Development, characterization and beam tests of a small-scale TORCH prototype module

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On behalf of the TORCH Collaboration (CERN, Bristol and Oxford Universities, UCL)

Industrial Partner: Photek

Fast Cherenkov Detectors session – 12th November 2015

Layout

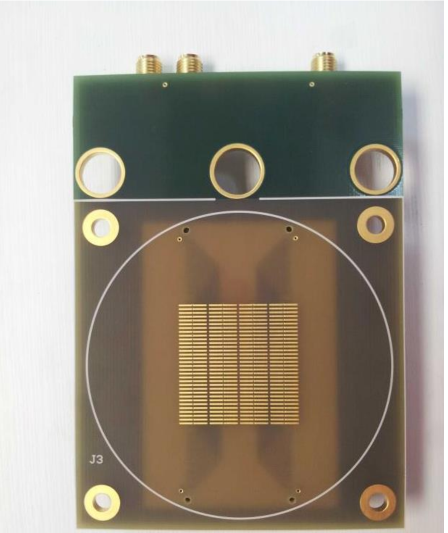
- Photon detector characterization and performance
- NINO-32 chip calibrations
- Spatial resolution
- CERN SPS beam test
- Conclusions and perspectives

Photon detectors

- TORCH requirement:
  - Asymmetric anode segmentation 8x128 channels for ~2” sq. tube

- Customized MCP (Phase2 tube prototype, Photek):
  - Quarter-size customized circular-shape MCP with finely segmented anode (32x32 channels in 26.5x26.5 mm^2 area)

- Backplane anode: metallic pads connected to an interface PCB and merging channels by groups of 8 in horizontal direction
  - Asymmetric segmentation 4x32 readout channels



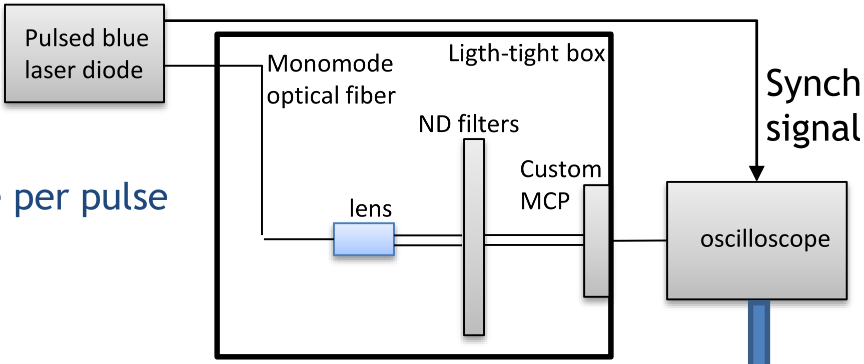
Photek interface PCB

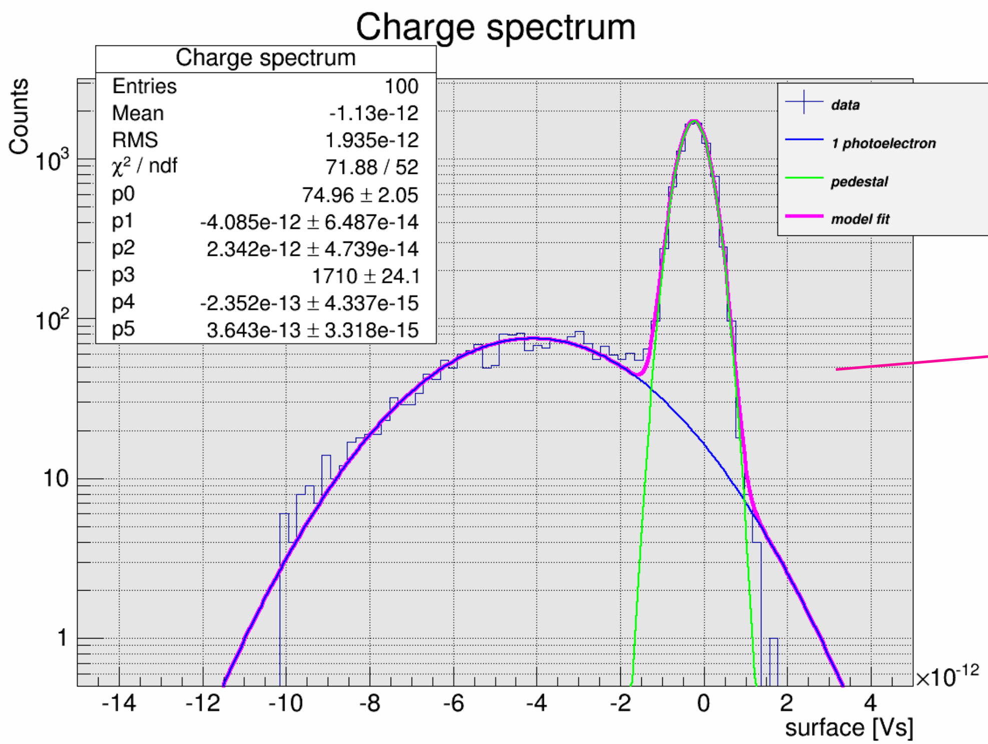
- Charge-sharing technique:
  - Reduce the number of channels
  - Achieve the spatial resolution required by TORCH

$$\frac{53\,mm}{128\,channels} = 0.414\,mm \rightarrow \frac{0.414\,mm}{\sqrt{12}} = 0.12\,mm$$

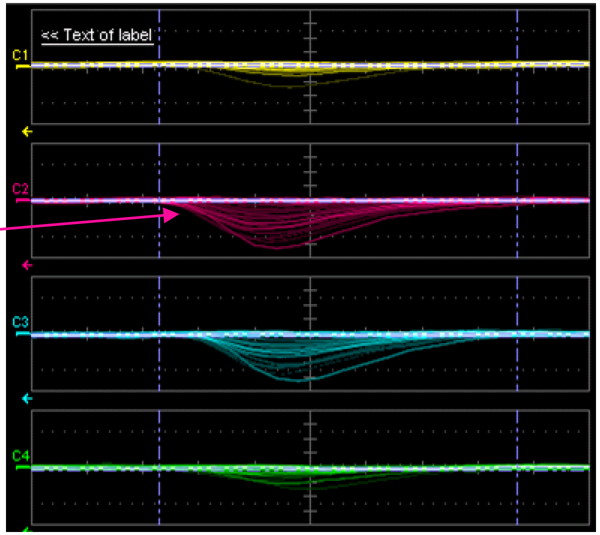
Charge estimate with oscilloscope

- Light calibration setup:
  - Pulse height spectrum (PHS)
  - Standard Poisson distribution to fit data
  - Photon yield: **0.24** photo-electrons on average per pulse
  - Charge **~70 fC**
  - Gain **~4.8x10^5 e**





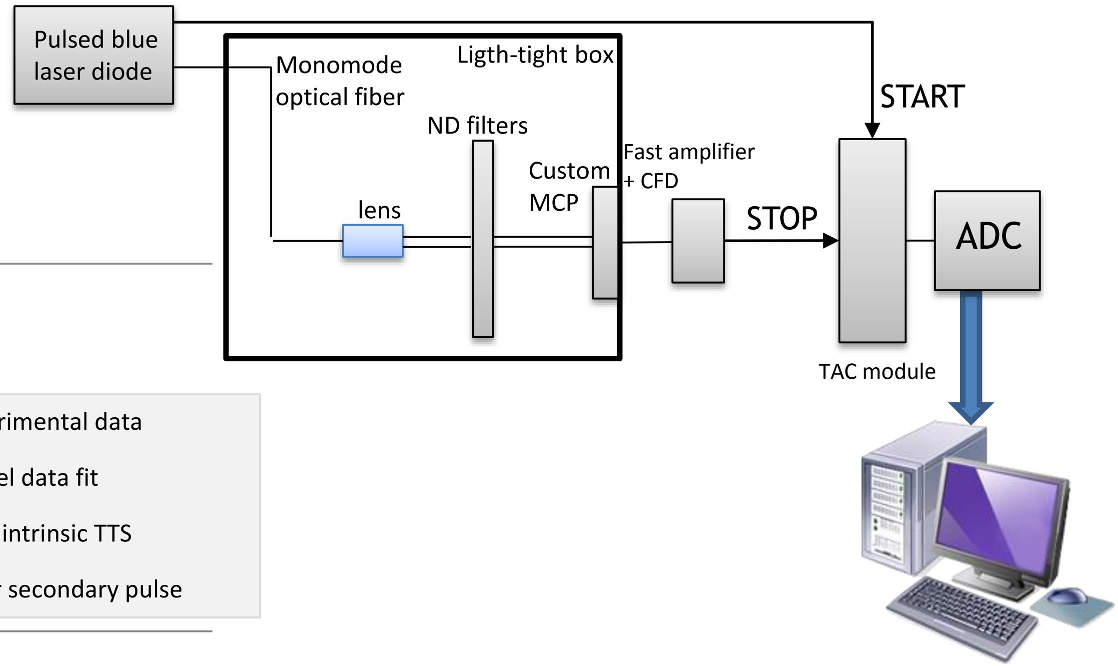
Oscilloscope display:

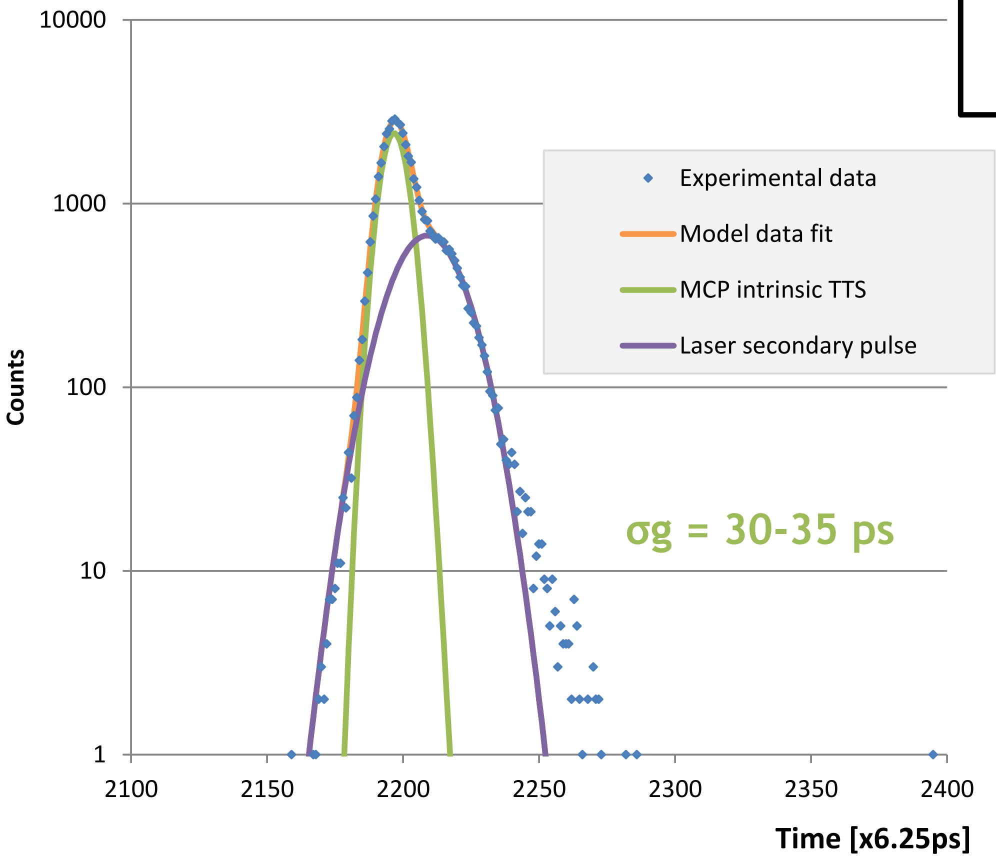


Charge is spread over four channels

Timing performance with single-channel commercial electronics

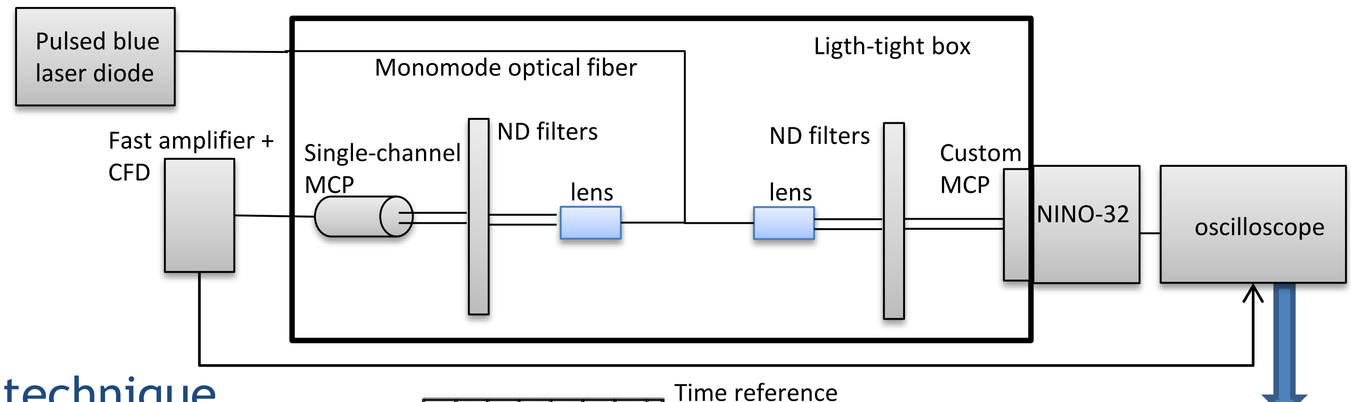
- Measure time response of an individual channel



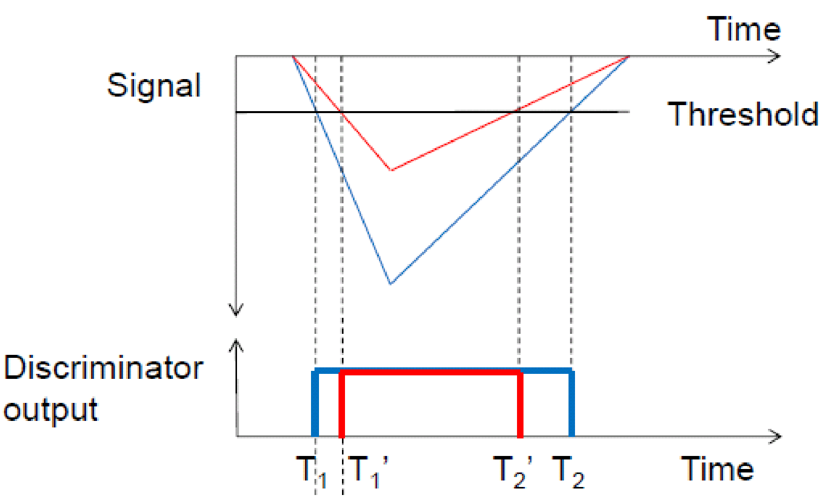


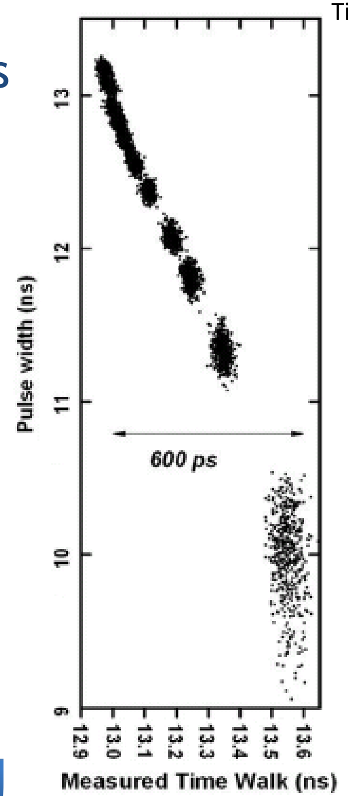
- Main peak fitted with an exponentially-modified Gaussian
- Asymmetry due to back-scattering photo-electrons at the input surface of first MCP
- Gaussian fit to laser secondary pulse contribution

Timing performance with NINO-32 and oscilloscope

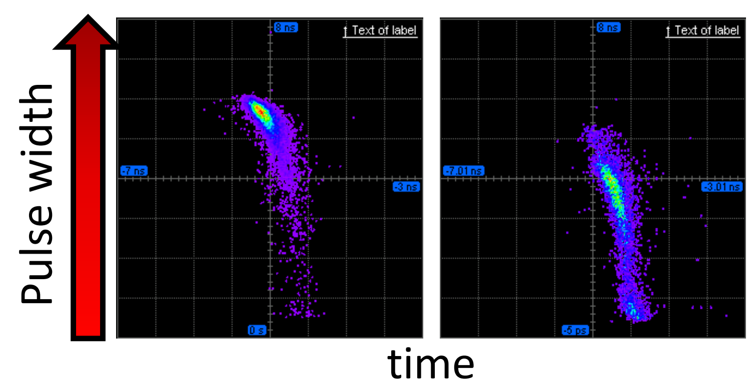


Time over threshold technique used to correct for time walk effects





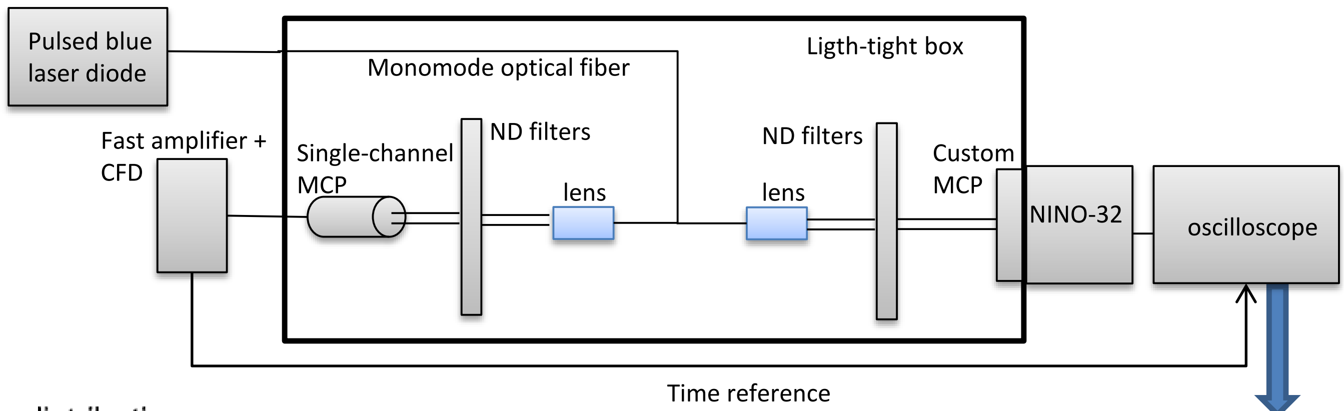
Oscilloscope display:

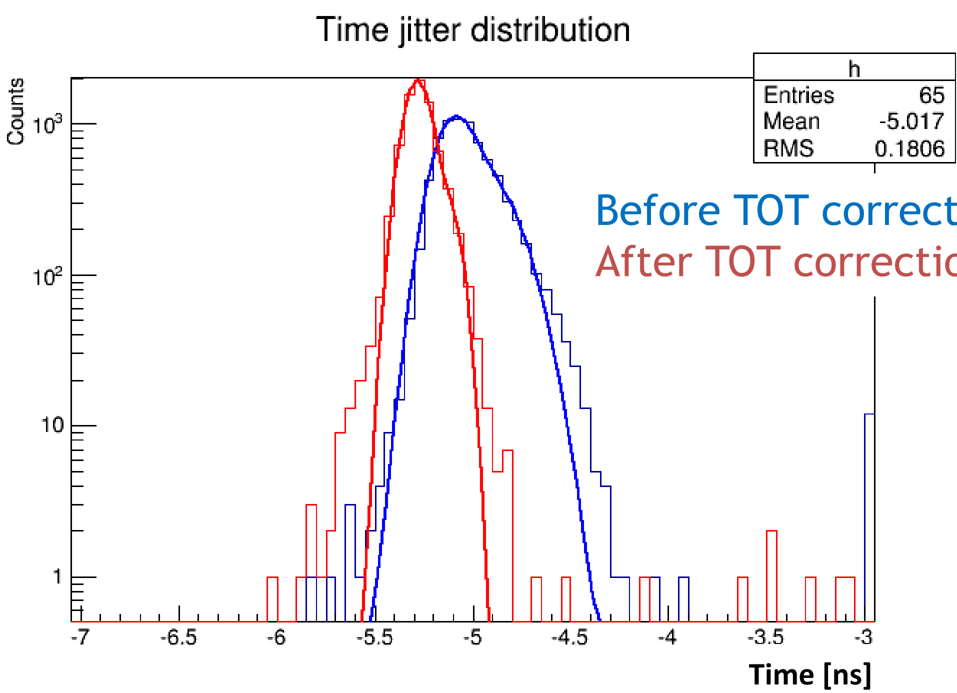


Pulse width:

$$W = T_2 - T_1 > W' = T_2' - T_1'$$

Timing performance with NINO-32 and oscilloscope

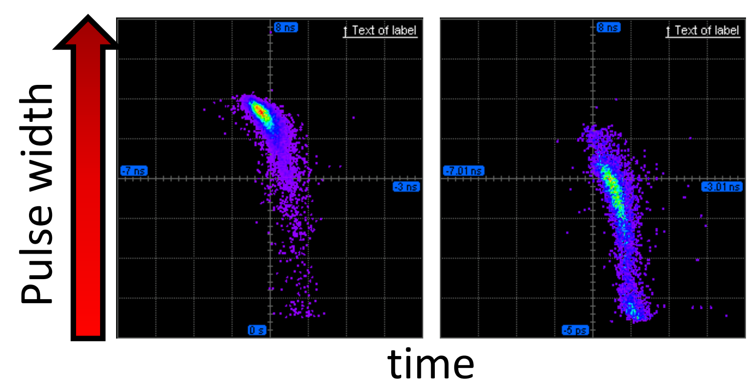




Before TOT correction: σ ~90 ps

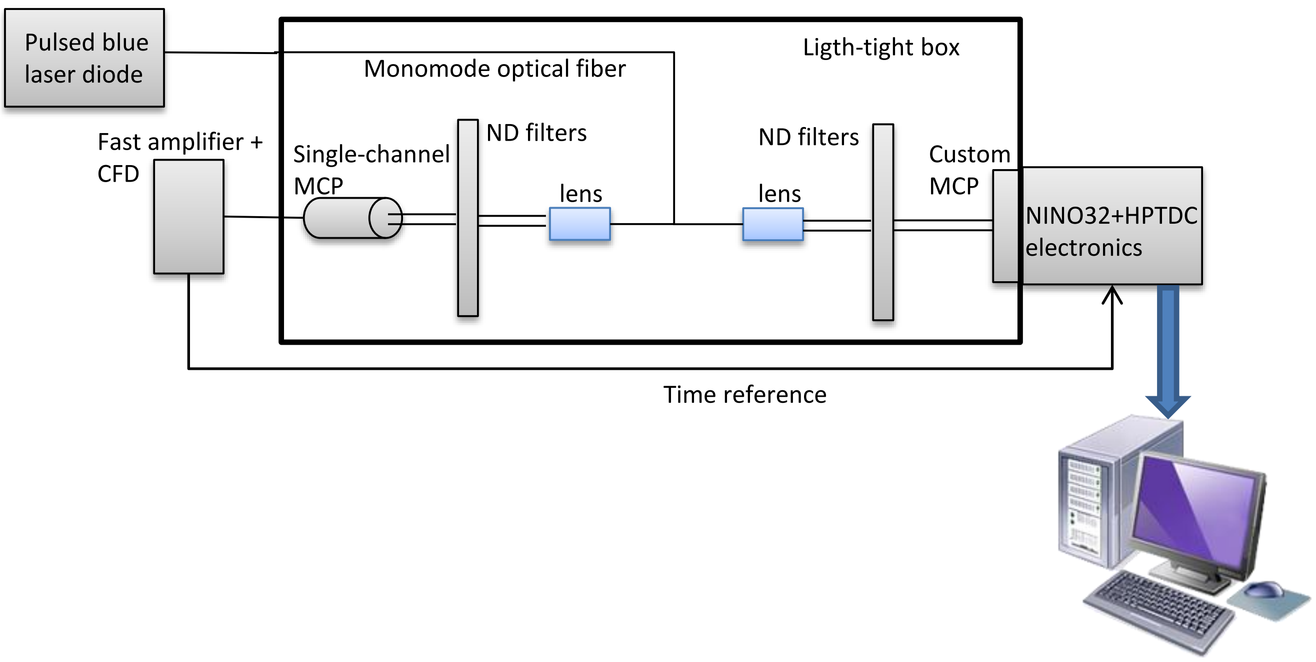
After TOT correction: σ ~65 ps

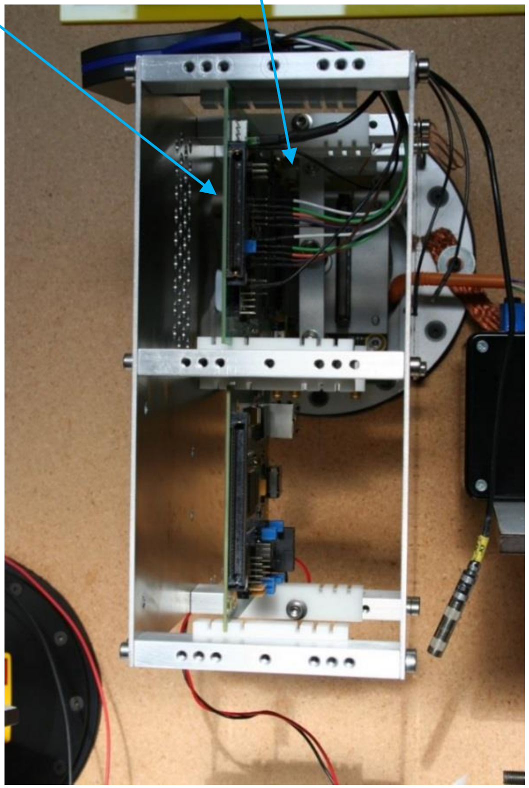
Oscilloscope display:



Timing performance with multi-channel electronics

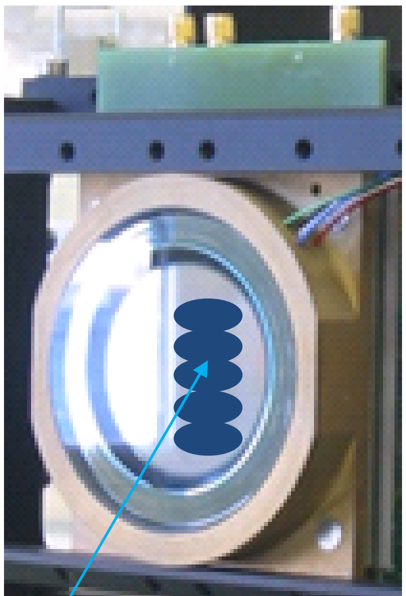
- Using custom multi-channel front-end electronics, mechanically mounted on light-tight box:
  - fast amplifier and Time-Over-Threshold (TOT) discriminator (NINO-32 ASIC)
  - time digitization converter (HPTDC ASIC @100 ps resolution mode)



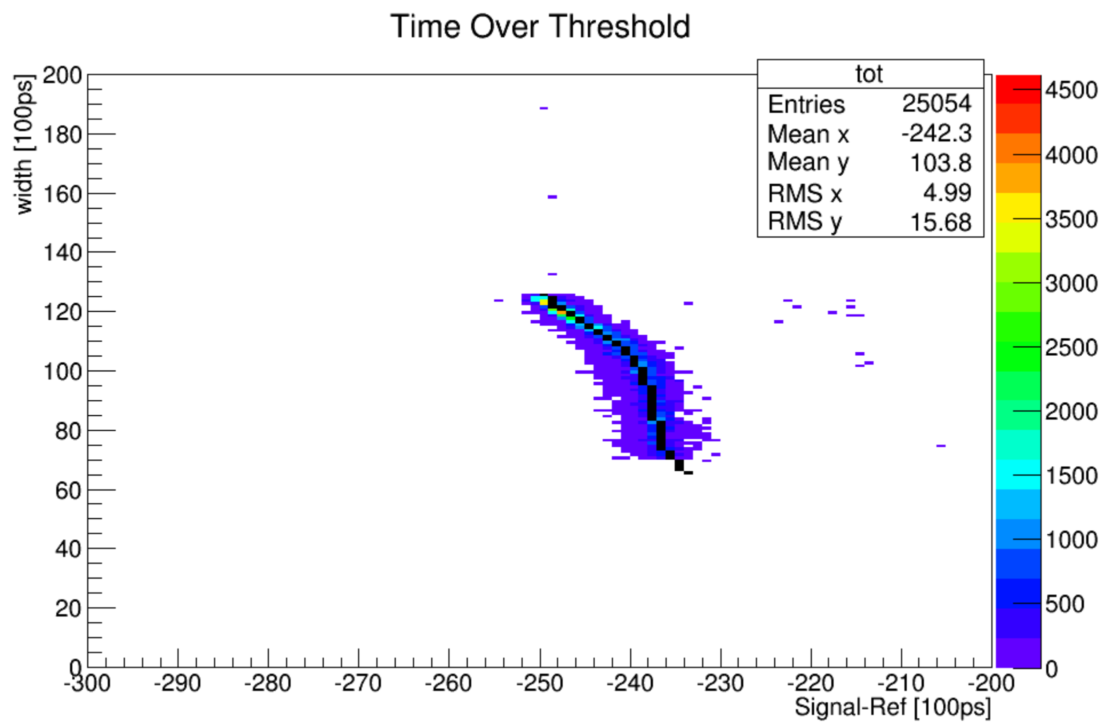


TOT calibration with multi-channel electronics

- Vertical scan with laser for a single column
- Colour plot is cumulative data from all laser alignments



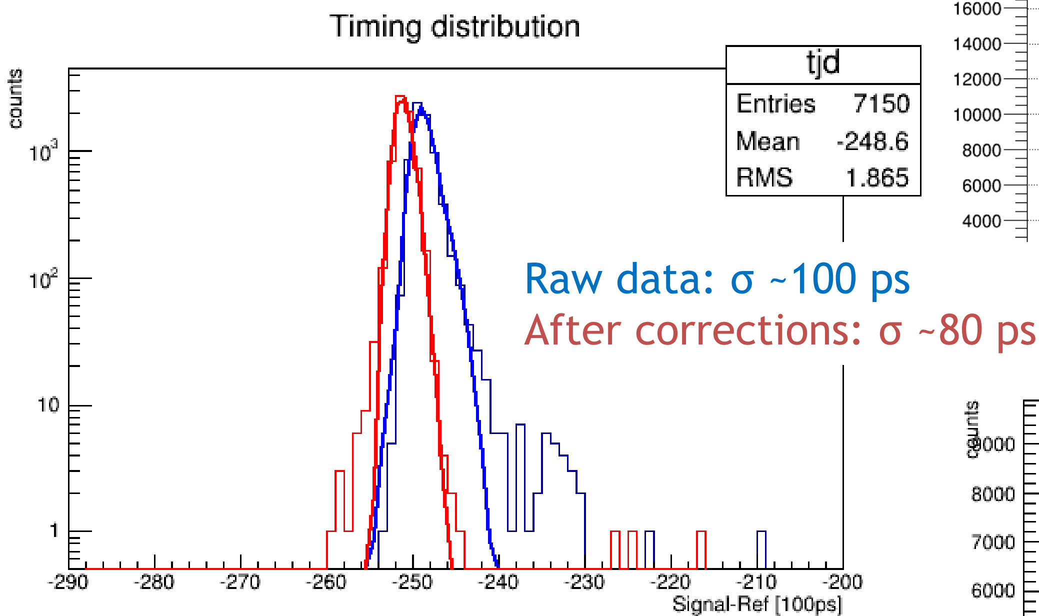
Laser positions

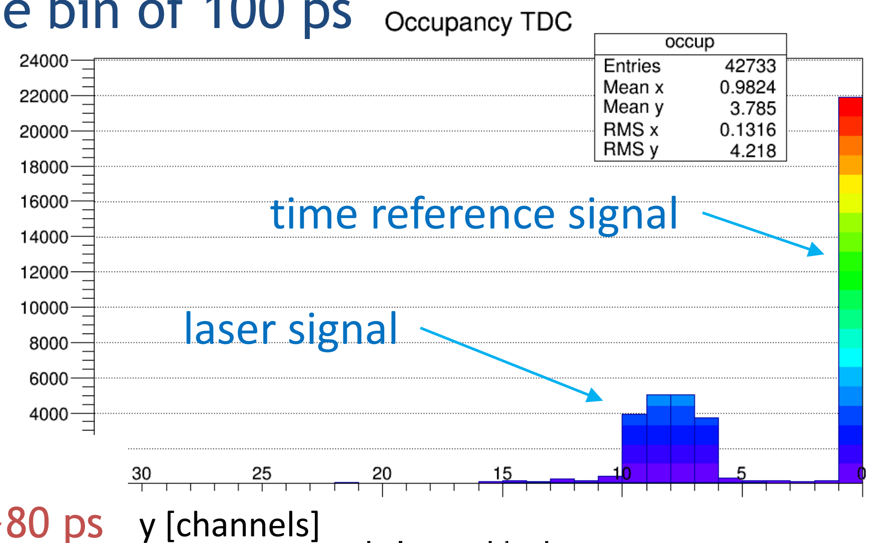


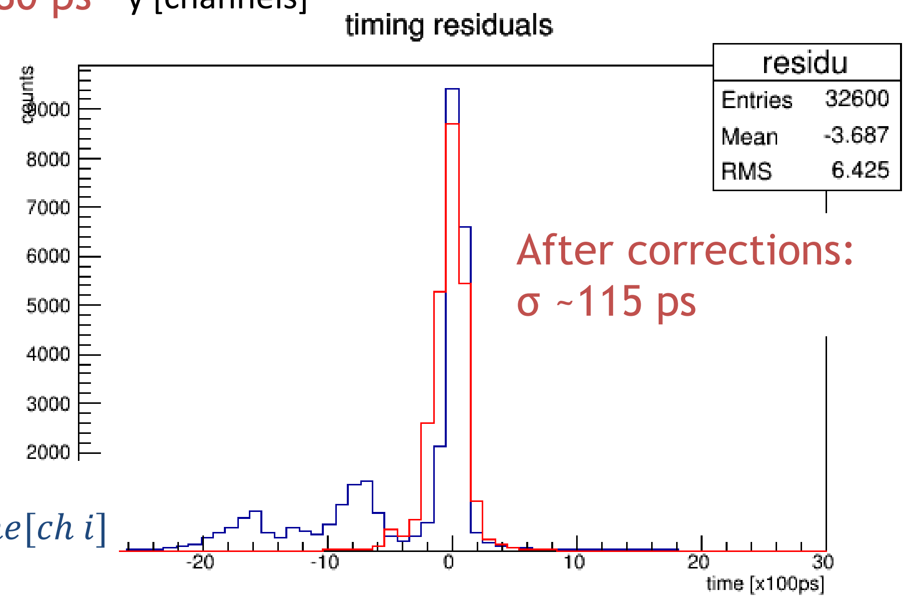
- Slices of 1ns in y axis (width), fitting the projection on x axis (timing distribution)
- Spline fit of above set of points → TOT calibration curve
- TOT correction is applied to all channels using this calibration curve

Timing performance with multi-channel electronics

- INL correction from HPTDC: ±1 time bin of 100 ps
- Photoelectron efficiency: ~88%
- Distribution is shrunk





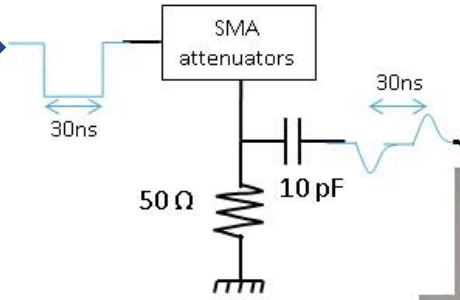


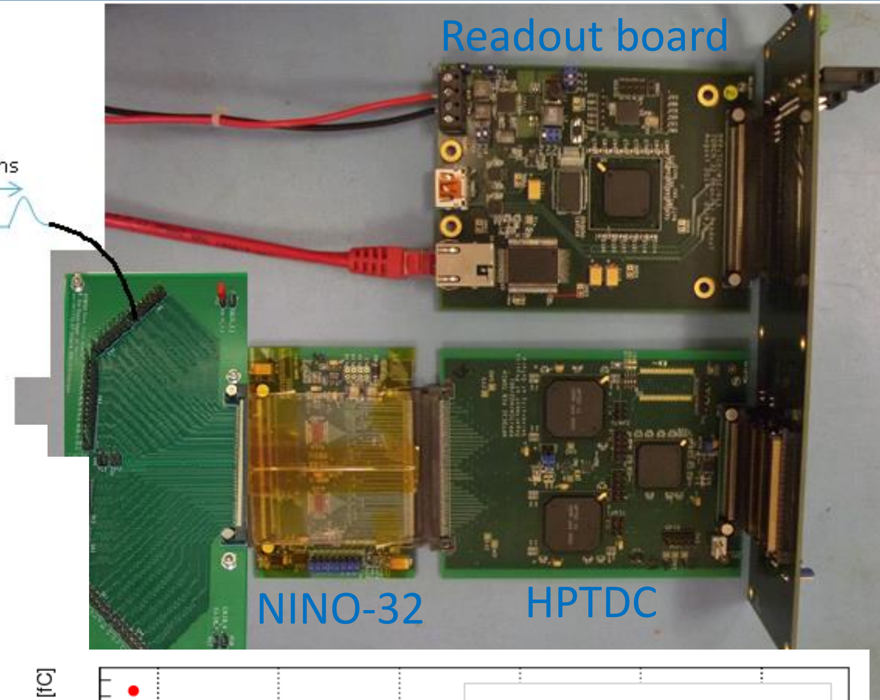
- Timing residuals:
  - Calculated for 32 channels in a column at a given laser position

$$\sum_{i=0}^{31} arrival\ time[ch\ with\ most\ of\ the\ charge] - arrival\ time[ch\ i]$$

