TORCH : a fast timing detector for low-momentum particle identification

Rui Gao on behalf of the TORCH collaboration

The 2023 international workshop on the high energy Circular Electron-Positron Collider (CEPC), 23rd – 27th October 2023

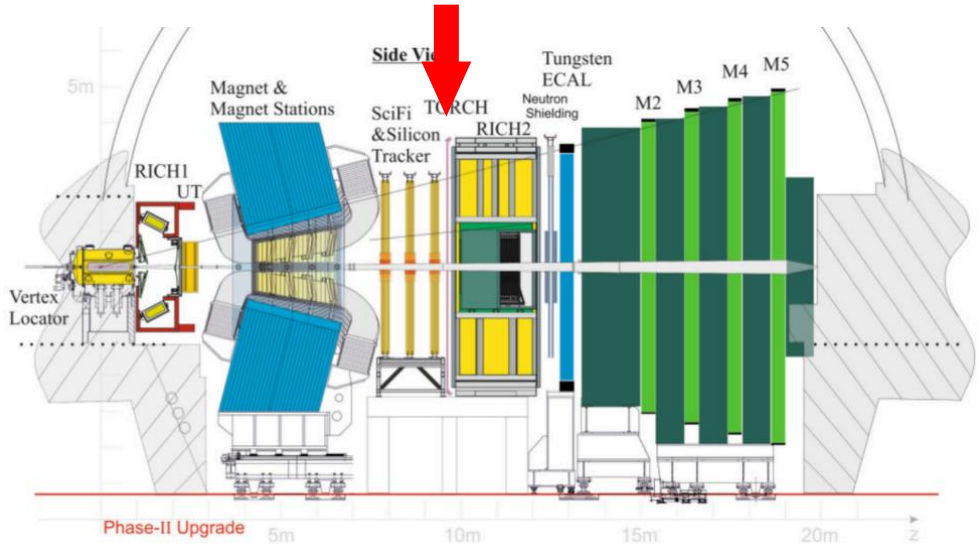
Original TORCH R&D is supporting by ERC grant

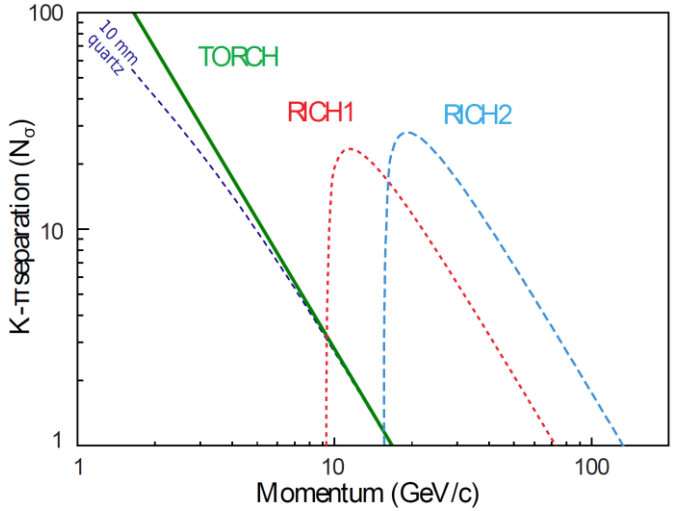
Overview

- TORCH is a large-area time-of-flight detector, designed to enhance the particle identification performance, in a momentum range 2–15 GeV/*c*, for time-of-flight over 10m

- High-granularity Micro-Channel Plate Photomultiplier Tubes (MCP-PMTs) and fast electronics are developed to meet the requirement of timing resolution of 15ps per track

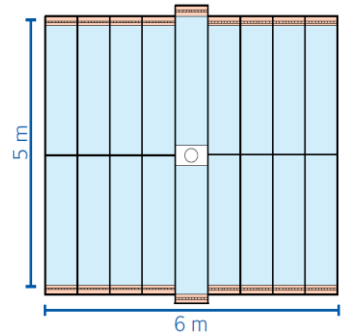
- It is foreseen to be installed in 2033–34 as part of Upgrade II of the LHCb experiment



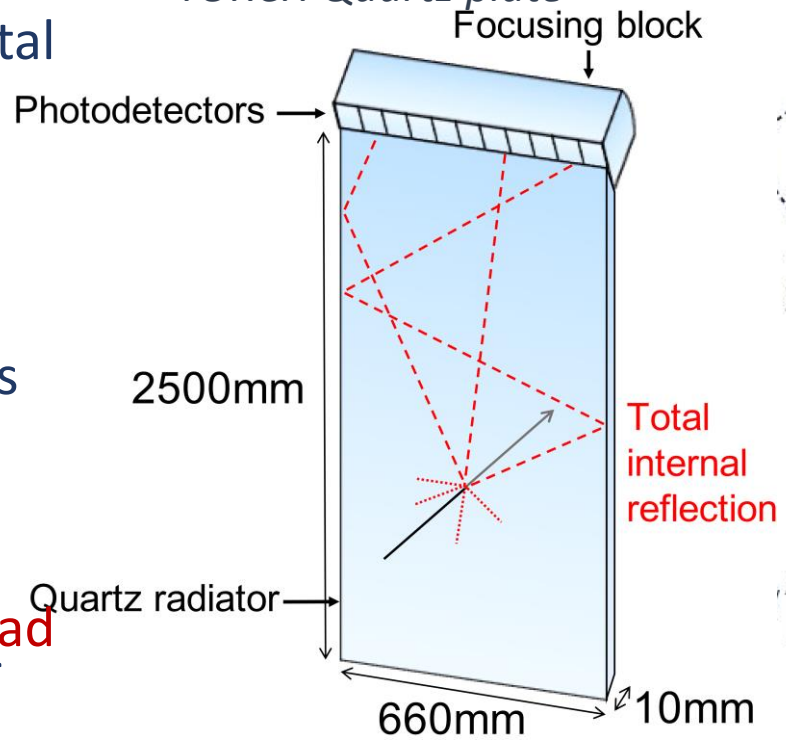


TORCH concept

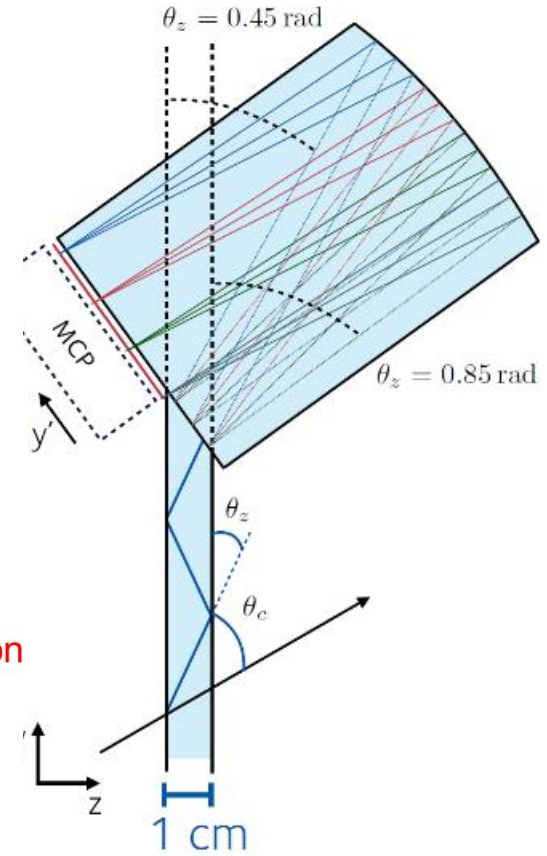
- Cherenkov photons are generated in a modelized 5m x 6m quartz plate
- The photons propagate to the periphery of the detector through total internal reflection
- A focusing block directs photons to Micro-Channel Plate Photomultiplier Tubes (MCP-PMTs)
- It requires a timing resolution of 15ps per track, translated to 70ps for individual Cherenkov photons, 30 photons per track
- It requires an angular resolution 1mrad translated to spatial segmentation of 128 X 8 pixels in a 53mm X 53mm active area



TORCH Quartz plate



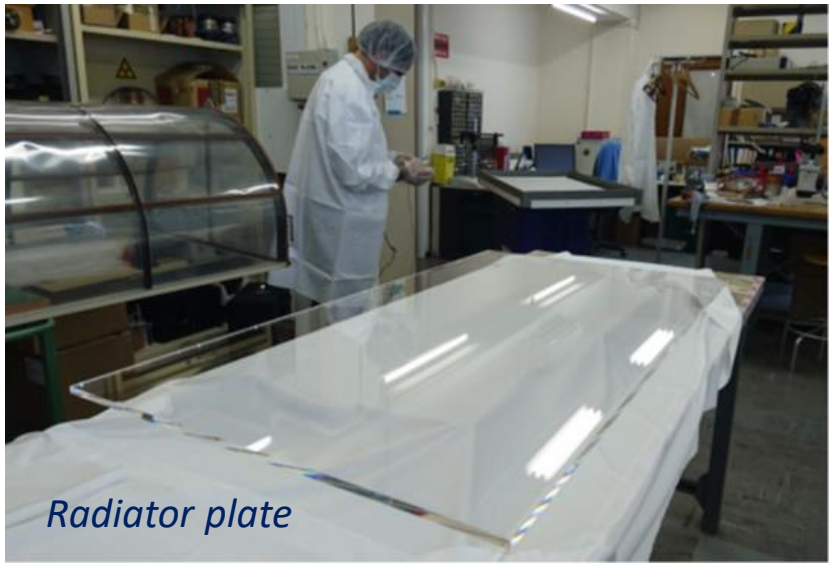
TORCH Quartz module



Focusing block

Optical components

- A full width (66cm), half-height (125cm) fused silica plate has been manufactured by Nikon Glass
  - thickness variation ≤ 3 μm
  - surface roughness ≤ 0.5 nm
- Full-size focusing block is manufactured and glued to the plate with Pactan 8030



