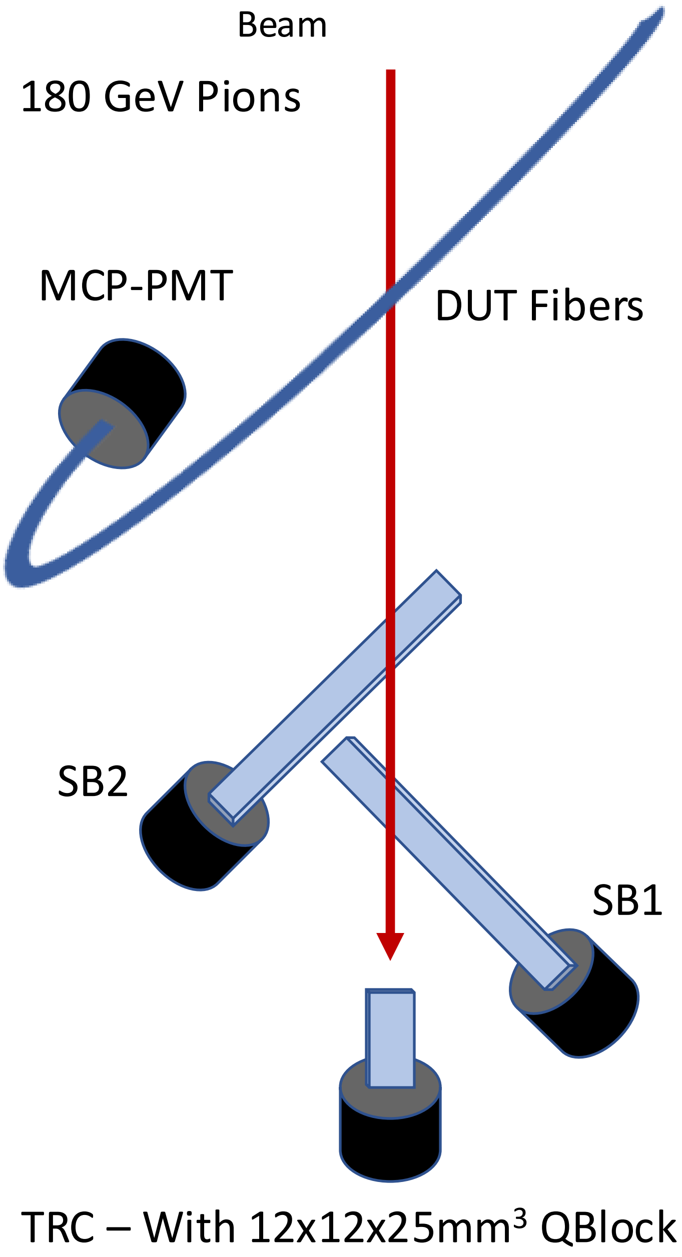
DUT Setup

Timing measurement was performed using both short and long fibers for different distances and angles to the photodetector.

For the High NA fiber time resolution, we obtain ~26 ps. (Next page)

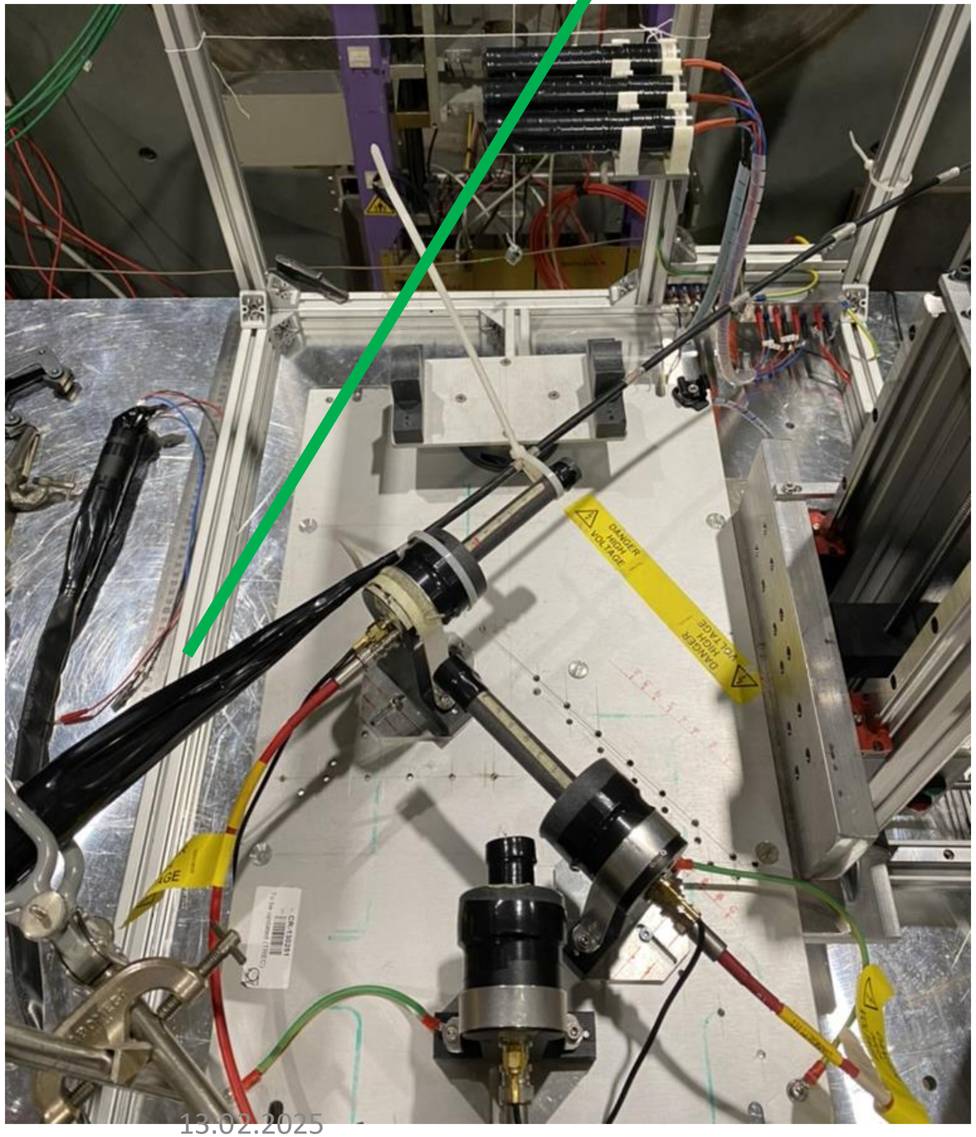
Analysis still on going.