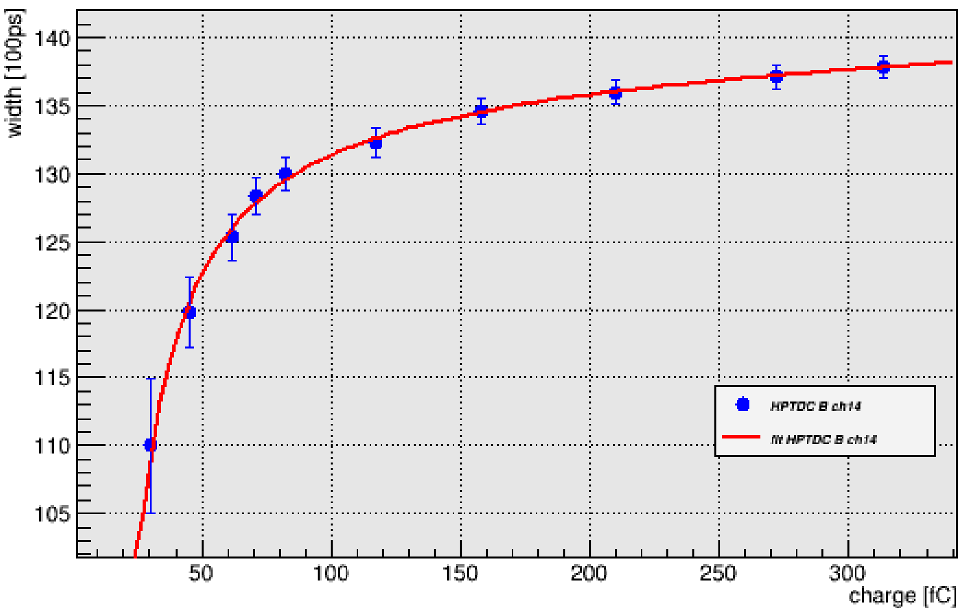
NINO-32: Charge-to-width curves

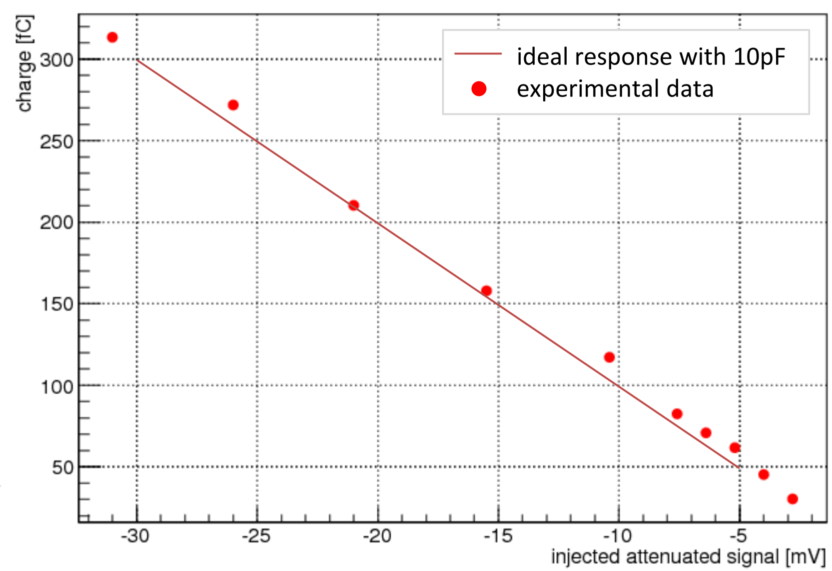
Pulse generator →





Calibration curve from a single NINO channel



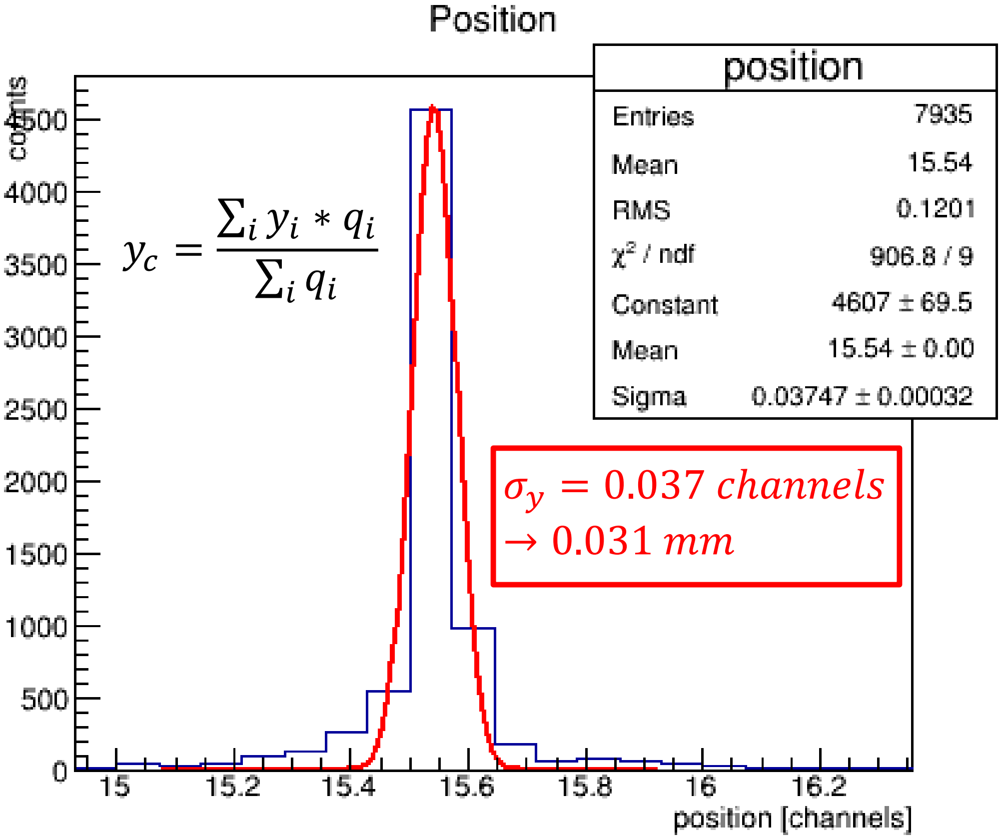


Position resolution with laser

- Required spatial resolution:

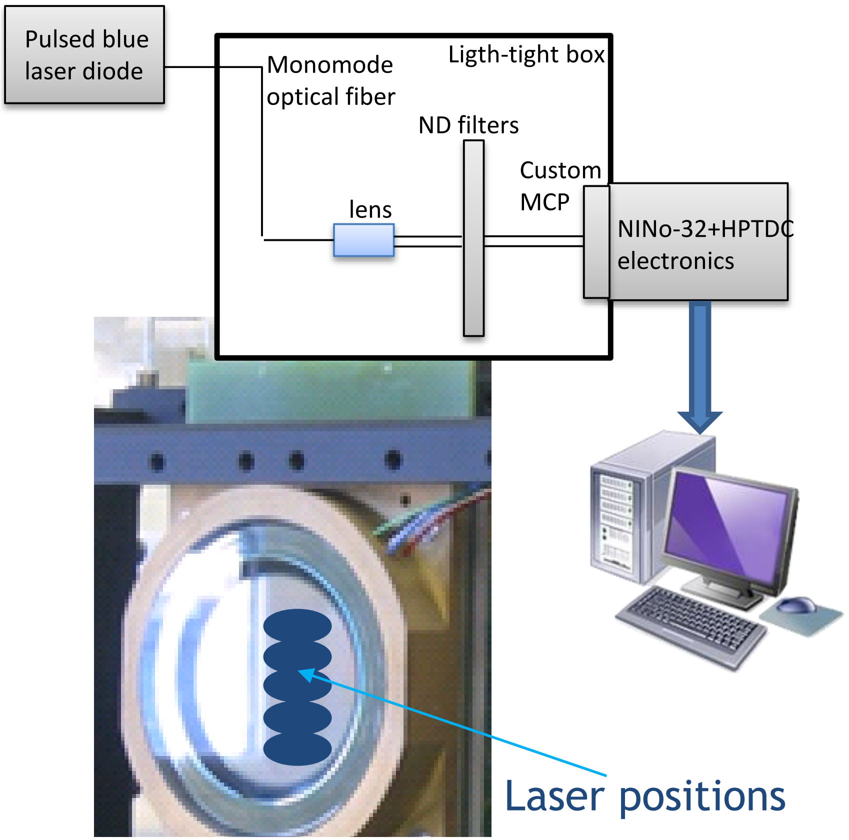
$$\frac{53\ mm}{128\ channels} = 0.414\ mm \rightarrow \frac{0.414\ mm}{\sqrt{12}} = 0.12\ mm$$

- Position using centroid algorithm



$$y_c = \frac{\sum_i y_i * q_i}{\sum_i q_i}$$

$$\sigma_y = 0.037\ channels \rightarrow 0.031\ mm$$

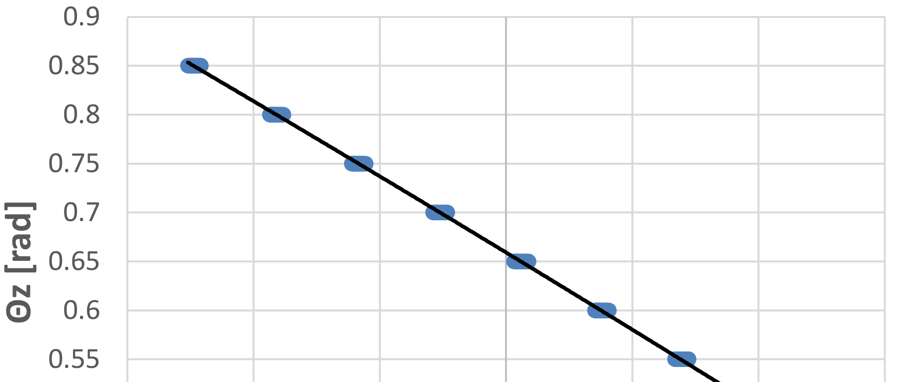


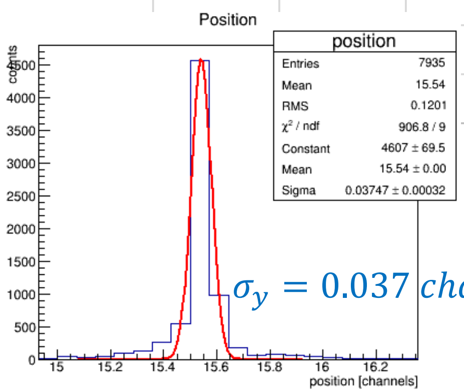
Vertical scan with laser

Spatial resolution contribution to $\sigma_{\theta z}$

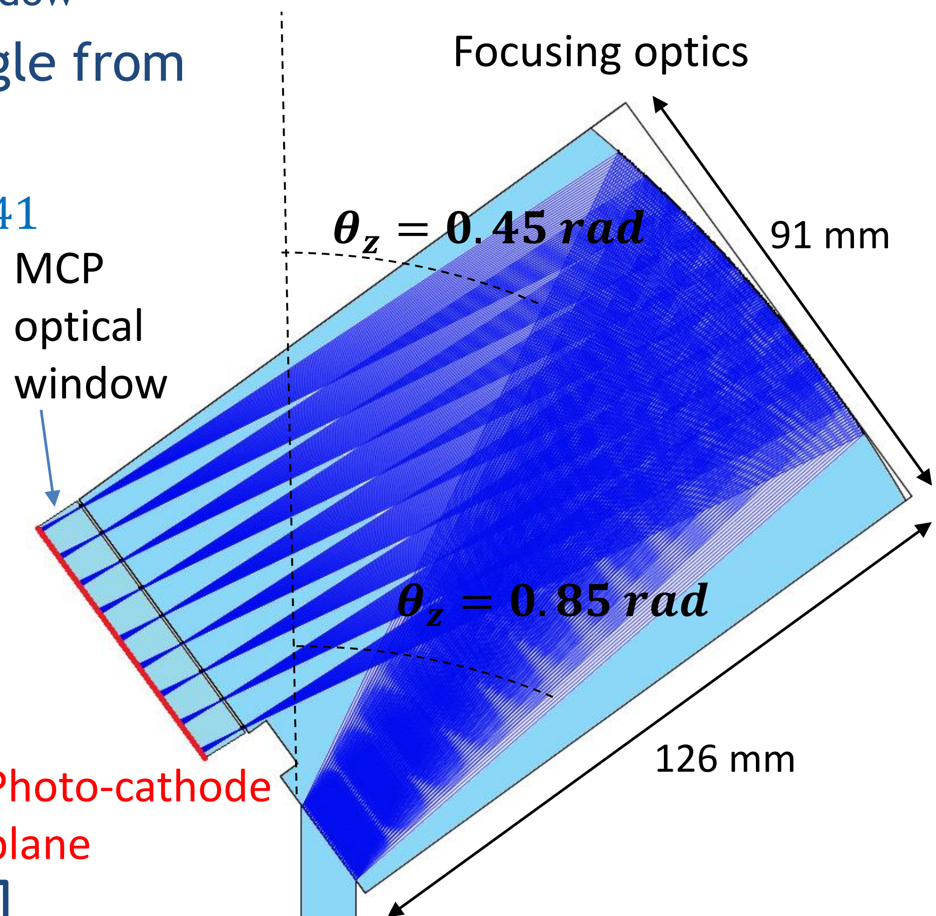
- At an airgap of 0.5 mm for θ_z in the range of [0.45-0.85] rad:
  - σy <0.4mm for a 9 mm fused silica window
- Determine photon propagation angle from vertical position on focal plane (y):

$$\theta_z = -0.000005y^2 - 0.007830y + 0.659141$$





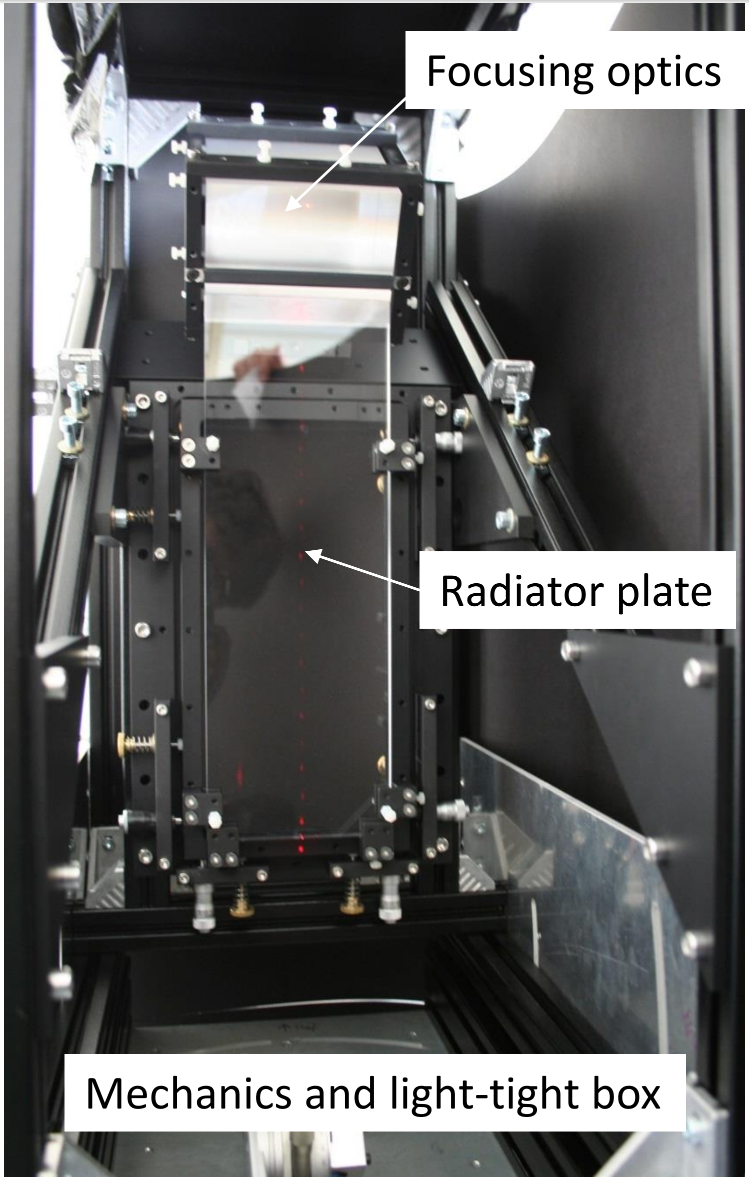
$\sigma_y = 0.037\ channels \rightarrow$ $\boldsymbol{\sigma_{\theta_z} = 0.29\ mrad}$



