CERN LHCb

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

MCP photon detectors studies for the TORCH detector

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

Ring Imaging Cherenkov Detectors session – 2nd July 2014

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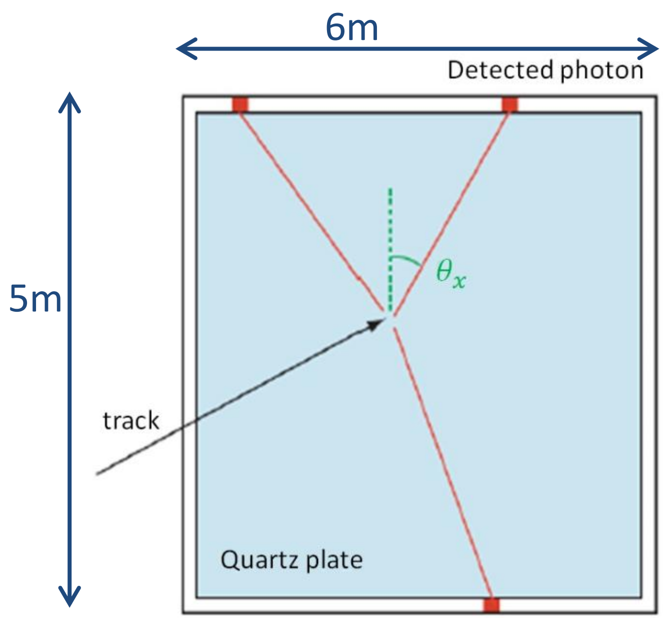
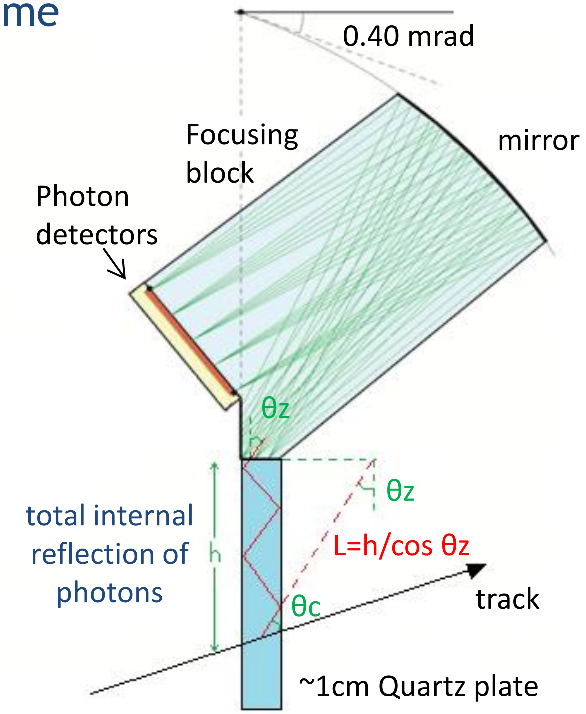
Layout

- Introduction to TORCH
- Photon detector characterization:
  - Commercial MCP devices performance with single-channel and custom multi-channel front-end electronics
  - Custom MCP devices performance with single-channel electronics
- Simulation and optical studies
- Beam test preparation
- Conclusions and perspectives

TORCH detector

- **Time Of internally Reflected Cherenkov light (TORCH)**
  - a proposed precision Time-of-Flight (TOF) detector for particle identification (PID) at low momentum [M.J. Charles, R. Forty, Nucl. Instr. Meth. A 639 (2011) 173] [R. Forty, 2014 JINST 9 C04024]
  - Motivation for TORCH development is LHCb upgrade [CERN-LHCC-2011-001]
  - Measure the TOF of charged-particle tracks with **12.5ps precision/track**
  - Path length reconstruction → **~1mrad precision** required for (θ_x, θ_z)
  - Photon propagation time in quartz → crossing time

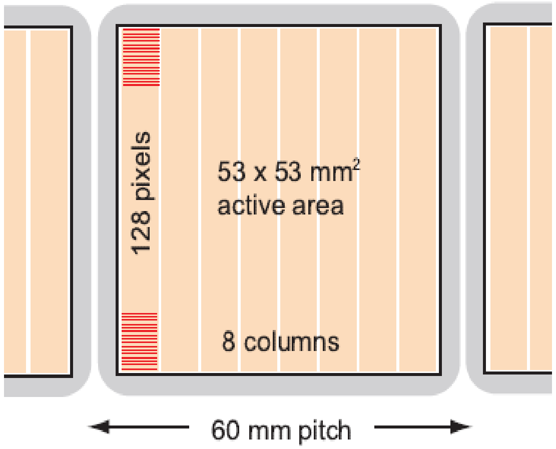




Photon detectors requirements

- Single photon sensitivity → MCPs best for fast timing of single photons
- Development of photon detectors with **finely segmented anode** (8x128 channels)
  - Propagation angle projected on the quartz plate (θ_x) → coarse segmentation (~6mm) sufficient
  - Propagation angle (θ_z) → fine segmentation (~0.4mm) → **50ps smearing of photon propagation time due to pixellization**
- **Arrival time precision of ≤50ps** for single photon signal at a gain of $\sim 5x10^5$

$$\sqrt{\sigma_{pixellization}{}^2 + \sigma_{timing}{}^2} \sim 70ps \; / \; detected\ photon$$



- Lifetime aspects:
  - detected photon rate: 1-10MHz/cm²
  - Integrated anode charge per year: 1-10C/cm²

TORCH R&D project

- 4 year TORCH R&D project awarded by ERC, started 2 years ago (collaboration between CERN, Bristol and Oxford Universities)

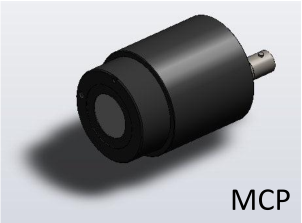
[ERC-2011-AdG, 291175-TORCH, http://cordis.europa.eu/projects/rcn/103813_en.html]

  - Proof-of-principle with a prototype TORCH module

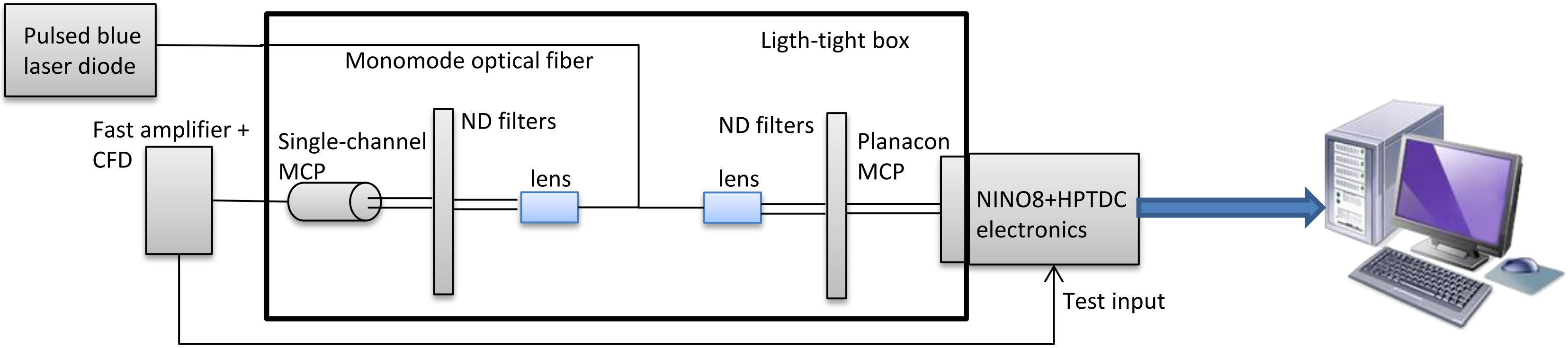
- Development of suitable MCP photon detectors with industrial partner: Photek (UK)
  - 1^{st} phase: Circular MCP with extended lifetime (~5C/cm^2)
    - Atomic layer deposition (ALD) coating
  - 2^{nd} phase: Circular MCP with fine granularity
    - Modelling studies to achieve the required granularity
  - 3^{rd} phase: Final square MCP with extended lifetime and fine granularity
    - High active area (>80%)

