TORCH test beam analysis and developments in MCP-PMTs and electronics

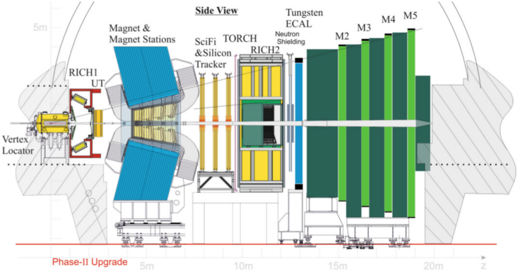
Martin Tat, on behalf of the TORCH collaboration

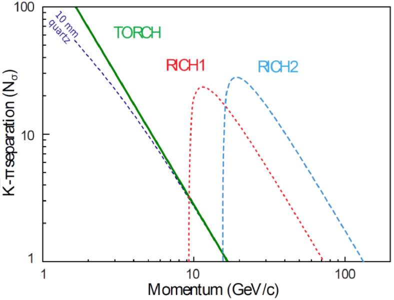
LHCb-UK annual meeting, RAL

8th-10th January 2024

TORCH: Time Of internally Reflected CHerenkov light

- Particle identification at LHCb at low momentum (2-20 GeV/c)
- Ensure full coverage of LHCb's flavour physics programme
  1. Boost signal efficiencies and suppress mis-ID backgrounds
  2. Improve flavour tagging efficiency

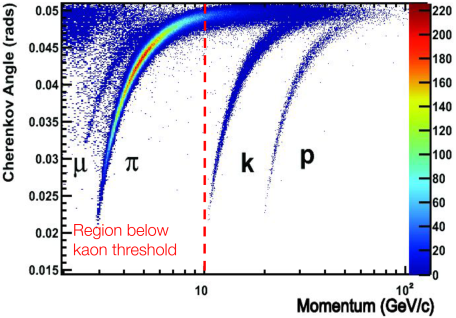


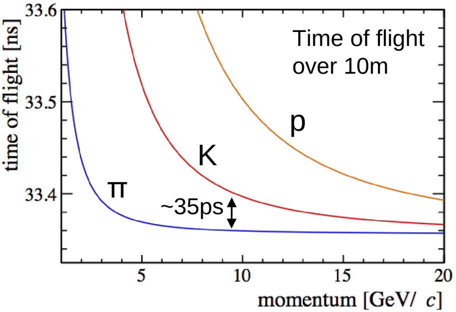


Introduction to TORCH

PID with Time-of-Flight, combined with Cherenkov information

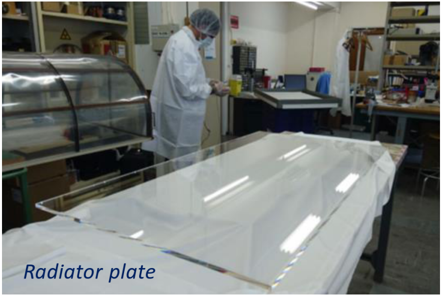
- Cover physics region inaccessible to RICH
- π-K ToF difference over 10 m $\implies$ Aim for 10-15 ps resolution
- Single-photon precision of 70 ps with $\sim$ 30 detected photons

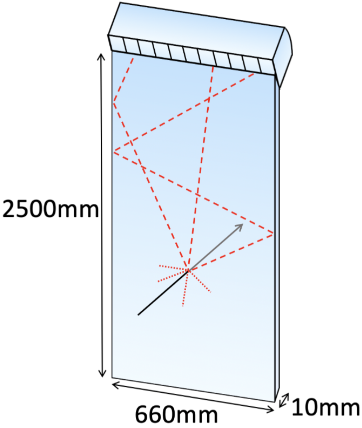




TORCH working principle

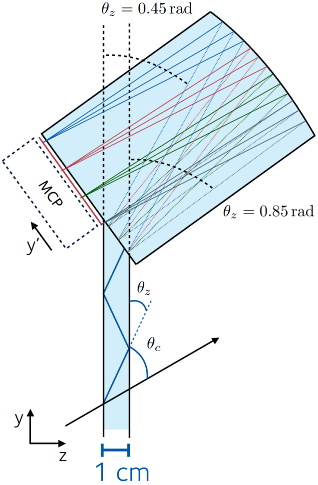
1. Charged particle enters quartz
2. Cherenkov photons promptly emitted
3. Photons undergo internal reflection until they reach the top of the plate