9mm-thick fused silica input window → out of focus

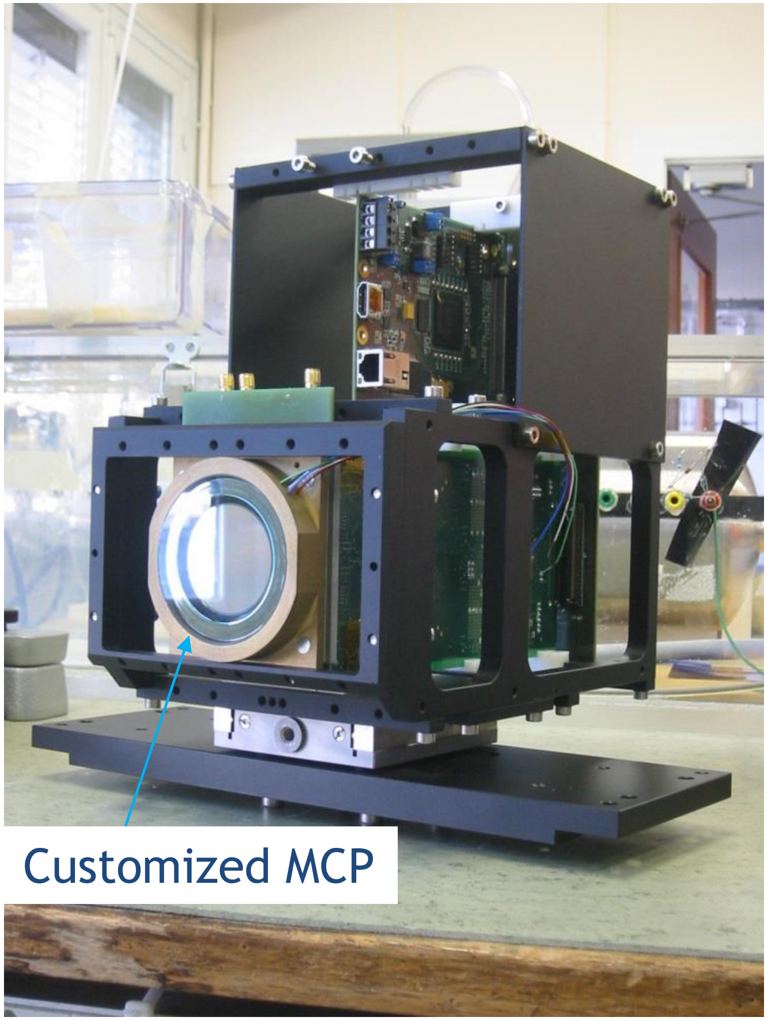
TORCH prototype module

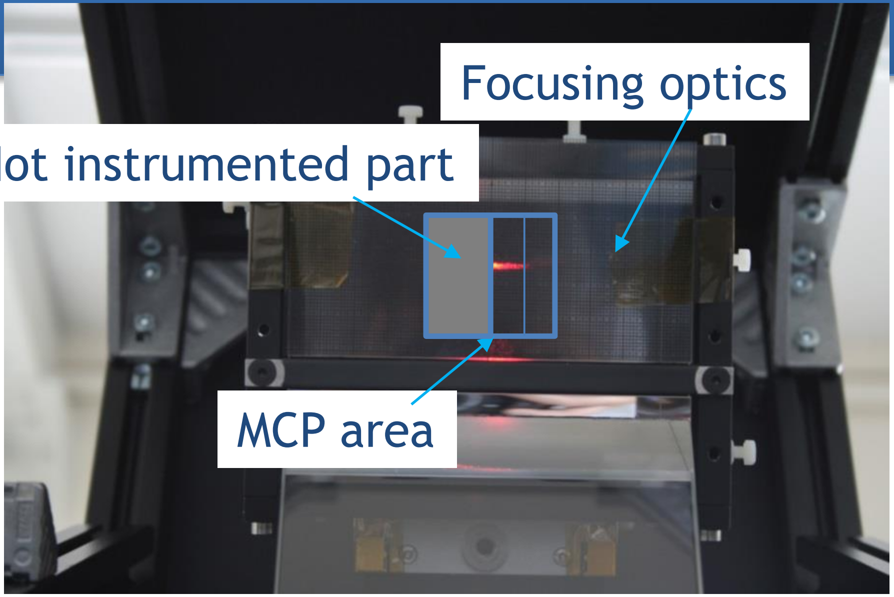
- Radiator plate ($10x120x350mm^3$) and focusing prism → Fused Silica
- High polished surfaces: ~1 nm
- Cylindrical mirror reflectivity over photon wavelength range: 85-90%
- Optical quality of various glued glass samples investigated
  - Measure and optimize transmission in UV region for radiator/optics coupled with different glues
- Quality of focusing optics is verified by simulation

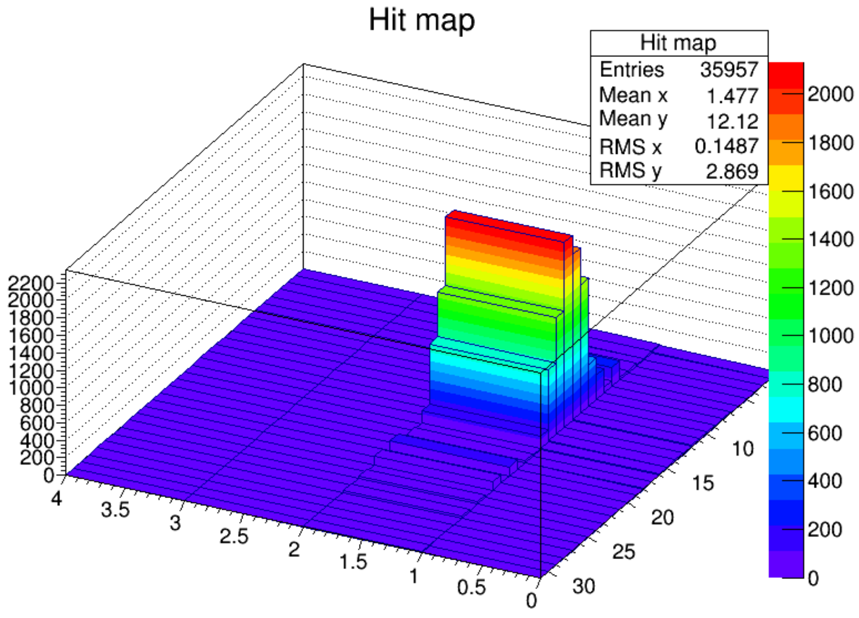


TORCH prototype coupled to customized MCP + readout electronics

- MCP + electronics mounted on a micrometric transportable "chariot"

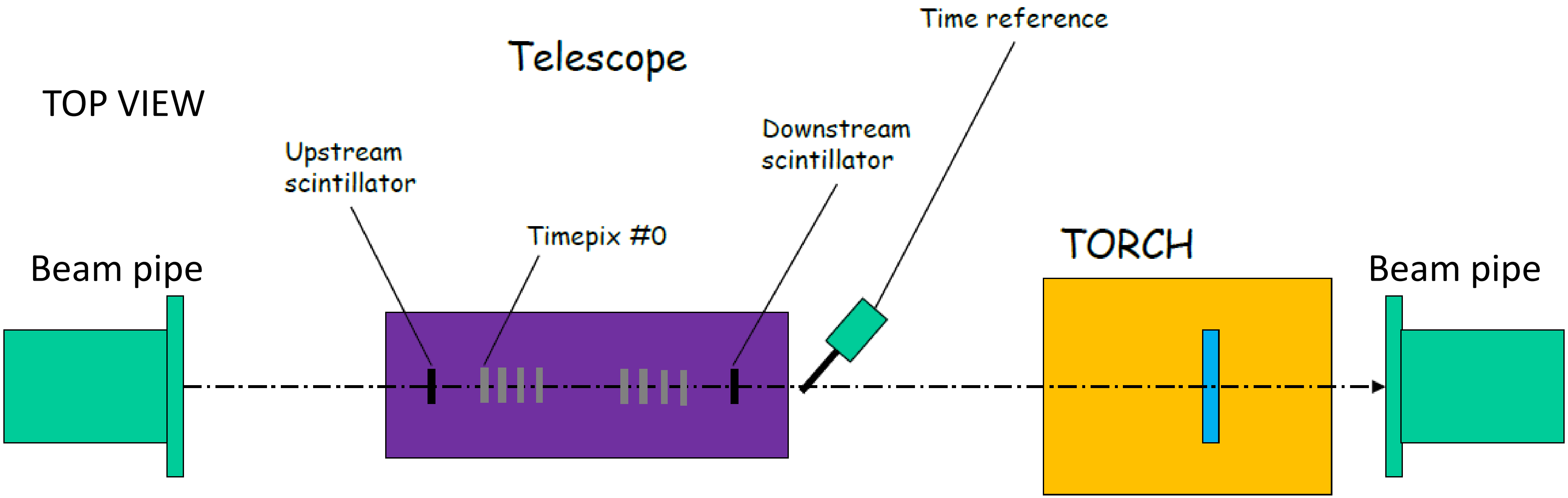




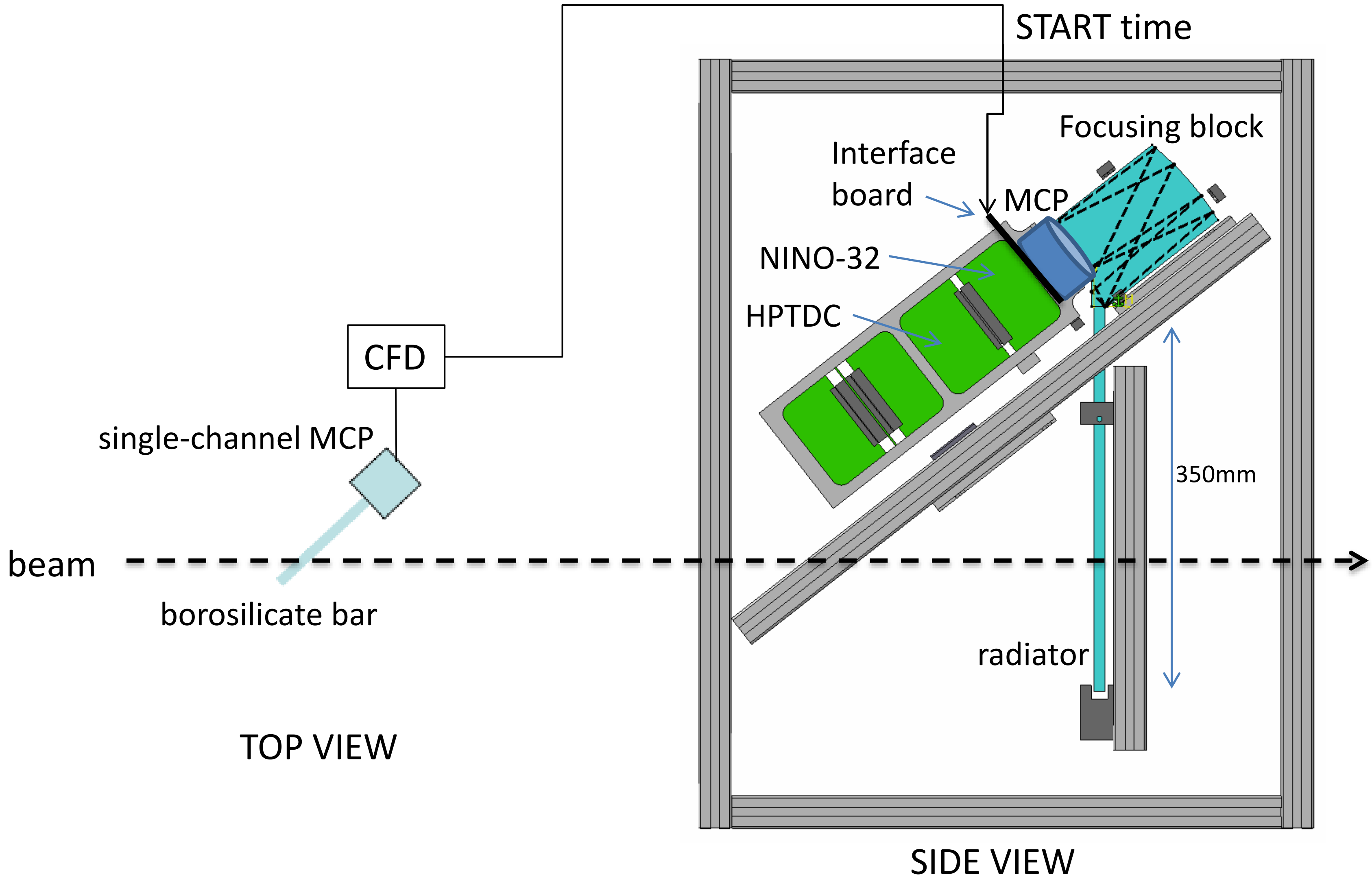


CERN SPS beam test

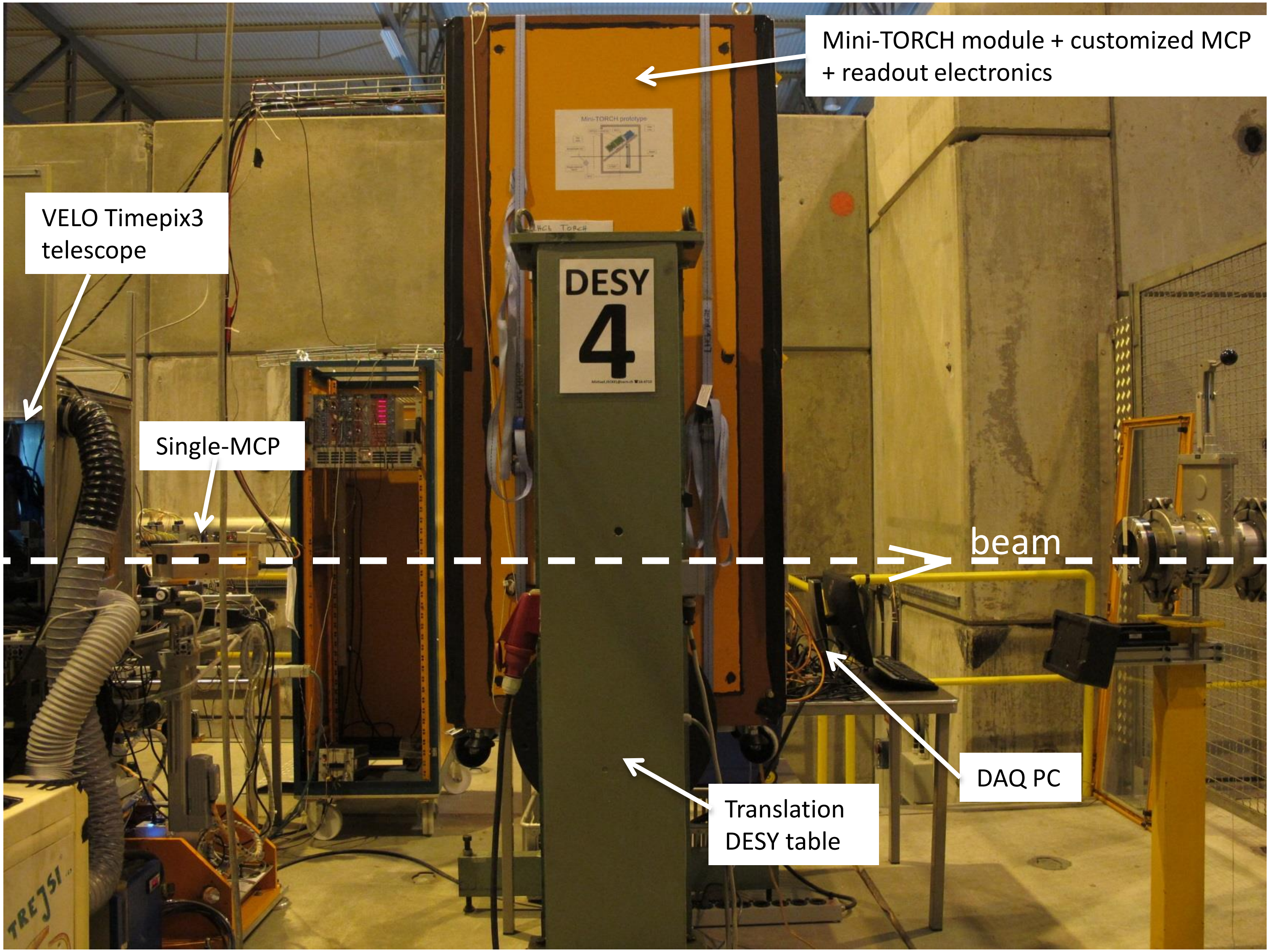
- Beam test periods:
  - May 2015 → TORCH prototype module + Customized MCP and electronics performance
  - July 2015 → Time reference jitter calibration
- Beam conditions:
  - $p = 180\ GeV/c$ charged hadrons (essentially p's)
  - Low intensity rate ($1 - 1.2 \cdot 10^5$ tracks/spill)
- Pixel telescope from the VELO group of the LHCb experiment to provide particle track information
- Coincidence signal from scintillators of the VELO telescope used as trigger
- A trigger logic unit synchronized the telescope with the TORCH electronics



Schematic view of beam test configuration

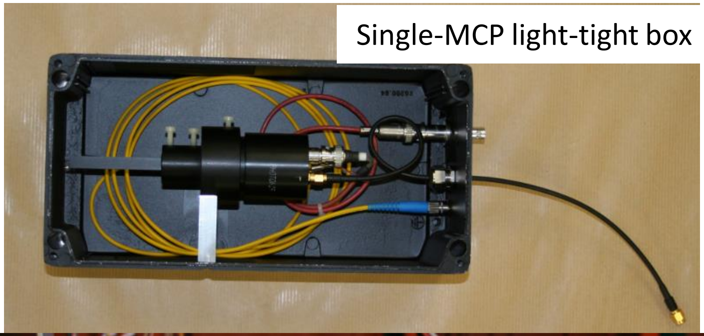


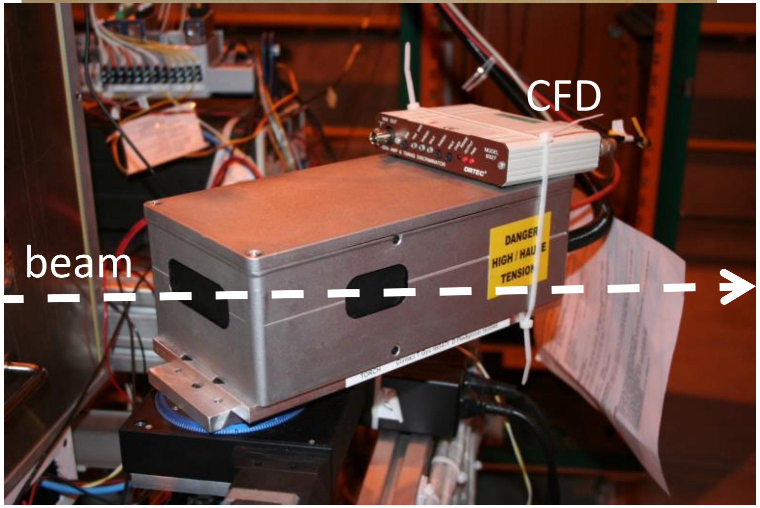
CERN SPS beam test area

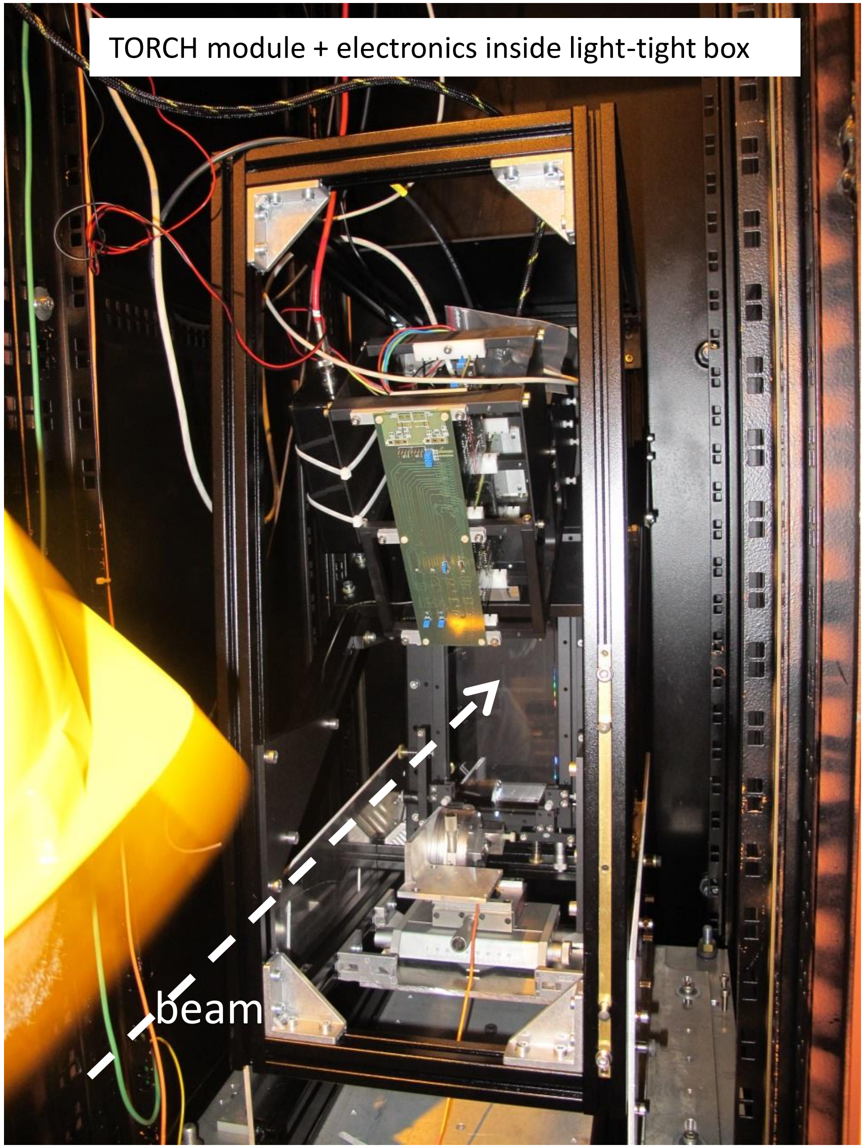


Time reference station and TORCH prototype module

- TORCH module:
  - tilted 5º and beam centred on radiator plate
- Time reference:
  - Single-channel MCP (Photonis)
  - Blackened borosilicate bar as Cherenkov radiator

