TheTORCH time-of-flight detector

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On behalf of the TORCH collaboration

(University of Bristol, CERN, University of Oxford and Photek)

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Outline

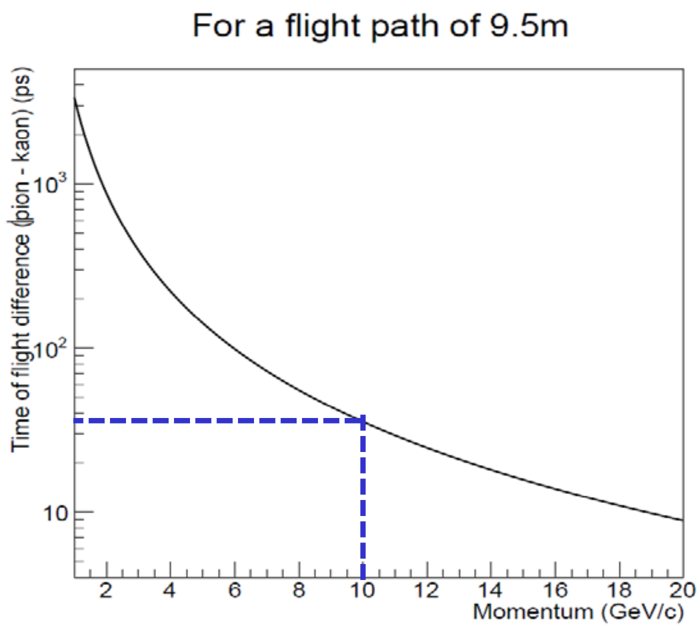
- Introduction
- TORCH design and principles
- Development of Microchannel Plate (MCP)-PMTs
  - Lifetime
  - Time resolution
  - Charge sharing
- Test beam preparation
- Summary

Introduction

- The TORCH (Time Of internally Reflected CHerenkov light) detector is an R&D project to develop a large-area time-of-flight system.
- TORCH combines timing information with DIRC-style reconstruction (cf. Belle TOP detectors & the PANDA DIRC) : aiming to achieve a ToF resolution ~10-15 ps (per track).
- A 4-year grant for R&D on TORCH has been awarded by the ERC: to develop customised photon detectors in collaboration with industrial partners and to provide proof-of-principle with a demonstrator module.

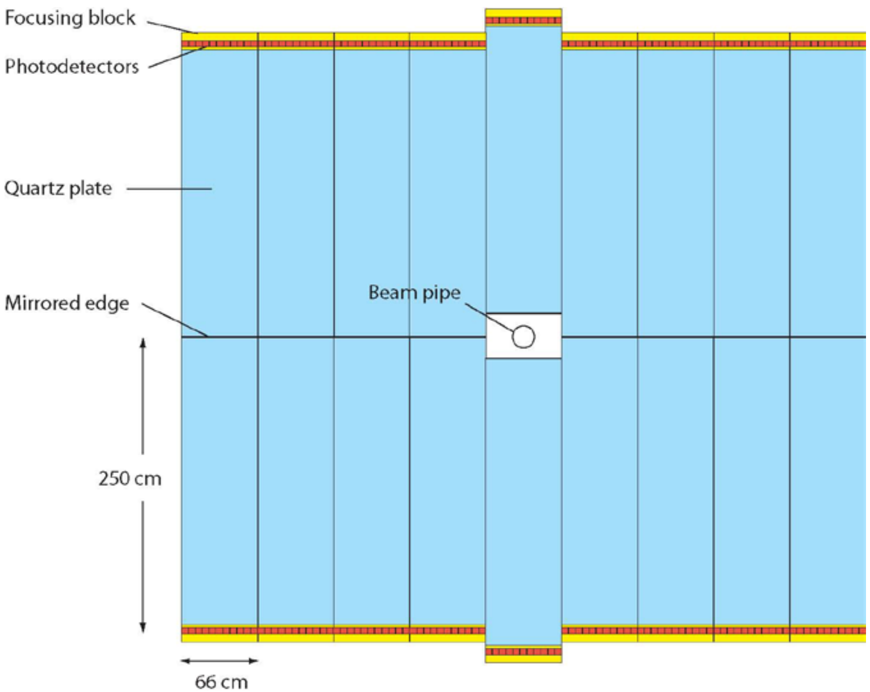
The TORCH detector

- To achieve positive identification of kaons up to p ~ 10 GeV/c, ΔTOF (π-K) = 35 ps over a ~10 m flight path → need to aim for ~ 10-15 ps resolution per track



- Cherenkov light production is prompt → use a plane of quartz (~30 m^2) as a source of fast signal

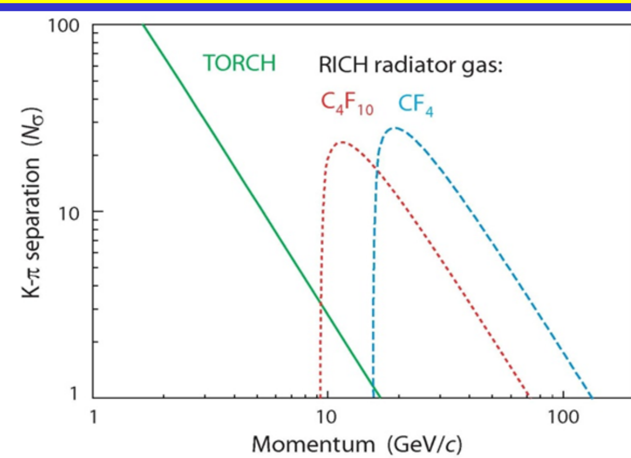
- Cherenkov photons travel to the periphery of the detector by total internal reflection → time their arrival by Micro-channel plate PMTs (MCPs)

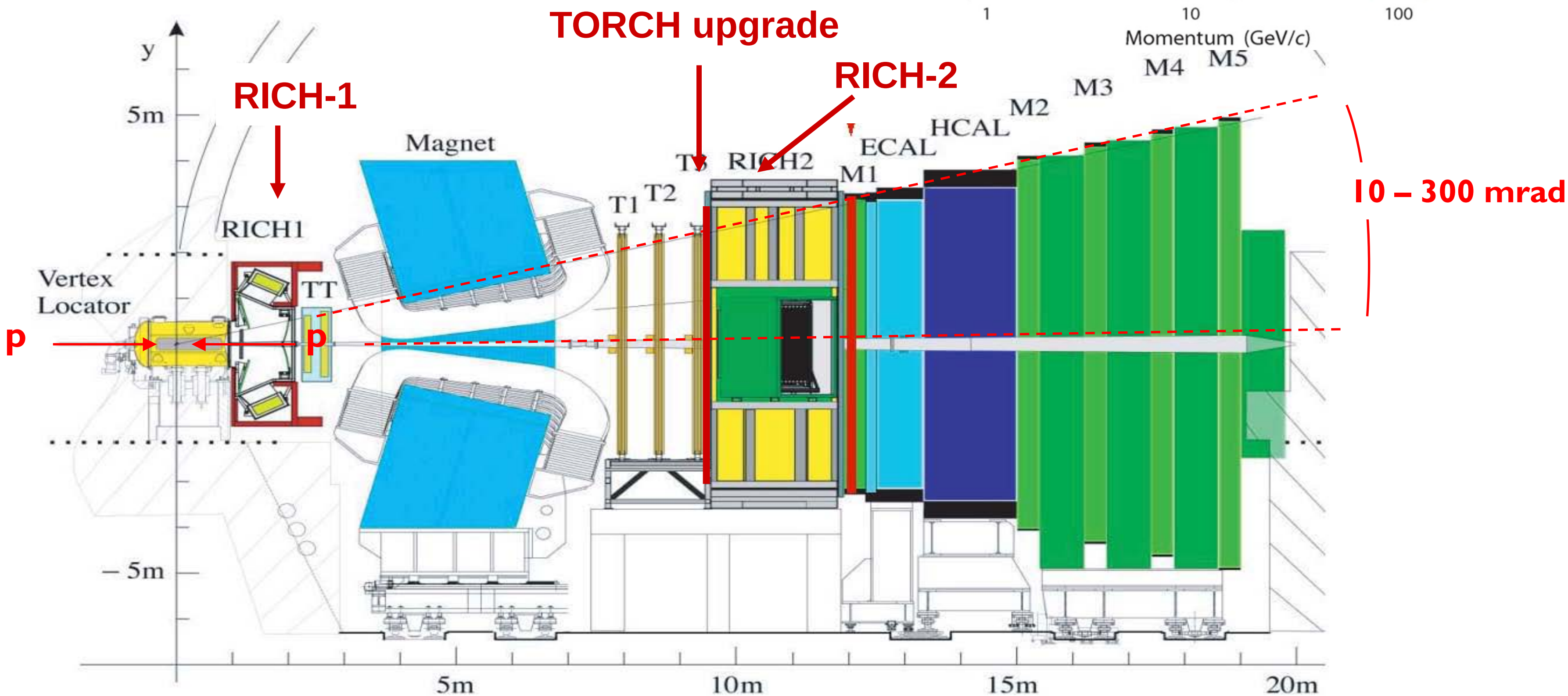


- The ΔTOF requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons)

TORCH application : the LHCb Upgrade

- The RICH system will be retained for particle ID, but no aerogel radiator
- The aim is to install TORCH in front of RICH2 for a 2nd phase of upgrade

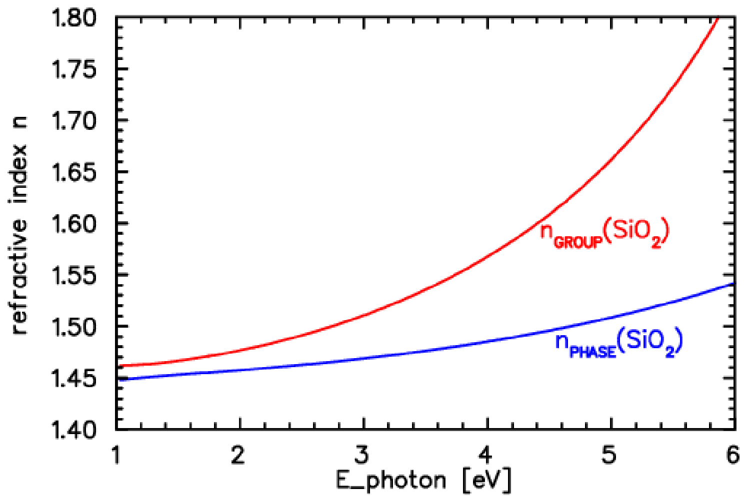




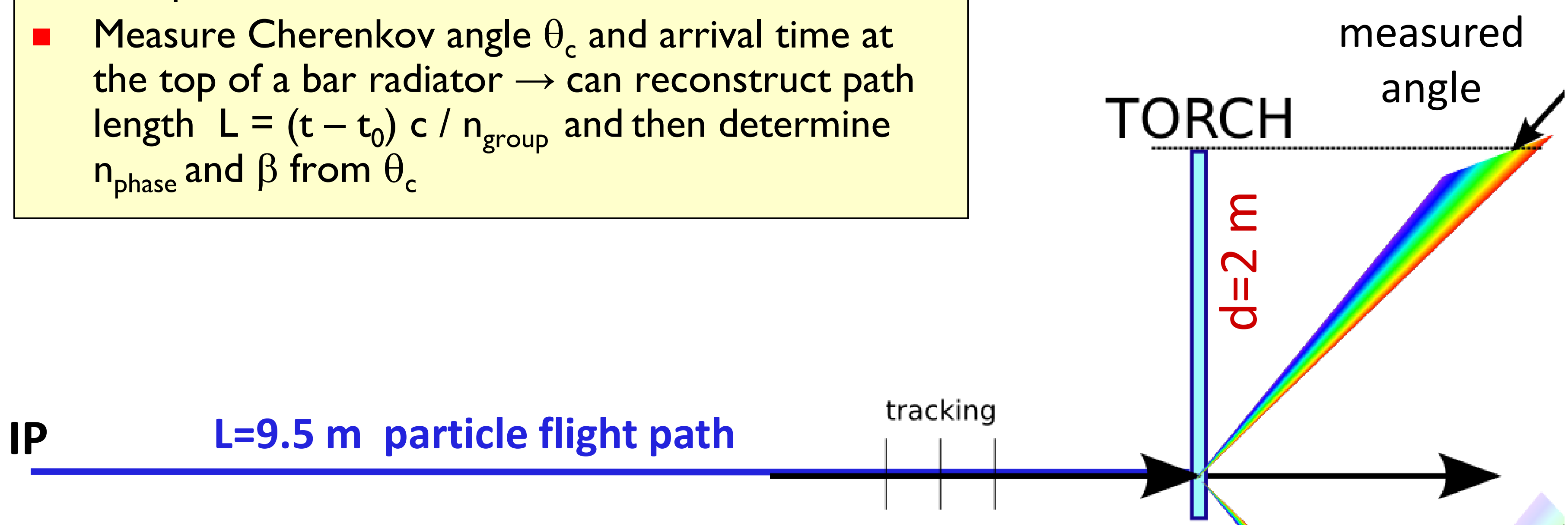
Principles

Cherenkov angle : $\cos\theta_c = (\beta\, n_{phase})^{-1}$

Time of propogation : $t = L / v_{group} = n_{group}\, L / c$

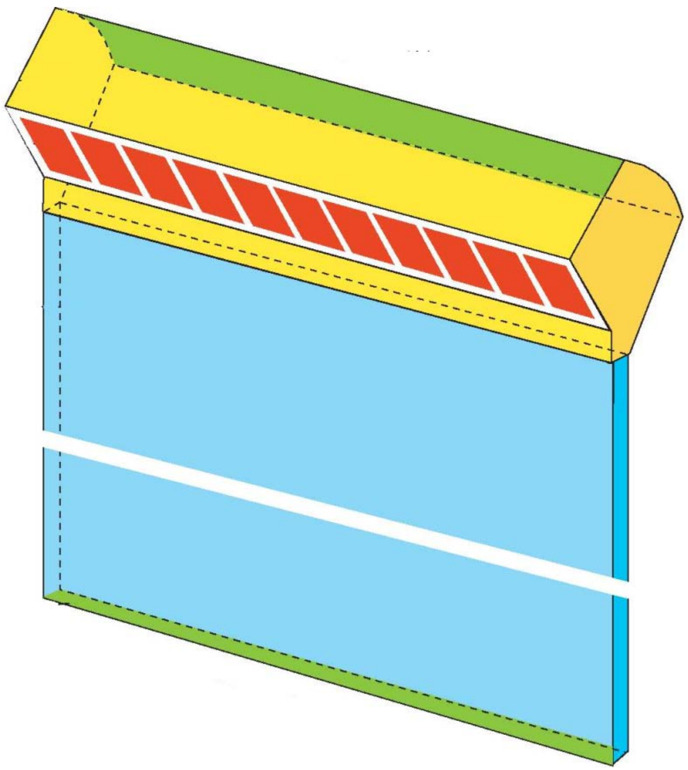


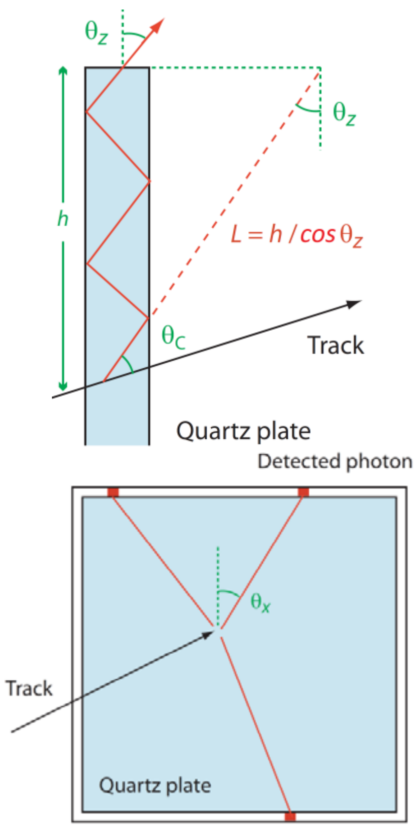
- Need to correct for the chromatic dispersion of the quartz
- Measure Cherenkov angle θ_c and arrival time at the top of a bar radiator → can reconstruct path length $L = (t - t_0)\, c / n_{group}$ and then determine n_{phase} and β from θ_c