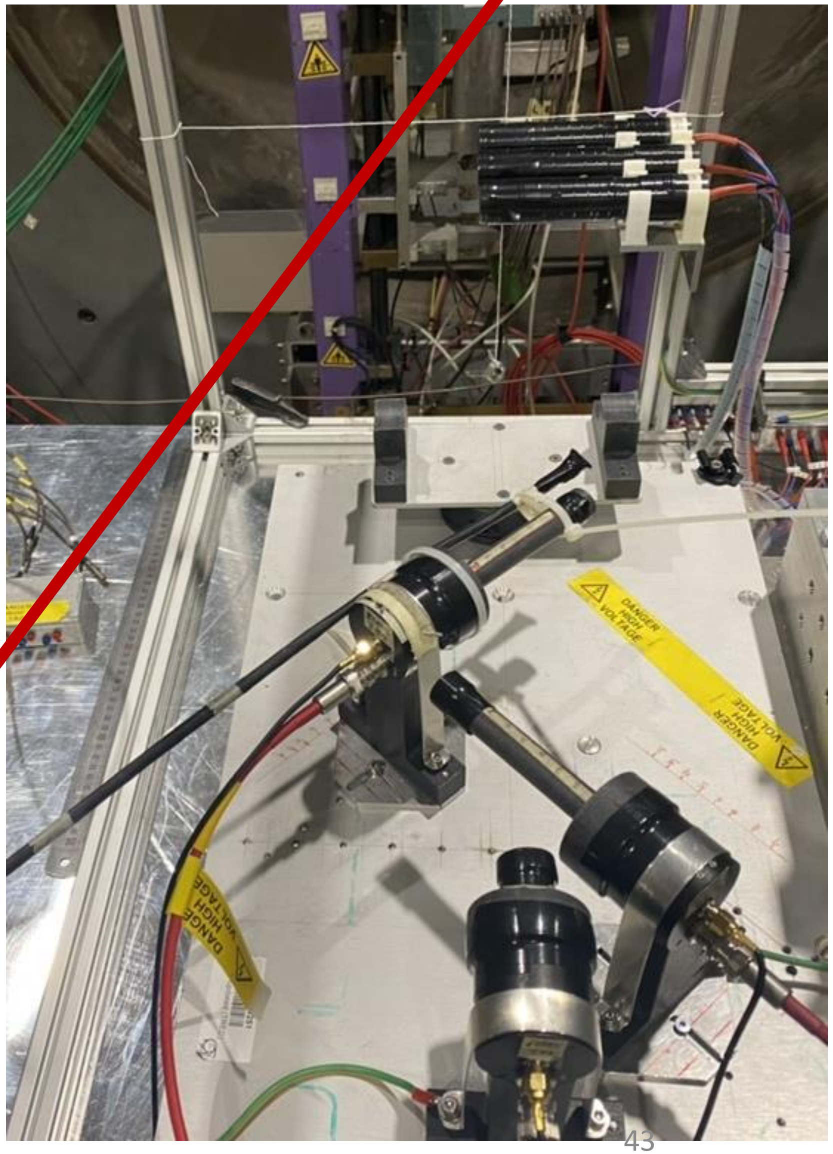
PPP (HF PreProduction Prototype) Fibre bundle