Radiator plate

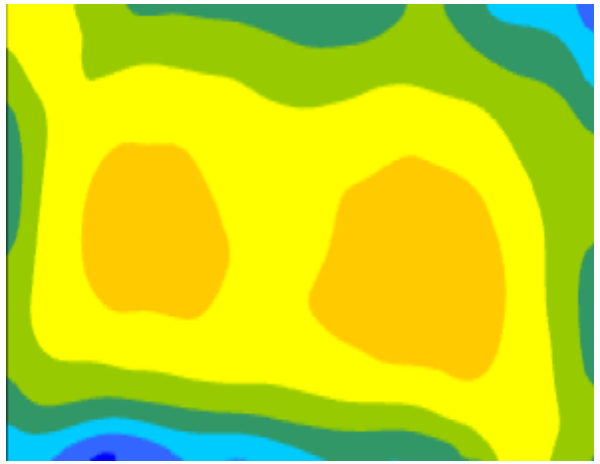
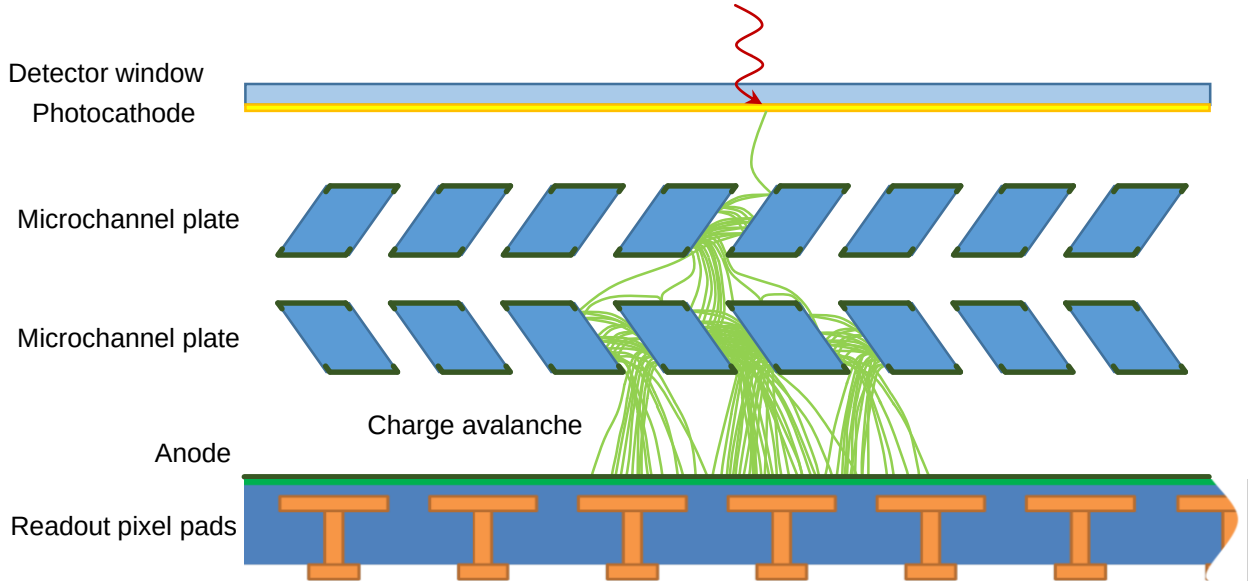


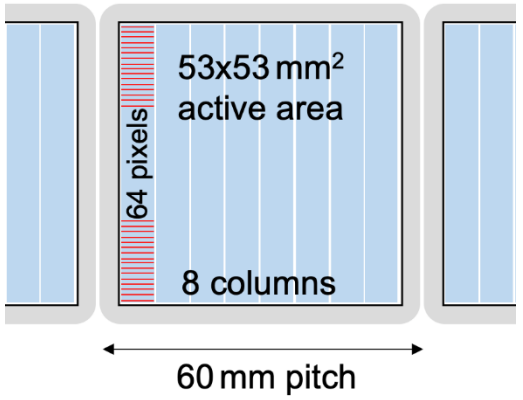
Plate surface flatness: measured 1 μm contours

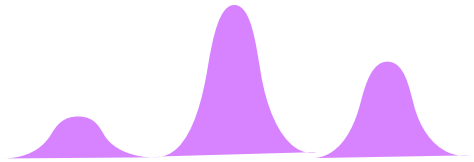
Focusing block

The TORCH MCP-PMT

- MCP-PMT chosen as fast photodetector developed by Photek, U.K.
- 2-inch square MCP allow close packed to instrument a 66cm module with minimum dead space
- 64X64 capacitive coupled pixels allow charge sharing to achieve 128 equivalent pixels on one direction
- 8 pixels are grouped on the other direction to achieve 8 columns
- ALD coating to increase life time
- MCP instrumented with high density connectors on the back







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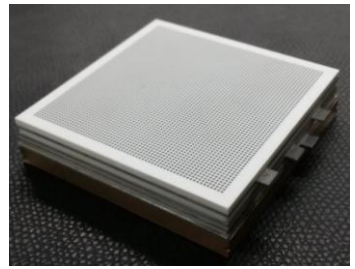
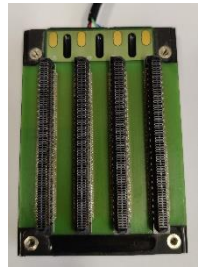
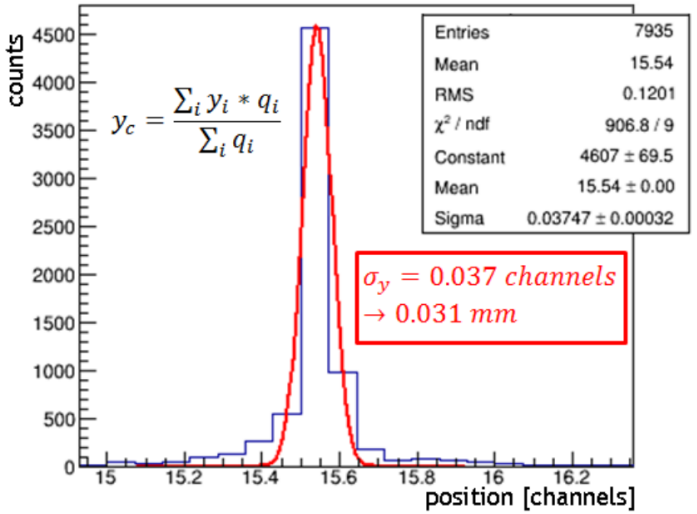




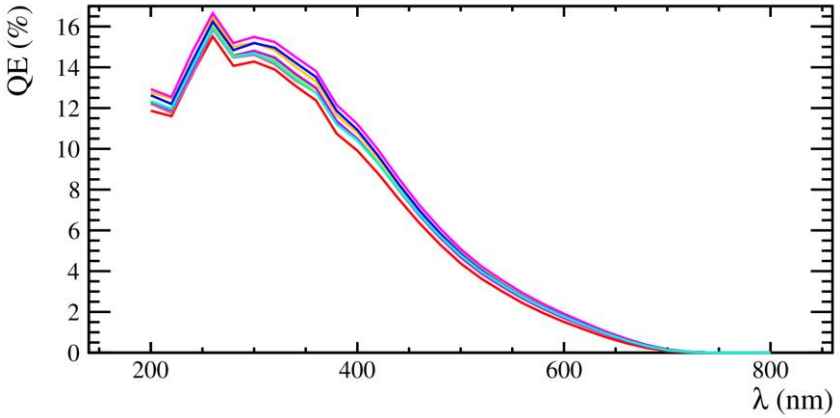
MCP lab testing

- Quantum efficiency (QE) and gain uniformity typical gain ~10^6(160 fC)
- Intrinsic time response of MCP and electronics tested with 405 nm picosecond pulsed laser
- Spatial resolution from charge sharing (using an earlier prototype tube)