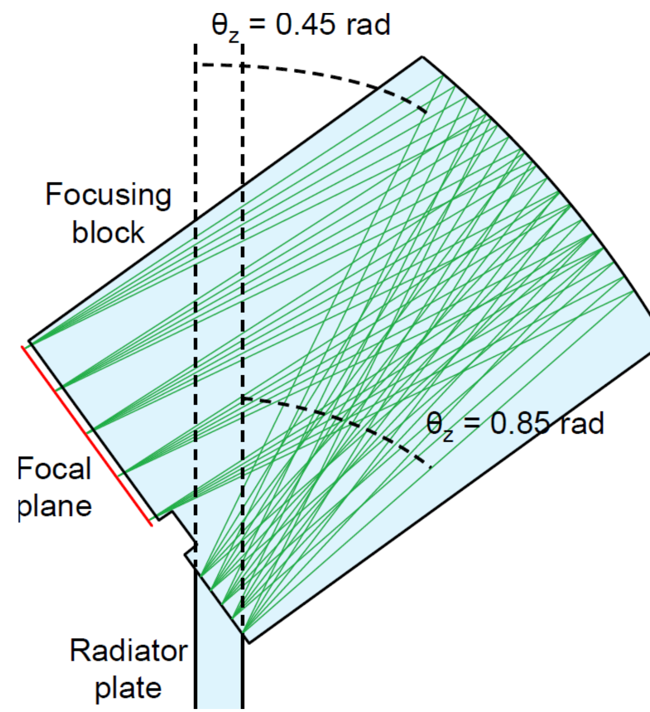


Basics of the TORCH design

- Measure *angles* of photons: then reconstruct their path length L
- For the required resolution : ~1 mrad precision required on the angles in the 2 planes
- Measurement of θ_z (longitudinal direction) → use a focusing block (quartz) to convert photon angle into position on photon detector
- Need ~128 x 8 pixels of an MCP of 53x53 mm^2 ("standard 2 inch") active dimension

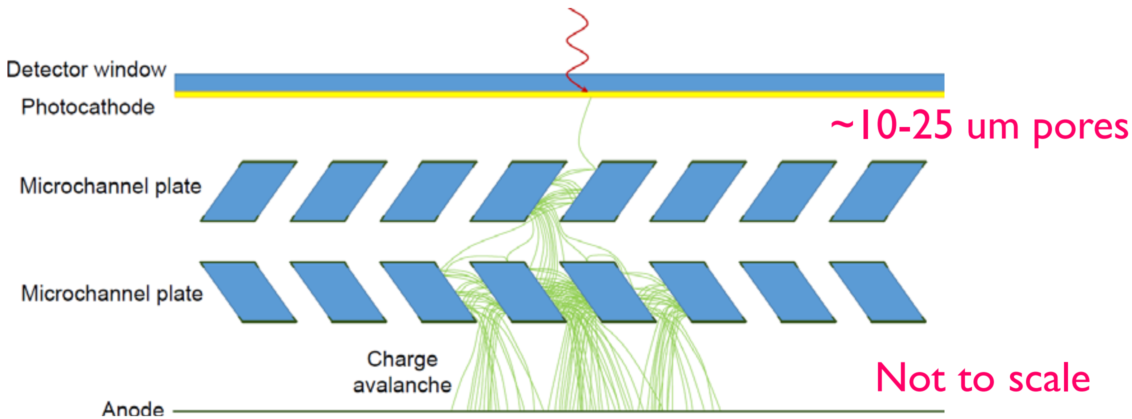




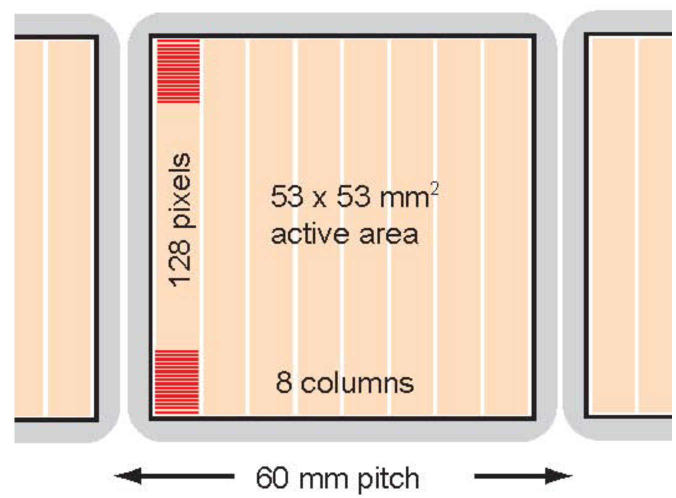


Overview of MCP requirements

- Micro-channel plate (MCP) photon detectors are well known for fast timing of single photon signals (~20 ps). Tube lifetime has been an issue in the past.



- Anode pad structure can in principle be adjusted according to resolution required as long as charge footprint is small enough: →tune to adapted pixel size: 128 × 8 pixels



TORCH MCP development

A major TORCH focus is on MCP R&D with an industrial partner : Photek (UK).

PHOTEK
ENVISAGE THE FUTURE

Three phases of R&D defined:

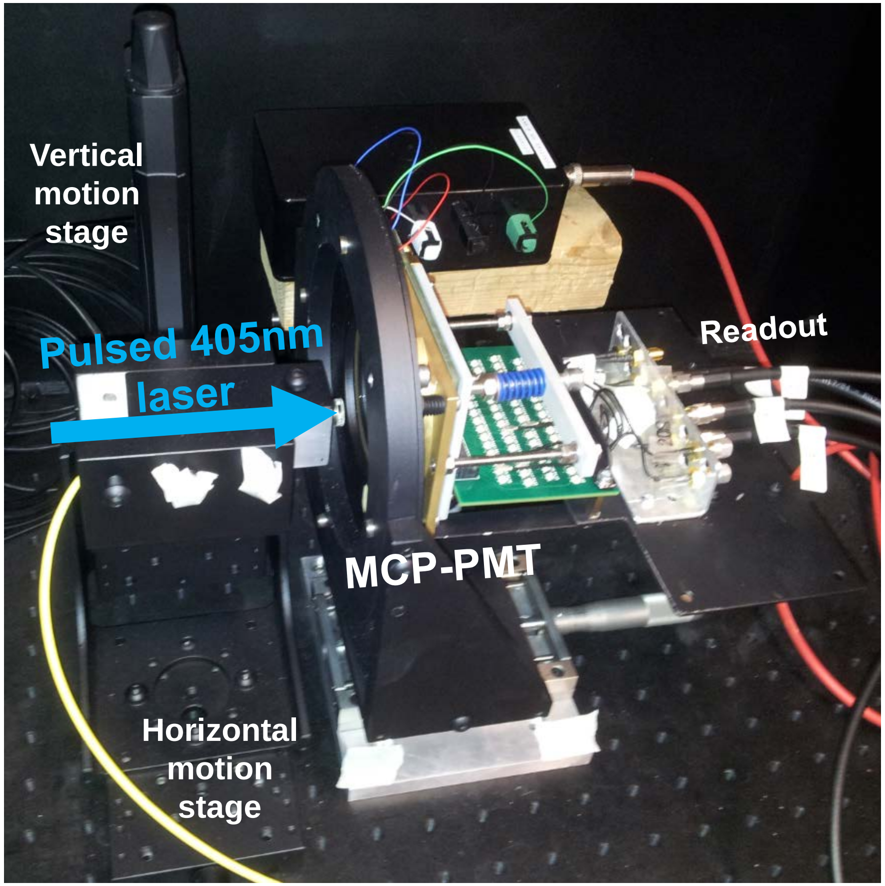
- Phase 1 : MCP single channel focuses on extended lifetime (> 5 C/cm^2) and ~35ps timing resolution.
  COMPLETED

- Phase 2 : MCP with customised granularity (128×8 pixels equivalent – in this case 64 × 8 with charge-sharing between neighbouring pads).
  TUBES UNDER TEST

- Phase 3 : Square tubes with high active area (>80%) and with required lifetime, granularity and time resolution. IN PREPARATION

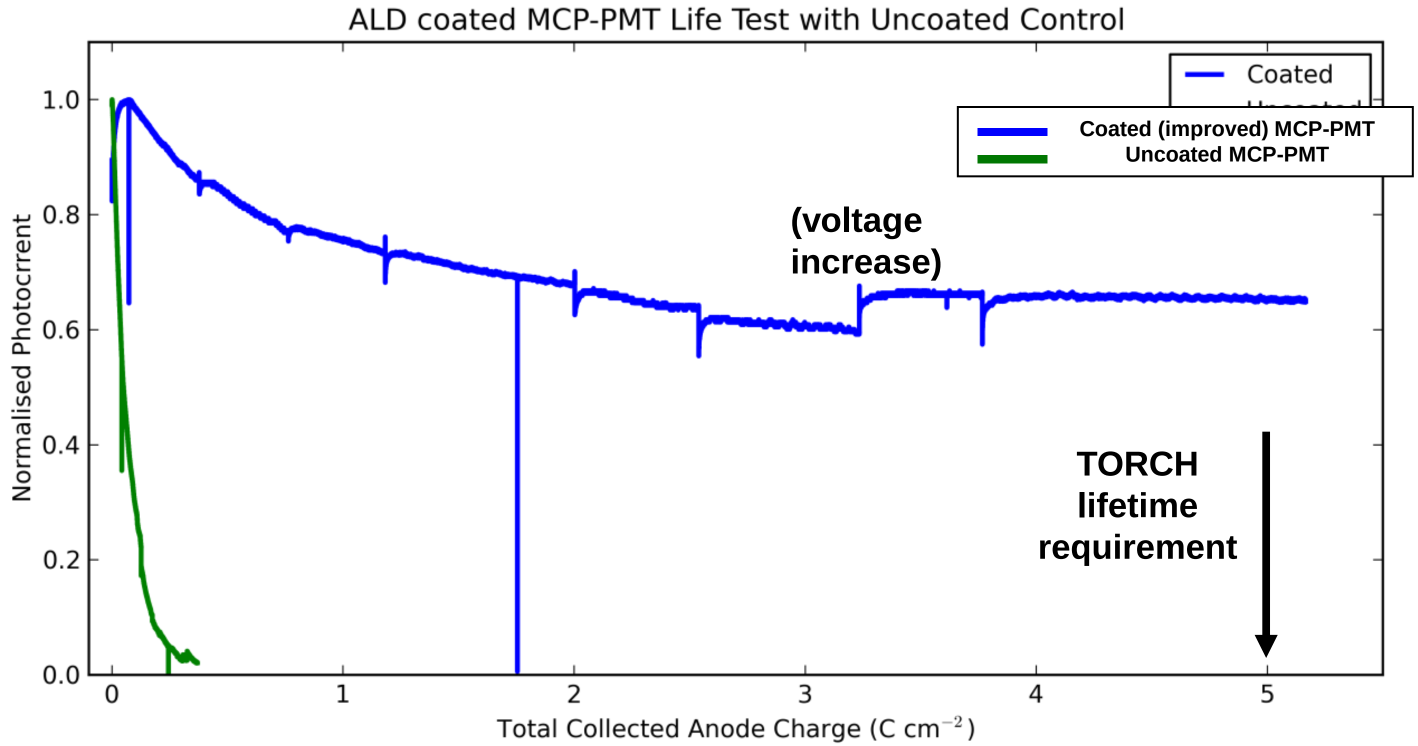
MCP laboratory testing

- Phase 2 MCP detectors currently being tested in the lab
- Laser is attenuated to single photon level using variable attenuator
- Use precision laser focus (several 10's of microns)
- Laser is scanned over surface using motion stages



Lifetime measurements at Photek

- Use Atomic Layer Deposition (ALD) techniques to coat atomic layers onto the MCP
- The ALD coated MCPs significantly outperform the uncoated MCPs for lifetime (good up to beyond 5 C cm^{-2}).
- The photocathode's quantum efficiency does not significantly change.