With Hamamatsu R7525



1.5 m long PPP fibers attached to the different PMTs

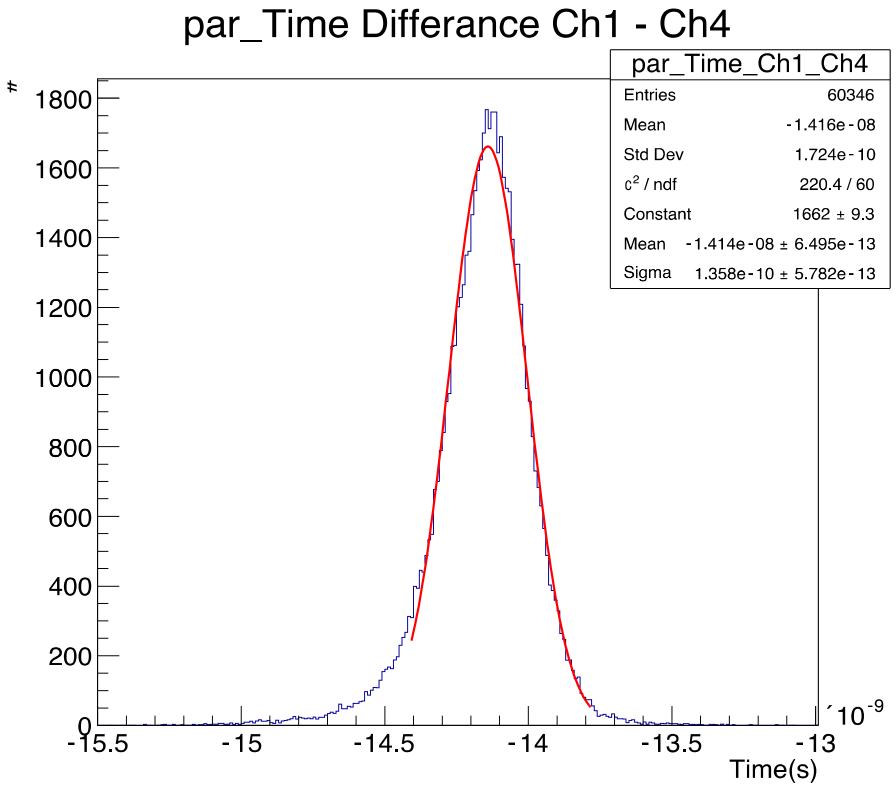
With MCP-PMT



Time resolution of HF-PPP fiber 20 cm away from the photodetector