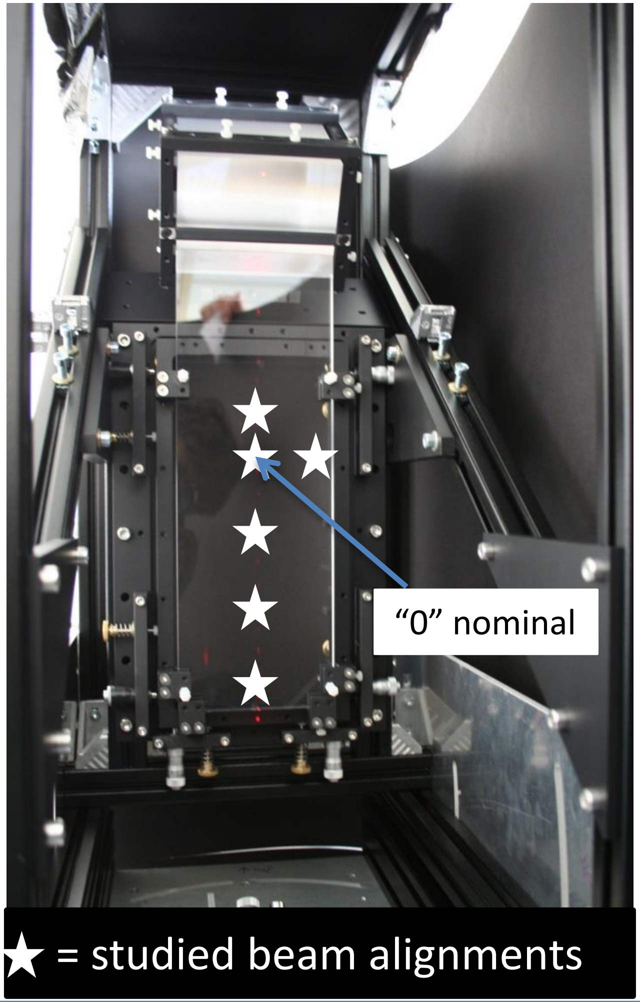


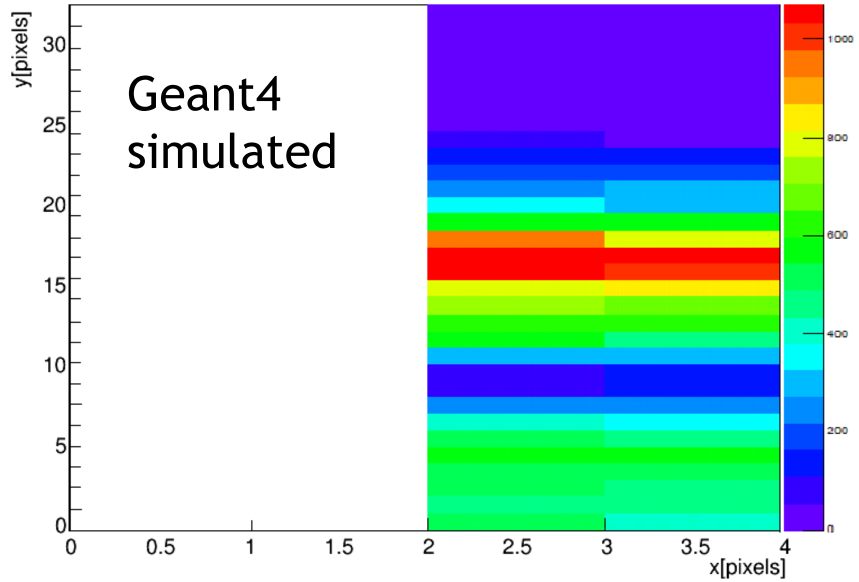


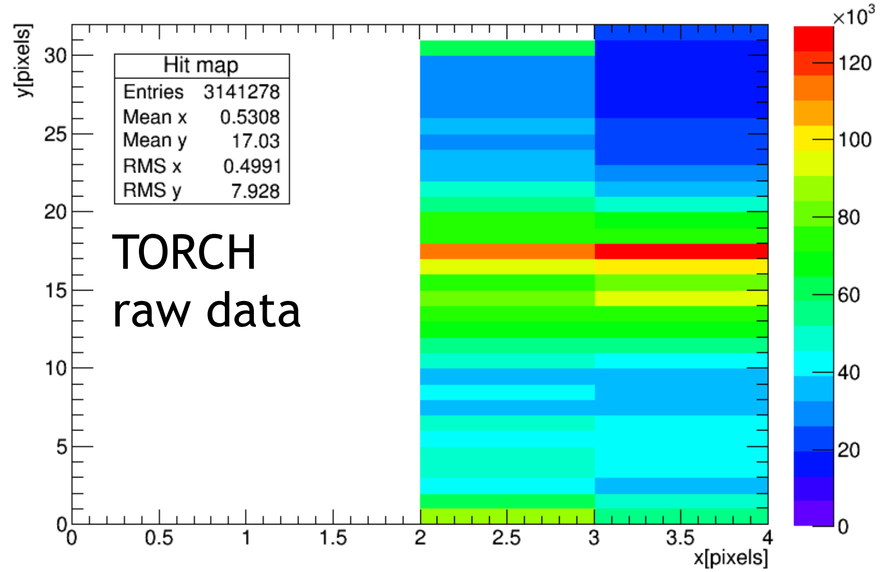


Pattern at photon detector plane

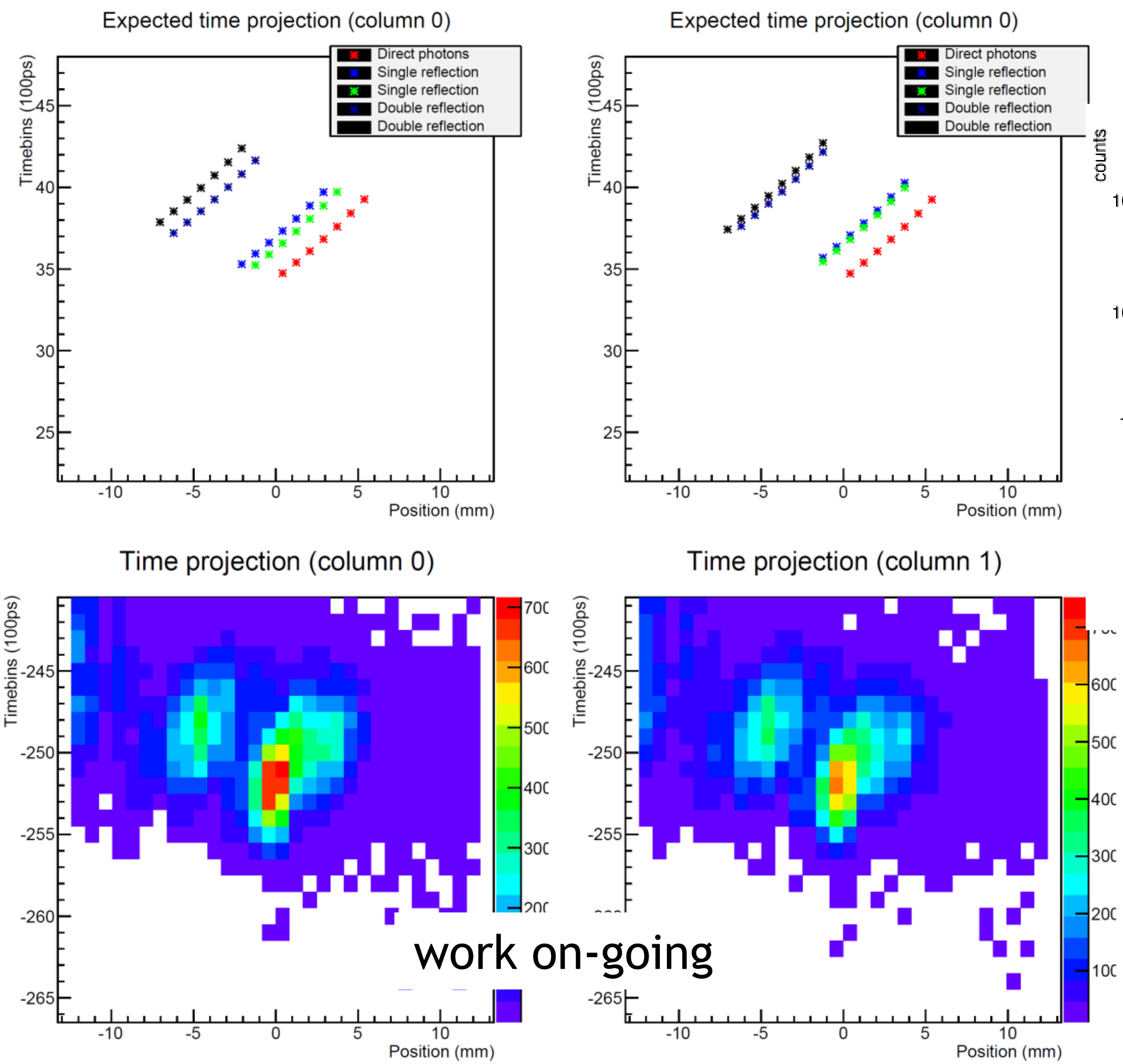
- Beam crossing at "0" nominal position



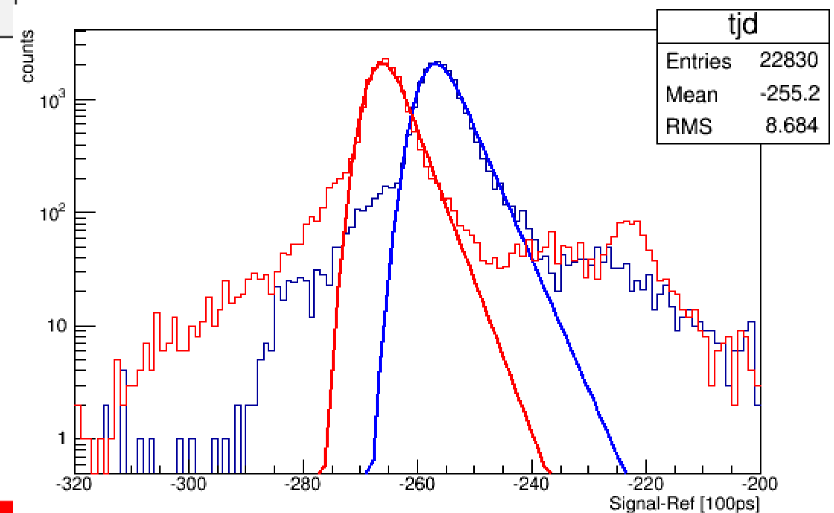




Timing performance (preliminary results)



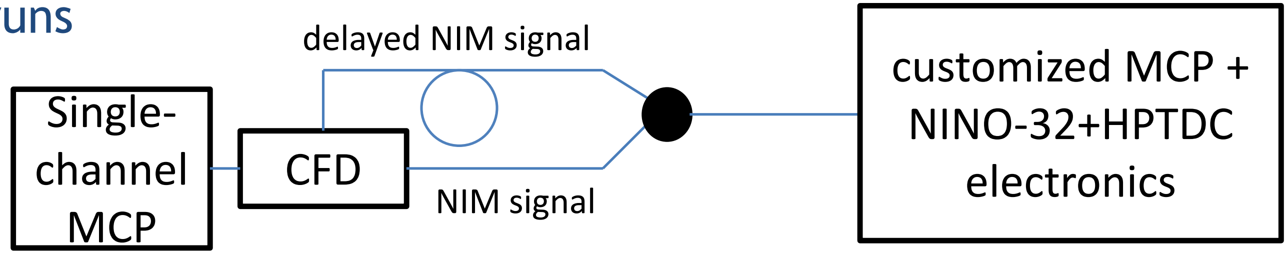
Raw data: σ = 242.6 ps
After TOT: σ = 220.6 ps

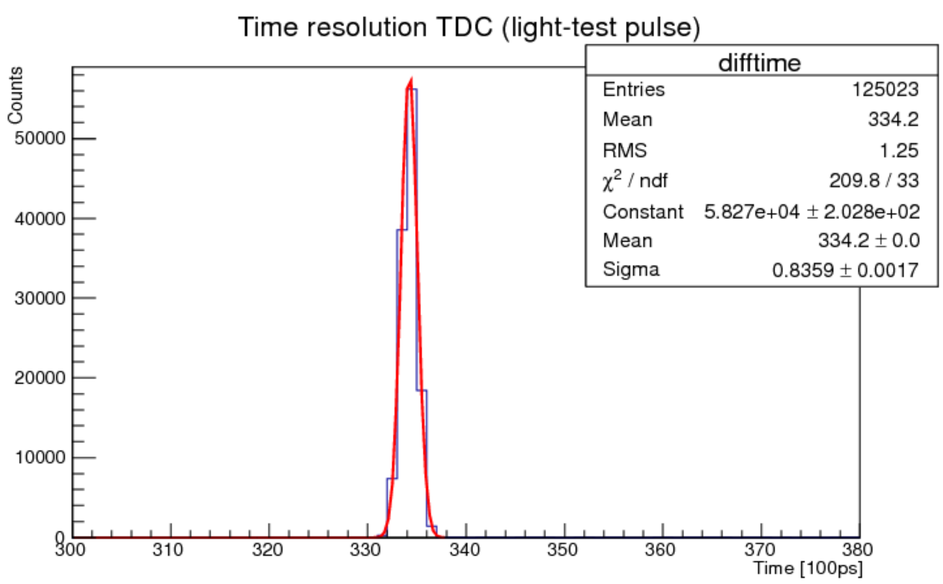


- Single-channel response
- Remind: 80 ps obtained from MCP + electronics with laser
- No full reconstruction: Including chromatic dispersion, photon time of propagation, emission point error

Electronics jitter from time reference signal

- Measured electronics contribution from the time reference signal
  - Laser and beam runs