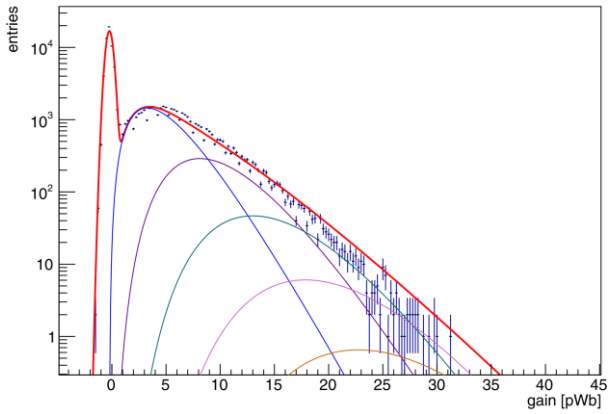


Spatial resolution ~0.037 Channels

JINST 11 (2016) C05022

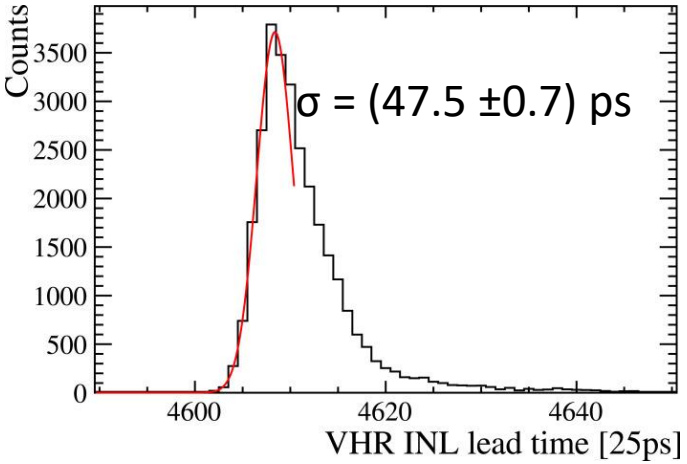


QE at differ positions using xenon lamp and monochromat Orent



Gain distribution fit with Polyamodel

NIMA 1045(01-01-2023) 167535

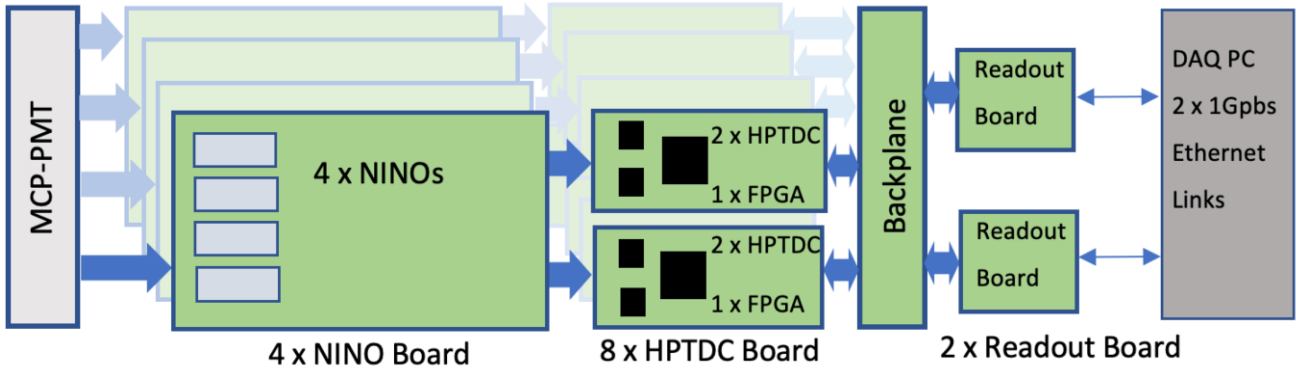


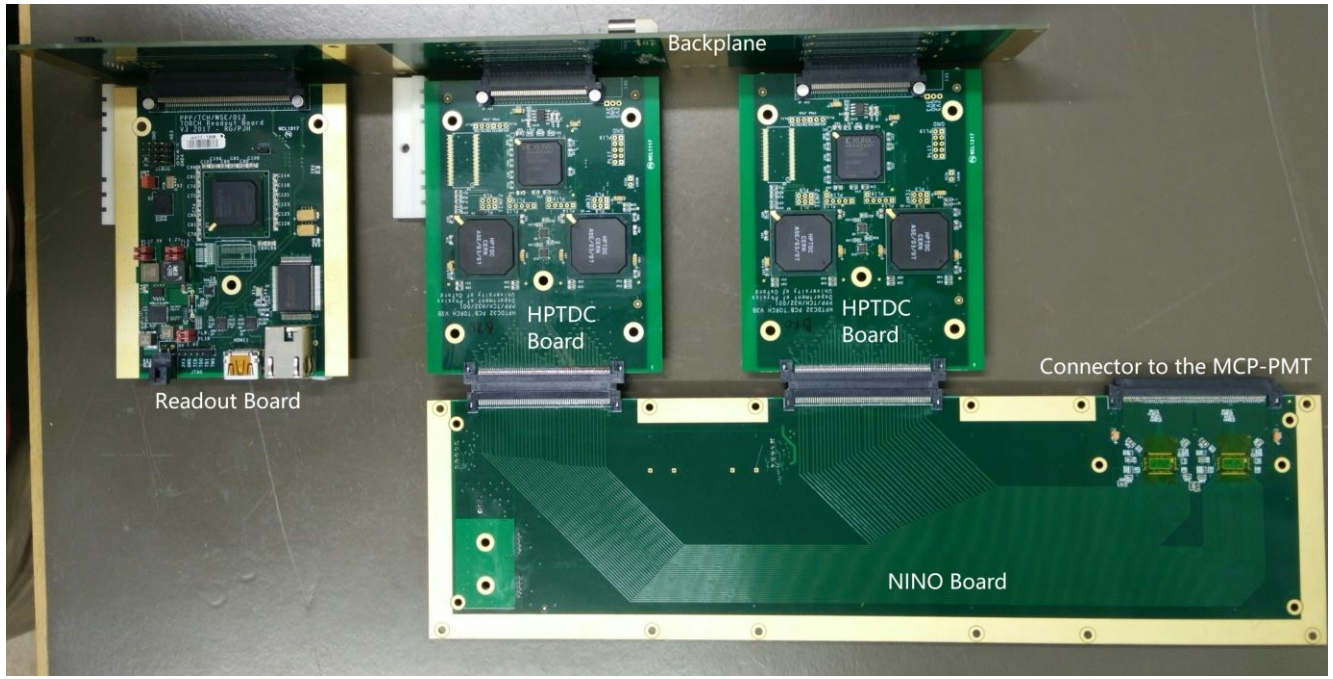
MCP and Electronics Timing resolution

NIMA 1038(01-09-2022) 166950

Readout electronics

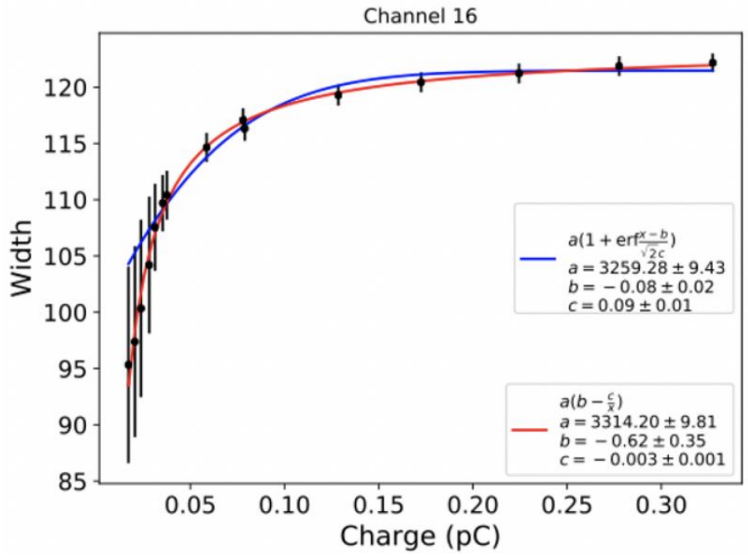
- Readout based on NINO and HPTDC chips
  - NINO – Amplifier and discriminator *10.1109/TNS.2010.2100409*
  - HPTDC – Time to digit convertor *10.1109/NSSMIC.2000.949889*
  - Instrument a MCP with 4 X 128 channel NINO boards and 8 HPTDC boards
- The measurement
  - Triggered measurement
  - Time of arrival
  - Time-over-Threshold (TOT)
  - 100 ps bin time
  - Extended timestamp for up to 8 hours
  - Intrinsic time resolution is 26.8ps *JINST(2014) 9 C02025*
- Custom Gigabit Ethernet Readout board
  - Raw MAC protocol for maximum efficiency
  - Use commercial router with 10 Gigabit uplink to minimum links in DAQ
- Latest DAQ based on EUDAQ framework



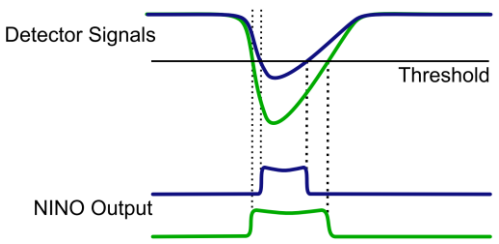


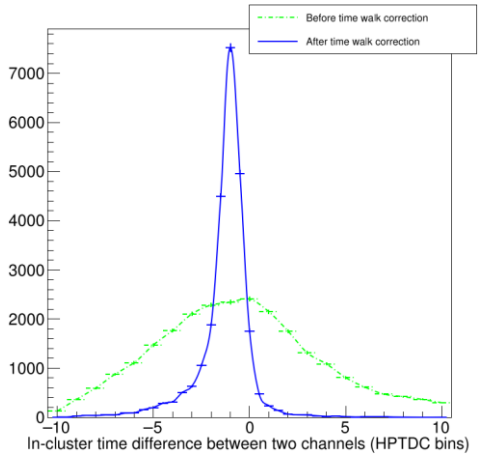
Data processing

- The following techniques are applied to improve time resolution
  - Time walk correction
  - Clustering position and time information for neighboring pixels
  - Integral Non-Linearity calibration for HPTDC
  - Charge to width calibration