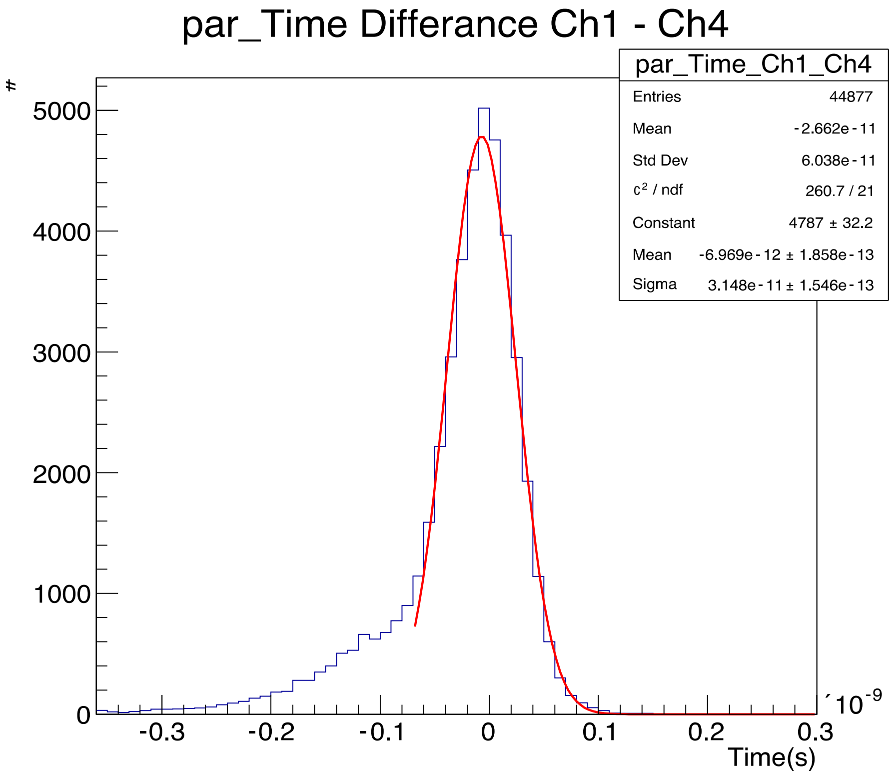
HF-PPP + R7525

135.8 ps



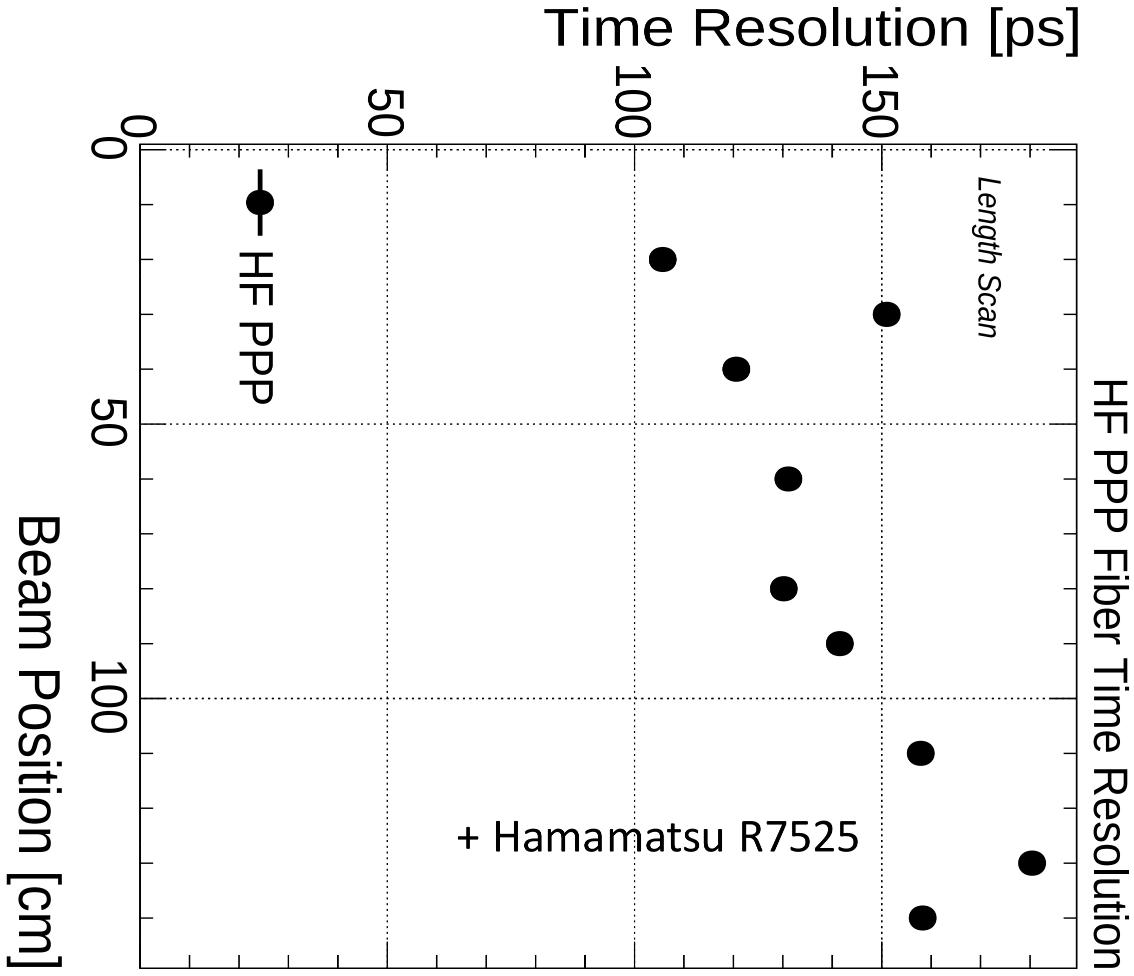
HF-PPP + MCP-PMT

31.48 ps

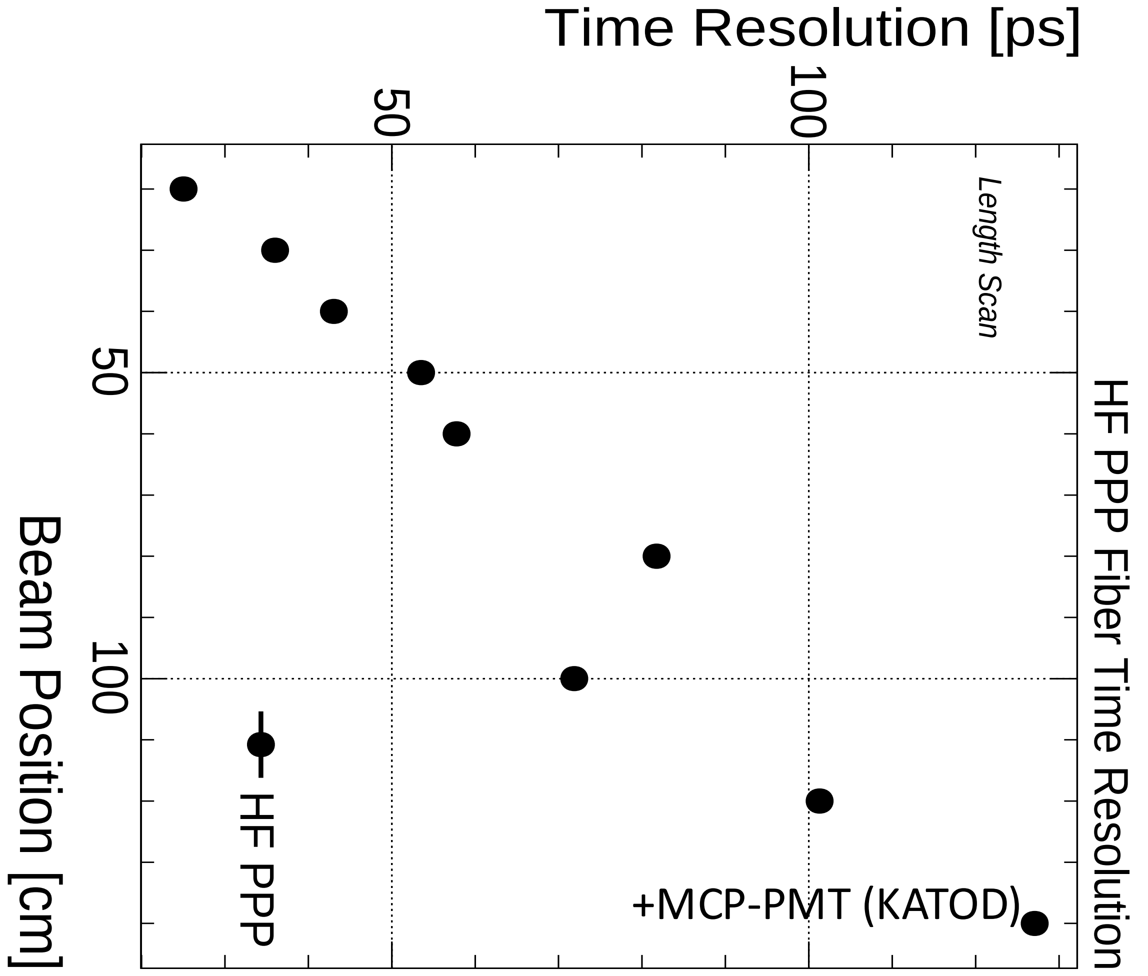