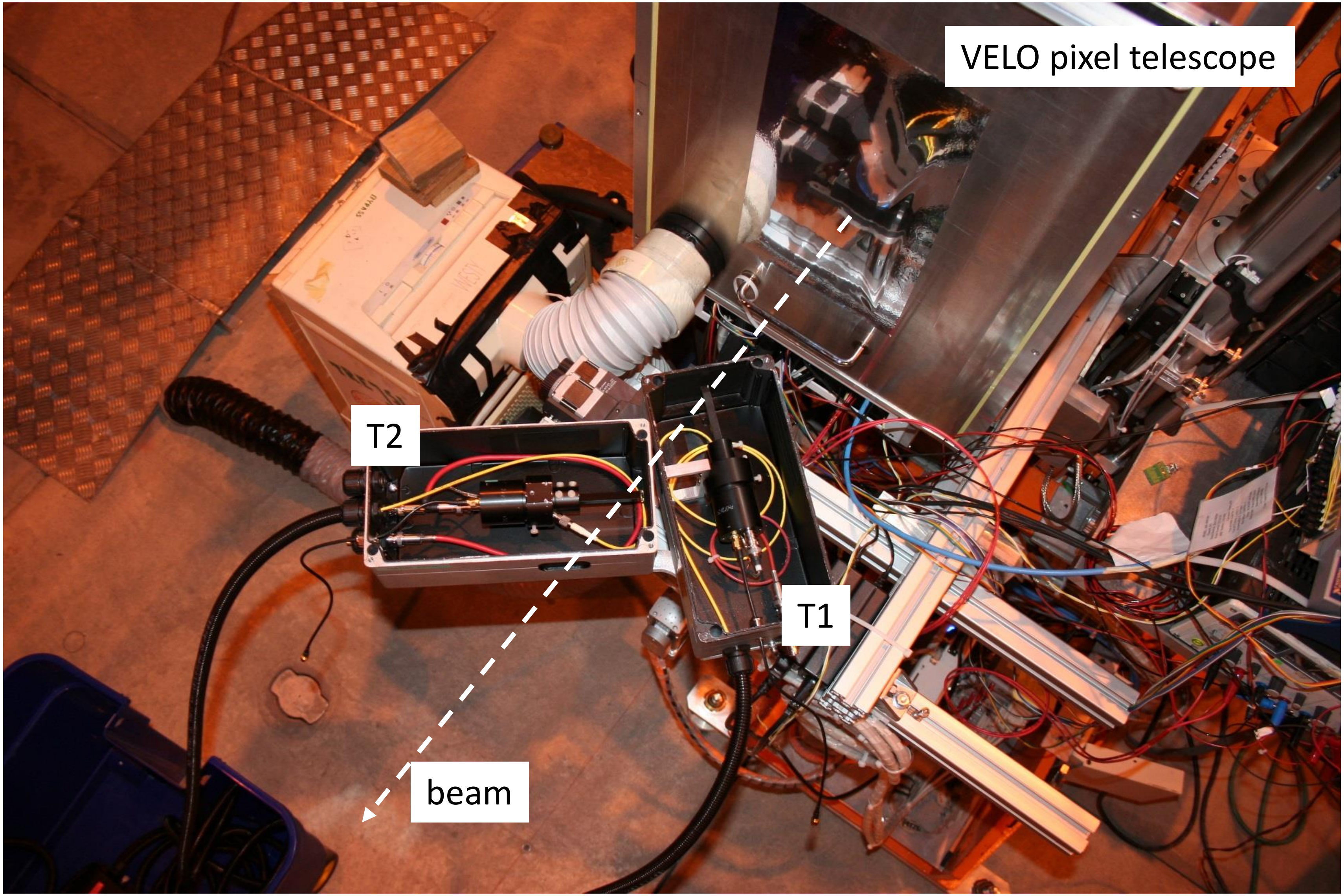




$$\sigma = \frac{84ps}{\sqrt{2}} = 59.4ps$$

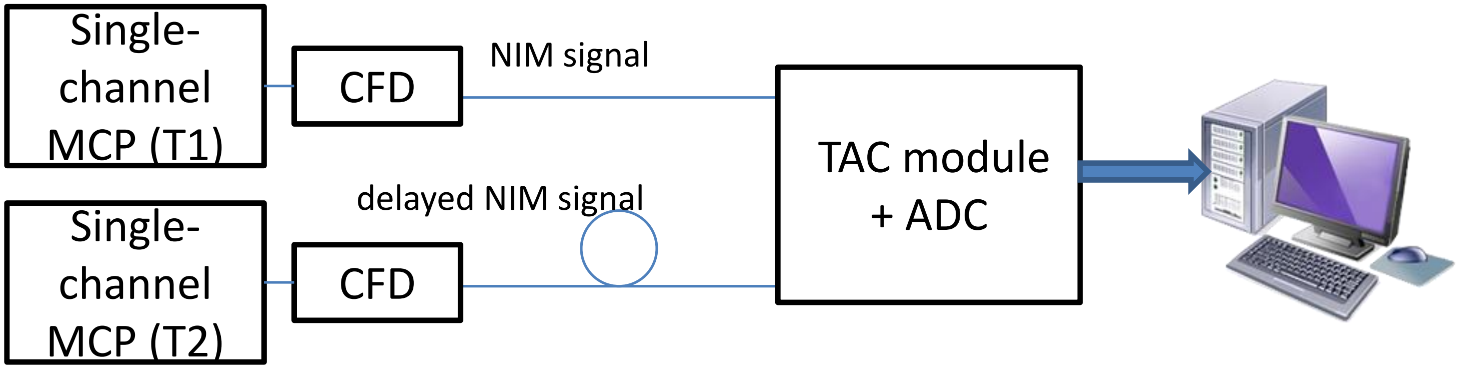
Dominated by the HPTDC binning

MCP stations



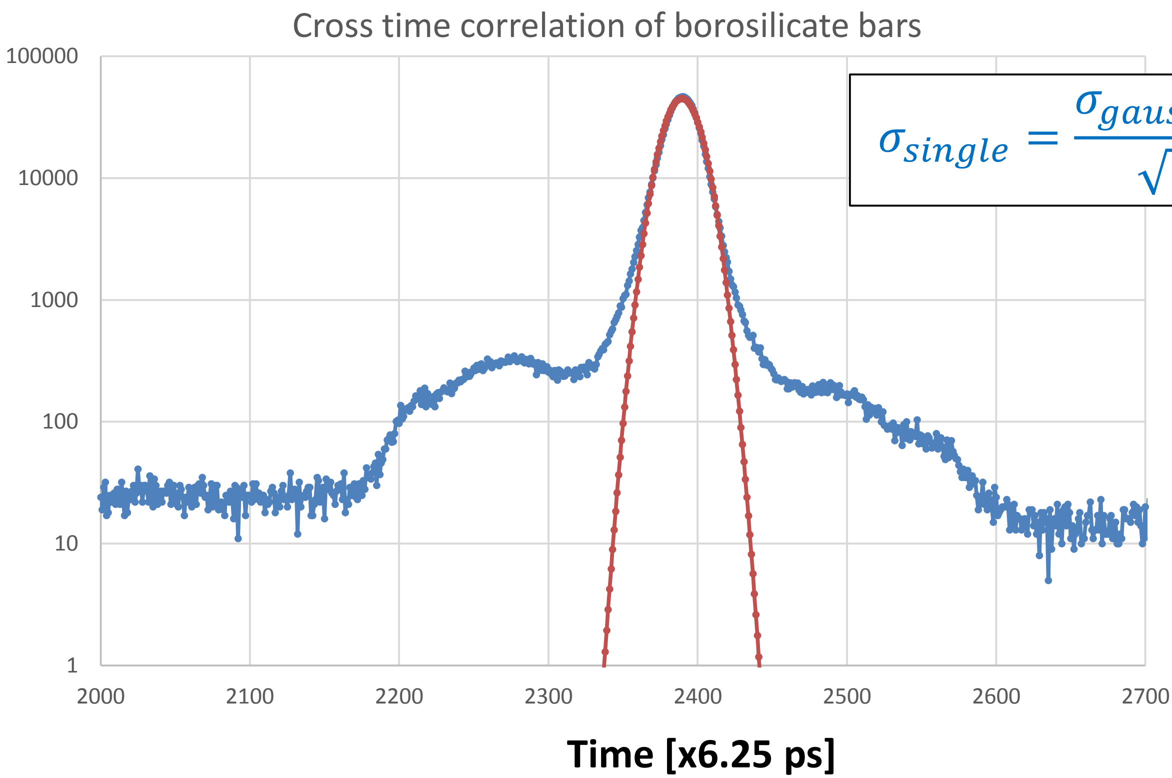
Jitter from time reference signal

- 2 Cherenkov radiator configurations:
  - Borosilicate blackened bar
  - Borosilicate non-blackened bar
- Scintillator coincidence from VELO telescope signal used as trigger
- Runs independently from telescope at low intensity rate
- Single-channel MCP stations → XY and θ alignment
- Measurements:
  - 2 charge preamplifiers → charge spectrum and photon yield
  - 2 CFDs (one delayed) input to a TAC module → time jitter



Time jitter estimate (blackened bars)

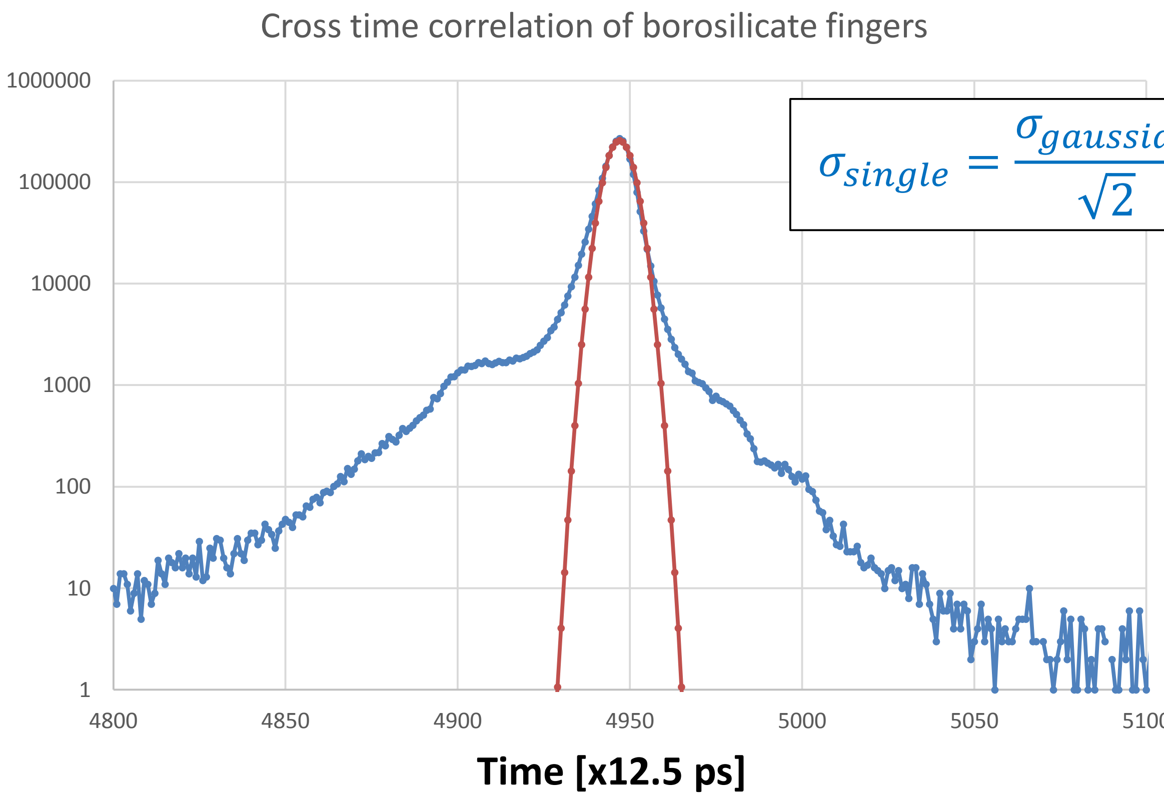
- "beam" tube + CFD as START time
  - Photon yield: 1.7 photo-electrons on average
- "lab" tube + CFD + 16ns as STOP time
  - Photon yield: 1.6 photo-electrons on average



$$\sigma_{single} = \frac{\sigma_{gaussian}}{\sqrt{2}} = 49.7\ ps$$

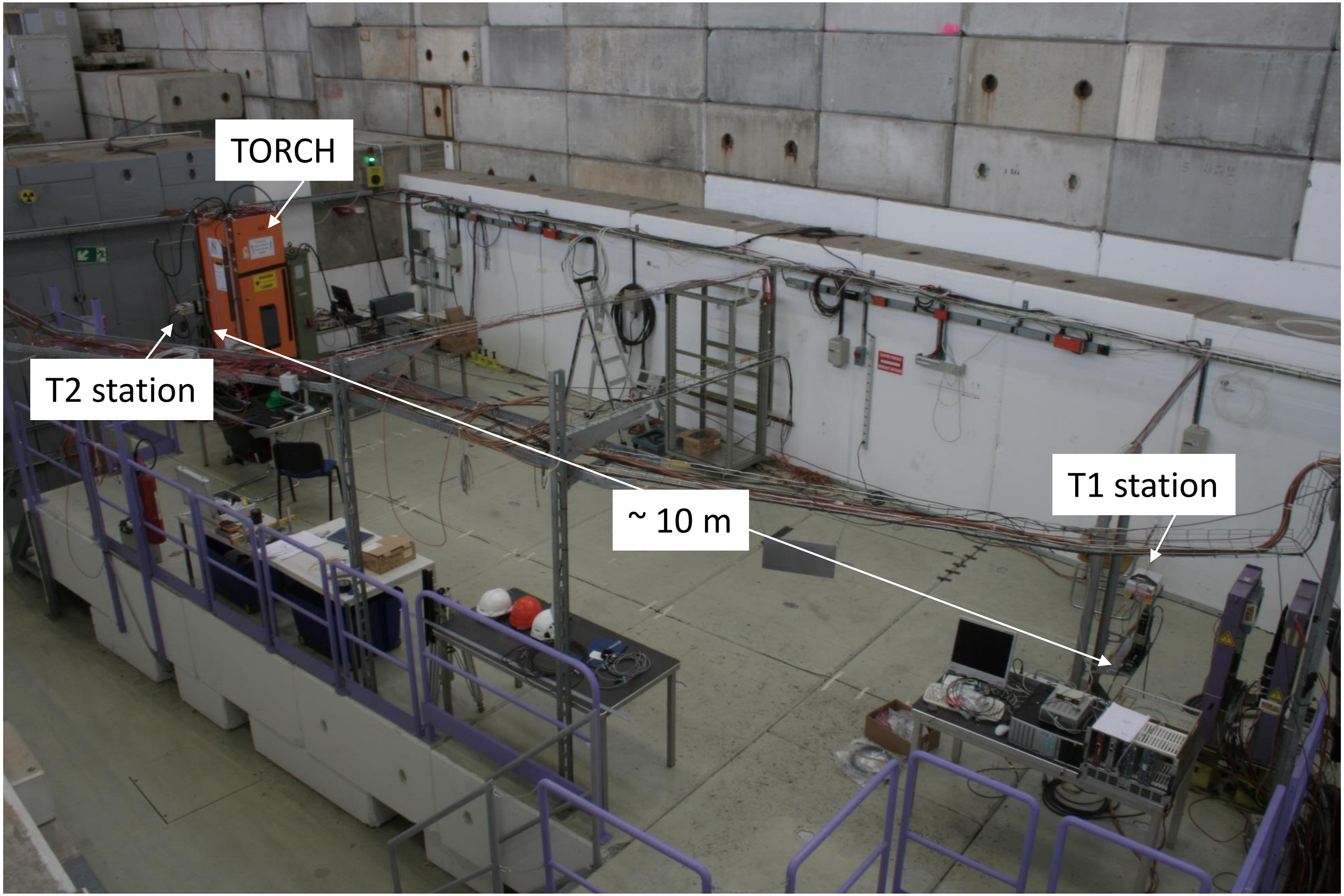
Time jitter estimate (non-blackened bars)

- "beam" tube + CFD as START time
  - Photon yield: 8.5 photo-electrons on average
- "lab" tube + CFD + 16ns + 3x(16ns) as STOP time
  - Photon yield: 8.7 photo-electrons on average