Charge to width calibration *J. Smallwood, TIPP2021*





Time walk correction and clustering. *M. Van Dijk RICH2022*

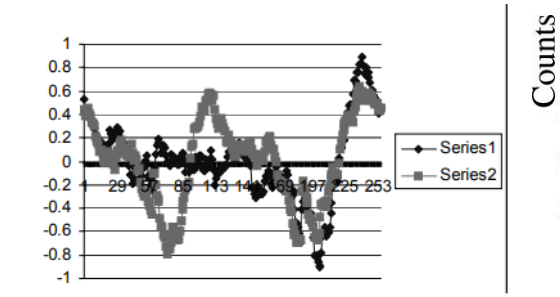
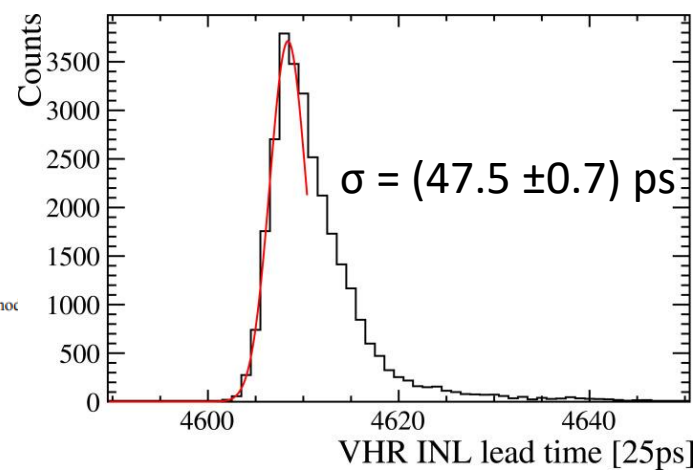


Fig. 38 INL with 40MHz and 80MHz core logic clock in high resolution mod

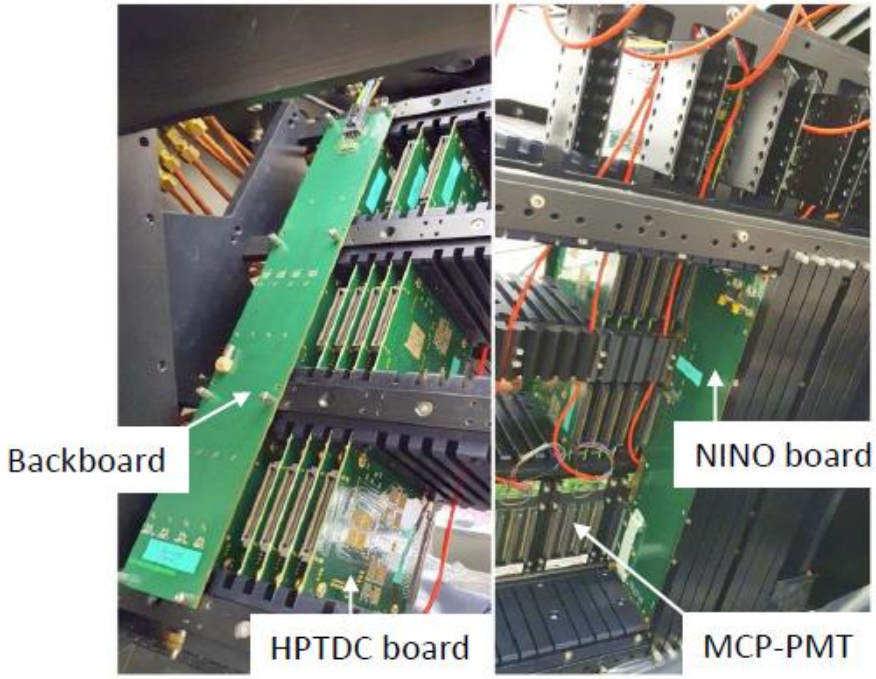
Non-Linearity in HPTDC

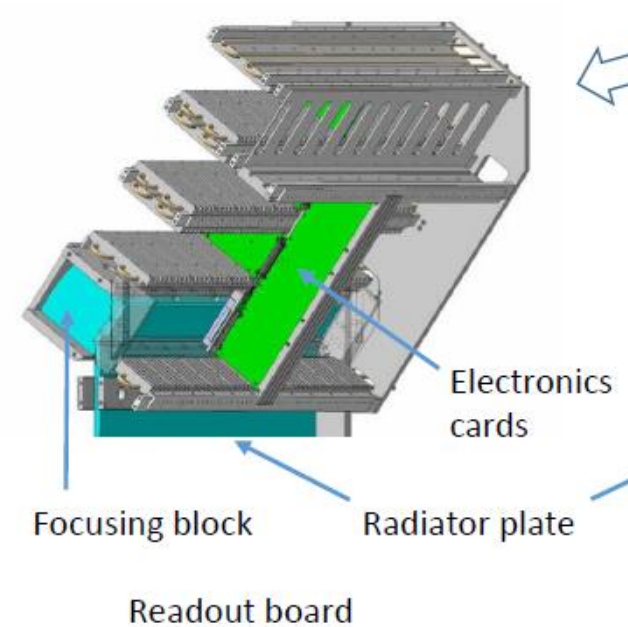


Intrinsic Time resolution MCP+ readout after INL correction

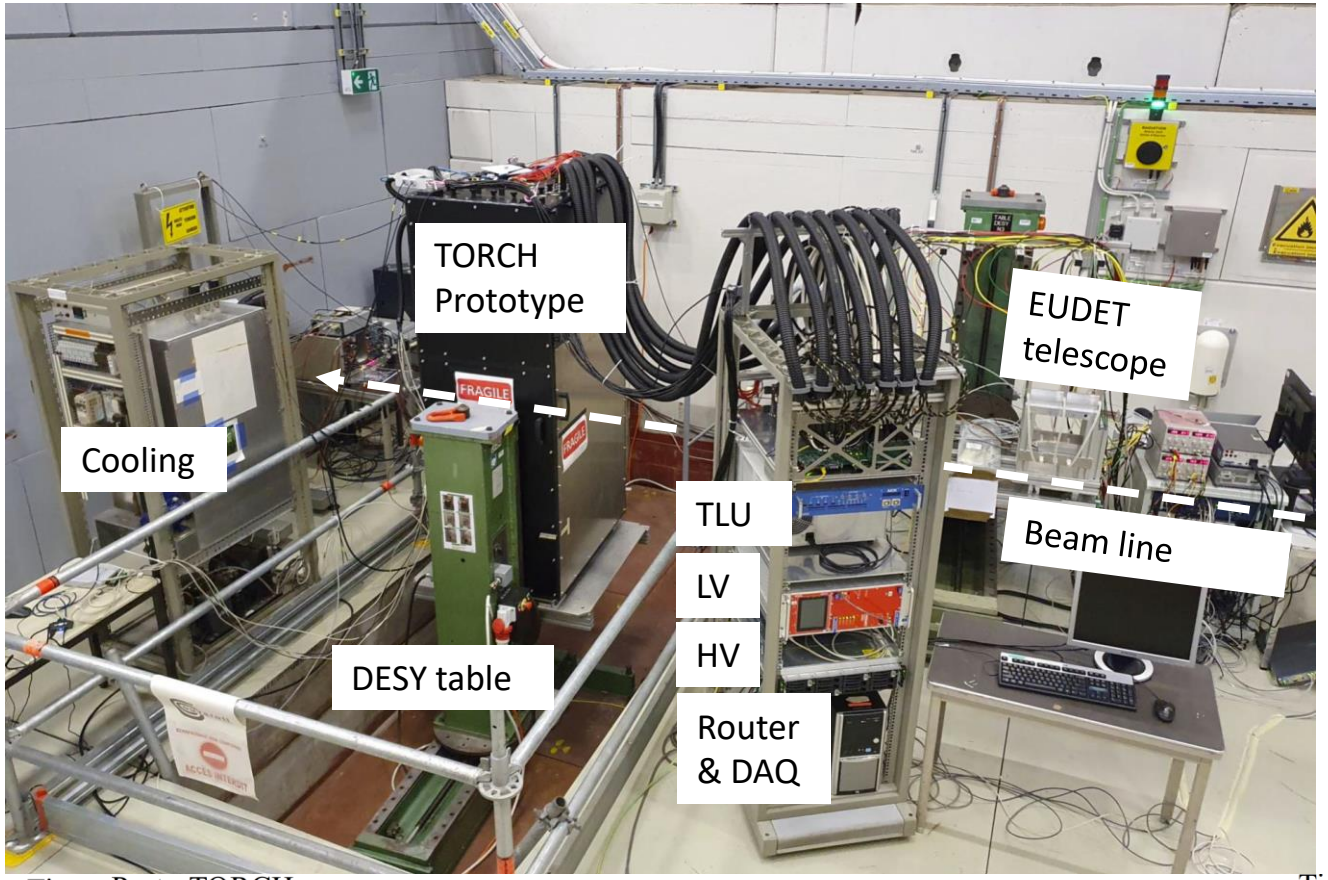
Module prototype

- The large scale TORCH prototype was constructed and initially tested in beam with two MCP-PMT tubes in 2018
- Last year the instrumentation was extended to 6 MCP-PMTs with a total of 3072 channels, and returned to the (renovated) T9 test beam area at the CERN PS