Commercial MCP devices (Photonis)

- Initial tests with commercial devices
  - Poster @NDIP11 showed tests with single-channel electronics → TTS≤ 40ps in single photon regime and MCP gain $5x10^5$ [L. Castillo García, Nucl. Instr. Meth. A 695 (2012) 398]
  - Custom multi-channel electronics → beam and laboratory tests (see later)
- Photon detectors from Photonis:
  - 8x8 array Planacon MCP (test tube)
  - Single-channel MCP (as time reference)



- Using custom multi-channel front-end electronics: [R.Gao et al., 2014 JINST 9 C02025]
  - fast amplifier and Time-Over-Threshold (TOT) discriminator (NINO8 ASIC) [F. Anghinolfi et al., Nucl. Instr. and Meth. A 533 (2004) 183]
  - time digitization converter (HPTDC ASIC) [M. Mota et al., IEEE Nucl. Sci. Symp. Conf. Rec. 2 (2000) 155]



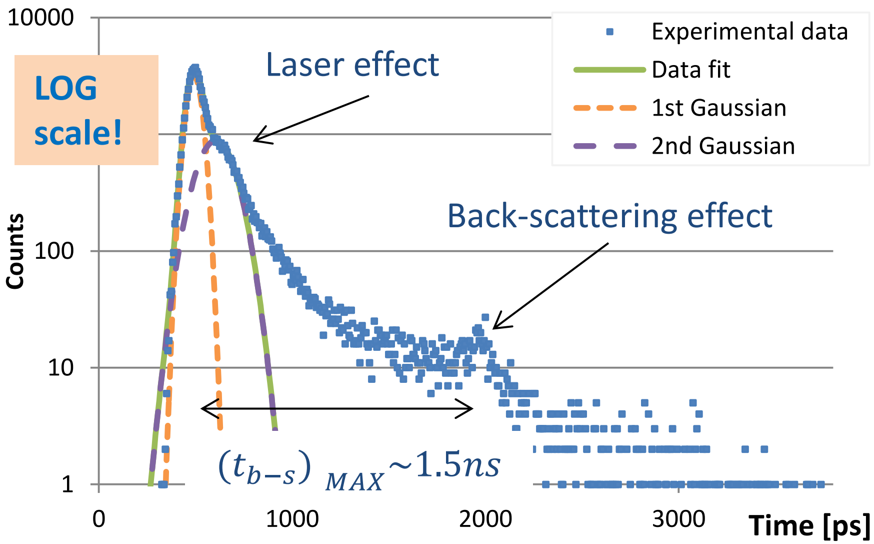
MCP 8x8array Planacon

- Single photon regime: 0.5 photoelectrons on average per pulse
- Modest Planacon gain (6×10^5) → for lifetime aspects
- Planacon large input gap → long back-scattering tail

Single-channel electronics

START signal: time reference from laser sync. signal
STOP signal: Planacon pad

$\sigma_{single-channel\ electronics}$ ~38ps

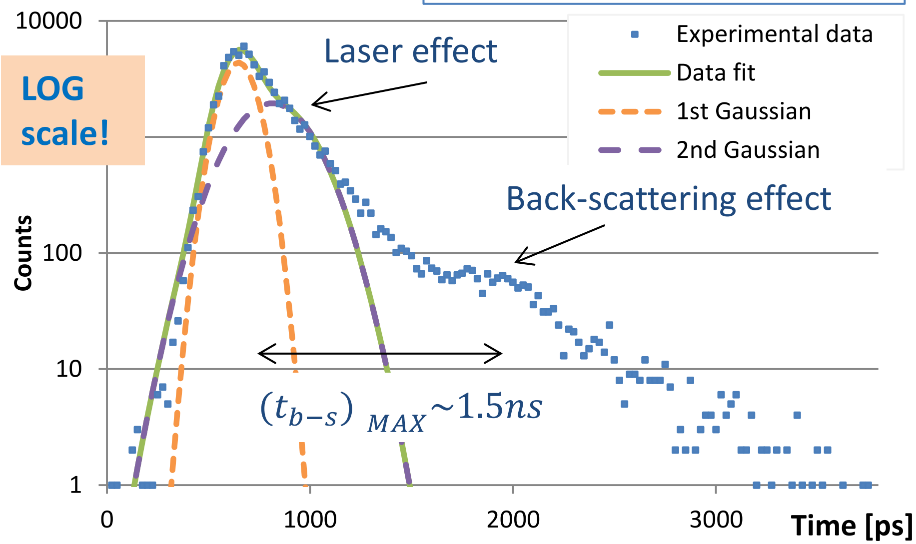


[L. Castillo García, Nucl. Instr. Meth. A 695 (2012) 398]

Custom front-end electronics (NINO8+HPTDC)

START signal: time reference from single-channel MCP (<20ps) coupled to CFD and injected on a test channel of the NINO8+HPTDC electronics
STOP signal: Planacon

$\sigma_{NINO+HPTDC}$ ~77ps



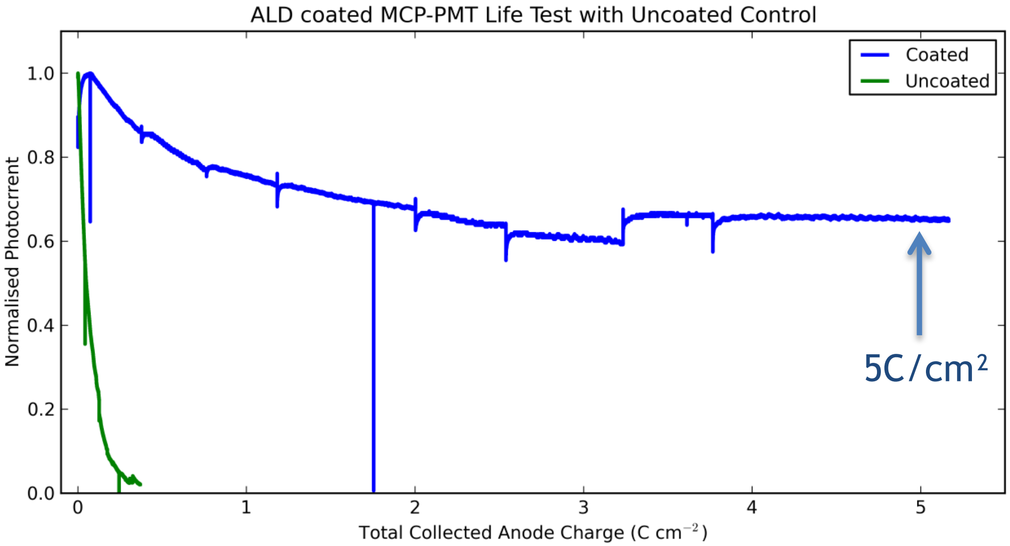
Without time walk correction and INL calibration of HPTDC chip
83% efficiency → NINO8 threshold not optimal