The time resolution of HF-PPP fiber along 1.5 m with different PMTs

Hamamatsu
R7525



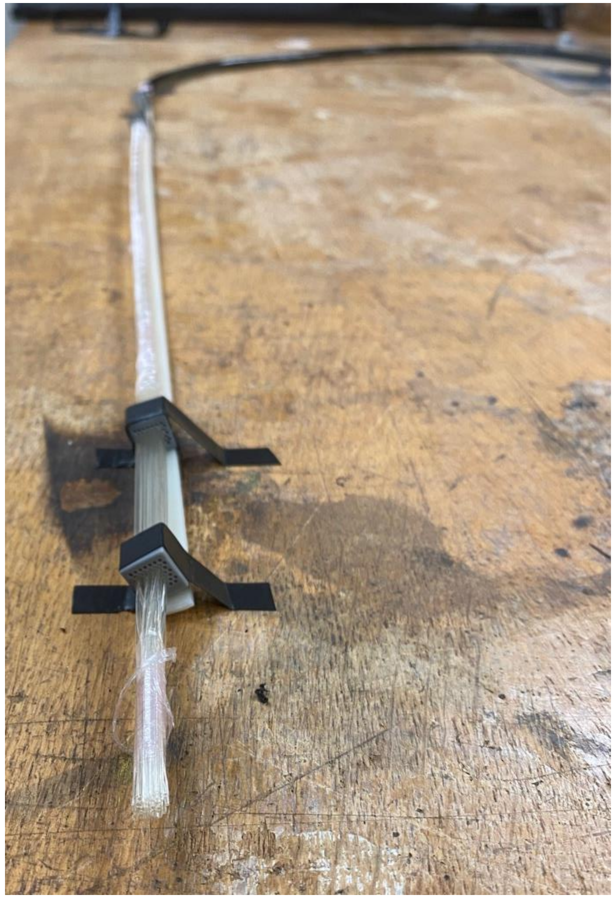
KATOD UFK-5G-2D
MCP-PMT

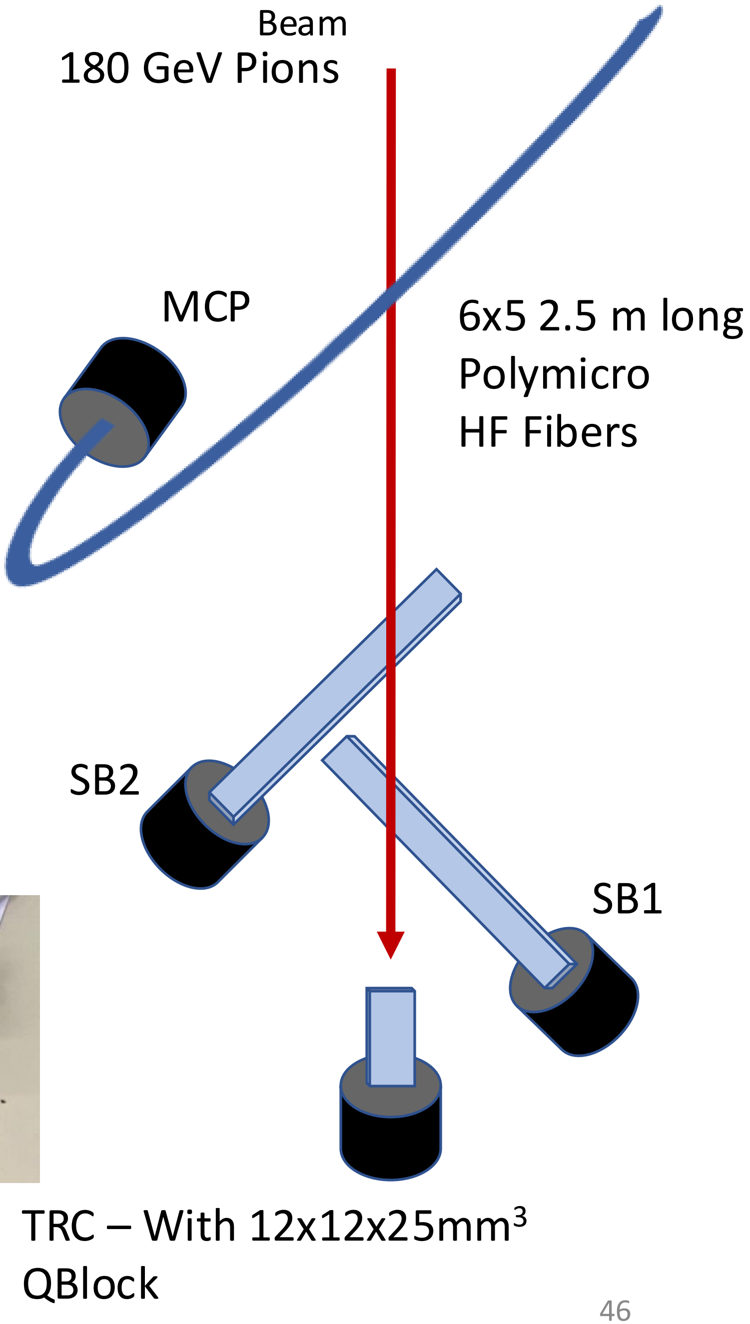


2.5m long Fiber - Bundle