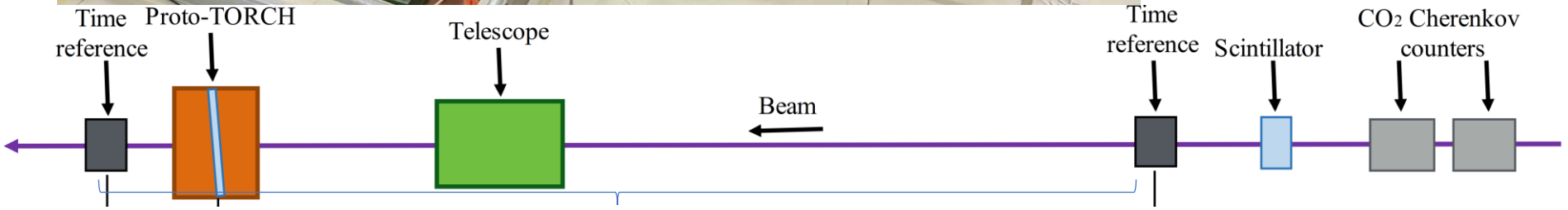




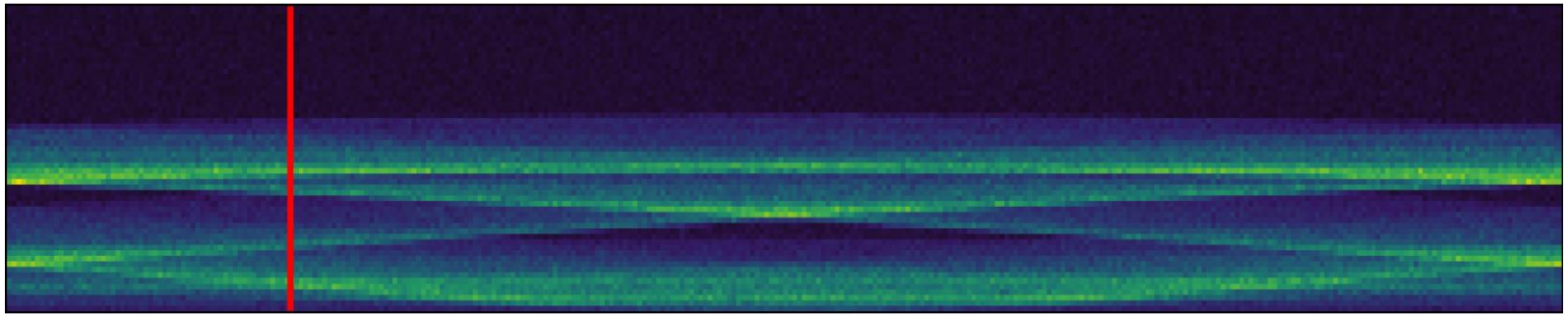
Test beam 2022



- Previous test beam in 2018 with two MCPs
- Picture shows the test beam setup with 6 MCPs, in PS, CERN November 2022
- Mixed p/π beam at energy 3–10 GeV
- Equipments include beam Cherenkov counters, two timing stations, AIDA TLU, 10Gigabit router, DAQ and control computers

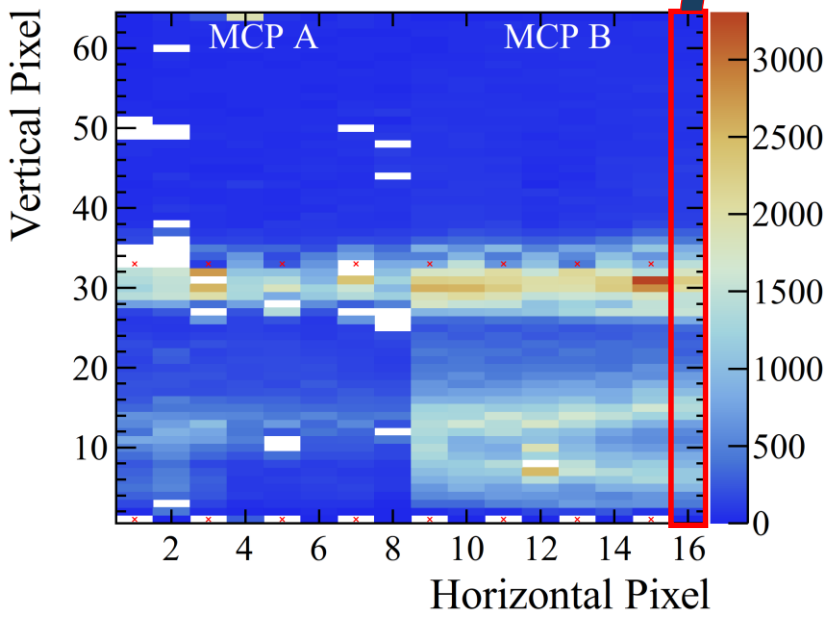


Test beam result 2018: hit map, time projection

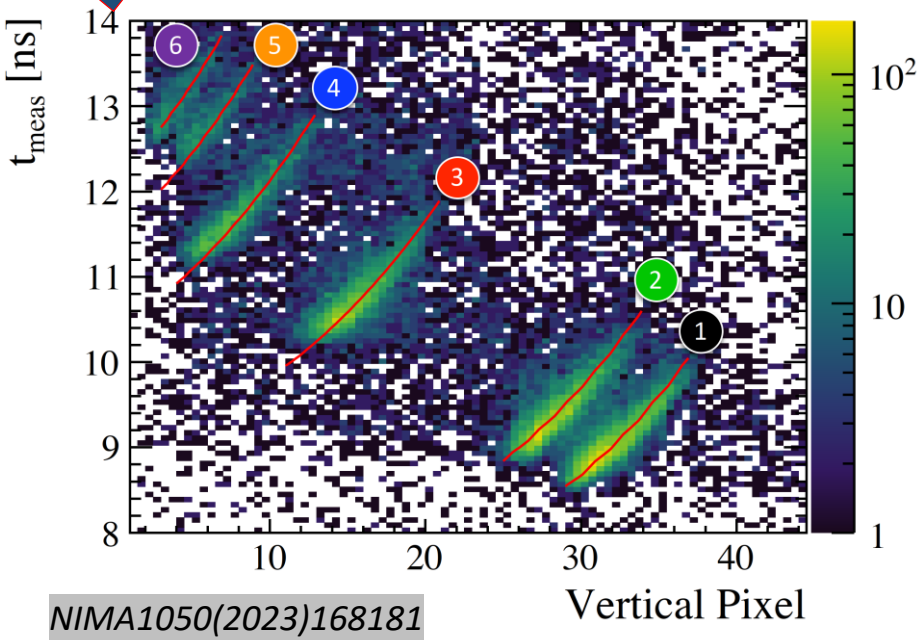


Simulation of TORCH pattern across the whole 660mm width. Red line indicates the region covered by MCPs A and B.

Data collected over area



Time projection of column 16



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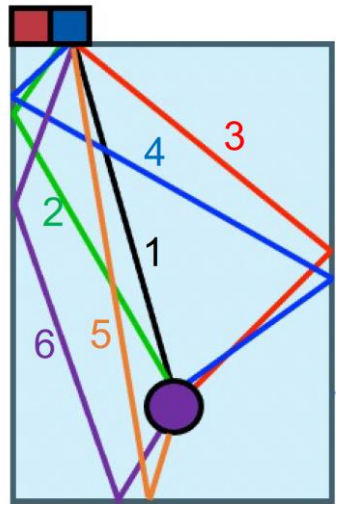
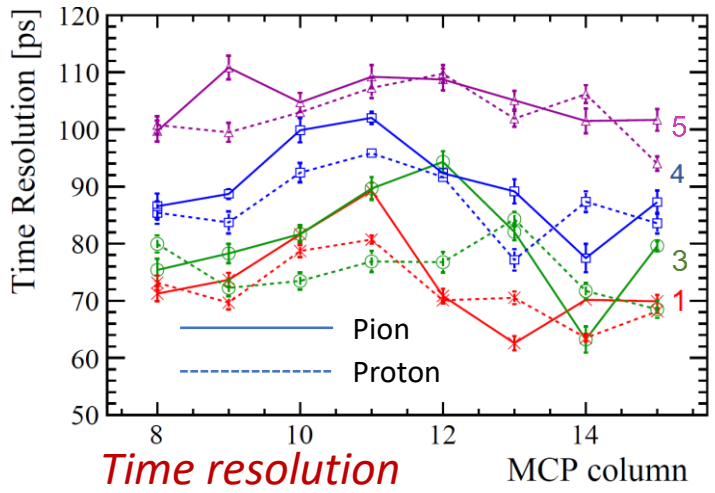
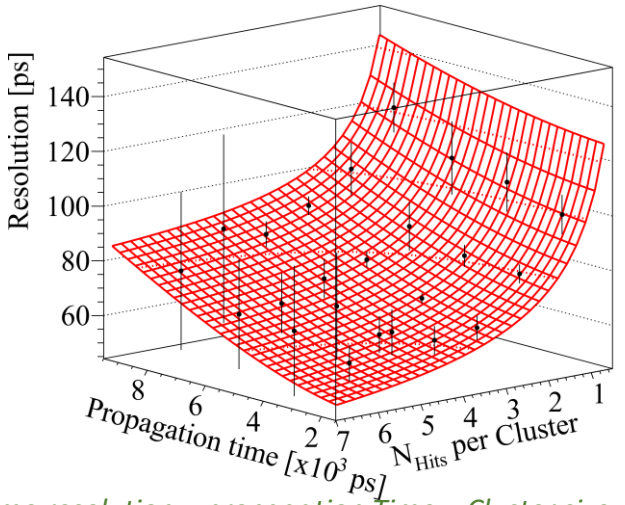


Test beam result 2018: time resolution

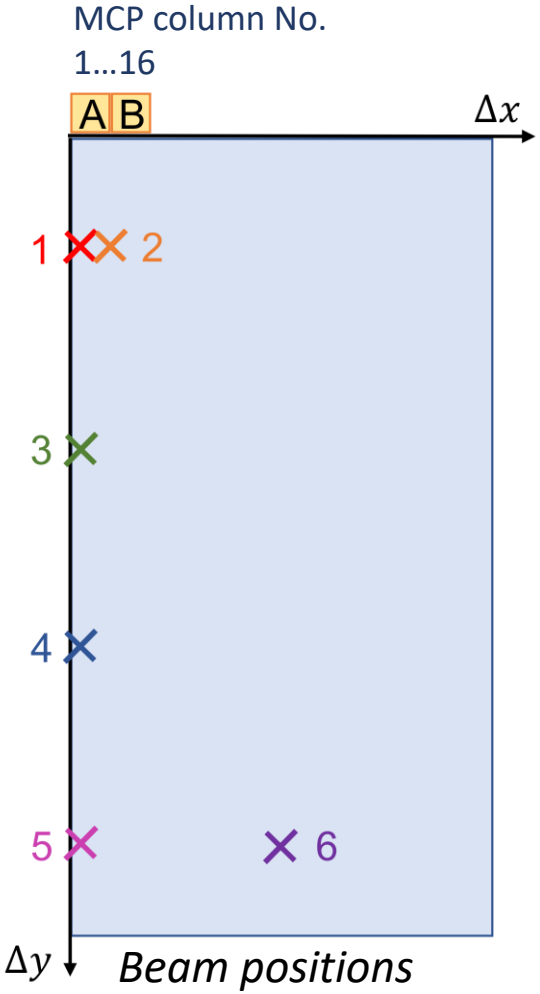
- For beam position close to MCP-PMT, 70ps time resolution is reached
- Further studies time resolution - propagation time-cluster size