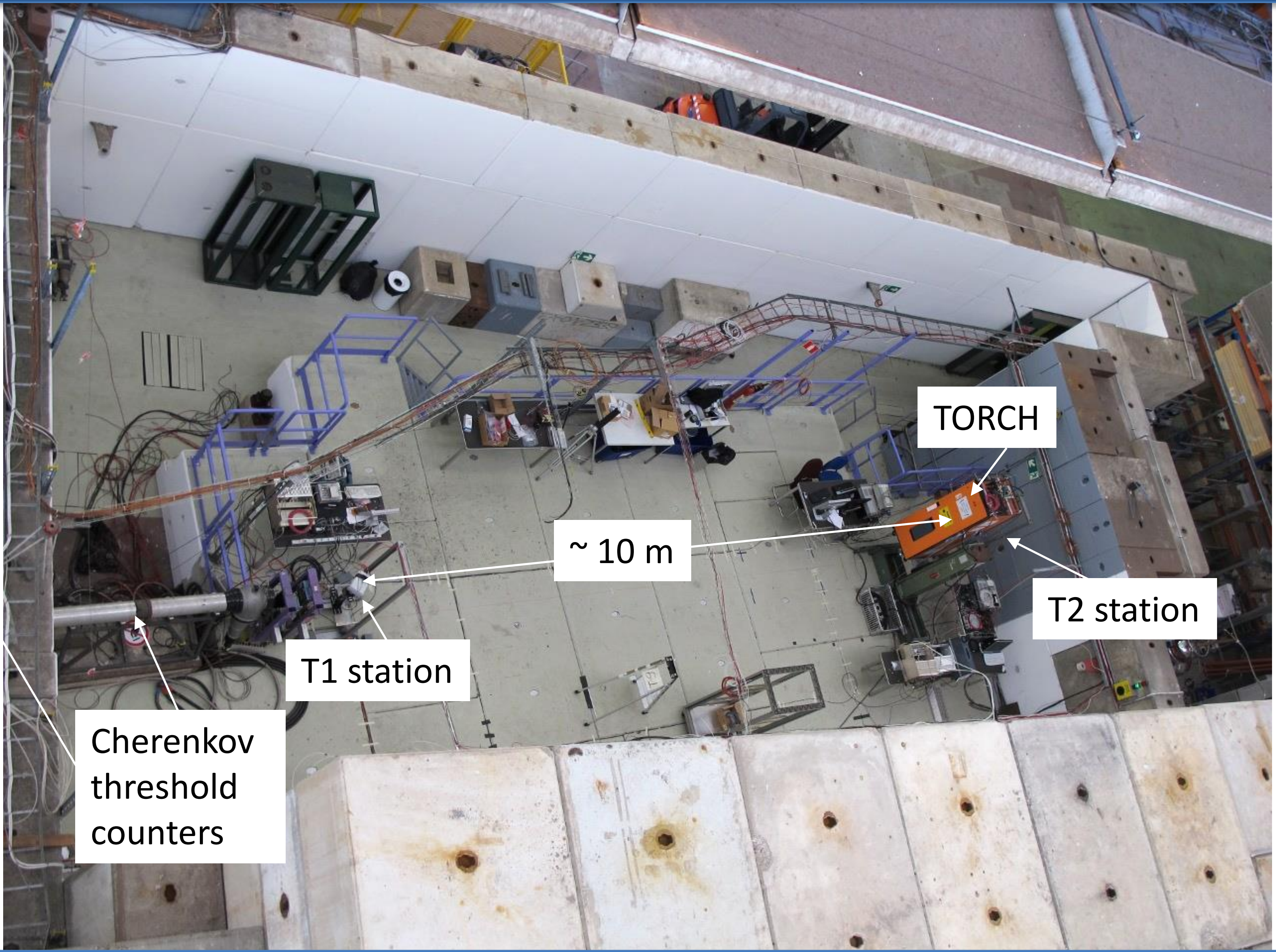


$$\sigma_{single} = \frac{\sigma_{gaussian}}{\sqrt{2}} = 32\ ps$$

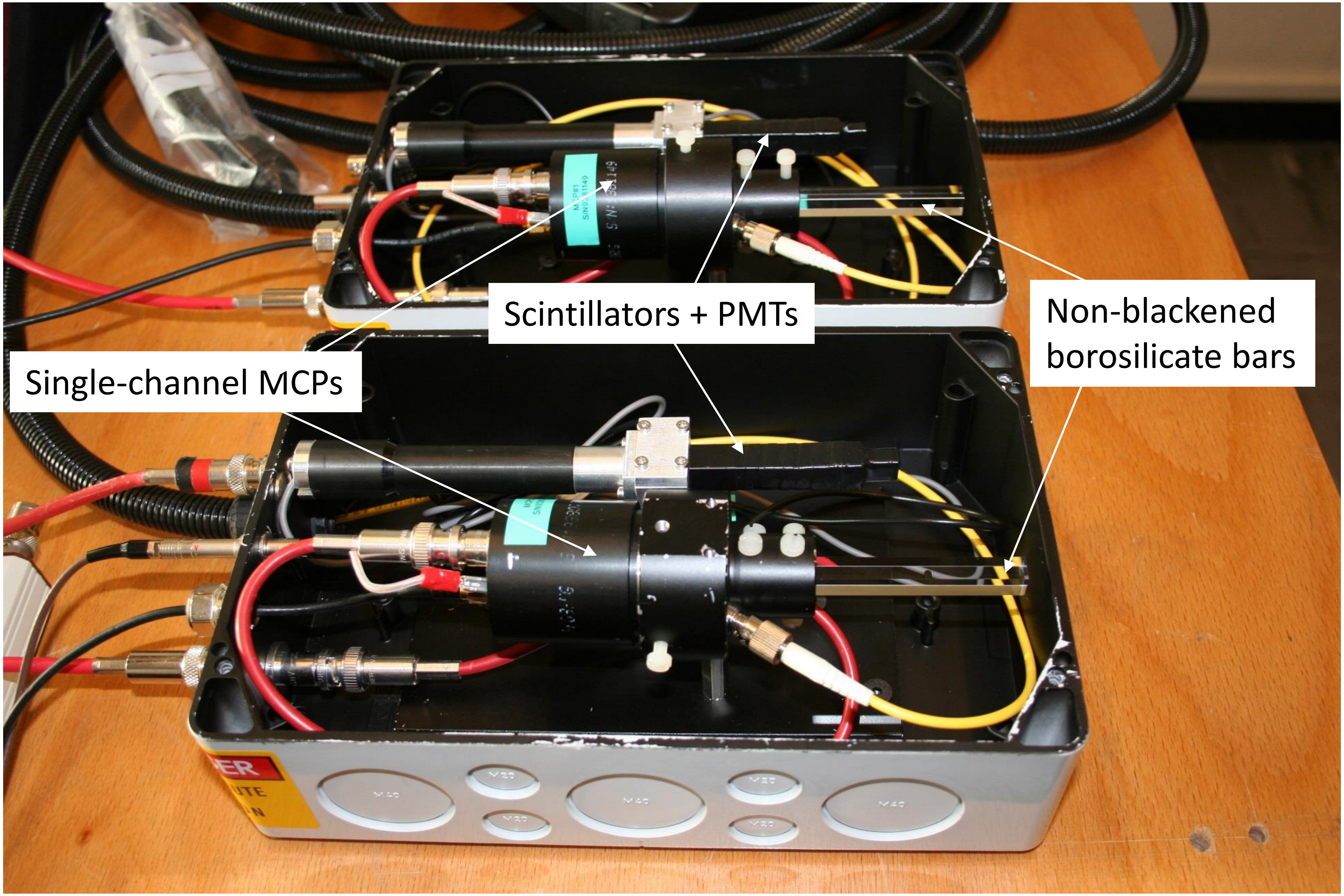
CERN PS beam test on-going



CERN PS beam test on-going

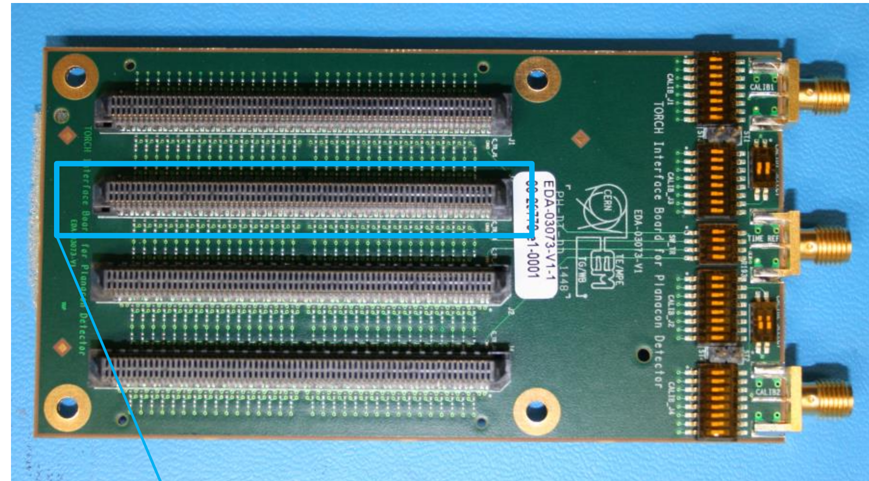


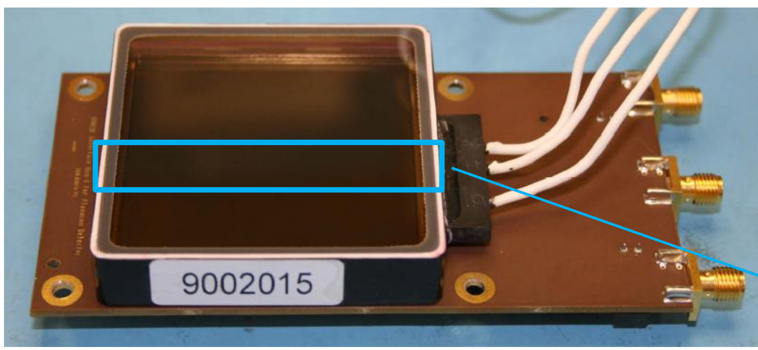
Timing/scintillator stations

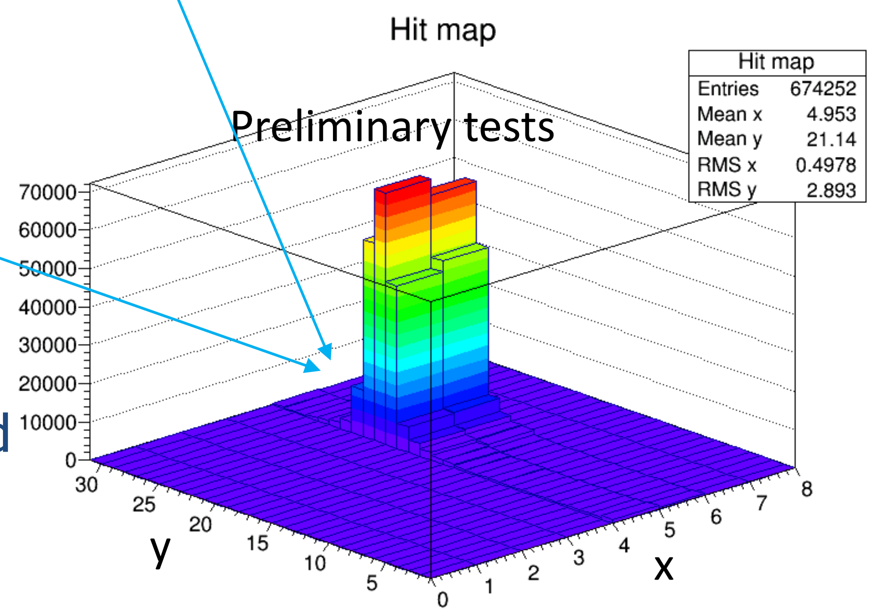


Commercial 32x32ch Planacon (Photonis)

- Development of an interface board grouping by 4 channels horizontally (4 samtec connectors)
- Gold plating anode pads
- Used silk-screen technique depositing conductive glue







- Data only from third connector
- Reference signal is well transmitted
- Good response

Conclusions and perspectives

- Timing resolution achieved from lab data of ~80 ps after INL and TOT corrections → Not too far from the required resolution (limited by the HPTDC binning)
- An excellent spatial resolution is achieved
- TORCH prototype module has been developed and its performance is being assessed in beam tests
- Time resolution per single channel of 220 ps includes all effects: chromatic dispersion, photon time of propagation, emission point error, etc. → Still work in progress
- Time jitter from time reference station is not dominant to the overall resolution from TORCH prototype system
- Current PS beam test aims to perform real particle identification at low momentum below 10 GeV/c
- PS beam tests foreseen for next year

The support of the European Research Council in funding this work is gratefully acknowledged

- ERC-2011-AdG, 291175-TORCH (http://cordis.europa.eu/projects/rcn/103813_en.html)

European Research Council
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Thank you for your attention

Spare slides

How to determine the TOF?

- Why do we measure θ_C? $\cos\theta_C = 1/n\beta$

$$TOF = t_{TORCH} - t_{PV} = \frac{|x_{TORCH} - x_{PV}|}{\beta c}$$

$$t_{TORCH} = t_{photon\ arrival} - TOP$$

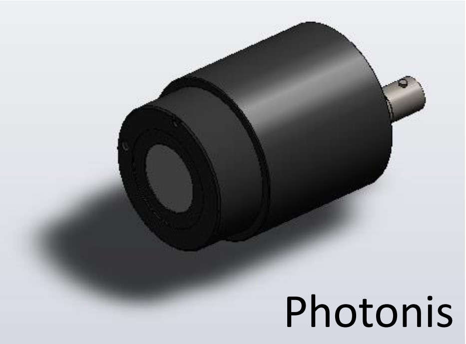
- Correct for the chromatic dispersion of quartz: n(λ)
  - Cherenkov angle → phase velocity: $\cos\theta_C = 1/\beta n_{phase}$
  - Time of Propagation (TOP) → group velocity: $TOP = path\ length\ \frac{n_{group}}{c}$

- θ_C → n_{phase} → λ → n_{group} → TOP → t_{TORCH} (crossing time)

- To obtain the TOF, we need the start time t_{PV}
  - Use other tracks from PV, most of them are pions → t_{PV}: average time assuming they are all pions

Single-channel MCP tube (Photonis)

- Photon detector:
  - single channel MCP-PMT (Photonis NL)



- PP0365G specifications:
  - MCP-PMT tube
  - single channel (SMA connector)
  - 6µm pore diameter, chevron type (2), ~55% open-area ratio
  - low MCP gain typ. $<10^5$
  - Small gaps:
    - PC-MCPin: 120µm
    - MCPout-anode:1mm
  - S20 photocathode on quartz
  - 18mm active diameter
  - 6pF anode capacitance
  - Rise time 20-80% >700ps
  - HV applied 2.93kV (1.95 kV across the MCP) filter and bleeder chain 1+(1-10-3)

Experimental setup

- Pulsed blue (405nm) laser diode @1KHz (20ps FWHM, sync<3ps)
- Monomode fibers
- ND filters: **single photon regime**
- Single-channel ORTEC electronics

- **Light calibration setup:**
  - Pulse height spectra (PHS)
  - Standard Poisson distribution to fit data
  - Average number of photoelectrons per pulse (μ) inferred from P(0)

Light source fluctuation →

$$P_{\mu}(N) = \frac{\mu^{N}}{N!} e^{-\mu} = \frac{A_N \sigma_N \sqrt{2\pi}}{total\ surface}$$

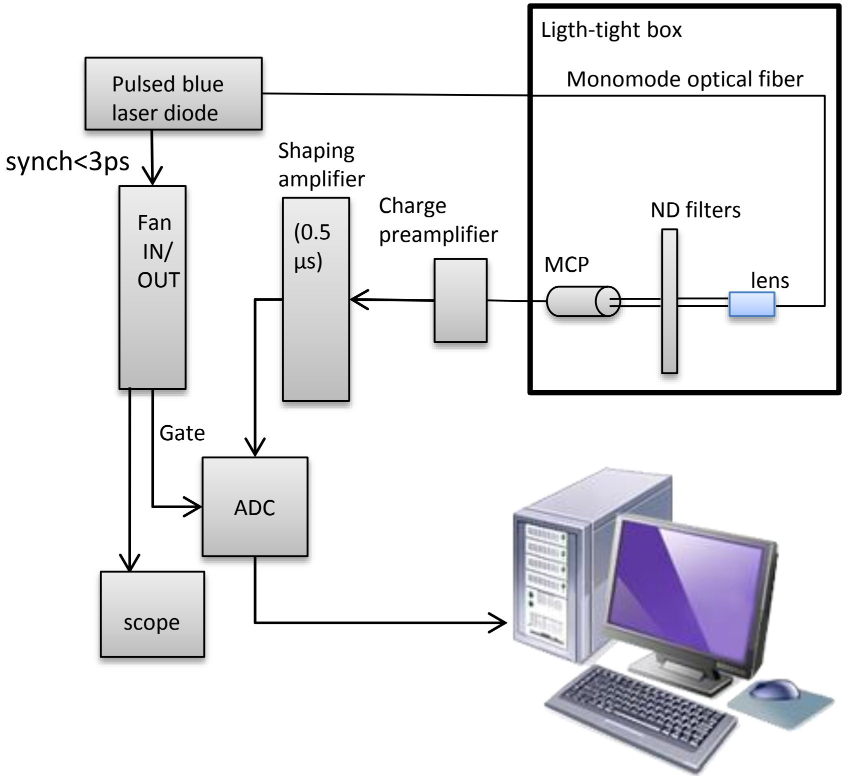
N: number of photoelectrons per pulse

N-photoelectron peak width scales as:

MCP gain fluctuations →

$$\sigma_{Nphe} = \sqrt{N}\sigma_{1phe}$$

where σ_{1phe} is the 1-photoelectron peak width



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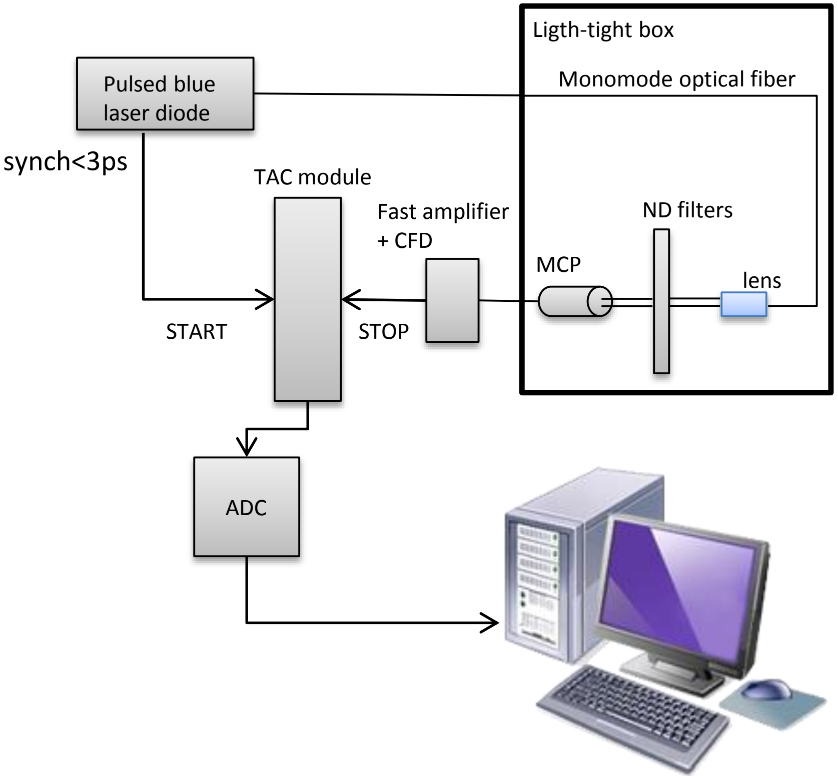
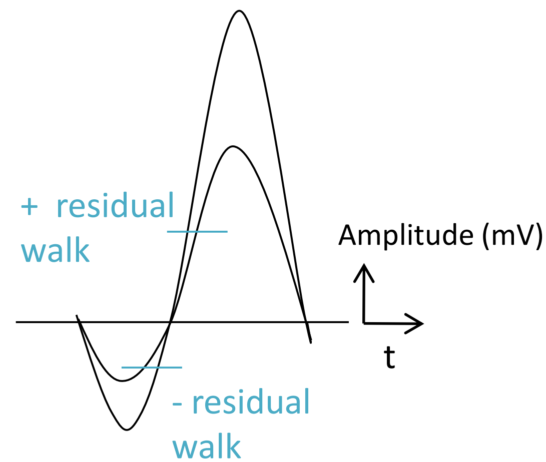
- **Timing setup:**
  - Time jitter distribution
  - Exponentially-modified Gaussian distribution to fit prompt peak → time resolution (σ)



Discriminator behaviour

- For a given discriminator threshold:
  - The noise induces a **jitter** → signal is detected earlier or later in time
  - The signal height variation induces a **walk**:
    - Large signals are detected earlier
    - Small signals are detected later
- Constant Fraction discriminator:
  - Based on zero-crossing techniques

CFD {
- Large amplitudes:
  +walk → earlier / -walk → later
- Smaller amplitudes:
  +walk → later / -walk → earlier



  - Produce accurate timing information from analog signals of varying heights but the same rise time
  - Principle: splitting the input signal, attenuating half of it and delaying the other half, then feeding the two halves into a fast comparator with the delayed input inverted
  - Effect: to trigger a timing signal at a constant fraction of the input amplitude, usually around 20%

Single-channel timing fitting model

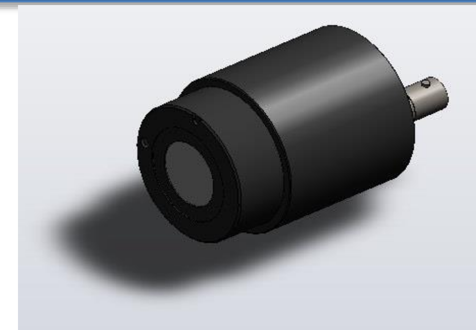
- Single-channel MCP investigated at several light intensities and laser tune setting [L. Castillo García, LHCb-INT-2013-042]
- Main peak of timing distributions represents the MCP intrinsic time response → fitted with an **exponentially-modified Gaussian distribution** [I. G. McWilliam, H. C. Bolton, Analytical Chemistry, Vol. 41, No. 13, November (1969) 1755-1762]

$$f(t, A, t_c, \sigma_g, \tau) = \frac{A}{\tau} \exp\left(\frac{1}{2}\left(\frac{\sigma_g}{\tau}\right)^2 - \frac{t - t_c}{\tau}\right)\left(\frac{1}{2} + \frac{1}{2}\operatorname{erf}\left(\frac{\frac{t - t_c}{\sigma_g} - \frac{\sigma_g}{\tau}}{\sqrt{2}}\right)\right)$$

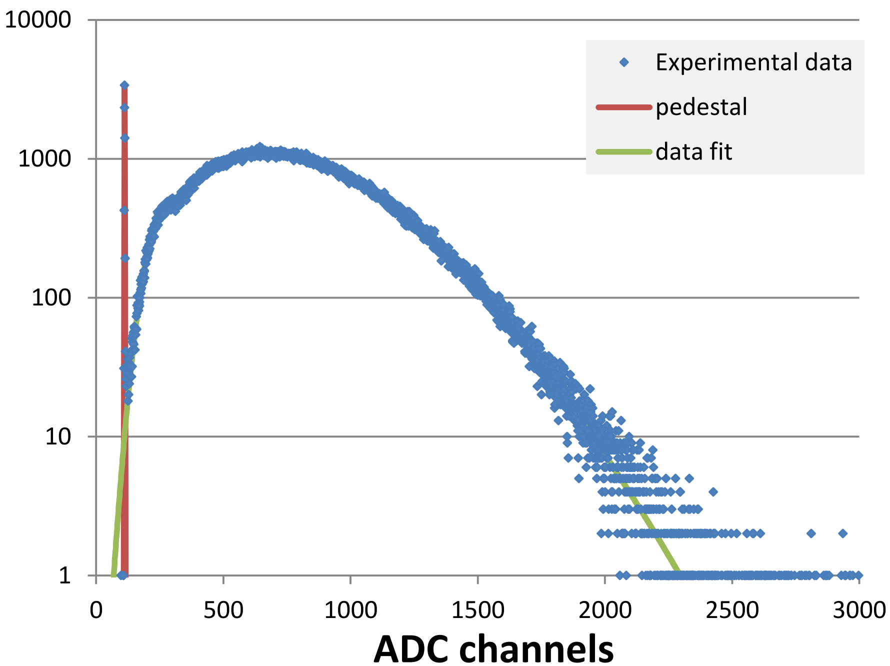
t: time, A: amplitude, t_c: centroid at maximum height of the unmodified Gaussian, σ_g: standard deviation of the unmodified Gaussian, τ: time constant of exponential decay used to modify the Gaussian and $erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$.