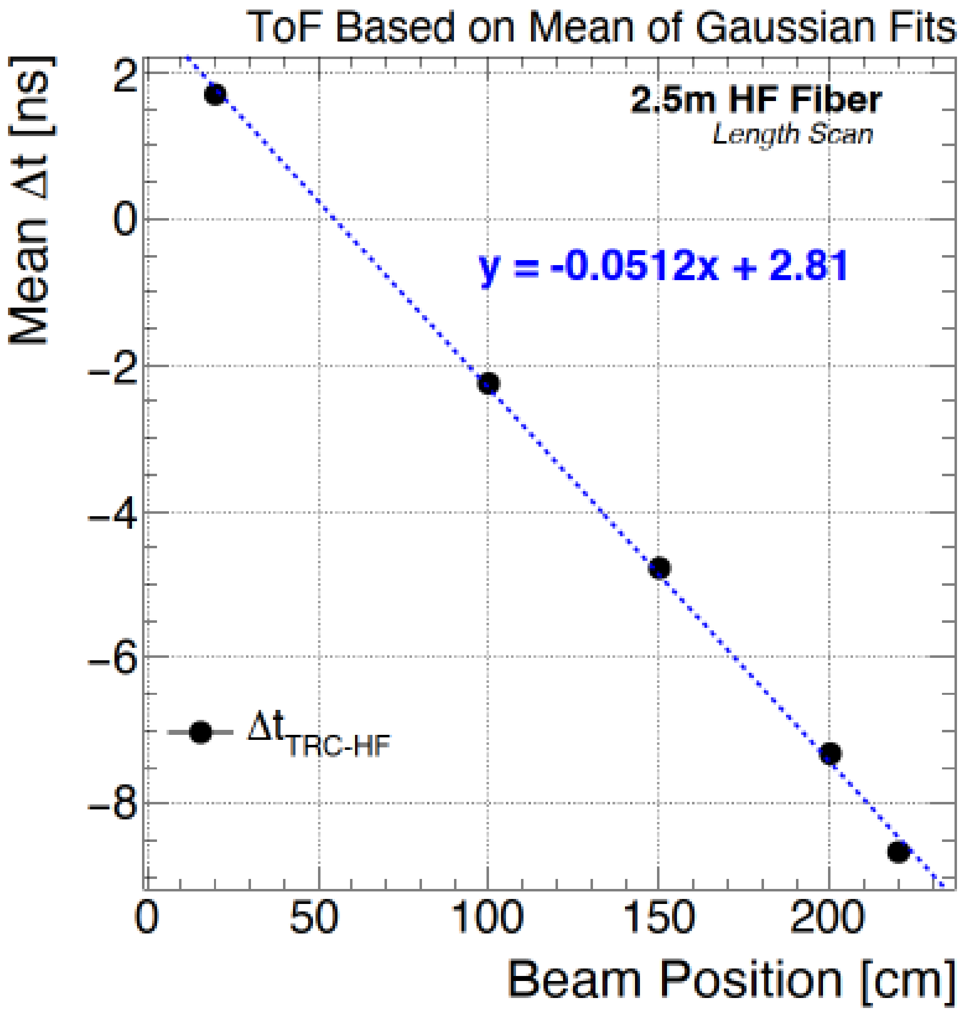
- HF fiber bundle
  - Attenuation
  - Time Resolution
  - Time propagation

Measurements were performed along 2.5 m long HF fibers bundle coupled to Katod MCP-PMT