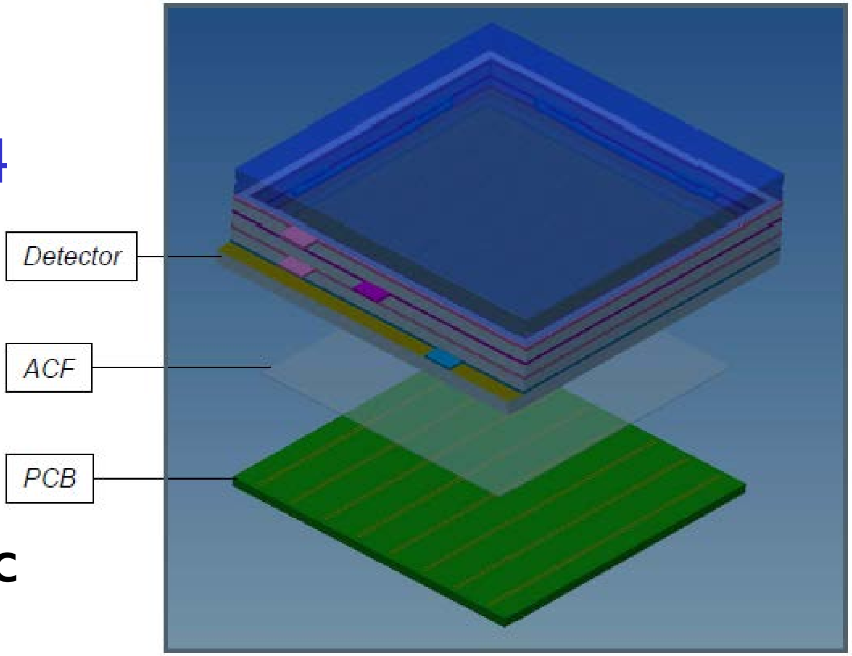


Photocathode response as a function of collected charge.

Photek Ltd., Ref NIM A 732 (2013) 388391 **(TORCH measurements are ongoing.)**

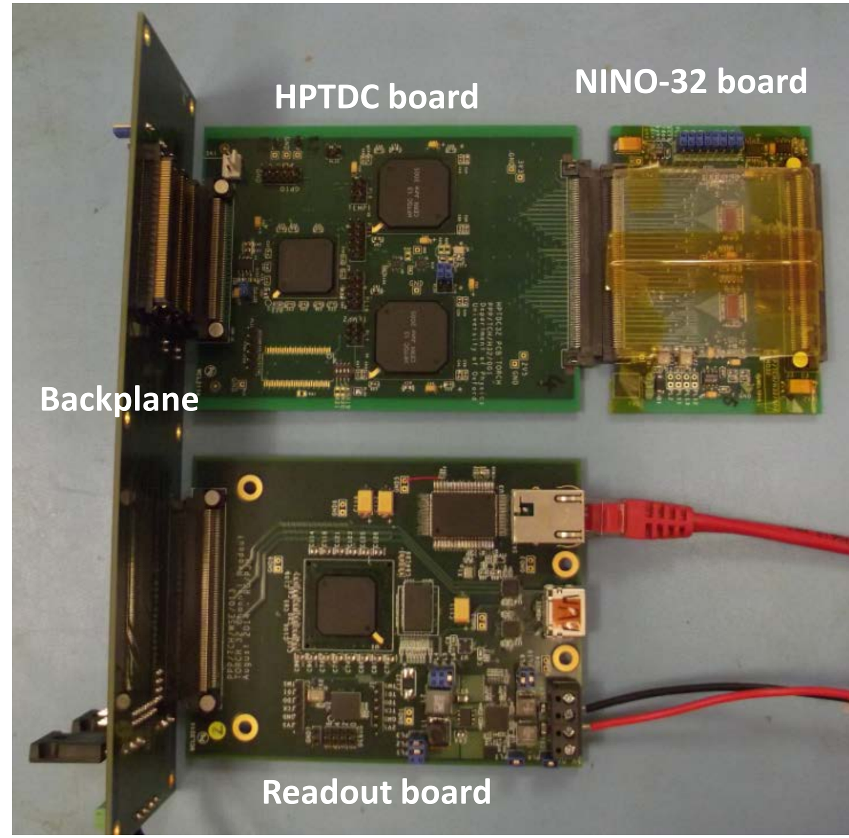
Phase 2 MCPs customized pad layout

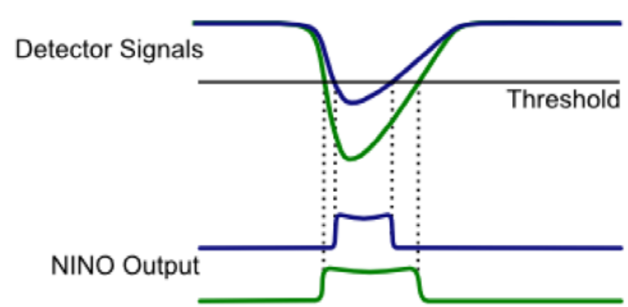
- Traditional multi-anode manufacturing uses multiple pins : difficult for a 128 x 8 array – plan therefore for 64 x 8.
- Phase 2 tubes have 32x32 pixels (1/4 size) in a circular tube : gang together 8 pixels in coarse direction
- TORCH pixel pads are 0.75 mm wide on a 0.88 mm pitch. Contact made to readout PCB by Anisotropic Conductive Film (ACF)
- Charge division between a pair of pads recovers pixel resolution 64→128 and reduces total number of channels



Readout Electronics

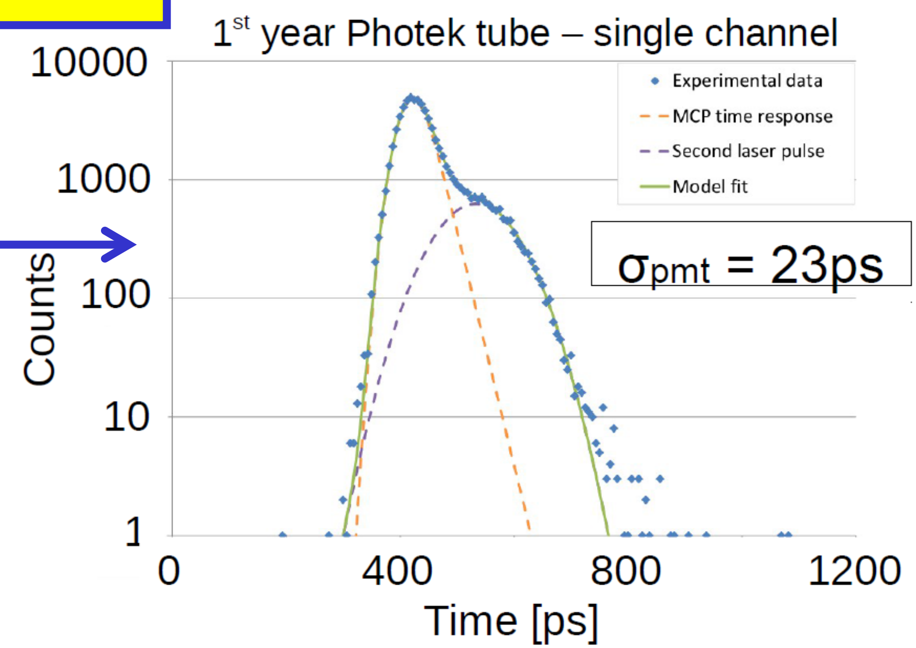
- Readout electronics are crucial to achieve desired resolution.
- Suitable front-end chip has been developed for the ALICE TOF system: NINO + HPTDC [F. Anghinolfi *et al*, Nucl. Instr. and Meth. A 533, (2004), 183, M. Despeisse *et al*., IEEE 58 (2011) 202]
- TORCH is using 32 channel NINOs, with 64 channels per board
- NINO-32 provides time-over-threshold information which is used to correct time walk & charge measurement - together with HPTDC time digitization





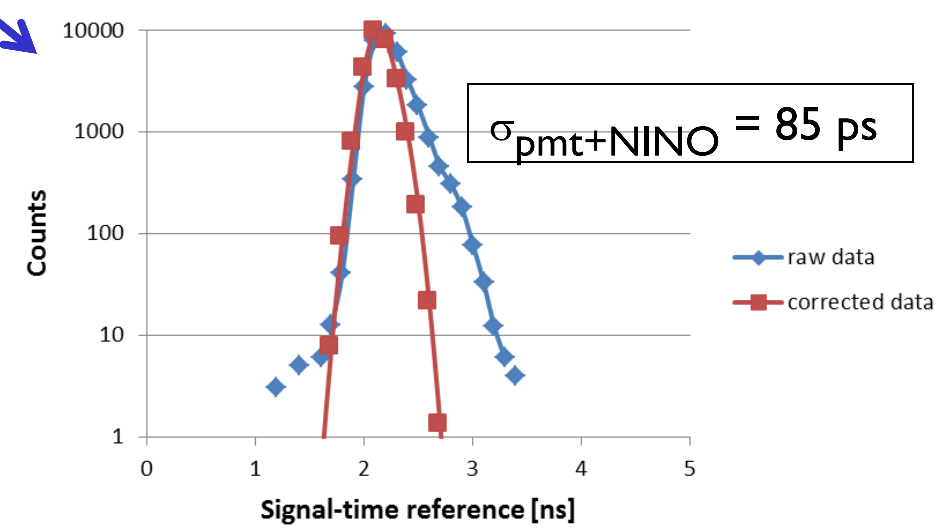
MCP timing resolution

- Phase I Photek tubes : timing resolution obtained with fast laser and with commercial electronics
- Phase 2 Photek tube : timing resolution obtained with fast laser and customised NINO-32 and HPTDC electronics with HPTDC time binning set to 100 ps
  - Correction made for integral non-linearity (INL) of the HPTDC and time-walk effects from the time-over-threshold (TOT) information from the NINO
- All timing properties measured at an MCP gain of 1 x 10^6