Time resolution



Time resolution – propagation Time – Cluster size



- Time resolution expression

$$\sigma^2_{\mathrm{TORCH}} = \sigma^2_{\mathrm{const}} + \sigma_{\mathrm{prop}}(t_P)^2 + \sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})^2,$$

Contribution	Fitted values (ps)		Target values (ps)
	Pion	Proton	
$\sigma_{\mathrm{prop}}(t_p)$	$(8.3 \pm 0.7) \times 10^{-3} \times t_p$	$(7.6 \pm 0.5) \times 10^{-3} \times t_p$	$(3.75 \pm 0.8) \times 10^{-3} \times t_p$
σ_{MCP}	34.5 ± 8.6	31.0 ± 7.6	33
$\sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})$	$(96.2 \pm 6.7)/\sqrt{N_{\mathrm{Hits}}}$	$(95.0 \pm 6.0)/\sqrt{N_{\mathrm{Hits}}}$	$60/\sqrt{N_{\mathrm{Hits}}}$

- Further calibrations in Readout Electronics are expected to improve timing resolution

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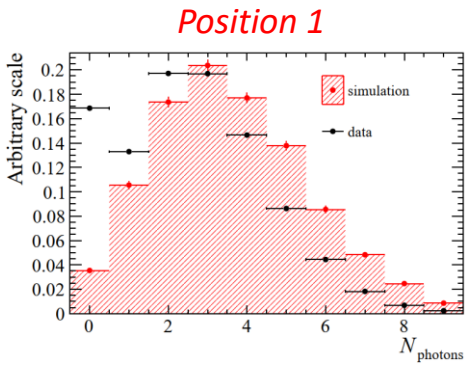
Test beam: photon counting

- Counting efficiency of incoming light is critical
- Compare with Geant4 simulation to benchmark
- Expected to improve further with calibration



Position	Mean $N_{photons}$		Mean(Data)/Mean(Simulation)	
	Data	Simulation	All	Excluding $N_{photons}$=0
1	2.605 ± 0.007	3.586 ± 0.020	0.726 ± 0.004	0.843 ± 0.005
3	1.419 ± 0.005	2.016 ± 0.029	0.704 ± 0.010	0.824 ± 0.010
4	0.937 ± 0.004	1.454 ± 0.024	0.644 ± 0.011	0.823 ± 0.008
5	0.677 ± 0.002	1.127 ± 0.022	0.600 ± 0.012	0.820 ± 0.009

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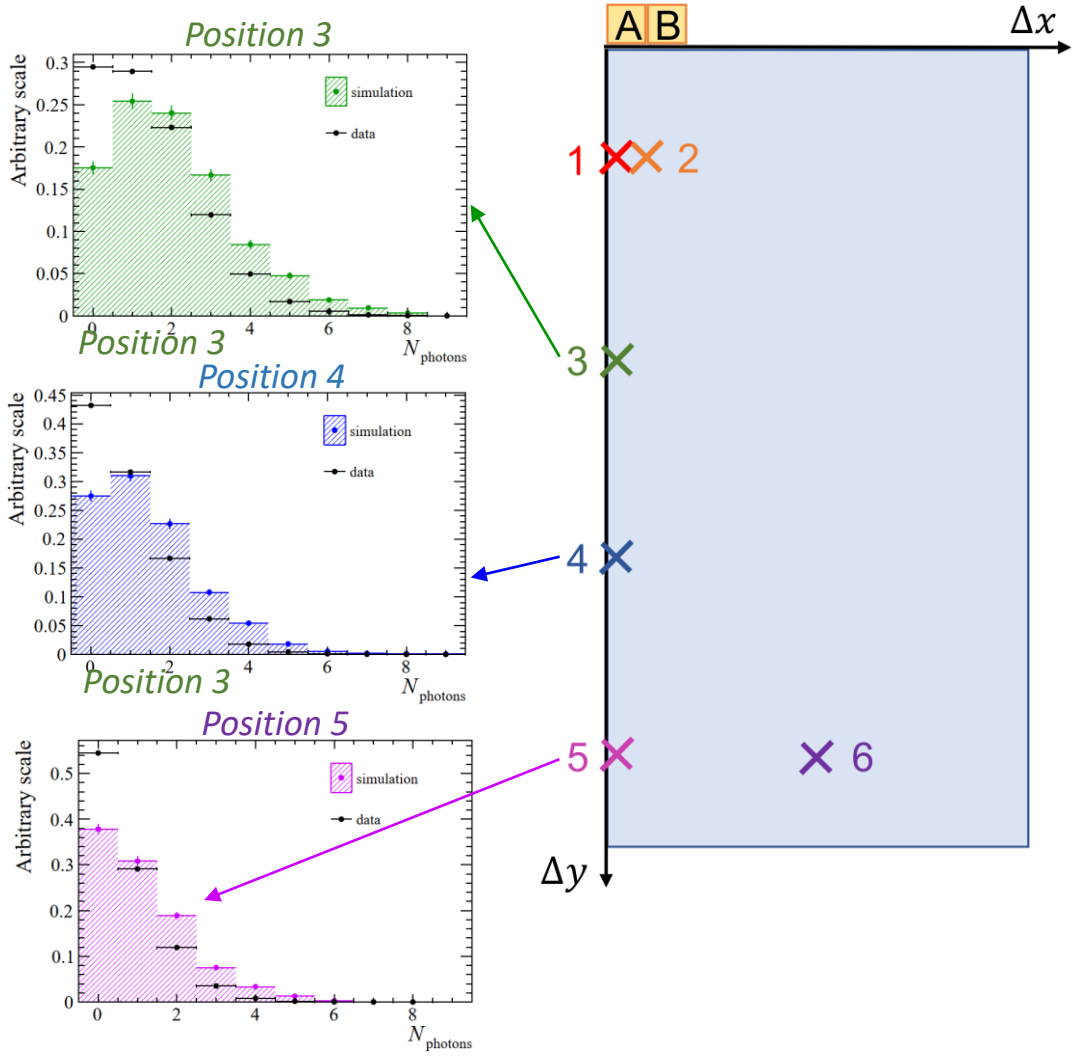
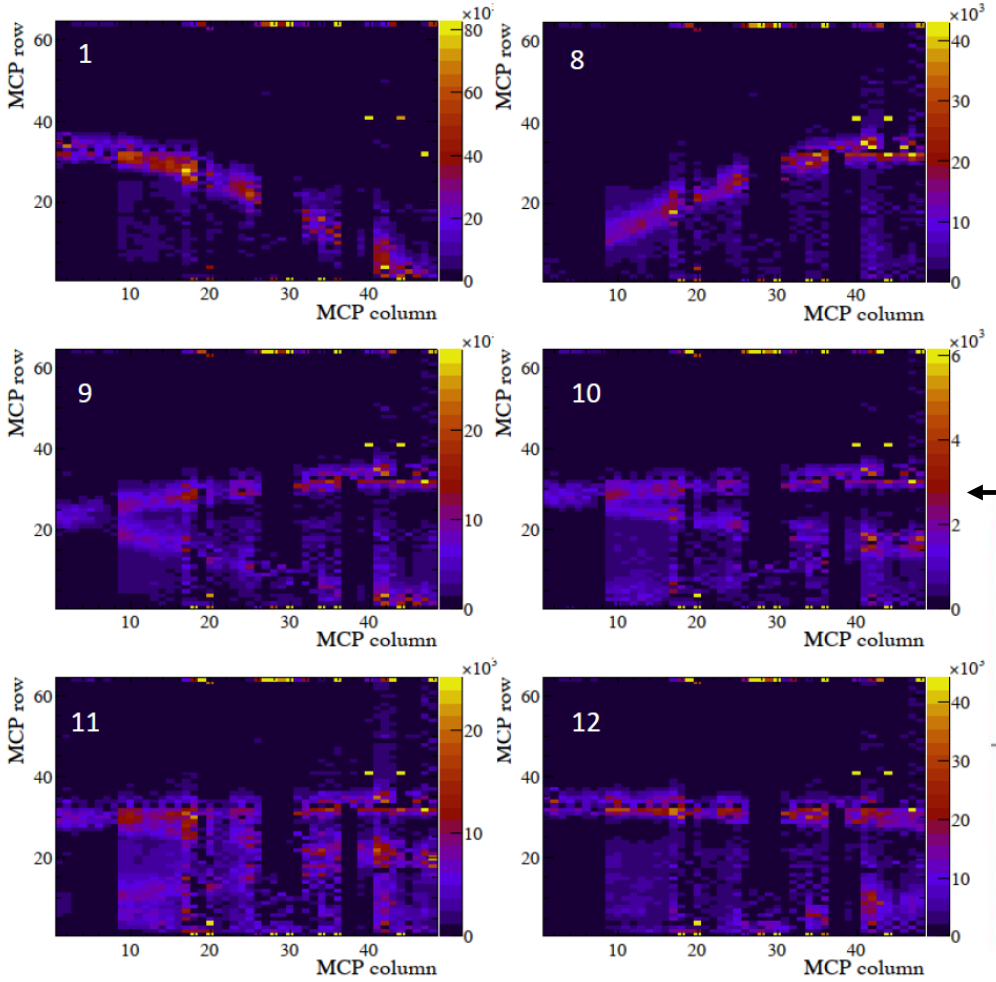
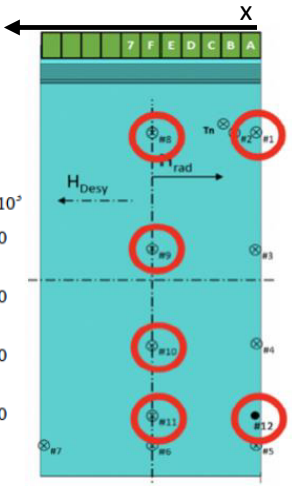