Custom MCP devices (Photek) - 1st phase

- 5 single-channel MCP-PMT225 with extended lifetime have been manufactured
  - Using ALD process coating on MCP
- Some devices have already been successfully characterized through accelerated ageing tests

[T. M. Connely et al, Nucl. Instr. Meth. A 732 (2013) 388]

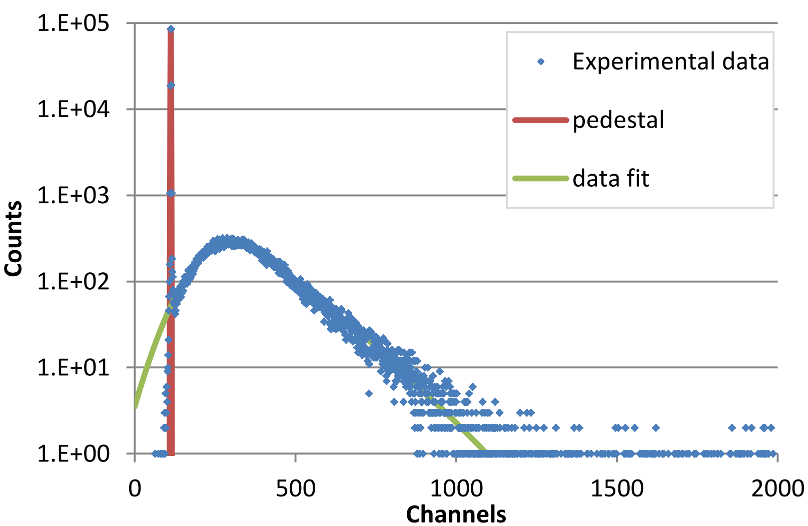
- Initial MCP gain set to 10^6
- Total accumulated anode charge: 5.16C/cm²
- 30% reduction in MCP gain
- No reduction in QE → no photocathode degradation

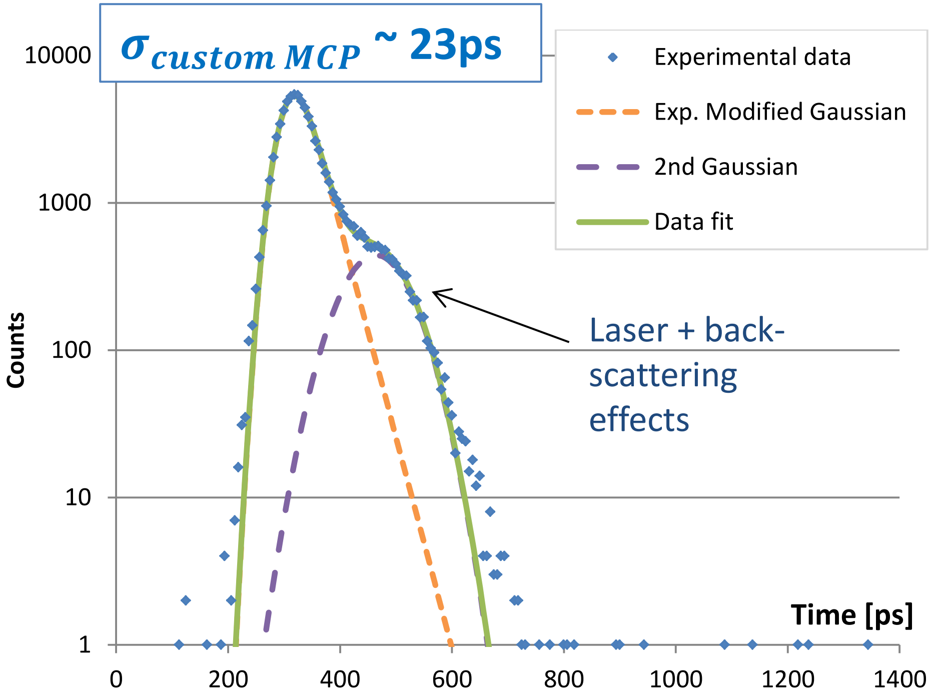


Custom MCPs characterization

[T. Gys, et al., Performance and lifetime of micro-channel plate tubes for the TORCH detector, NIM A (2014) http://dx.doi.org/10.1016/j.nima.2014.04.020]

- PMT225/SN G1130510
- Dark count rate: 3.3kHz
- Modest gain **$3x10^5$** @-2200V
- PHS → **μ ~ 0.35 photoelectrons**
- TTS → **σ ~ 23ps**

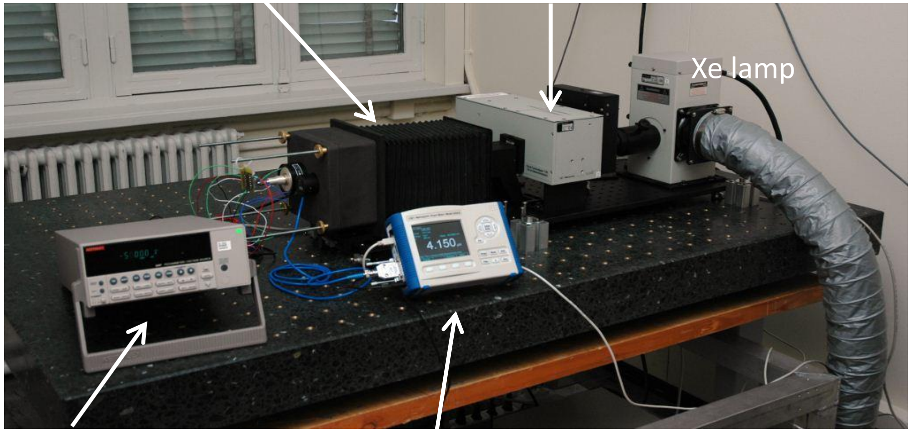


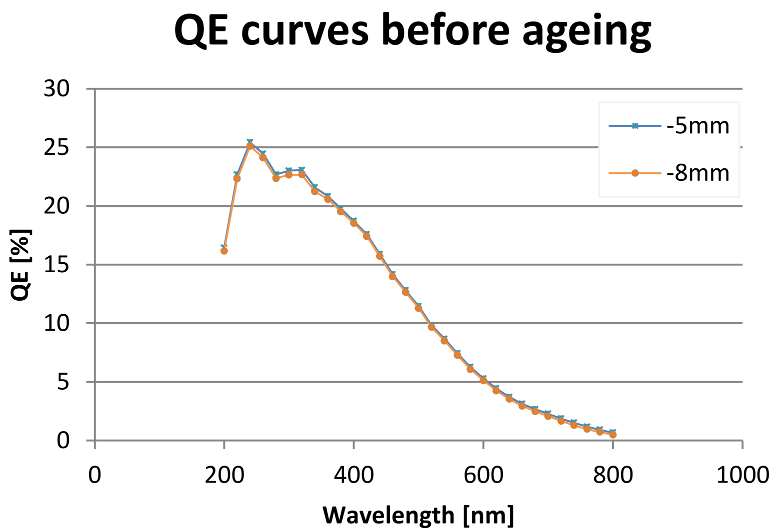


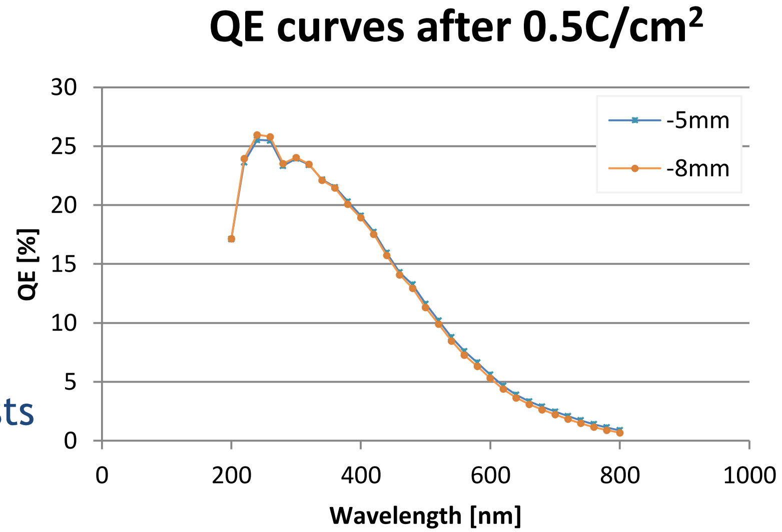
- Excellent timing performance → single-channel MCP
- Other 4 tubes show similar performance