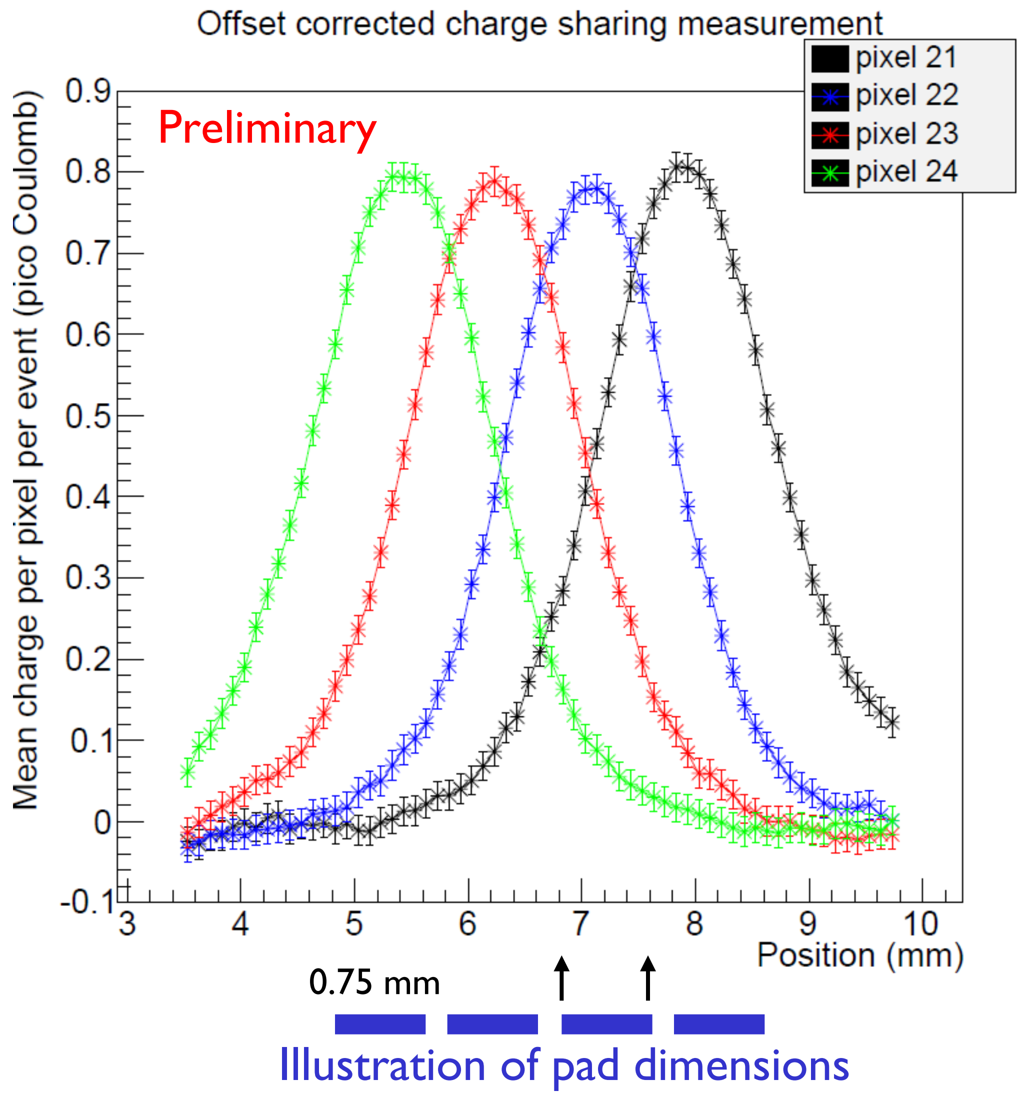
PRELIMINARY

Photek Phase 2 tube: NINO electronics

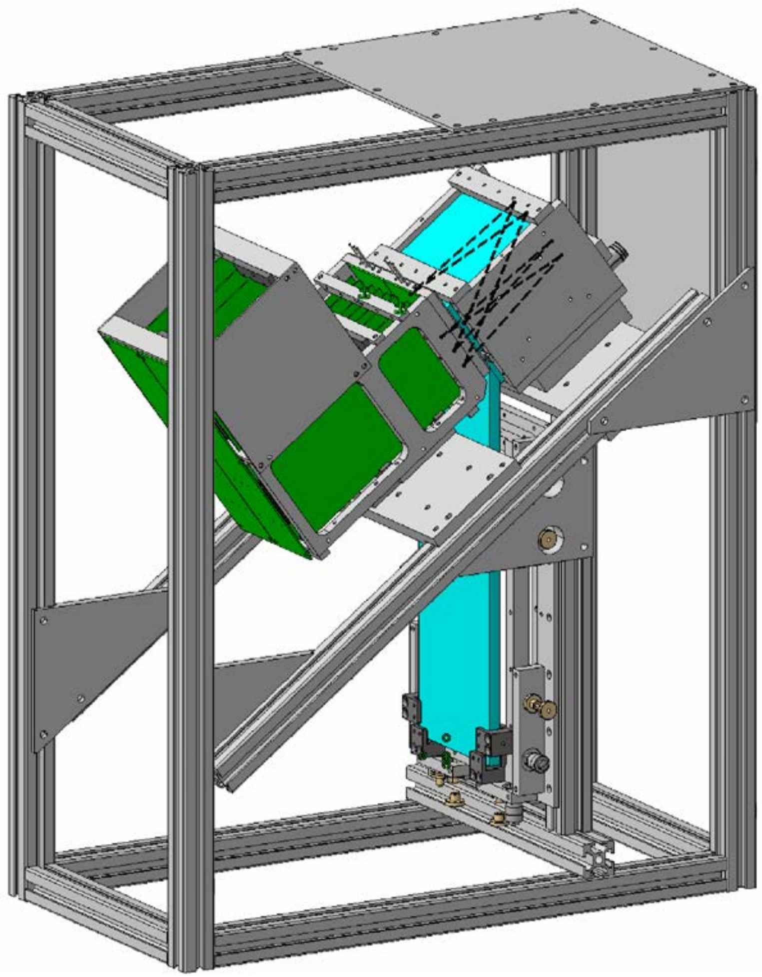


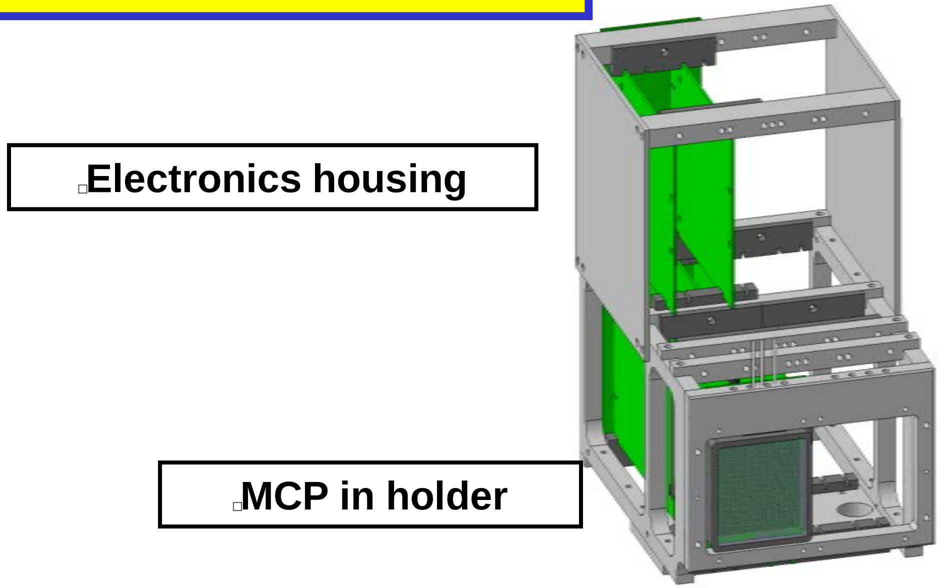
MCP charge sharing

- Tests of charge sharing between pixels is in progress
- TORCH requirement is ~ 0.41 mm. Expect at least x2 improvement with charge division between adjacent channels → 0.42 mm
- Work in progress to further reduce the charge footprint



Demonstrator TORCH module

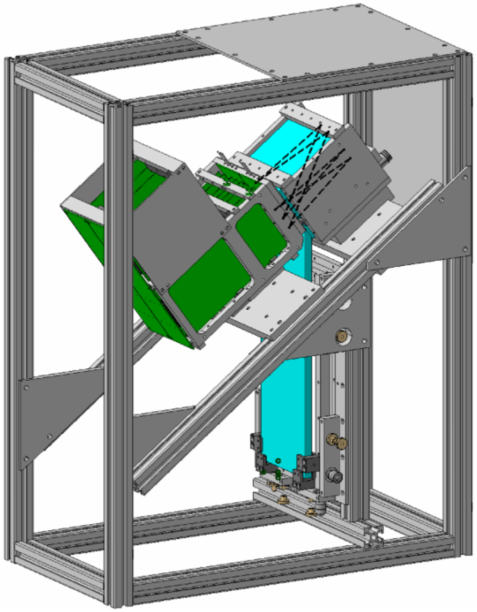


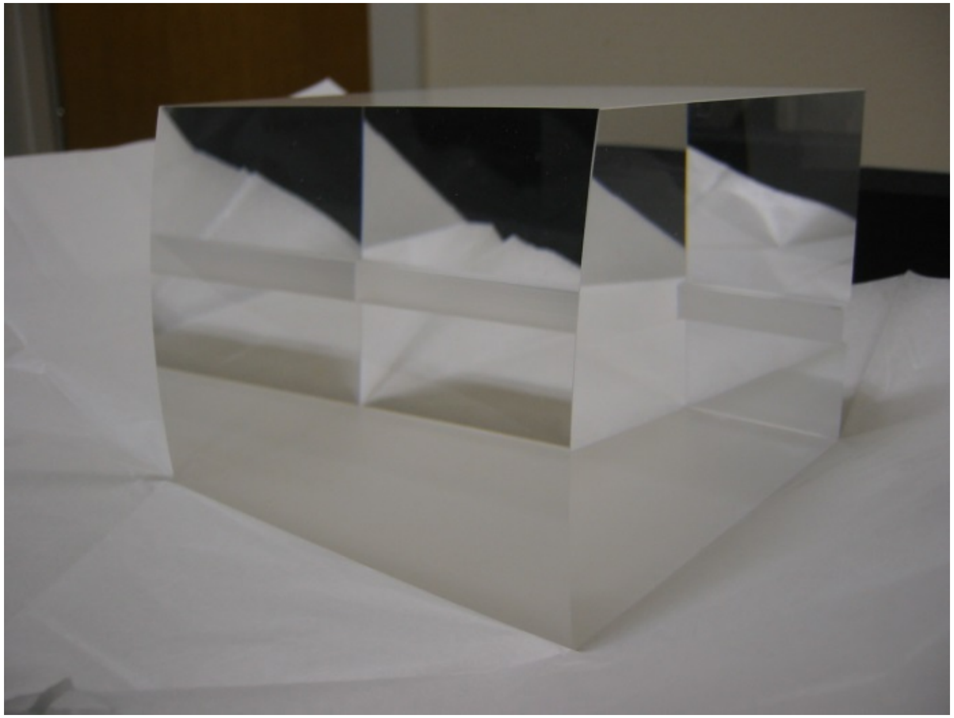


- We have fabricated a scaled-down version of TORCH module :
- Optical components from Schott:
  - quartz radiator plate (35 x 12 x 1) cm^3
  - plus focussing block
- Use Photek prototype Phase II MCPs
- Testbeam run now in progress