TORCH working principle

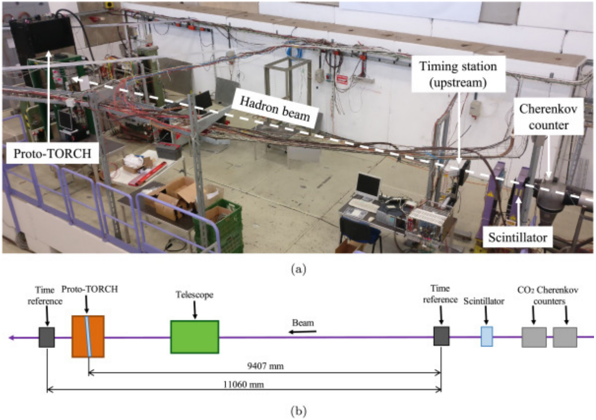
1. Focus photons with cylindrical mirrror
2. Image consists of hyperbolic "bands"
   - Compare with circular rings in RICH
3. Correct for chromatic dispersion using the Cherenkov angle obtained from y'



Test beam setup

Investigate TORCH performance with testbeam campaigns

- Beam of pions and protons from the CERN T9 beamline
- Similar test beam area in 2018 and 2022 testbeams

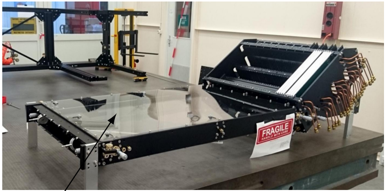


Reminder of Proto-TORCH

- Prototype of TORCH
- Full width, half height
- Nikon glass with polished surfaces

Focusing block

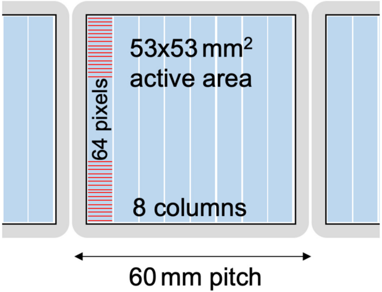
MCPs and electronics

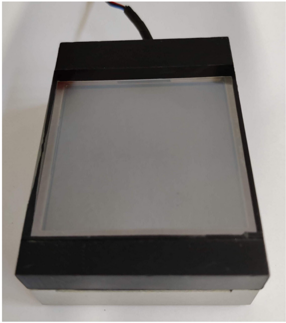


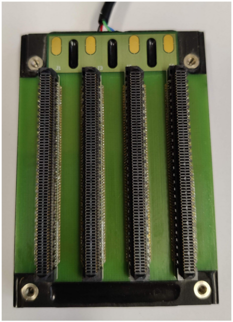
Half height quartz radiator plate

Reminder of Photek MCP-PMT

- Photon detector: MicroChannel Plate PhotoMultiplier Tube
  - T.M. Conneely *et al* 2016 *JINST* **10** C05003
- $53 \times 53\text{mm}^2$ active area
- 8 columns, each with 64 pixels
- Effectively 128 pixels with charge sharing