QE and ageing tests at CERN

- QE experimental setup





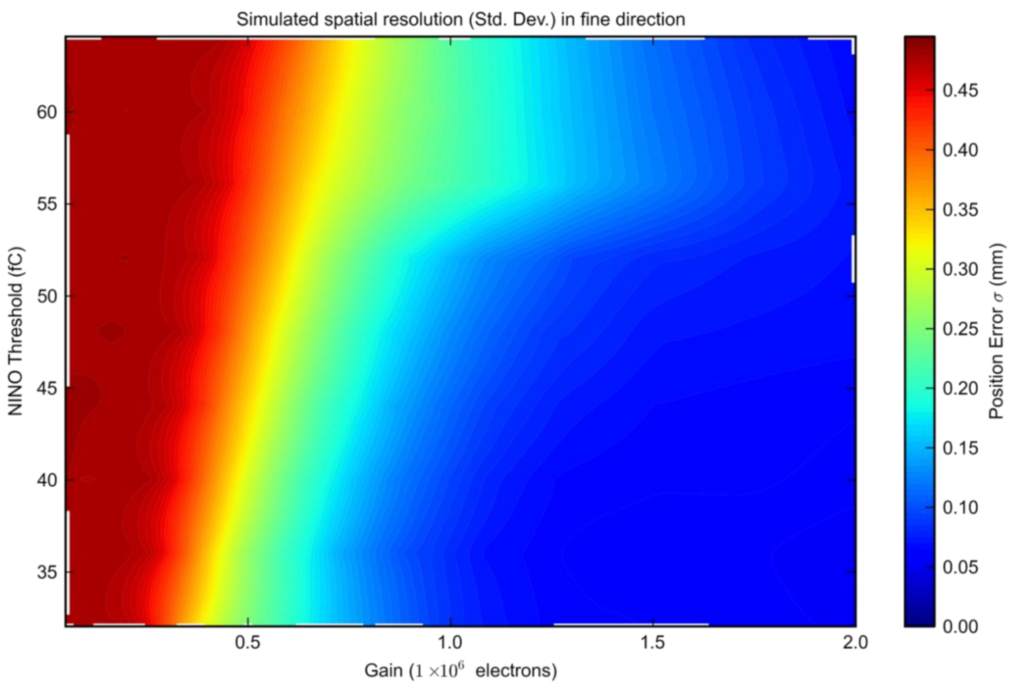


- One custom MCP tube is currently under ageing test
  - High dark count rate tube
  - Regularly monitoring of QE, gain and other parameters
  - After 0.5C/cm^2 no visible QE degradation, gain drop of 20% → in agreement with Photek tests

Custom MCP devices (Photek) – 2nd phase

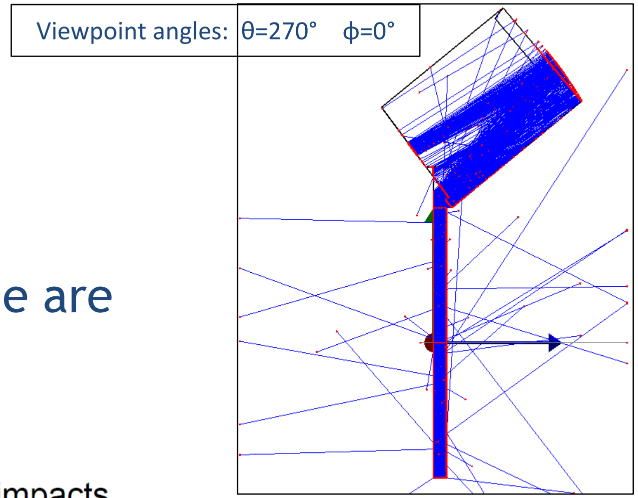
- Modelling studies on-going to achieve required granularity
- 8x64 sufficient if charge-sharing between pads is used → Improve resolution and reduce number of channels
- Simulated spatial resolution in the fine direction using charge-sharing (NINO+HPTDC electronics) as function of MCP gain and NINO threshold [J.S. Milnes et al., NIM A (2014), http://dx.doi.org/10.1016/j.nima.2014.05.035]

- Strong dependence on MCP gain and NINO threshold
- Resolution degradation at higher thresholds
- Operate at 10^6 MCP gain to achieve the required resolution



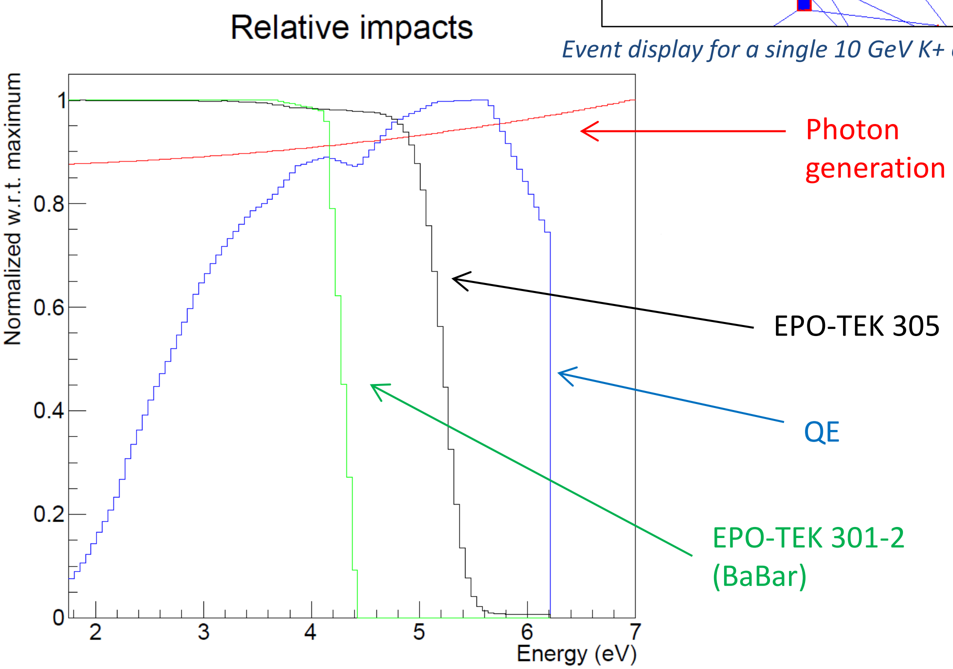
Simulation

- Geant4 software framework
  [M.Van Dijk et al, TORCH a Cherenkov based Time Of Flight detector, NIM A (2014) http://dx.doi.org/10.1016/j.nima.2014.04.083]
- Idealised TORCH detector
  - All photons arriving at the photo-detector plane are registered