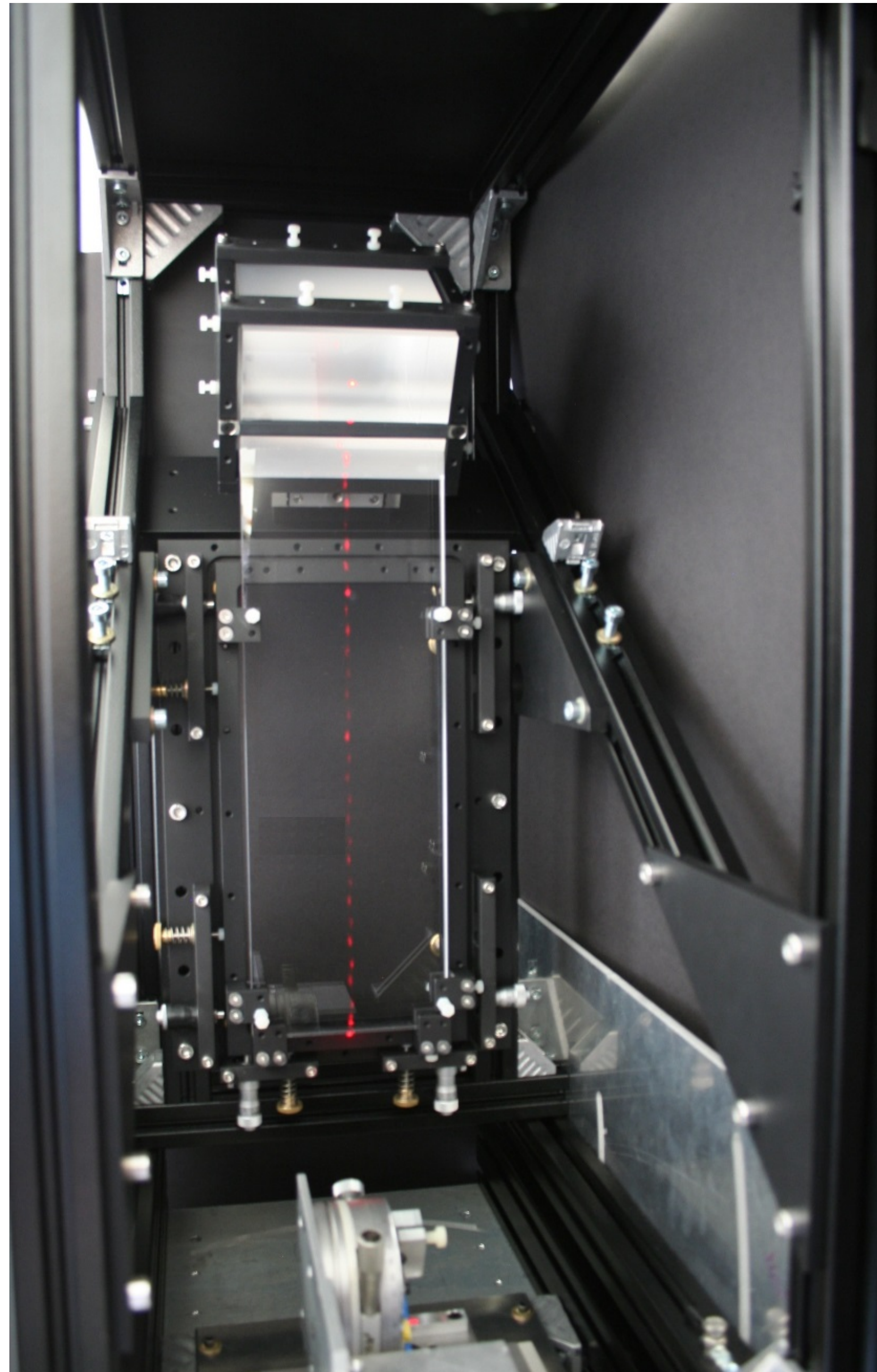
Test beam components

Optical components:
Radiator & focussing block



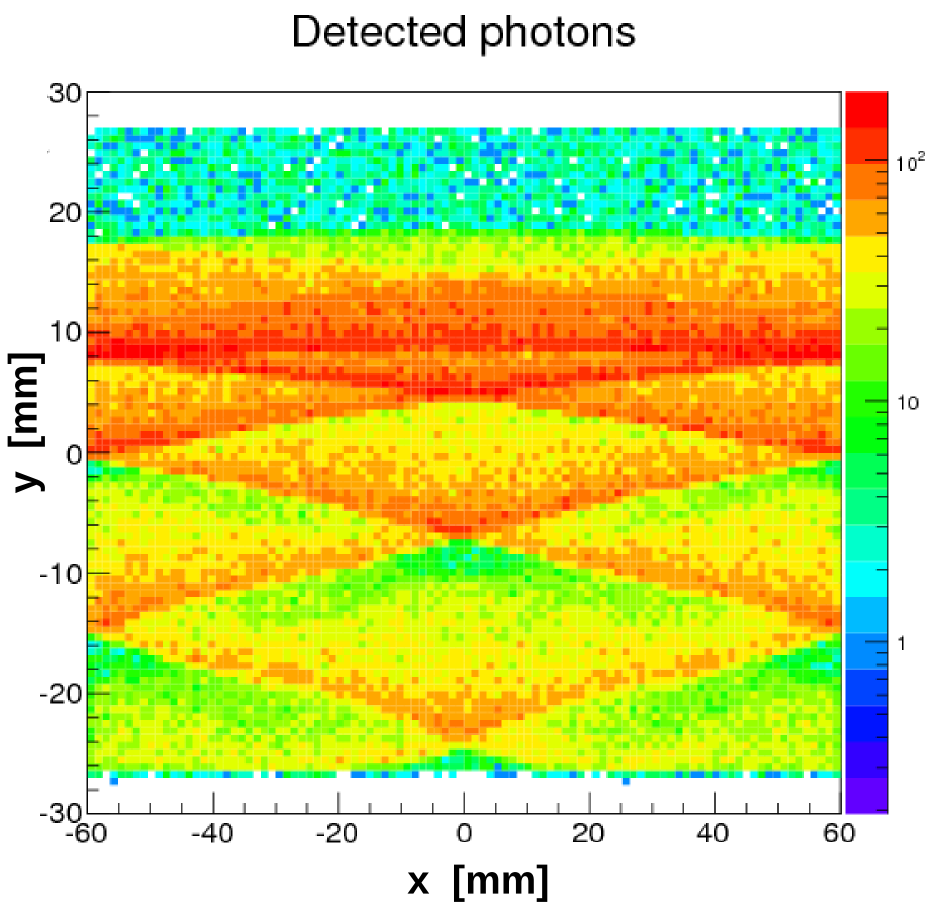


Demonstrator TORCH module

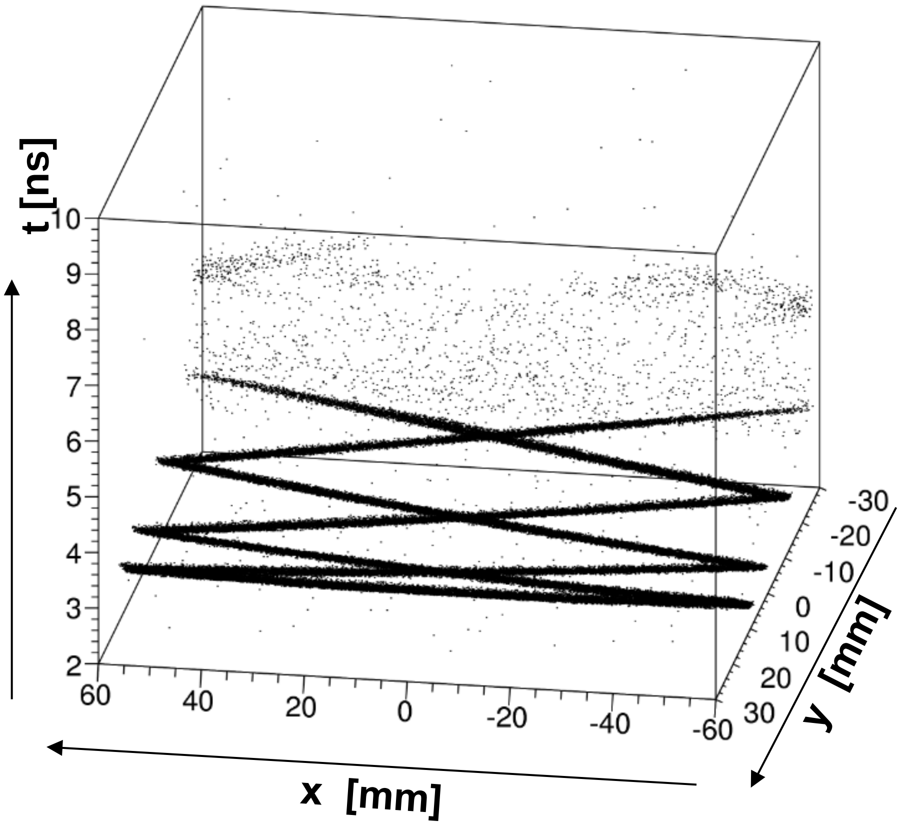


Testbeam simulations

Demonstrating the effect of time of propagation



pattern mapped onto the focal plane



3-d view including time

Summary

- TORCH is a novel concept for a DIRC-type detector to achieve high-precision time-of-flight over large areas.

- Given a per-photon resolution of 70 ps, aiming to achieve K-π separation up to 10 GeV/c and beyond (with a TOF resolution of ~15 ps per track)

- Ongoing R&D programme aims to produce suitable MCP within next 2 years, satisfying challenging requirements of lifetime, granularity, and active area.
  - First two phases of MCP results show promising results for lifetime and timing measurements. Granularity studies with charge sharing are ongoing

- A prototype module will demonstrate the TORCH concept. A testbeam programme is underway.

The TORCH project is funded by an ERC Advanced Grant under the Seventh Framework Programme (FP7), code ERC-2011-ADG proposal 299175.

European Research Council
Established by the European Commission

Spare slides from here on

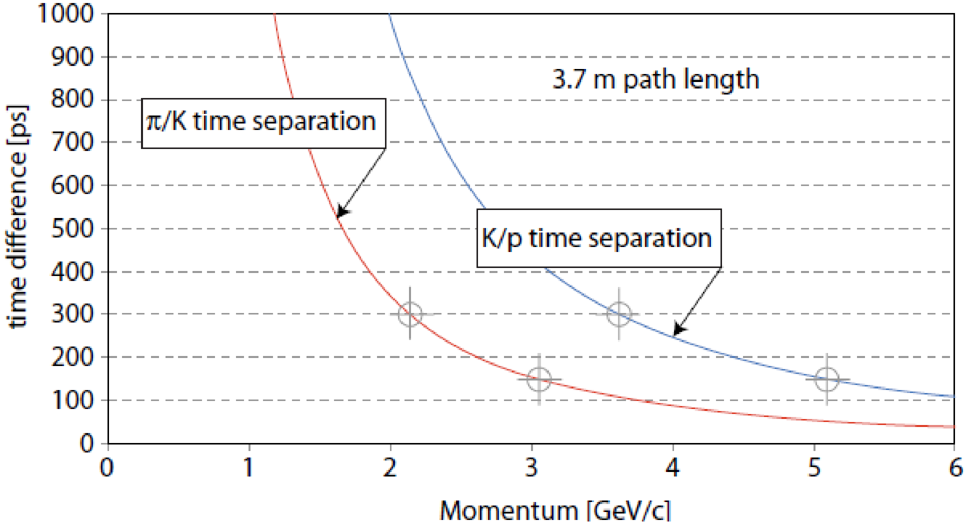
Time of Flight

- A simple well-known principle : measure time difference over path length L_{path}

$$\Delta t = (L_{path}/c)(1/\beta_1 - 1/\beta_2) = (L_{path}/c)[\sqrt{(1+(m_1c/p)^2)} - \sqrt{(1+(m_2c/p)^2)}]$$

$$\approx (L_{path}c/2p^2)(m_1^2 - m_2^2)$$

- Expected particle separation:



$$N_\sigma \approx (L_{path}c/2p^2)(m_1^2 - m_2^2) / \sigma_{Total}$$

where $\sigma_{Total} = \sqrt{\Sigma\sigma_i^2}$

with contributions from σ_{TOF}, $\sigma_{Tracking}$, $\sigma_{Electronics}$, σ_{t_0} … etc

- Order ~100 ps resolution is required for even modest momentum reach

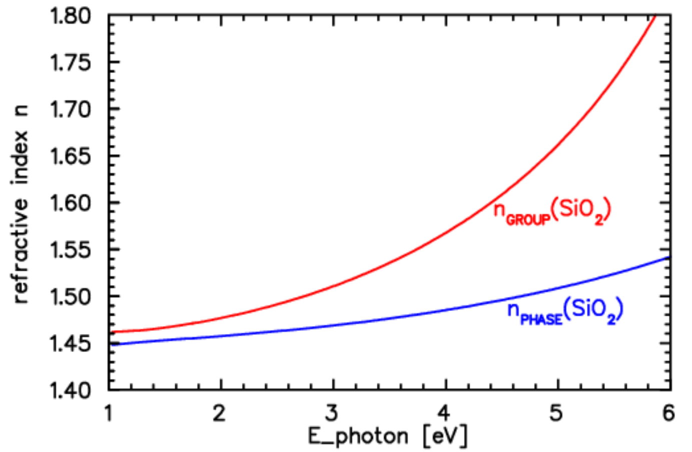
DIRC-like detectors: concepts & principles

- For a fast DIRC-like timing measurement, need to correct for the chromatic dispersion of radiator material (quartz) : Refractive index given by

$$n_{group} = n_{phase} - \lambda\,(dn_{phase}/d\lambda)$$

  - Dispersion: photons with different λ emitted with different $\cos\theta_C$
  - Photons emitted with Cherenkov angle : $\cos\theta_C = 1/\beta\, n_{phase}$
  - In visible, from $E\gamma$ = 3 to 5 eV, $\Delta\theta_C \sim 24$ mrad

- Measure Cherenkov angle and arrival time at the top of a bar radiator → can determine n_{phase} and reconstruct path length L of photon through quartz

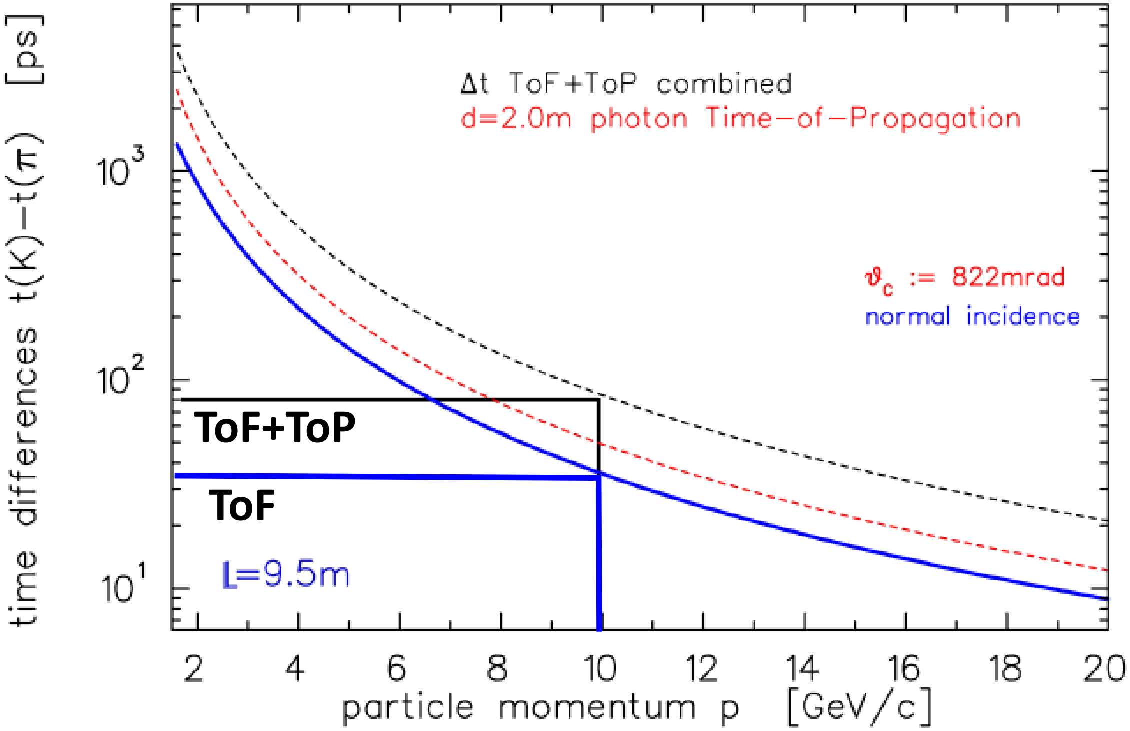


- The wavelength of the photon can be defacto determined via this reconstruction

→ Measure arrival time: $(t - t_0) = L\, n_{group}/c$

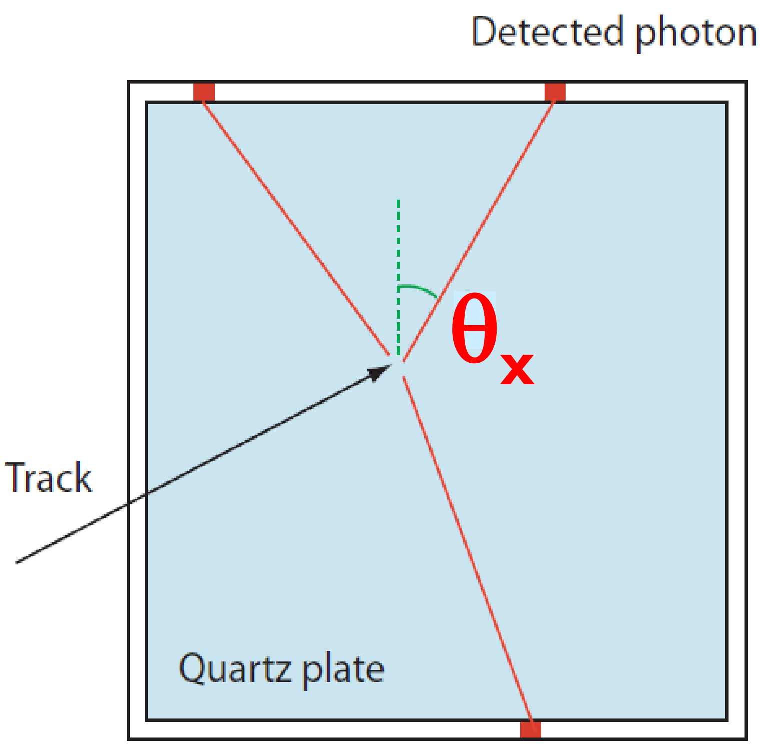
- 1 cm thickness of quartz can produce ~ 30 detected photons/track (assuming a reasonable quantum efficiency of the photon detector)

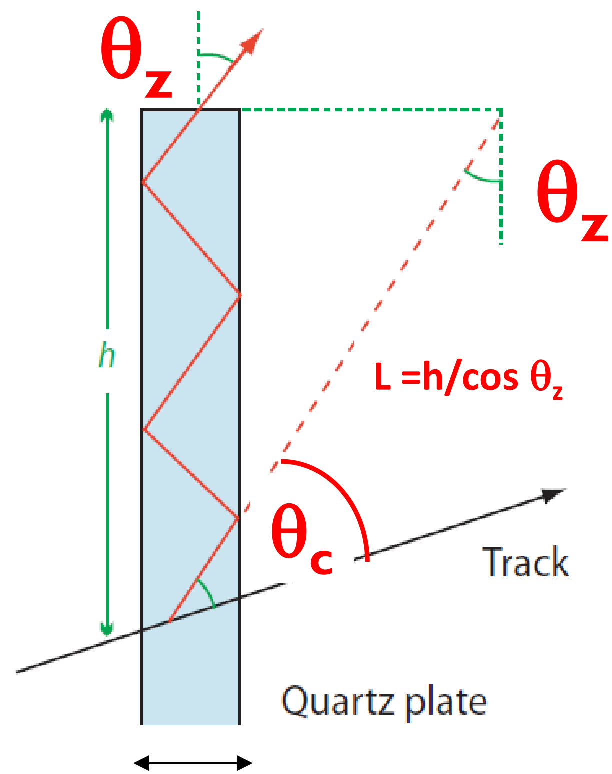
Time of flight and time of propogation



TORCH Angular measurement (θ_x)

- Need to measure *angles* of photons: their path length can then be reconstructed
- From simulation, ~1 mrad precision required on the angles in both planes for intrinsic resolution of ~50 ps
  - → Typical lever arm ~ 2 m
  - → Angular resolution ≈ 1 mrad x 2000 mm / √12
  - → Coarse segmentation (~6 mm) sufficient for the transverse direction (θ_x)
  - → ~8 pixels of a "Planacon-sized" MCP of 53x53 mm^2 active dimension