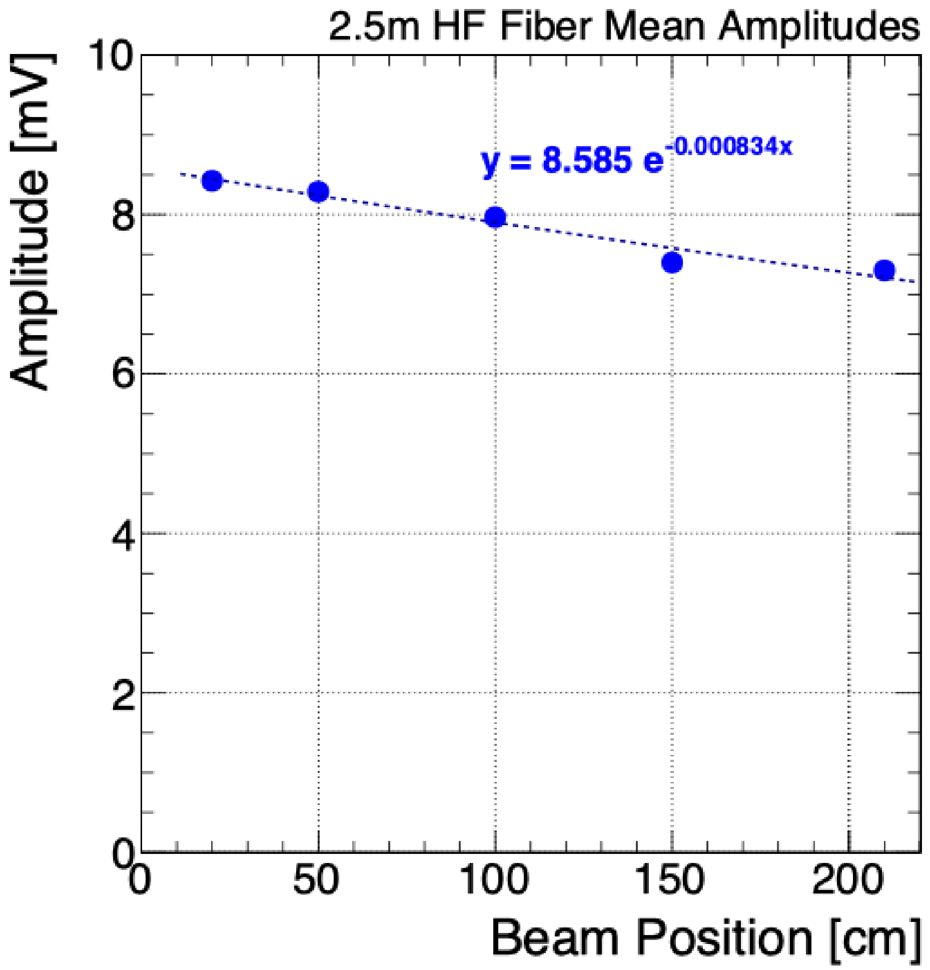




Time Propagation



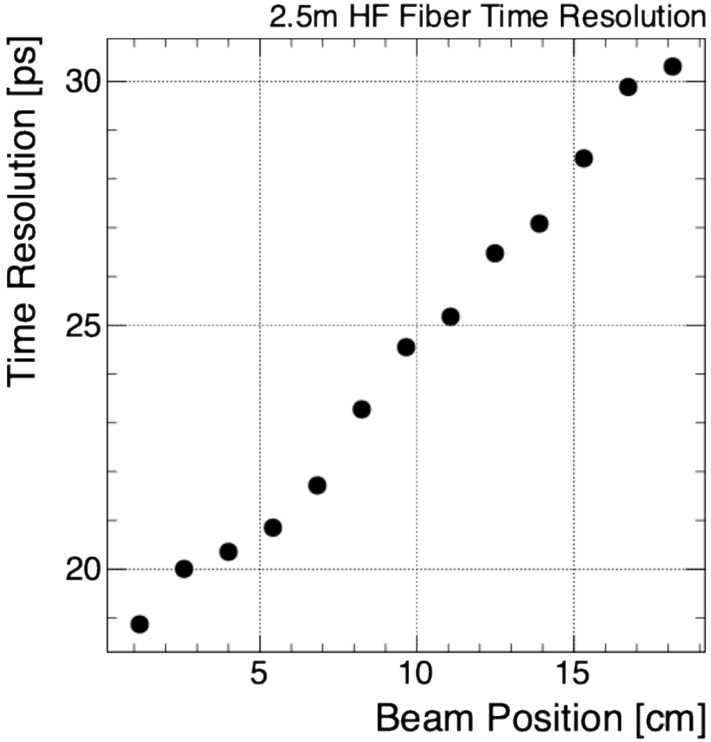
Attenuation

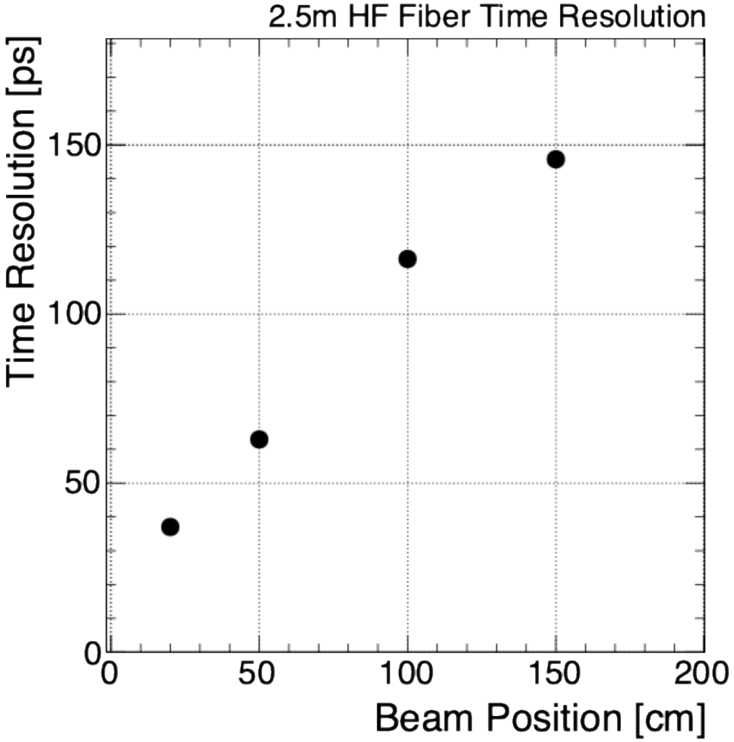


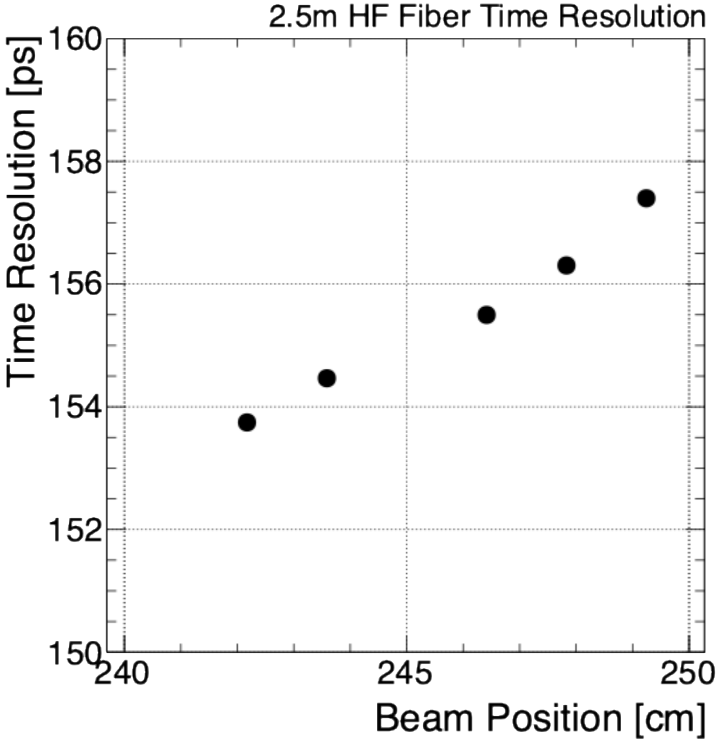
λ=1/k Attenuation Constant, k= 0.000834

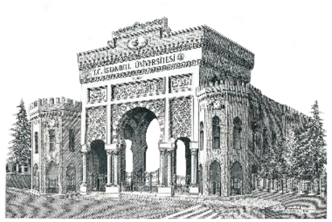
Attenuation Length, λ≈1199.52 cm

Time resolution along the 2.5 m HF fiber bundle

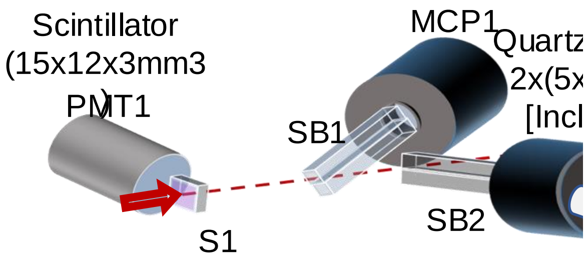




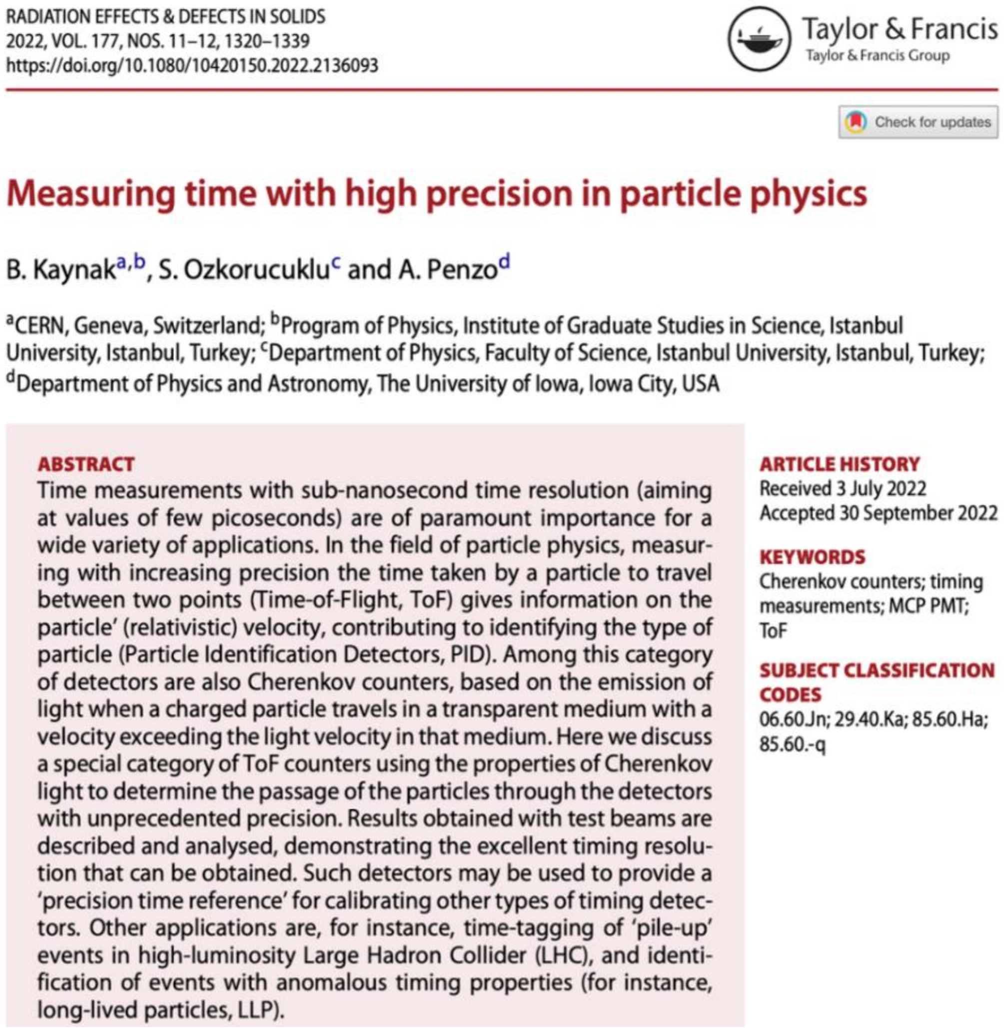




Timing detector R&D @ DESY



- **Bremsstrahlung γ beams**
  - converted to e+ e- pairs,
  - momentum/charge selected in magnet – collimator setup
- **3 Beam lines : T21, T22, T24**
- **Energy : 1 – 6 GeV**
- **Energy spread : 5%**
- **Divergence : ≈ 2mrads**
- **Flux : ≈ 0.3 – 1 kHz/cm2**



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Measuring time with high precision in particle physics

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ABSTRACT
Time measurements with sub-nanosecond time resolution (aiming at values of few picoseconds) are of paramount importance for a wide variety of applications. In the field of particle physics, measuring with increasing precision the time taken by a particle to travel between two points (Time-of-Flight, ToF) gives information on the particle' (relativistic) velocity, contributing to identifying the type of particle (Particle Identification Detectors, PID). Among this category of detectors are also Cherenkov counters, based on the emission of light when a charged particle travels in a transparent medium with a velocity exceeding the light velocity in that medium. Here we discuss a special category of ToF counters using the properties of Cherenkov light to determine the passage of the particles through the detectors with unprecedented precision. Results obtained with test beams are described and analysed, demonstrating the excellent timing resolution that can be obtained. Such detectors may be used to provide a 'precision time reference' for calibrating other types of timing detectors. Other applications are, for instance, time-tagging of 'pile-up' events in high-luminosity Large Hadron Collider (LHC), and identification of events with anomalous timing properties (for instance, long-lived particles, LLP).

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KEYWORDS
Cherenkov counters; timing measurements; MCP PMT; ToF

SUBJECT CLASSIFICATION CODES
06.60.Jn; 29.40.Ka; 85.60.Ha; 85.60.-q

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.