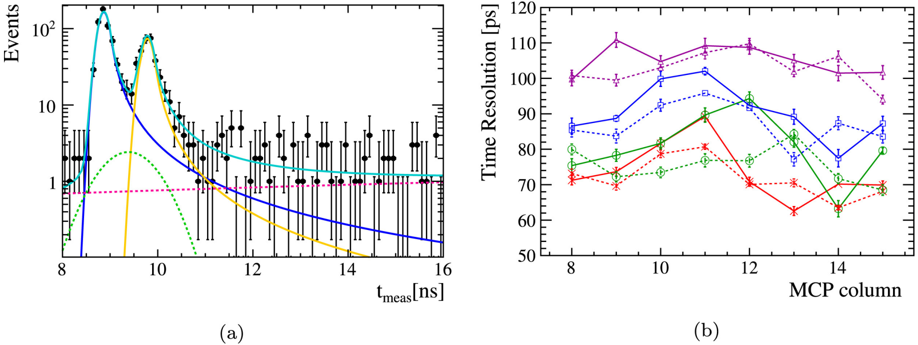




Reminder of 2018 test beam analysis

2018 test beam analysis paper recently published:
Nucl. Instrum. Methods **A1050** (2023)

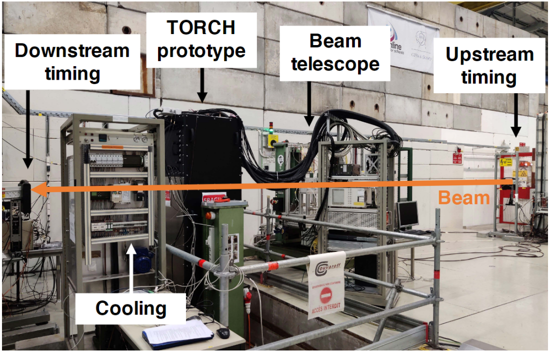
- Single-photon time resolution down to 70 ps achieved
- Degraded resolution for tracks entering at the bottom, as expected
  - Uncertainty in chromatic dispersion scales with photon path length
  - Improvements expected with further electronics calibrations



2022 test beam analysis

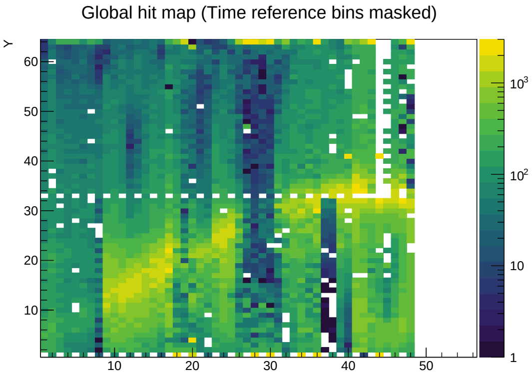
Back to T9, with several new goals:

1. Additional, fully instrumented, MCP-PMT tubes (7 in total)
2. Wide range of beam momenta (3, 5, 8, 10 GeV/c and higher)
3. Aim to achieve a first demonstration of PID separation in TORCH



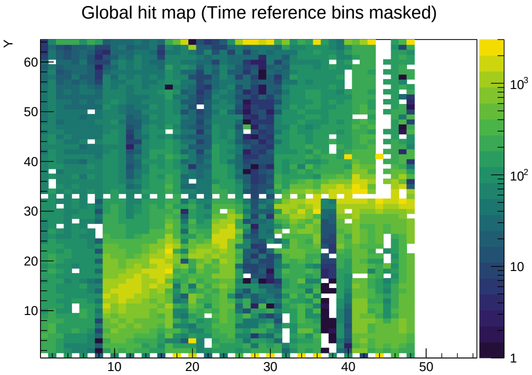
Global hit map looks as expected

1. Hit pattern seen across 6 MCP-PMT tubes
    - Original MCP B is fully efficient, while MCP A shows some degradation
2. Hit pattern shows some inefficient MCPs and miscalibrated electronics
3. Proper time reference channel present in (almost) all columns