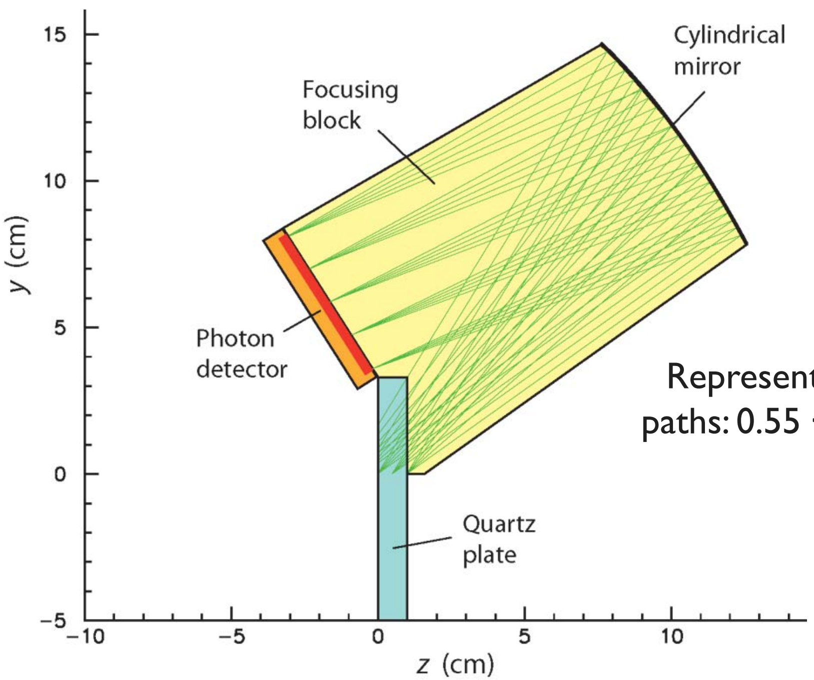


TORCH Angular measurement (θ_z)

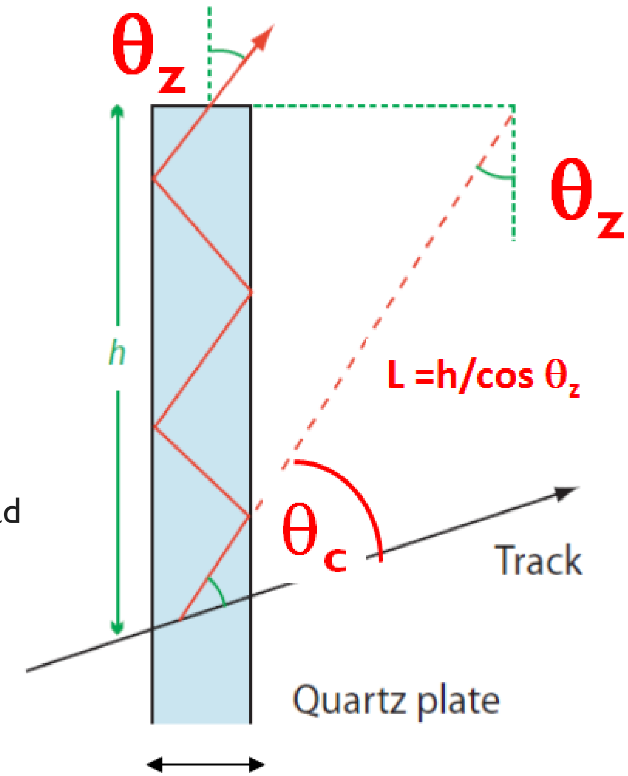
- Measurement of the angle in the longitudinal direction (θ_z) requires a quartz (or equivalent) focusing block to convert angle of photon into position on photon detector
- $\rightarrow$ Cherenkov angular range = 0.4 rad

  $\rightarrow$ angular resolution ~ 1 mrad: need ≈ 400/ (1 x √12) ~ 128 pixels

  $\rightarrow$ fine segmentation needed along this direction

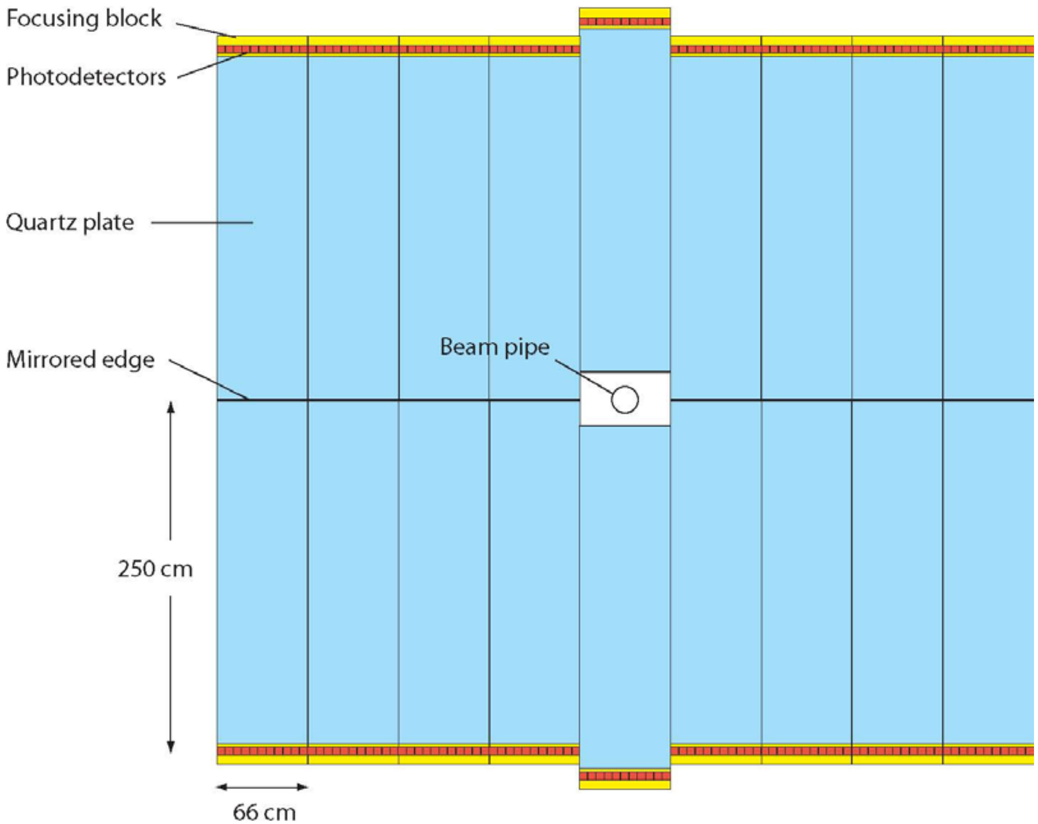


Representative photon paths: $0.55 < \theta_z < 0.95$ rad



TORCH modular design

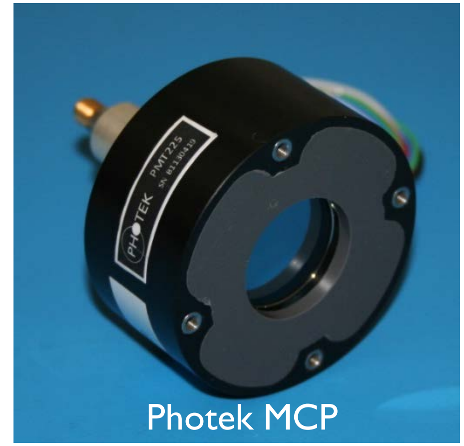
- Dimension of quartz plane is ~ 5 × 6 m^2 (at z = 10 m)
- Unrealistic to cover with a single quartz plate → evolve to modular layout



- 18 identical modules each 250 × 66 × 1 cm^3 → each with 11 MCPs to cover the length
- Possibility of reflective lower edge → increase the number of photons
- MCP photon detectors at the top and bottom edges
  18 × 11 = 198 units
  Each with 1024 pads
  → 200k channels total

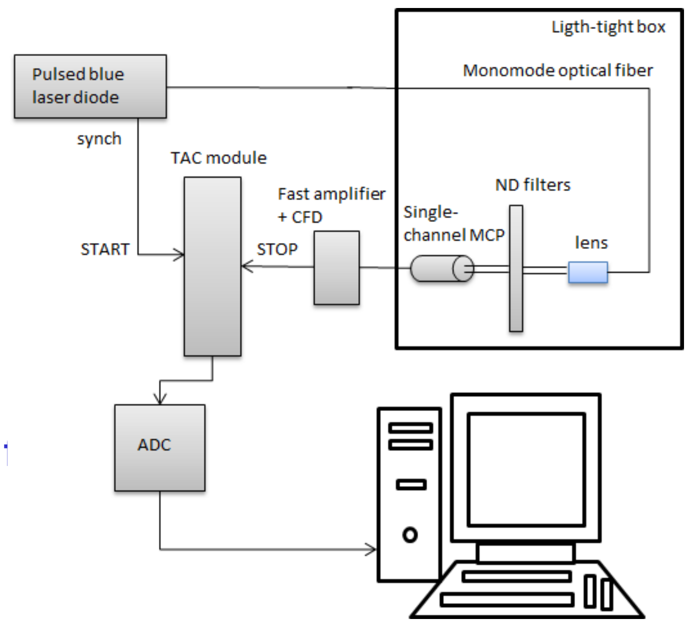
Photek Phase I: MCP lifetime & timing

- 4 single-channel MCPs produced by Photek and tested in-house and by the TORCH collaboration



- Use single-channel ORTEC electronics

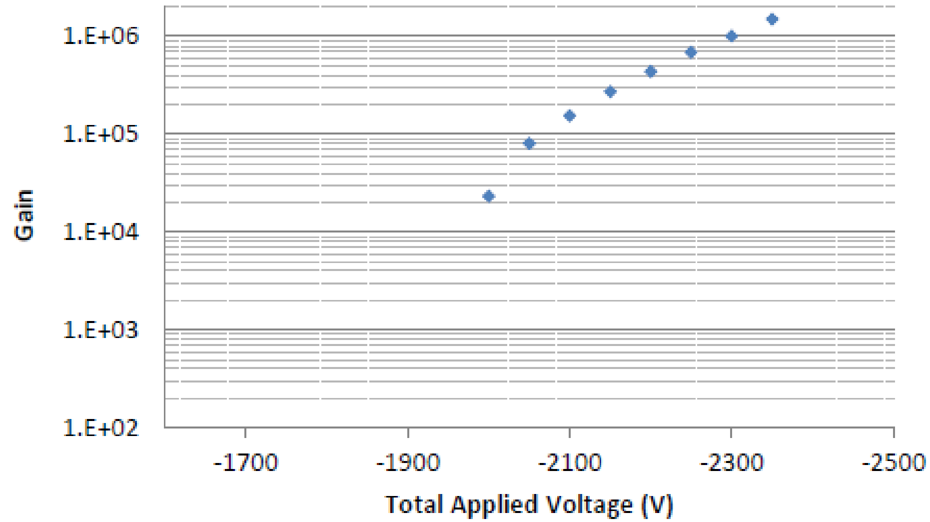
- Pulse height spectra:
  - Standard Poisson distribution to fit data
  - Average number of photoelectrons per pulse (μ) inferred from P(0)

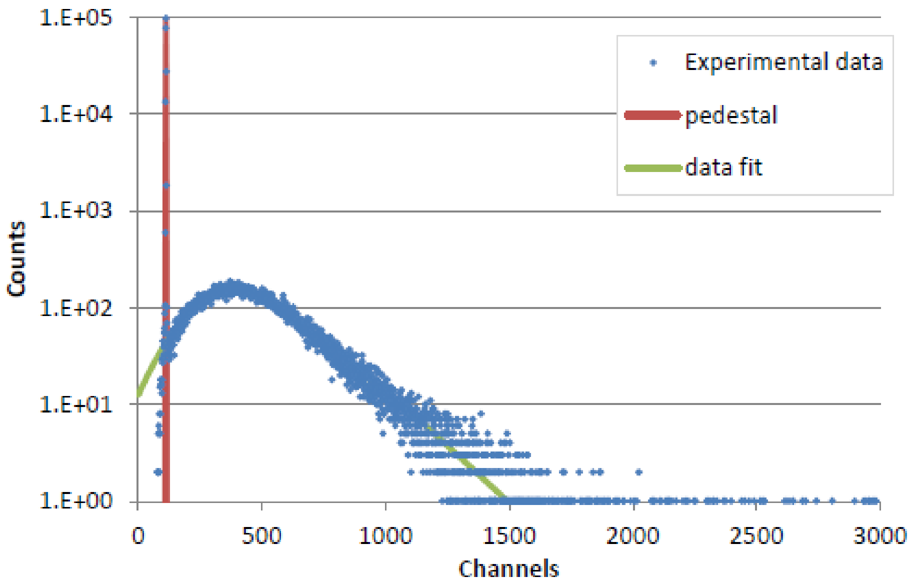


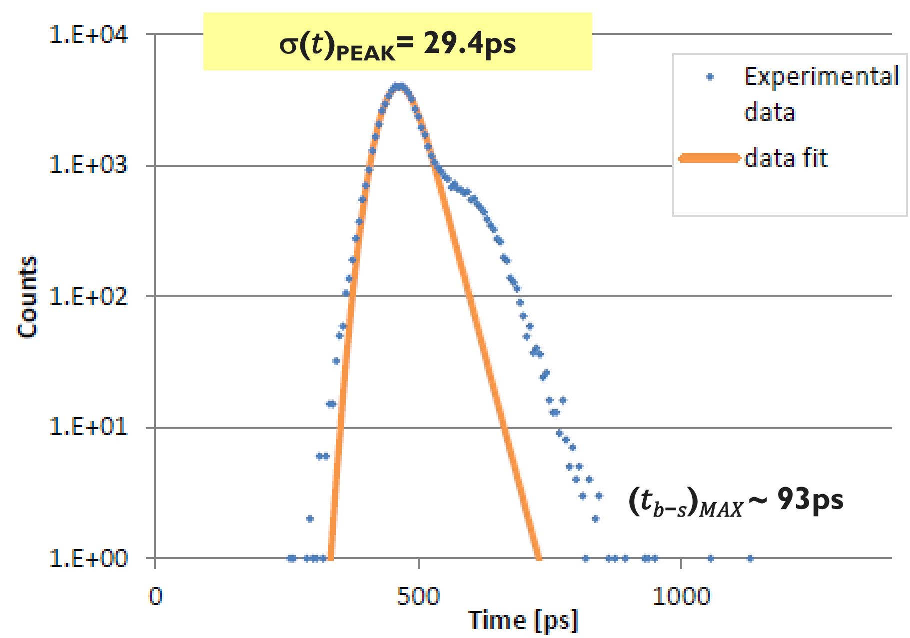
- Timing jitter distributions:
  - Exponentially-modified Gaussian distribution to
    prompt peak → time resolution (σ)