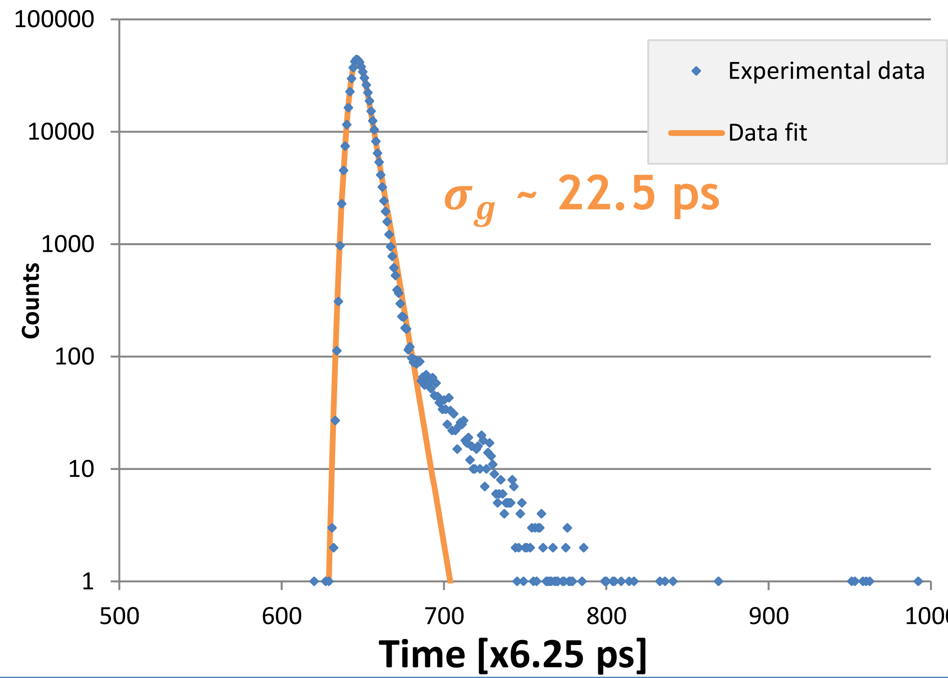
- Model chosen given the **asymmetry in the MCP time response** for large values of μ.
- **Time jitter** value defined as the standard deviation $\boldsymbol{\sigma_g}$ of the Gaussian.
- Use to extract the timing resolution for Planacon MCP

Commercial MCP devices (DEP-Photonis)



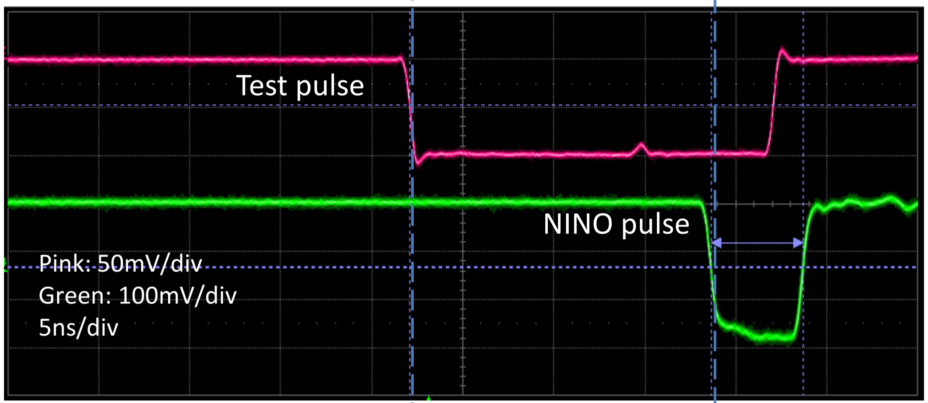
- Single-channel MCP device coupled to ORTEC CFD used as time reference for TORCH
- Standard Poisson distribution to fit data
- Photon yield: 4.5 photo-electrons on average
- Main peak of timing distributions represents the MCP intrinsic time response → fitted with an **exponentially-modified Gaussian distribution**





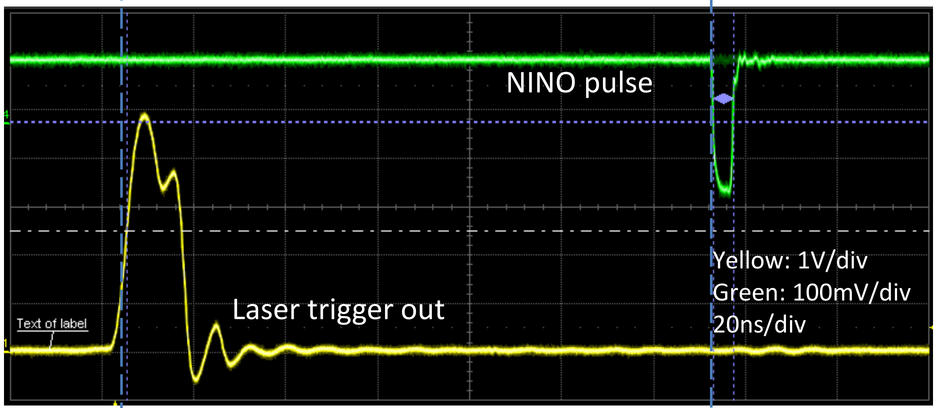
Results

Electrical pulse
(charge =261 fC)



t_{ref} t_{nino}

CFD signal
(charge = 552 fC)



t_{ref} t_{nino}

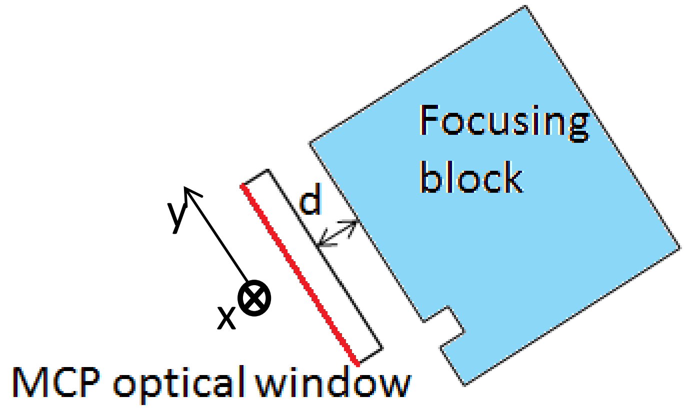
$$t_{resolution} = t_{nino} - t_{ref}$$

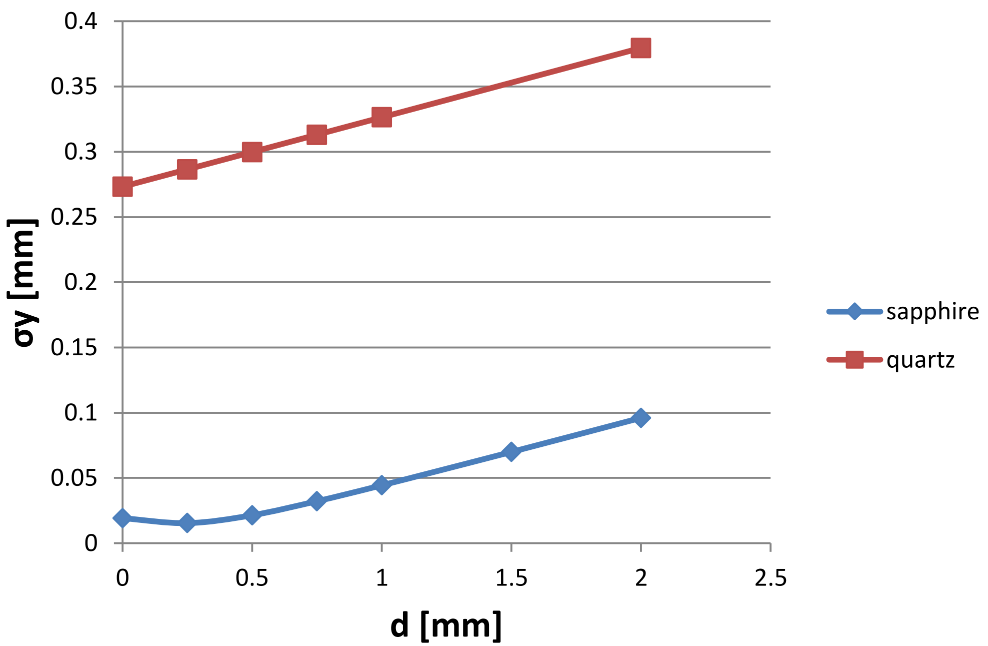
- Jitter pulser-scope: 11.51ps/$\sqrt{2}$ = 8.14ps
- Jitter NINO:
  - Chip 1 channel 31: 16.64ps → 14.51ps
  - Chip 2 channel 0: 18.27ps → 16.36ps

- Jitter ref-scope:
  - Laser wrt laser: 40.14 /$\sqrt{2}$ = 28.38ps
  (Nim wrt laser: 39.3ps → 27.19ps)
- Jitter NINO:
  - Chip 1 channel 31: 40.6ps → 29.03ps
  - Chip 2 channel 0: 41.2ps → 29.87ps

Optica3: optimal position MCPs windows

- Varying air gap (d) between focusing block and MCP window

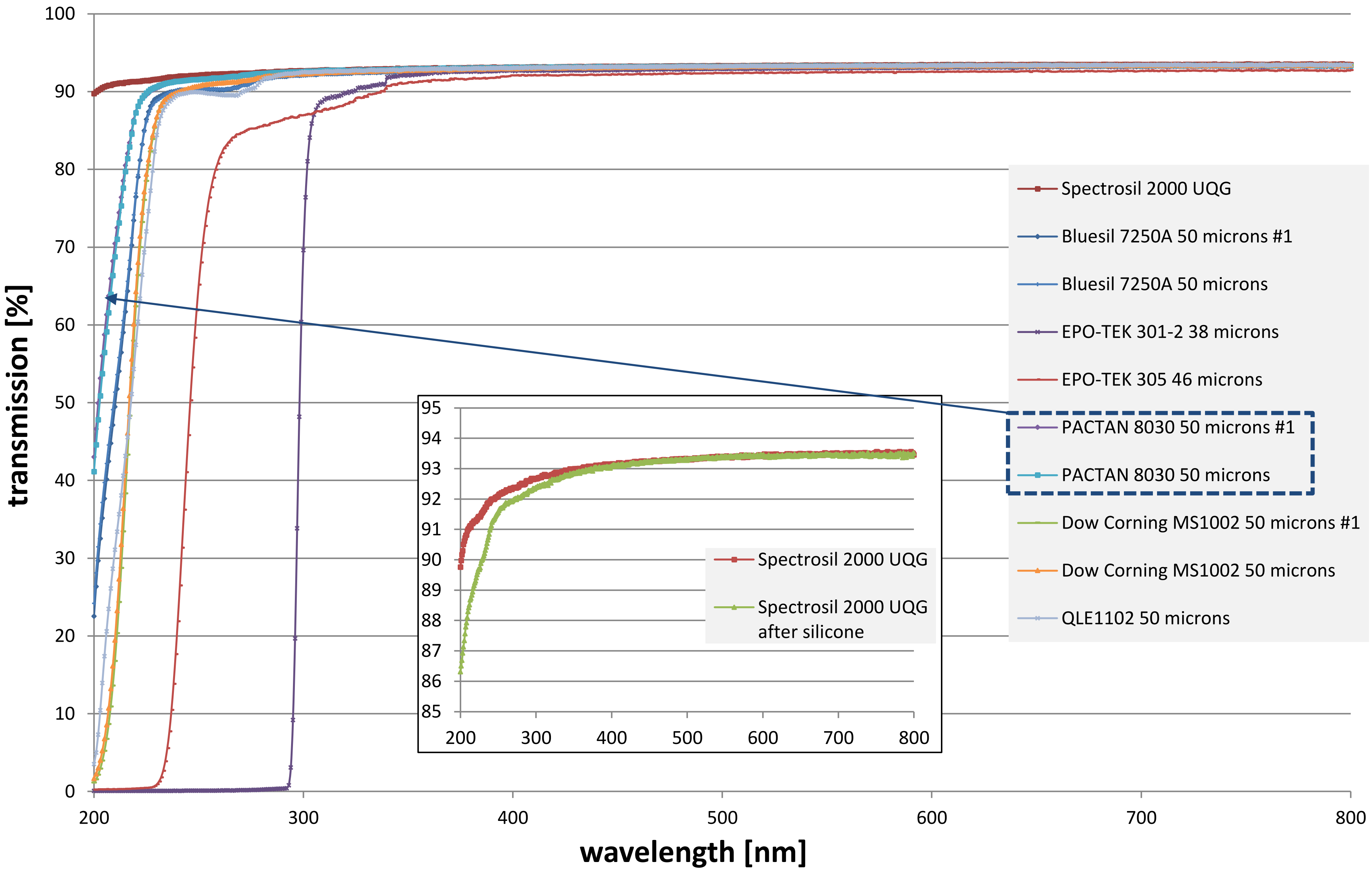




- 1mm-thick sapphire window (32x32ch Planacon)
- 9mm-thick quartz window (32x32ch Photek MCP)

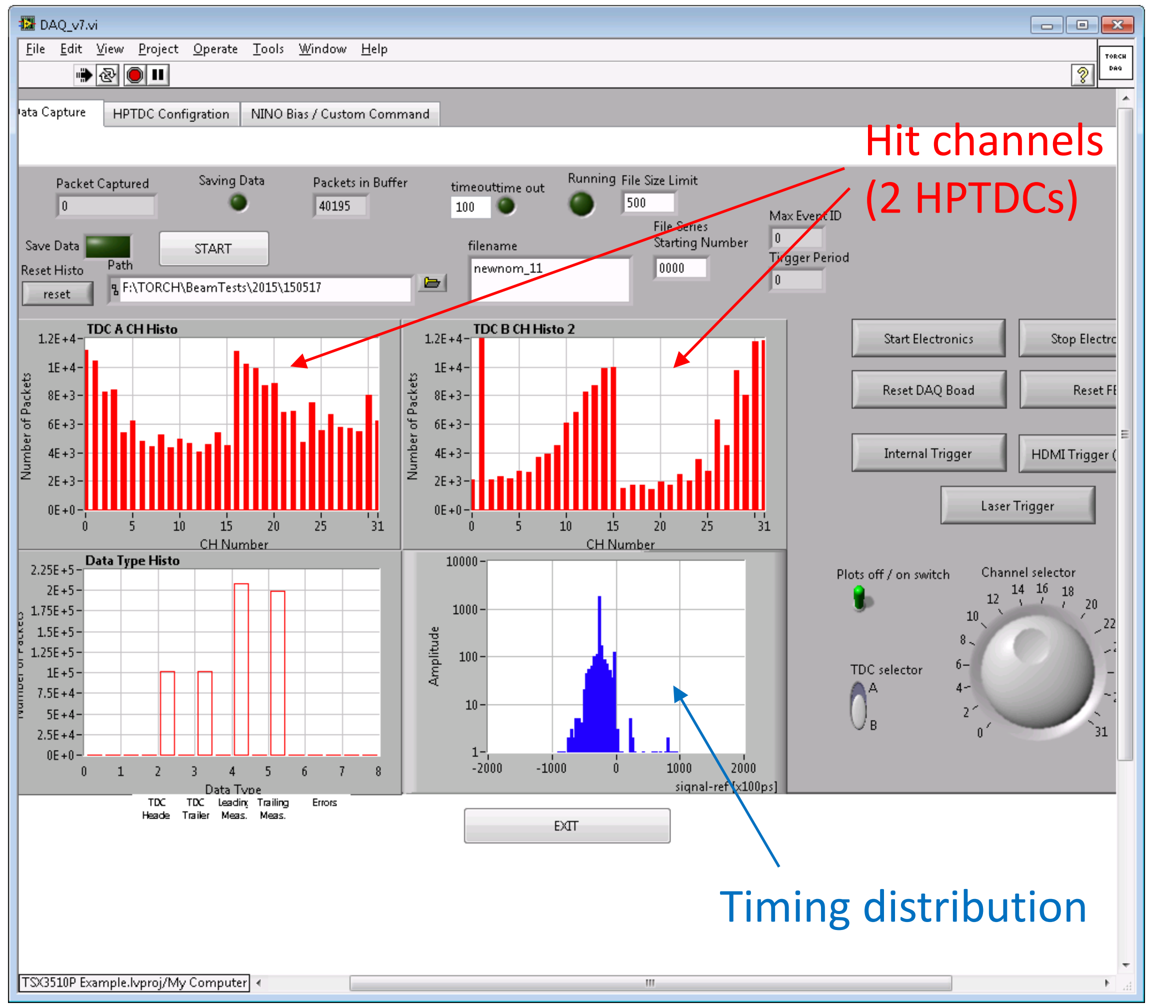
Decided position: ~0.5 mm

Transmission curves for Spectrosil + glues



DAQ, monitoring and data taking

- LabVIEW interface
- Single-channel MCP station ϴ and XY alignment
    - Find optimal position with hits on test channel (TDC B ch1)
- Used various NINO threshold
    - Optimized settings for odd and even channels
- Runs with telescope and independently
- TORCH module translations using a DESY table:
    - Vertical translation and fine scan (5 mm step)



CERN PS beam test on-going

- From Wednesday 28th October to Monday 16th November
- TORCH main and only user in T9
- Beam conditions:
  - ~5 GeV/c electron-rich beam
  - Low intensity rate: 100’s Hz

- 2 single-channel MCP tubes mounted on two independent micrometric stages and read out with single-channel ORTEC electronics
- Cherenkov radiator configuration:
  - Borosilicate non-blackened bars → Higher photon yield and better time resolution
- Coincidence signal from 3 scintillators + 3 PMTs used as trigger

- Test MCP tubes:
  - customized device fully instrumented with customized electronics
  - commercial device (32x32ch Planacon) half instrumented with customized electronics