Test beam 2022: first results



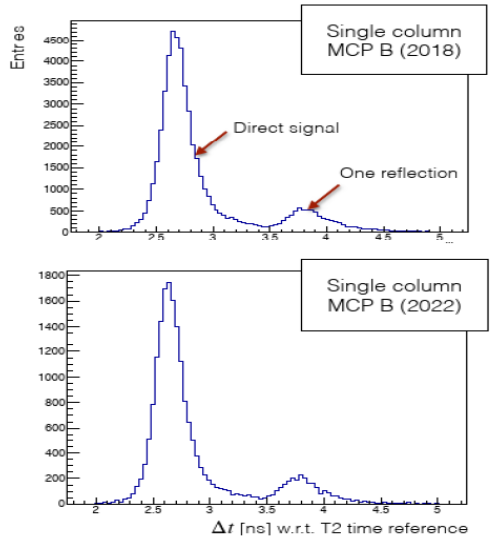
- Data taken for six beam positions over radiator plate at 3, 5, 8 and 10 GeV/*c* beam momenta
- Detailed analysis in progress, first indications that time resolution has been maintained with the larger system (or even slightly improved)
- Further improvement expected with better calibration and event-by-event tracking



Data from array of 6 MCPs at 10 GeV/*c* (labelled with the beam position)

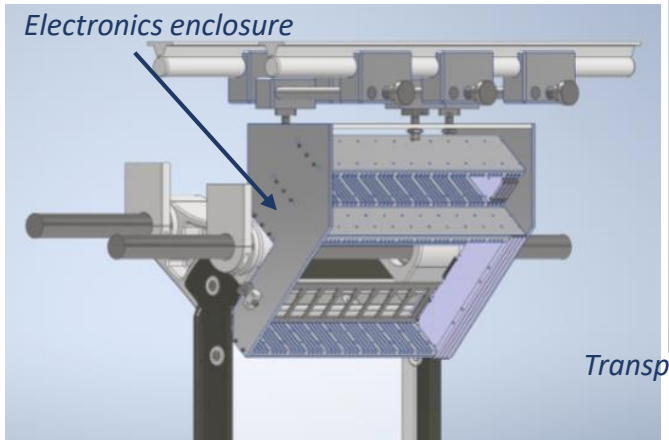
Striking patterns seen! Issues with configuring all of the electronics → some gaps in coverage

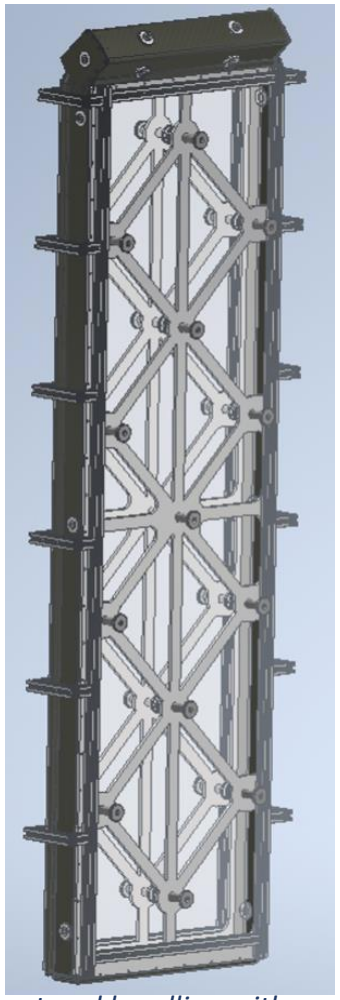
Timing comparison



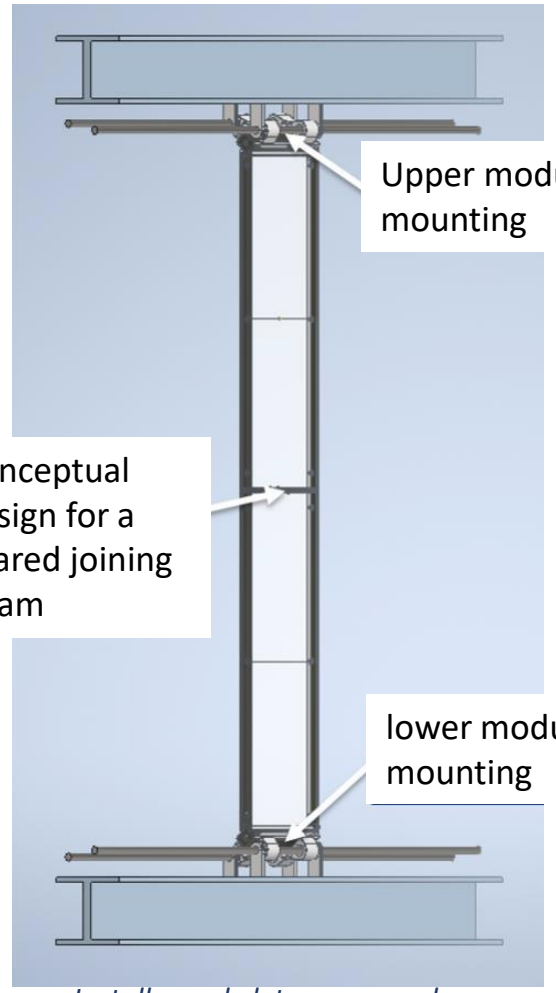
Future development: mechanical support in LHCb

- Conceptual design is in progress for a light-weight carbon-fibre housing and support for TORCH modules
- The design aims to minimize material in the detector acceptance to keep total material budget as low as possible
- Robust exoskeleton will be used for quartz handling and jigging, and removed once module is in place
- Separate support of the (heavy) readout electronics enclosure under study
- Finite-element analysis and prototyping underway





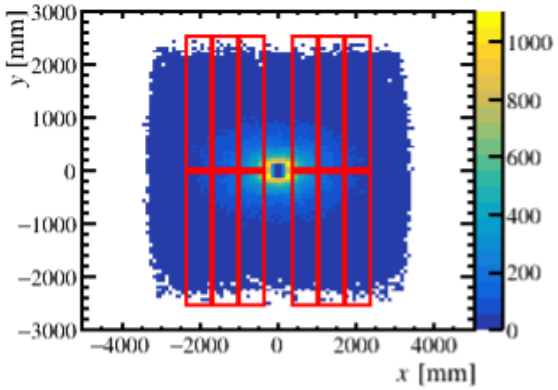
Transport and handling with exoskeleton



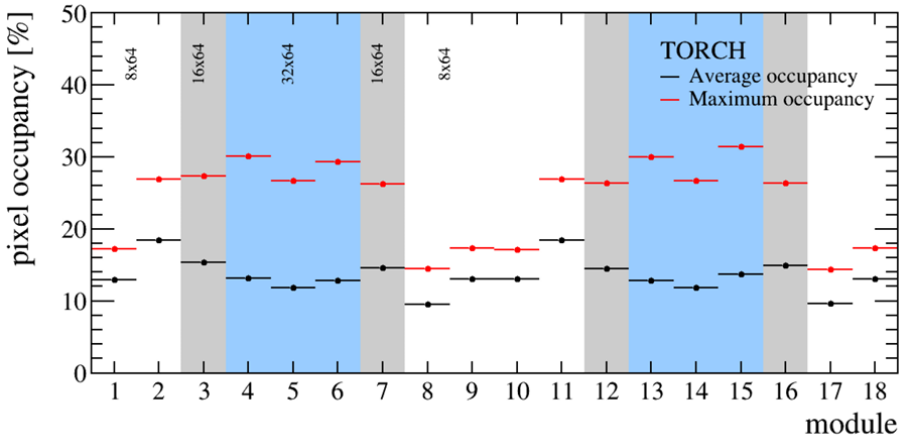
Install, exoskeleton removed

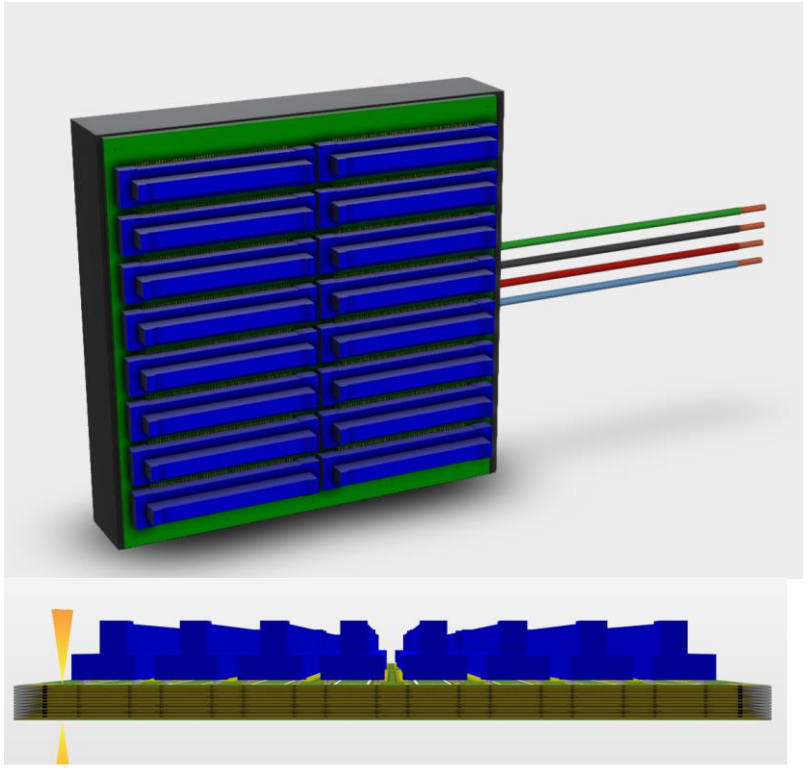
Future development: MCP

- New modular design with variable granularity MCPs to cope with non-uniformity in track distribution in LHCb
- New 96 X 16 DC coupled MCP is being developed by Photek U.K. (to reduce channel occupancy)