Photek tube PMT225/SN G1130614

- Dark count rate: 8800 Hz
- Operated range: -2000 to -2350V
- Modest gain 4.35×10^5 @-2200V
- Mean no. photoelectrons → μ ~ 0.3
- Timing resolution → σ = 29.4 ps





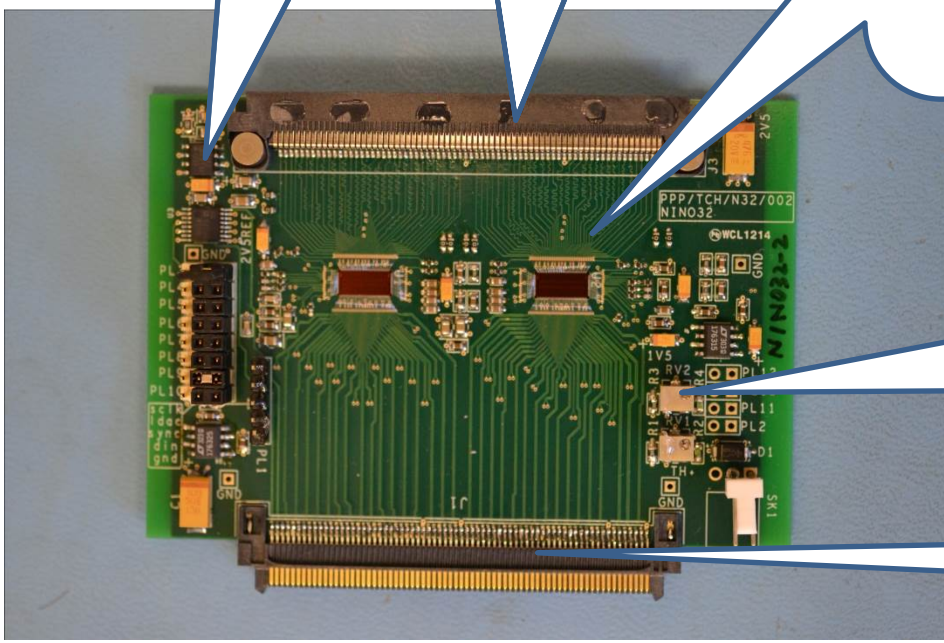


The other 3 tubes perform similarly well

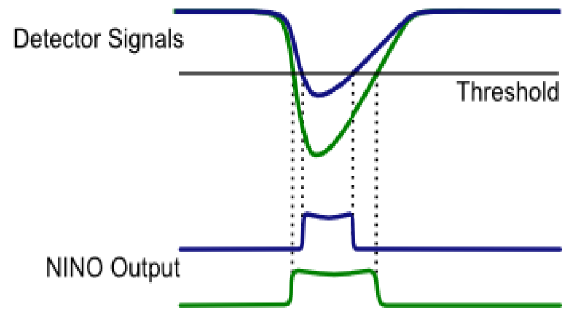
NINO analogue front end

DAC – Setting threshold

Input – negative phase only



2xNINO - Time Over Threshold Measurement, 64-ch per board



Potentiometer – threshold quick settings

LVDS output

Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

HPTDC board – Time to Digital conversion

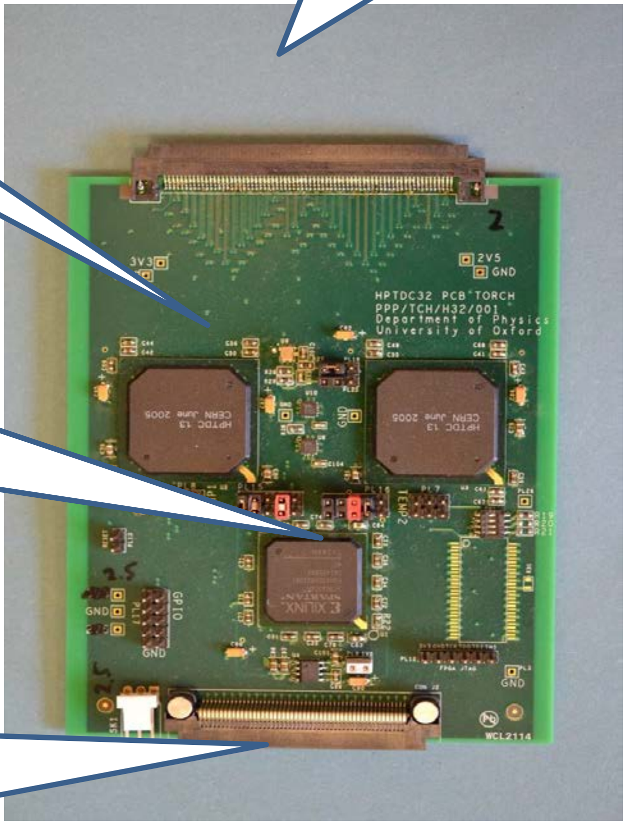
LVDS input from NINO

2x HPTDC[4]

ASICs 64ch

Spartan3AN
HPTDC configuration and control
Data formatting and buffering

Power
Input: clock, trigger, serial slow control, fast control
Output: TDC data, all signals in LVDS



Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

Readout board

LVDS I/O
Fan out 4 x clocks, 4 x triggers
and 36 pairs of LVDS signals
Standalone JTAG for TDC board
2.5v and 3.3v @ 3A max

Gigabit Ethernet

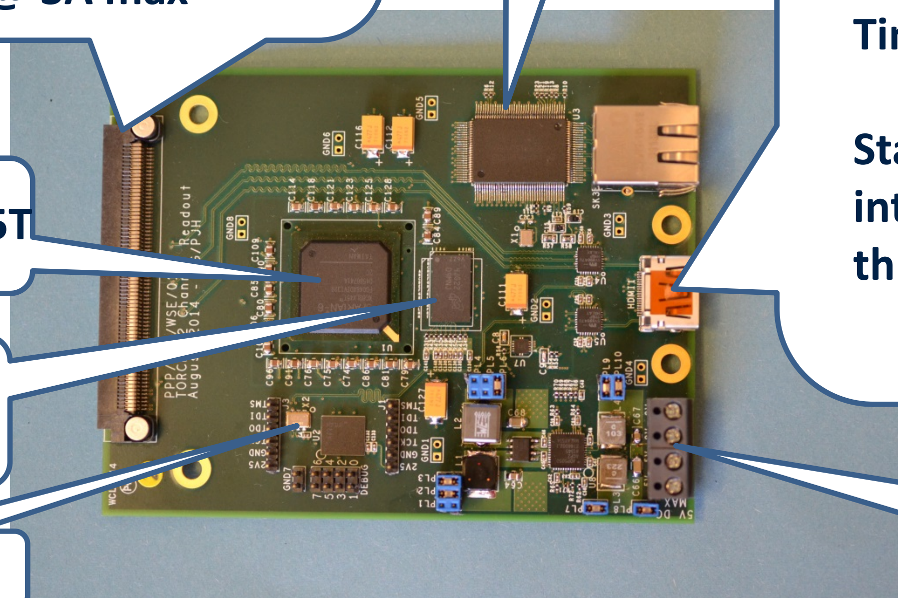
HDMI Connector
External clock and 3 bi-directional LVDS pairs, pinout compatible with Timepix3 Telescope TLU.

Standard LEMO/ SMA interface are available through adaptor.

Spartan6 LX45T

1Gbit DDR3 RAM

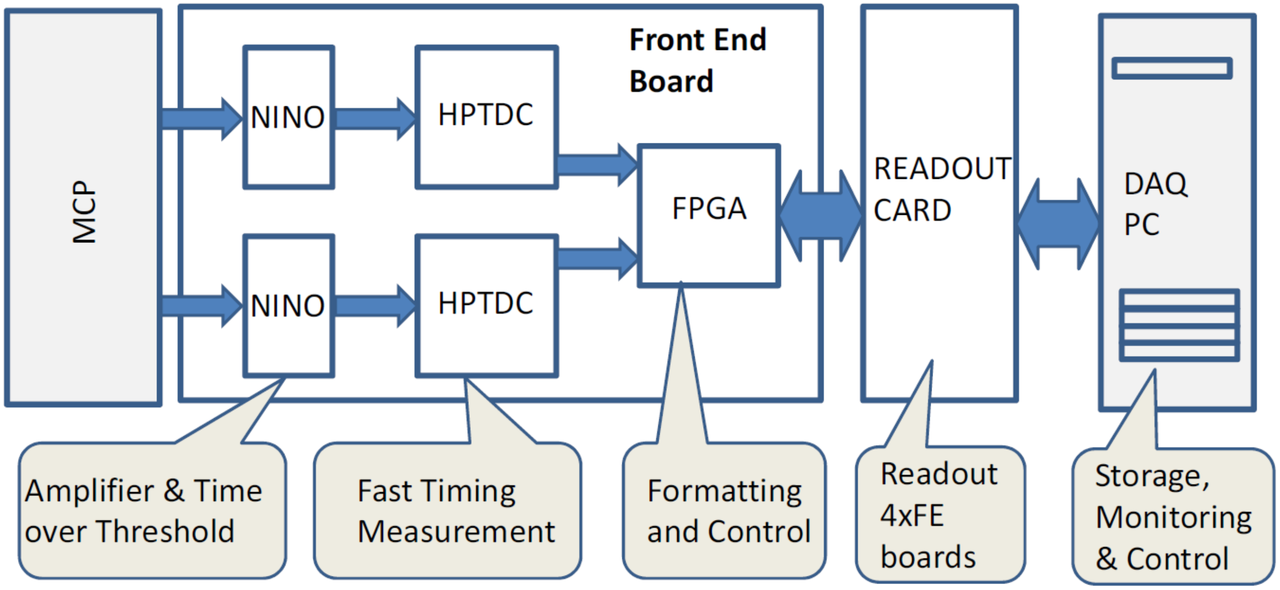
200MHz OSC



Single 5V power supply

Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

Data flow

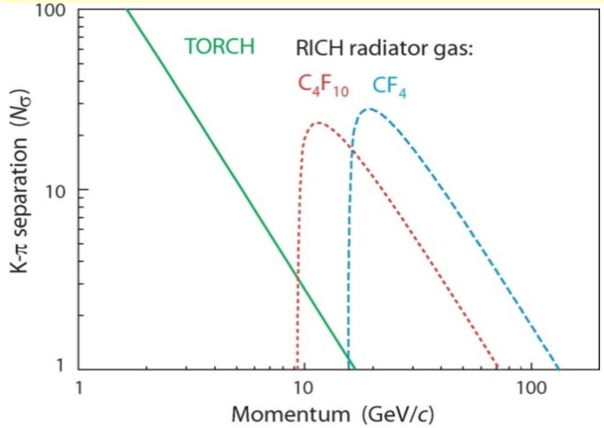


- 64 channels per board
- Laboratory and test-beam firmware have been developed
- Delay matched PCB tracks across all channels
- Giga-bit Ethernet-based readout for up to 4 Front-End boards
- Readout system provides NINO threshold control and HPTDC configuration.

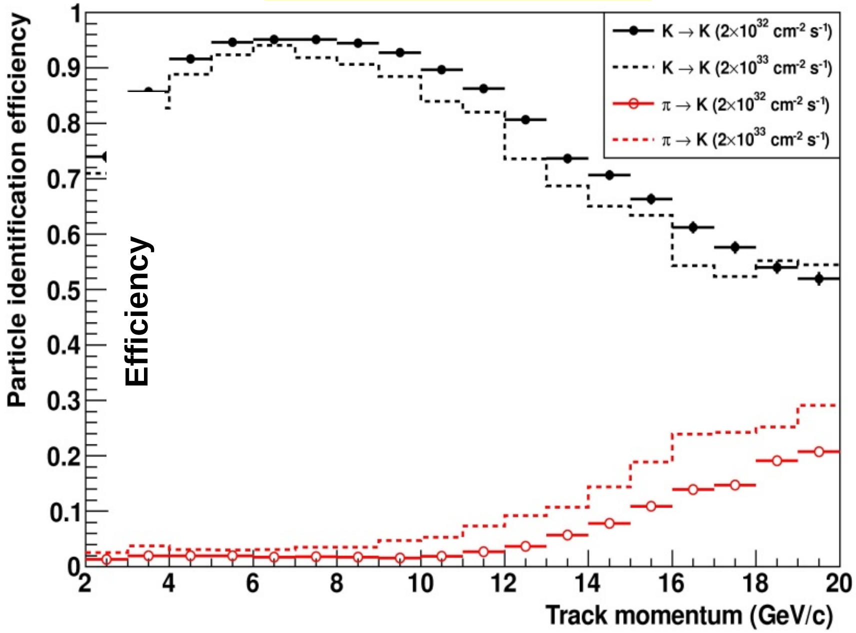
TORCH expected performance at LHCb

- Simulation of the TORCH detector & interface to a simulation of LHCb events, plus TORCH pattern recognition
- Obtain a start time t_0 from the other tracks in the event originating from the primary vertex
- The intrinsic arrival time resolution per photon is 50 ps giving a total resolution of:
  40 ps [MCP] $\oplus$ 50 ps [intrinsic] $\approx$ 70 ps
  with ~30 photons/track (1cm quartz),
  ~15 ps resolution per track obtainable
- Excellent particle ID performance achieved, up to and beyond 10 GeV/c (with some discrimination up to 20 GeV/c).
  Robust against increased luminosity [CERN-LHCC-2011-001]
- Re-use of BaBar DIRC quartz bars? Optimization of the modular layout in progress

(Ideal reconstruction, isolated tracks)