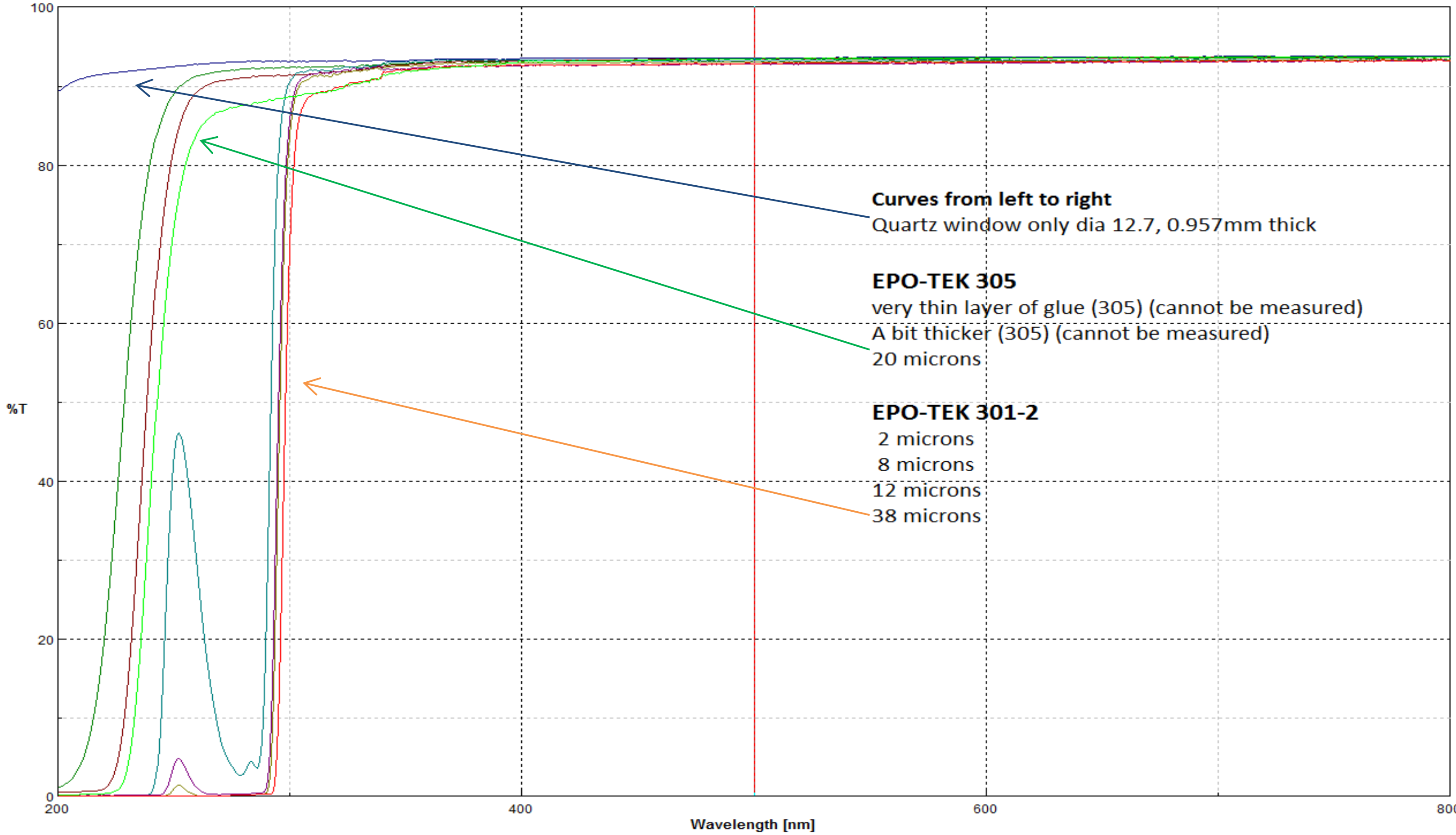
Event display for a single 10 GeV K+ crossing

- Photon loss factors:
  - Rough surface
  - Rayleigh scattering
  - Quartz spectral cut off
  - EPO-TEK glue spectral cut off
  - Mirror in focusing block
  - Quantum efficiency
  - Collection efficiency



Optical studies

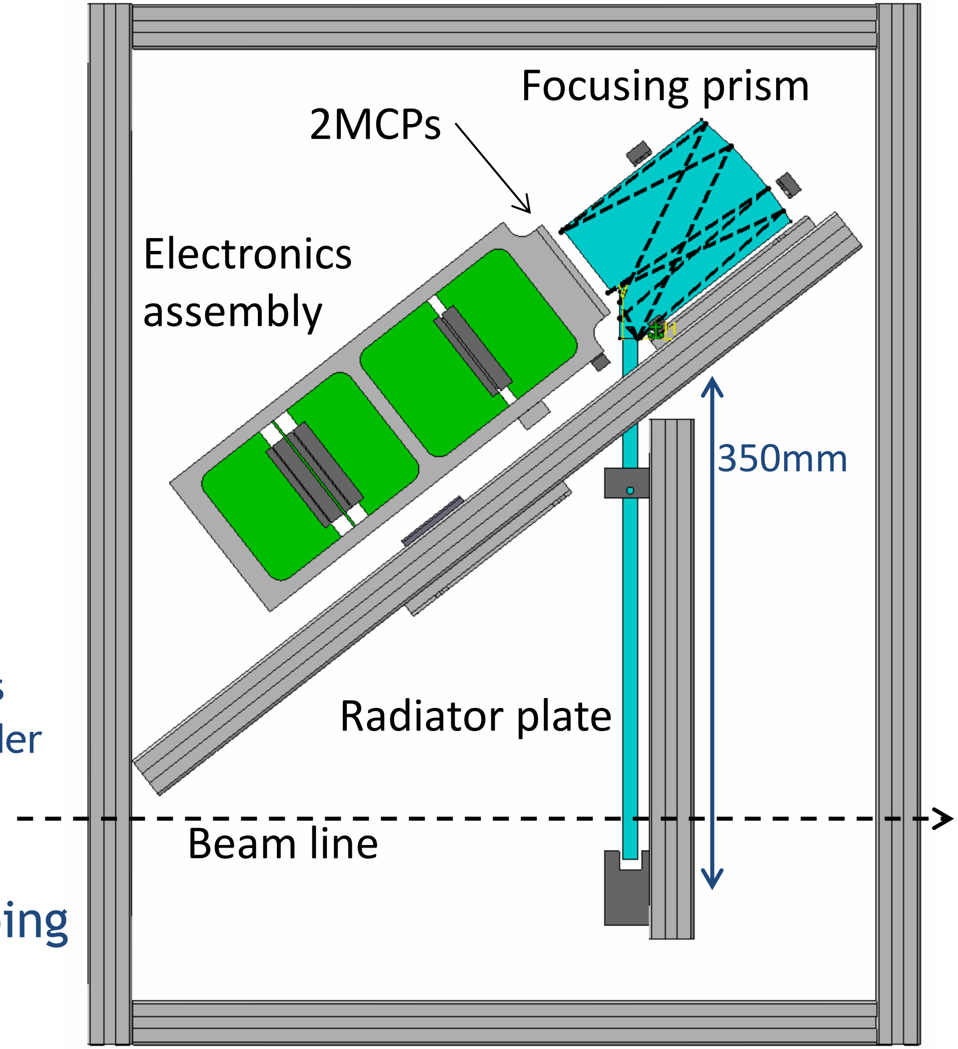
- Aim: measure and optimize transmission in UV region for radiator/optics coupled with UV epoxy glue
- Transmission curves for Quartz windows:



Beam test preparation

- Beam test periods:
  - SPS at CERN in October-November 2014 (high momentum beam: $p_{max} = 400GeV/c$)
  - PS at CERN in December 2014 (low momentum beam)

- TORCH prototype:
  - Radiator plate (10x120x350mm³) and focusing prism → Fused Silica
  - 2 photon detectors on focal plane → various MCPs to be used
  - Radiator glued to optics
  - Air gap between optics-photon detectors
  - Optics ordered → final design ready, under manufacturing



- New electronics development on-going
  - design new board NINO32+HPTDC
  - improve channel density
  - possible integration of INL calibration and time walk correction

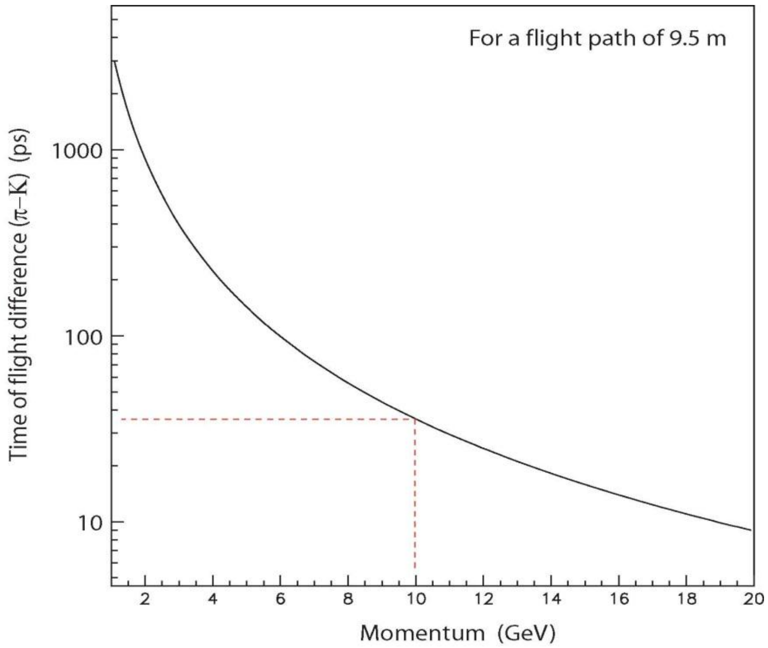
Conclusions and perspectives

- TORCH is an innovative detector proposed to achieve $\pi - K$ separation in the momentum range below $10GeV/c$
- Development of suitable photon detectors over a 3-phases R&D programme
  - 1st phase → COMPLETED
  - 2nd phase → ON-GOING
  - 3rd phase → next year
  - Finally, demonstration of TORCH concept with a prototype module
- Simulation studies on-going
- Development of next-generation custom front-end electronics (NINO32) on-going
- Beam tests foreseen end of 2014
- Further information → http://torch.physics.ox.ac.uk

Spare slides

TORCH detector

- It combines TOF and Ring Imaging Cherenkov (RICH) detection techniques
- $\Delta TOF\ (\pi - K)\ =\ 37.5\, ps$ at $10\ GeV/c$ over a distance of ~10m
- PID system to achieve positive π/K separation at a 3σ level in the momentum range below $10 GeV/c$
- 30 detected photons/track → Overall resolution per detected photon: ~70ps
- Cherenkov light production is prompt → use quartz as source of fast signal
- Single photon sensitivity



How to determine the TOF?

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

$$TOF = t_{TORCH} - t_{PV} = \frac{|x_{TORCH} - x_{PV}|}{\beta c} \qquad t_{TORCH} = t_{photon\ arrival} - TOP$$

- 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: $TOP = path\ length\ \frac{n_{group}}{c}$

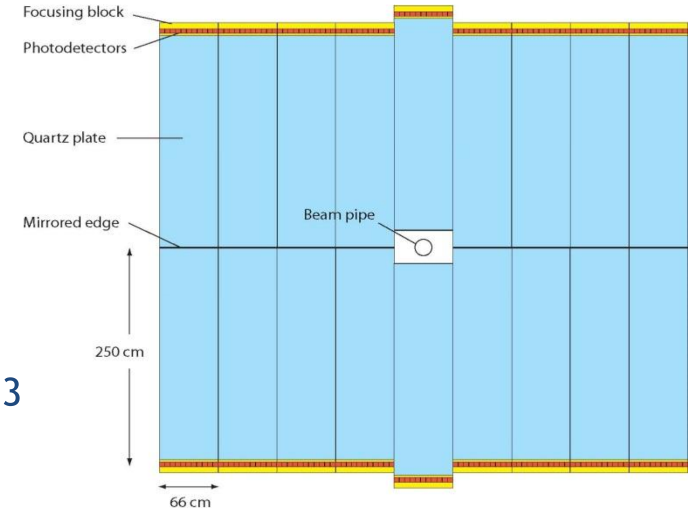
- θ_C → n_{phase} → λ → n_{group} → TOP → t_{TORCH} (crossing time)

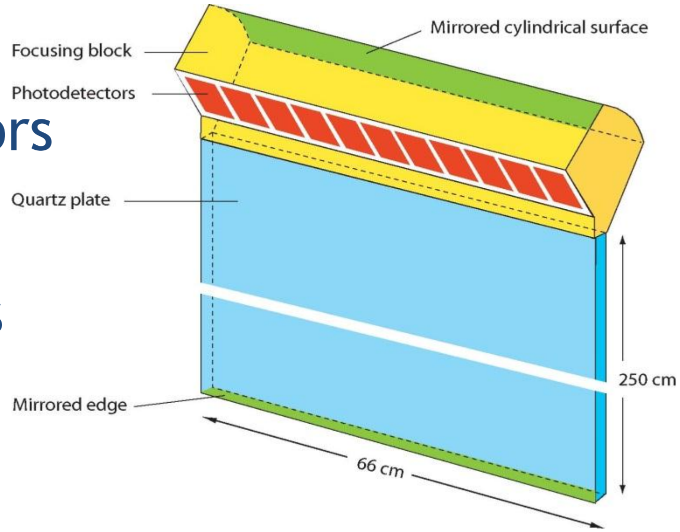
- To obtain the TOF, we need the start time t_{PV}
  - Use other tracks from PV, most of them are pions → t_{PV}: average time assuming they are all pions

TORCH detector

- Unrealistic to cover with a single quartz plate → evolve **to modular layout**
- For LHCb, surface to be instrumented is ~5x6m² at z=10m
- 18 identical modules, each 250×66×1cm³ → ~300 litres of quartz in total
- Reflective lower edge → photon detectors only needed on upper edge