LHCb track distribution



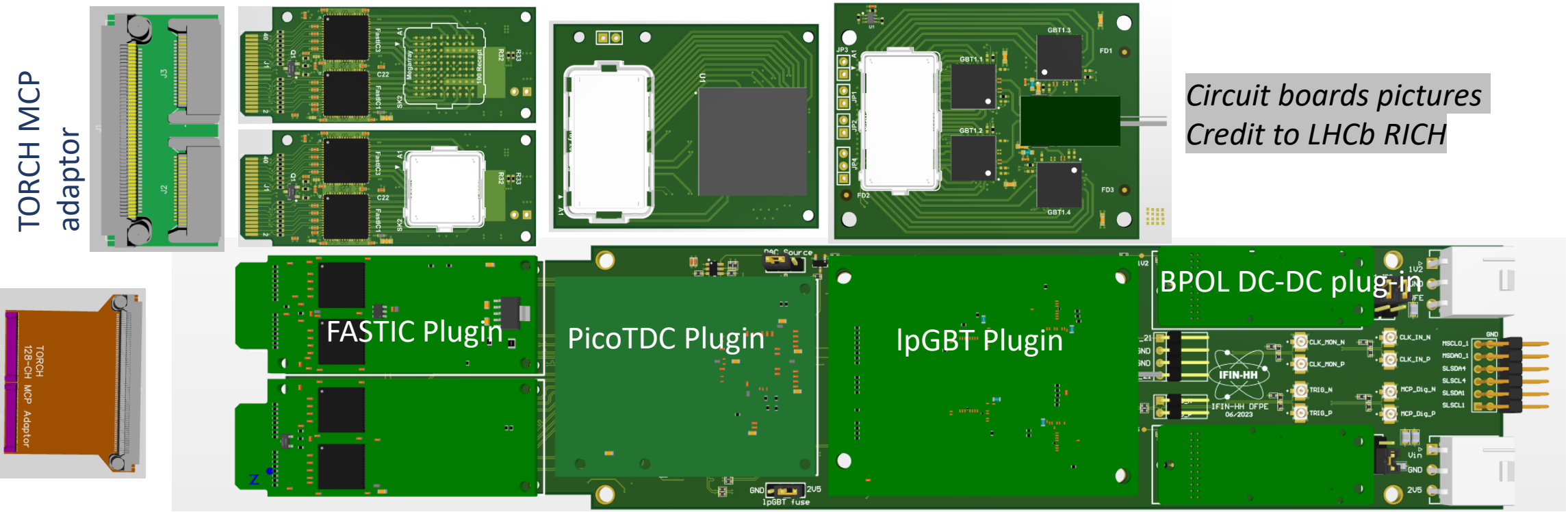


The physical envelope and the connector array on the back of the new 96X16 channel MCP

Future development: readout electronics

- Currently developing FastIC and PicoTDC based readout electronics with lpGBT optical links JINST17(2022) C05027 JINST18(2023) P07012 lpGBT Manual (2019)

- Synergy with LHCb RICH Upgrade - use RICH electronics for MCP testing

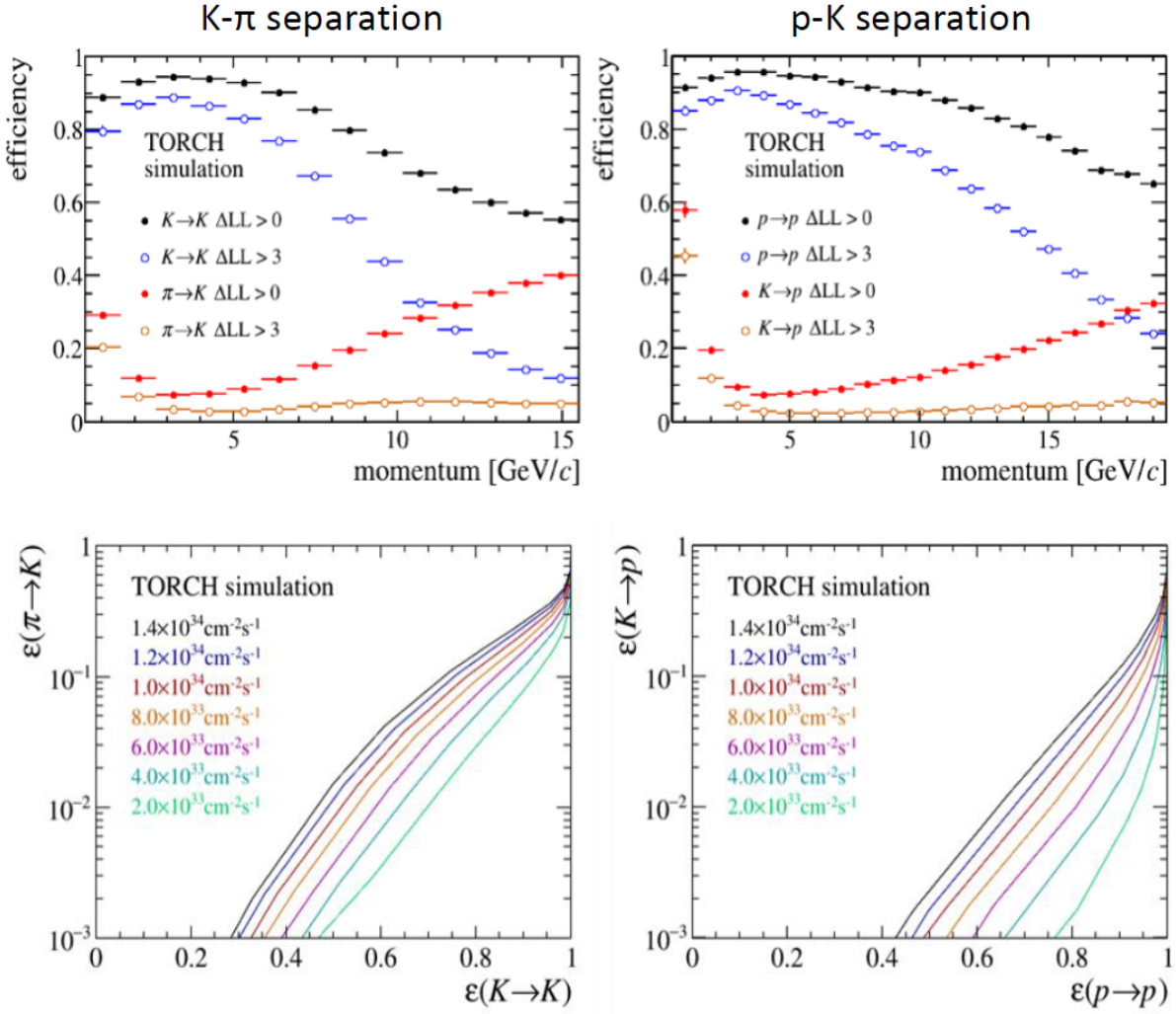


Circuit boards pictures Credit to LHCb RICH

Expected performance in LHCb

- Events fully simulated with Geant4 are merged to study expected particle ID performance of TORCH in LHCb as a function of luminosity
- Assumes that start-time information with 30 ps precision will be available from upgraded VELO

  If not, start-time can be reconstructed by TORCH using the other tracks from the primary vertex (predominantly pions) by running the usual reconstruction in reverse
- Good performance seen at Upgrade II luminosity (shown for two different cuts on the likelihood)
- Performance is strongly dependent on the detector occupancy—modules closer to the beam line have poorer performance



Conclusion

- TORCH is a cutting-edge detector providing Particle Identification (PID) in the energy range of 2-15 GeV, covering an area of over 30 square meters
- TORCH has developed customised Micro-Channel Plates (MCPs) and electronics, ensuring synergy with other LHCb groups, like RICH, to maintain commonality in electronic modules and Data Acquisition (DAQ) systems
- We have conducted beam tests with a large prototype featuring over 3000 channels, and we are currently in the process of analysing the results

- Future works:
  - Plans to use FastRICH - a Constant Fraction Discriminator (CFD) + 25ps TDC chip, being developed by CERN-ESE and University of Barcelona, expected in 2025
  - Characterising the new MCP with new readout electronics
  - Test beam campaign with new full size quartz module and new mechanical support

Thank you!