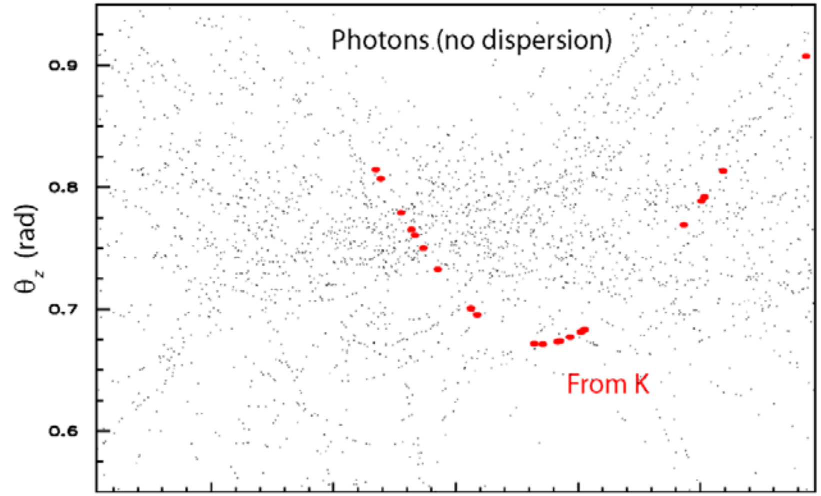


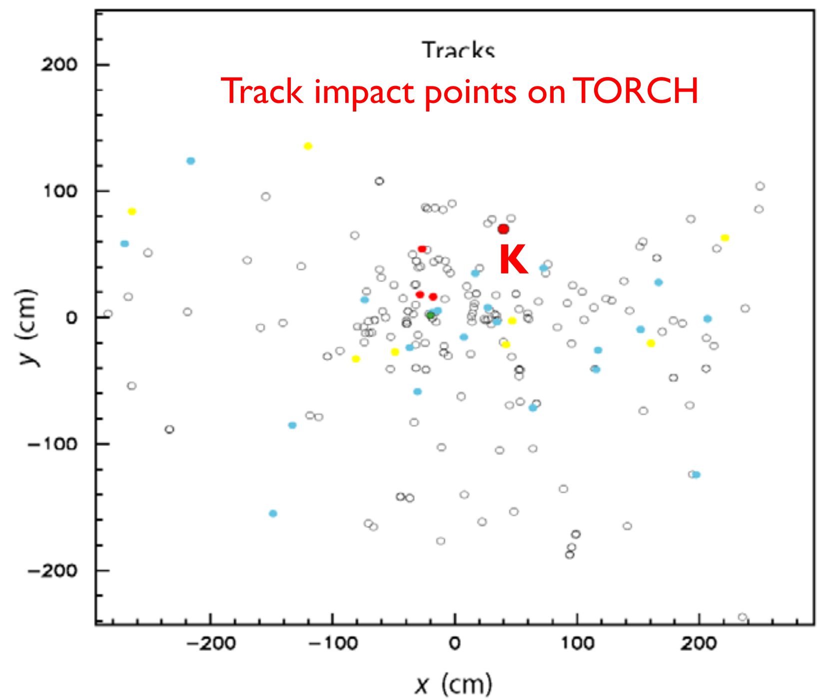
LHCb Simulation



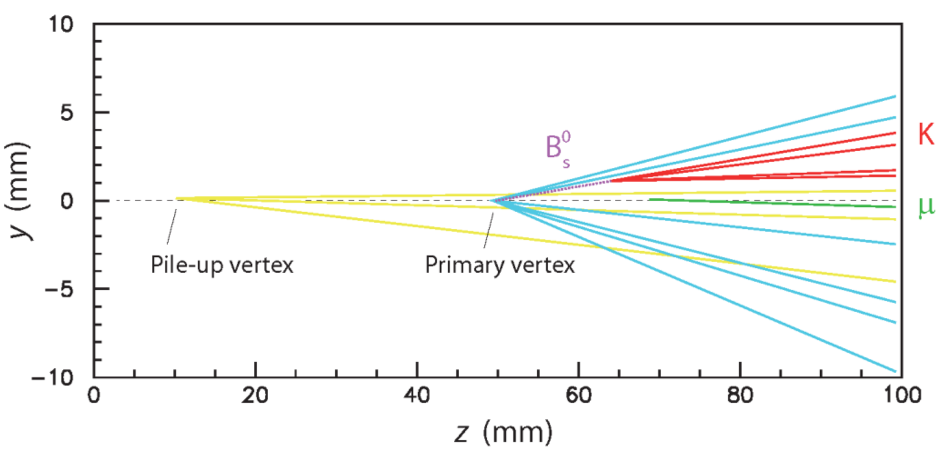
LHCb event

- Typical LHCb event, at luminosity of 10^{33} cm^{-2} s^{-1} (only photons reaching the upper edge shown)
- High multiplicity >100 tracks/event
- Tracks from vertex region colour-coded according to the vertex they come from (rest are secondaries)



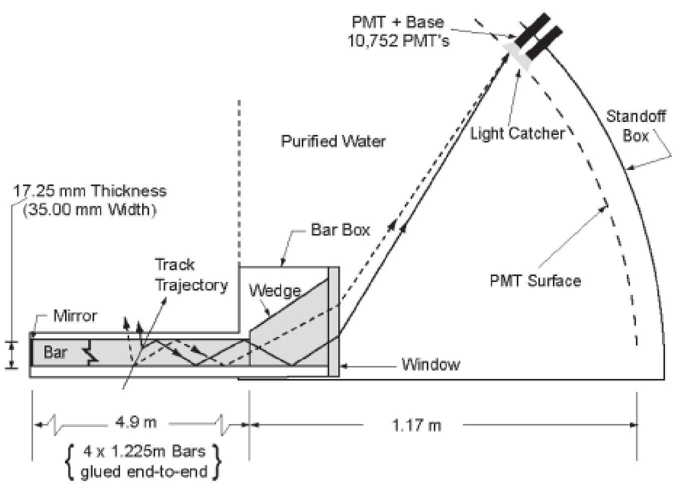


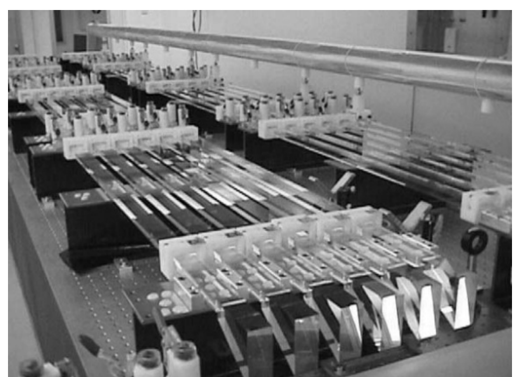
Zoom on vertex region

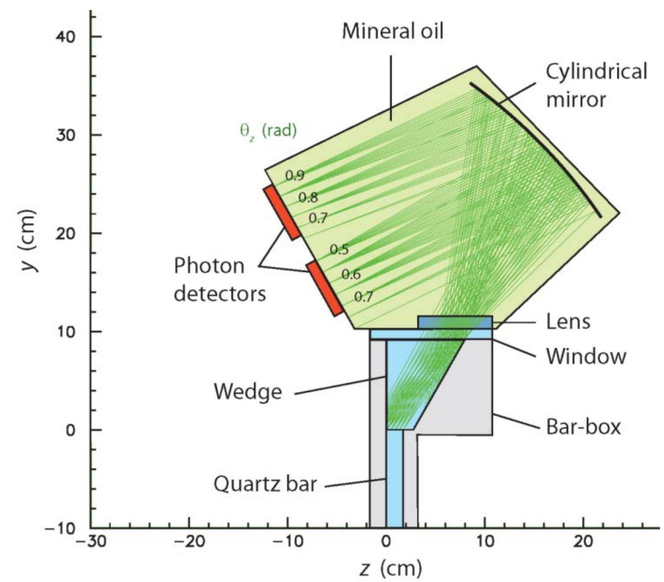


TORCH possible re-use of BaBar quartz bars

- BaBar DIRC quartz bars are available following SuperB cancellation : made up of 12 planar "bar-boxes" each containing 12 quartz bars 1.7 x 3.5 x 490 cm^3
- Bar length (at z = 950 cm) and total area ~ 30 m^2 matches TORCH needs. Adapting the bars requires focusing in both projections; can use a cylindrical lens for this, at the end of each bar.
- Effect of wedge (glued to bars) is to give two separate beams: depending on whether photons reflected or not.
- Split detector plane: assuming 60 mm square MCPs (53 mm active) requires two PMTs to cover $0.5 < \theta_z < 0.9$ rad
- Adapting the TORCH optics to re-use the BaBar DIRC seems viable: no degradation seen compared with single projection. Studies are ongoing.

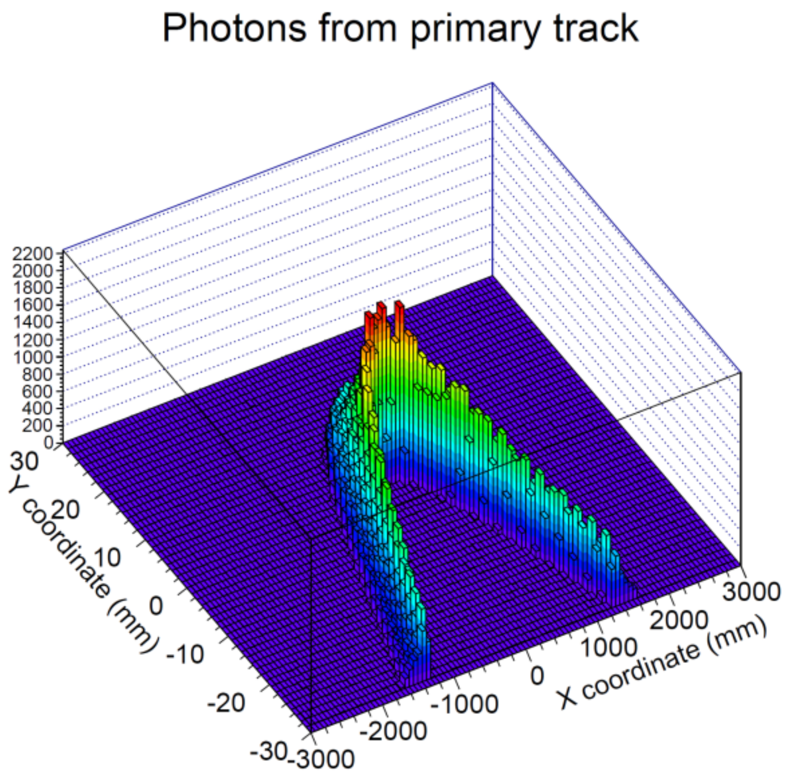


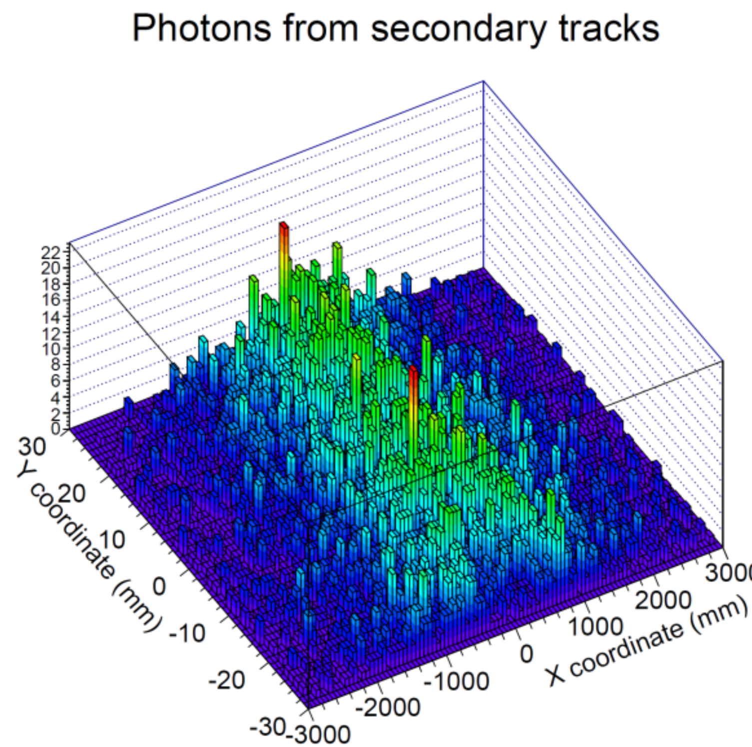




Full GEANT simulations

- Simulation of accumulated photons for a thousand 10 GeV/c kaons
- Background photons from secondary electrons that also give off Cherenkov radiation
- Width of Cherenkov ring segment is due to chromatic dispersion in quartz medium

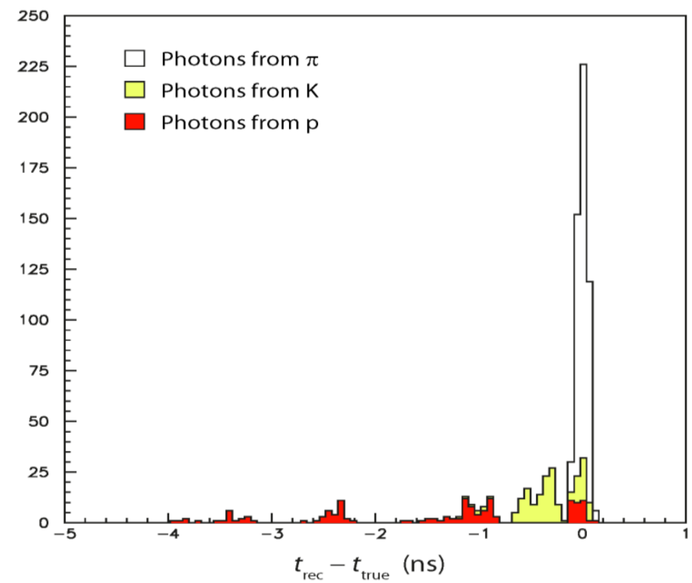




Measuring start-time at LHCb

- To determine the time-of-flight, also need a start time (t_0)
- This might be achieved using timing information from the accelerator, but bunches are long (~ 20 cm) → must correct for vertex position
- Alternatively use other tracks in the event, from the primary vertex
- Most of them are pions, so the reconstruction logic can be reversed, and the start time is determined from their average *assuming* they are all π (outliers from other particles removed)
- Can achieve few-ps resolution on t_0

Example from PV of same event



After removing outliers