  18 × 11 = 198 units, each with 1024 pads → 200k channels in total



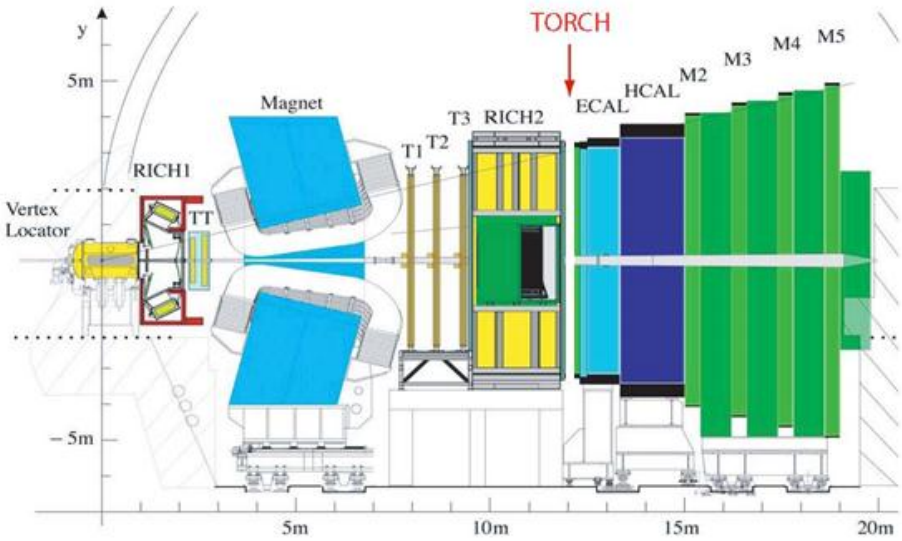


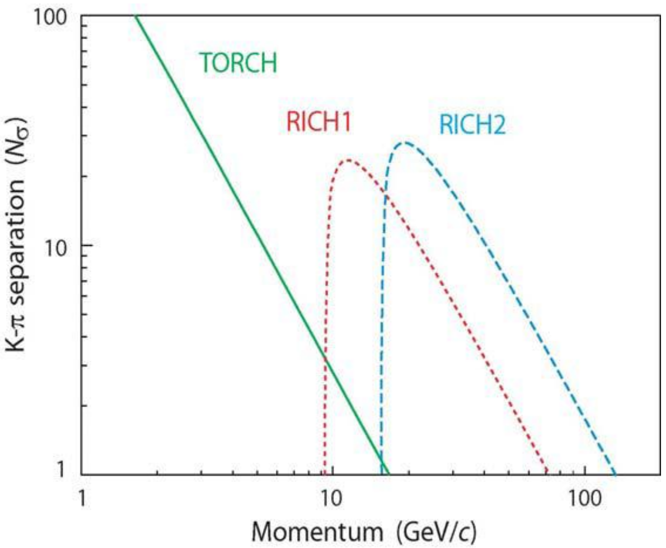
Application: LHCb experiment

- Motivation for TORCH development is LHCb upgrade [CERN-LHCC-2011-001]
  - Luminosity: $2 \cdot 10^{33} cm^{-2} s^{-1}$
  - Event read out rate increased to $40MHz$

- Currently, PID provided by two RICH detectors with three radiators (Silica aerogel, C_4F_{10}, CF_4) covering a momentum range from $\sim 2GeV/c$ up to $100GeV/c$

- PID Upgrade:
  - Silica aerogel will not give a good performance (low photon yield <10 detected photons/saturated track) → To be removed and possibly replaced later by TORCH





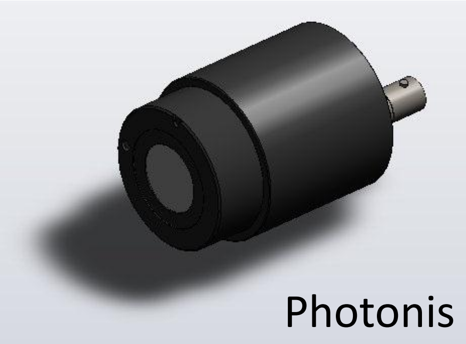
MCP-PMT Planacon tube (Photonis)

- Photon detector:
  - 8x8 channels MCP-PMTs (Burle/Photonis)

- XP85012/A1 specifications:
  - MCP-PMT planacon
  - 8x8 array, 5.9/6.5 mm size/pitch
  - 25 µm pore diameter, chevron configuration (2), 55% open-area ratio
  - MCP gain up to 10^6
  - Large gaps:
    - PC-MCPin: ~ 4.5mm
    - MCPout-anode: ~ 3.5mm
  - 53 mm x 53 mm active area, 59 mm x 59 mm total area → 80% coverage ratio
  - Total input active surface ratio ≤ 44%
  - Bialkali photocathode
  - Rise time 600 ps, pulse width 1.8 ns
  - HV applied 2.6 kV (1.75 kV across the MCP)

Single-channel MCP tube (Photonis)

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



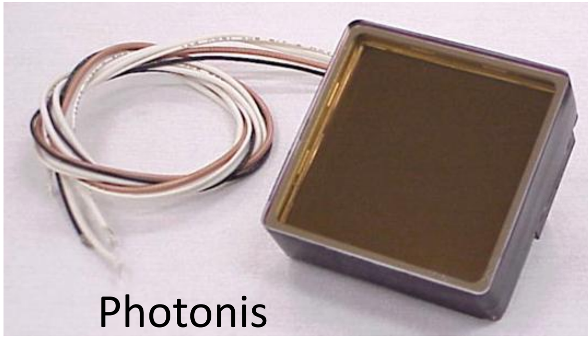
- PP0365G specifications:
  - MCP-PMT tube
  - single channel (SMA connector)
  - 6µm pore diameter, chevron type (2), ~55% open-area ratio
  - low MCP gain typ. <10^5
  - Small gaps:
    - PC-MCPin: 120µm
    - MCPout-anode:1mm
  - S20 photocathode on quartz
  - 18mm active diameter
  - 6pF anode capacitance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

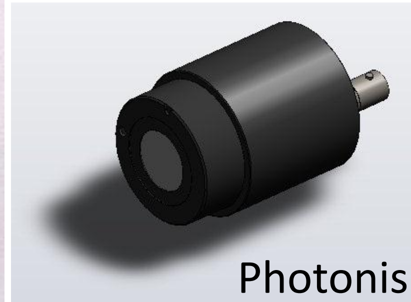
Custom MCP device (Photek)

- Photon detector:
  - single channel MCP-PMT225 (Photek Ltd)

- PMT225 SN-G specifications:
  - MCP-PMT tube
  - single channel (SMA connector)
  - 10μm pore diameter, chevron type (2), ALD coated
  - MCP gain typ. 10^6
  - Small gaps:
    - PC-MCPin: 200μm
  - S20 photocathode on quartz
  - 25mm active diameter
  - Rise time 360 ps
  - HV applied 2.25 kV (1.2 kV across the MCP)

MCP photon detectors tests – Summary





	8x8array Planacon MCP (Photonis)	Single-channel MCP (Photonis)	Single-channel MCP (Photek)
Pore diameter [μm]	25	6	10
PC-MCP/MCP-anode gaps	large	small	small
Photocathode	Bialkali on borosilicate	S20 on quartz	S20 on quartz
Typical MCP gain	10^6	10^5	10^6
Time resolution [ps]	Single-channel electronics: <40 Multi-channel electronics: <80	<40	<30