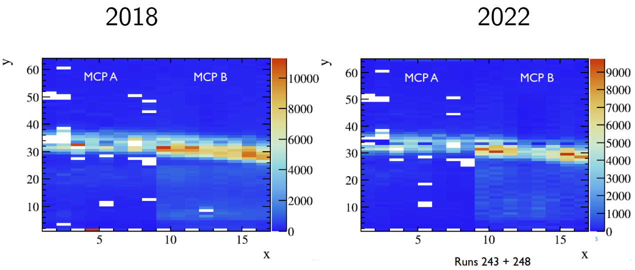
Focus on MCP A and B for now

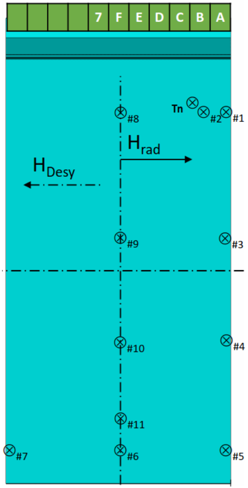
1. Some non-uniformity in QE and gain seen in MCP C, D and F
2. Electronics and new MCPs need to be understood better
   - Improve stability and reliability
   - NINO thresholds need to be optimised
   - Boards C-F are under calibration using a test system at Bristol



2022 test beam analysis

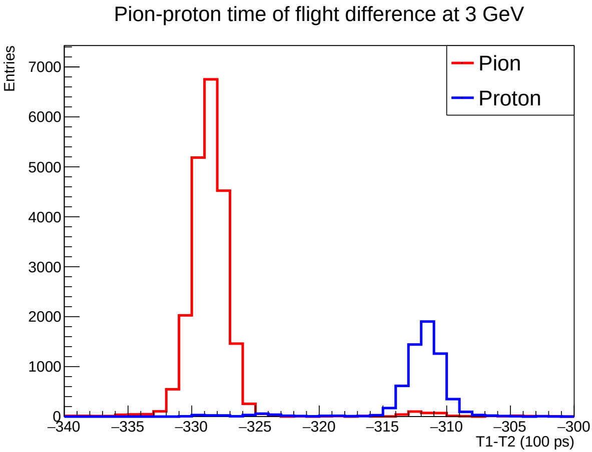
- Study positions 1, 8, 9, 10, 11, 12
- Below: Comparison of position 1 between 2018 and 2022 data $\implies$ Perfect agreement!





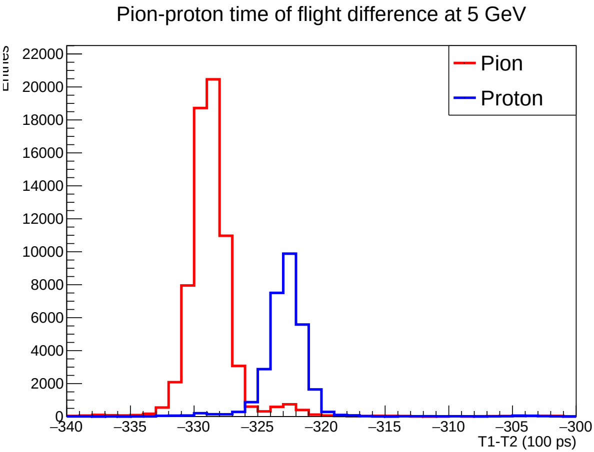
- This talk: Preliminary results from position 8
  - Never studied before!

Check time of flight between external time references
Expected time difference at 3 GeV/c: 1.6 ns



2022 test beam analysis

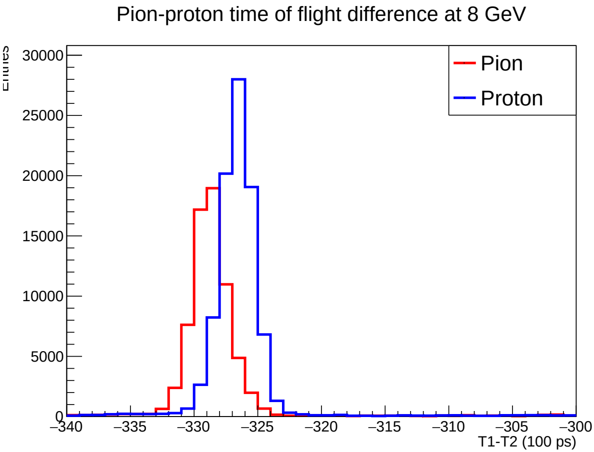
Check time of flight between external time references
Expected time difference at 5 GeV/c: 0.59 ns