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 →

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

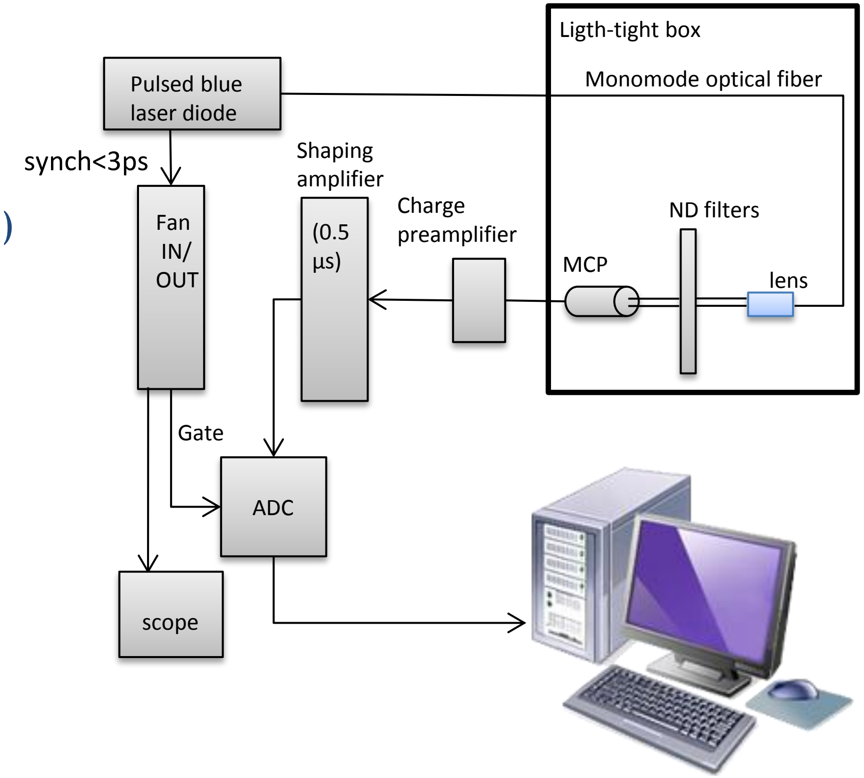
N: number of photoelectrons per pulse

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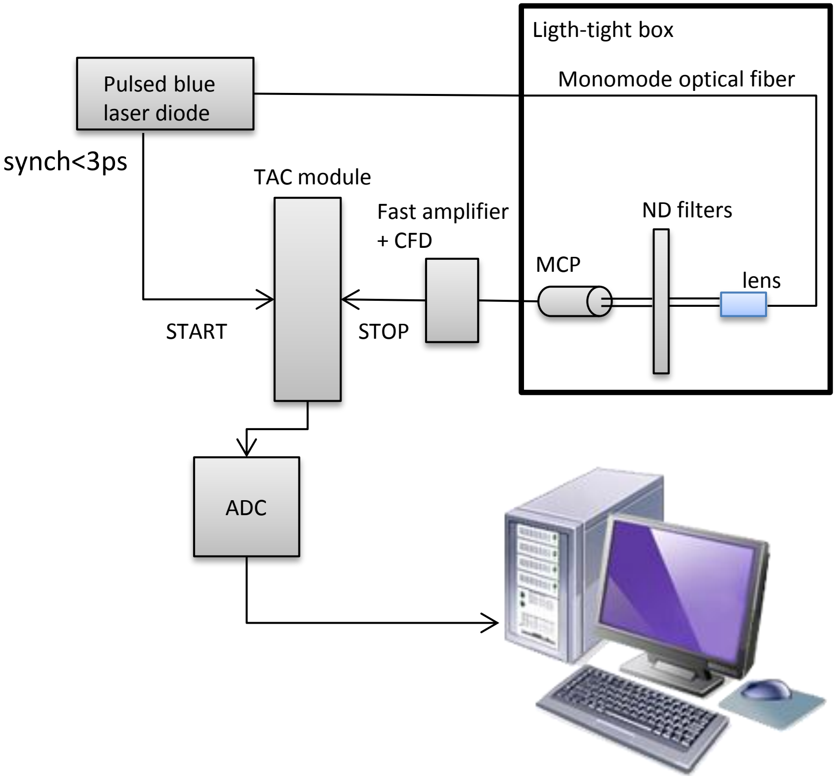
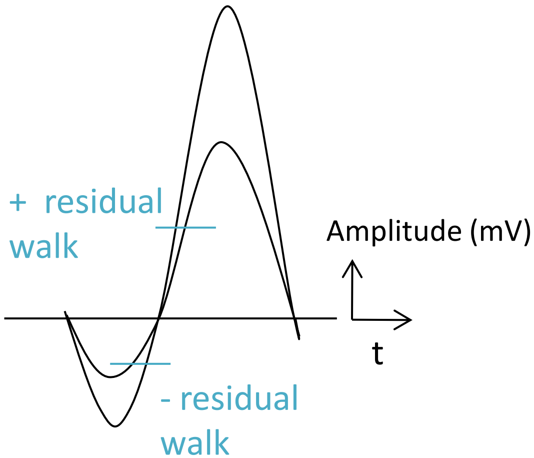
- **Timing setup:**
  - Time jitter distribution
  - Exponentially-modified Gaussian distribution to fit prompt peak → time resolution (σ)



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

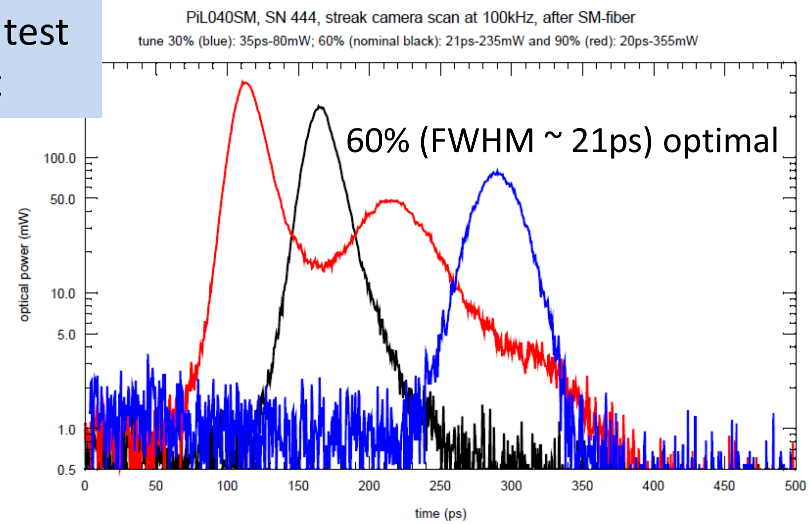


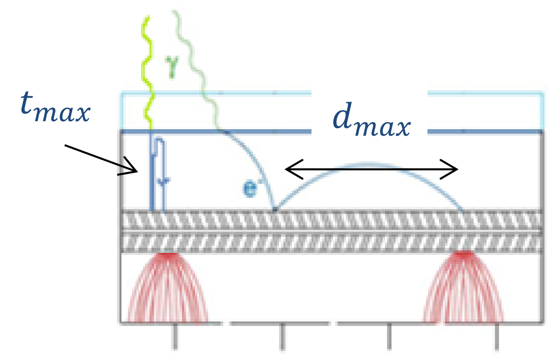
  - Produce accurate timing information from analog signals of varying heights but the same rise time
  - Principle: splitting the input signal, attenuating half of it and delaying the other half, then feeding the two halves into a fast comparator with the delayed input inverted
  - Effect: to trigger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

Contributions to MCP timing response

- Laser effect:
  - Second relaxation pulse clearly seen after ~(150 ± 50)ps on laser timing profile → visible on MCPs time response resulting in a shoulder after the main peak

PiLas test ticket





- Back-scattered photoelectrons:
  - Maximum back-scattered time (elastically at 90° with MCP input surface):

$$(t_{back-scattered})_{MAX} = 2 \times t_{transit}$$

  - Maximum back-scattered spatial range (elastically at 45° with MCP input surface):

$$(d_{back-scattered})_{MAX} = 2 \times \text{MCP input gap}$$

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