2022 test beam analysis

Check time of flight between external time references

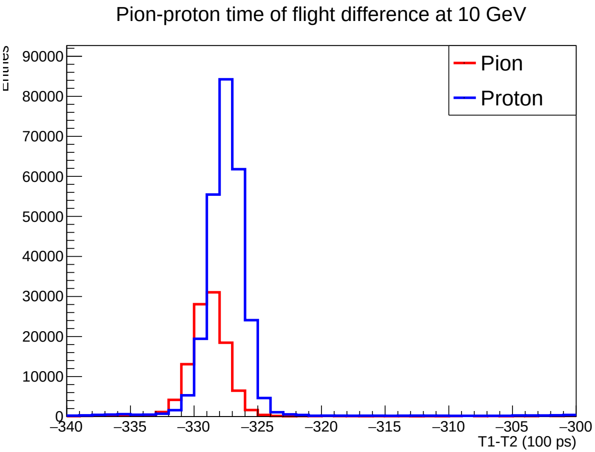
Expected time difference at 8 GeV/c: 0.23 ns



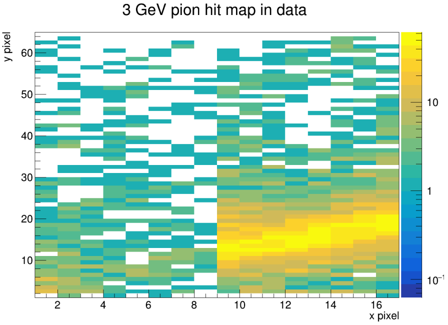
2022 test beam analysis

Check time of flight between external time references

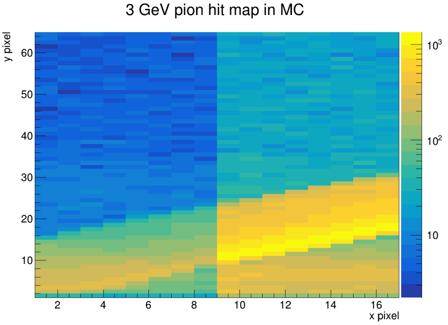
Expected time difference at 10 GeV/c: 0.15 ns



Let's look at hit maps of 3 GeV/c pions...

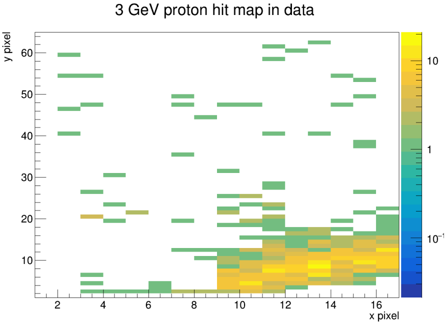


(a) Testbeam data

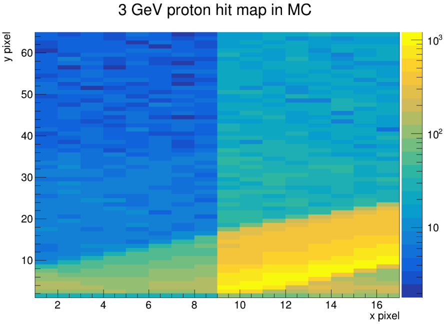


(b) Geant4 simulation

... and compare with hit maps of 3 GeV/c protons

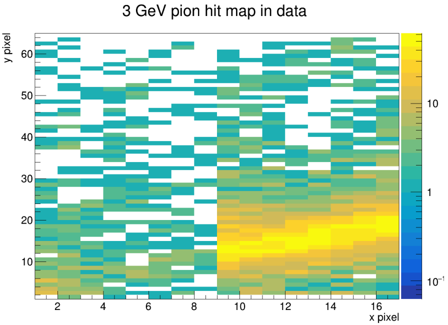


(a) Testbeam data

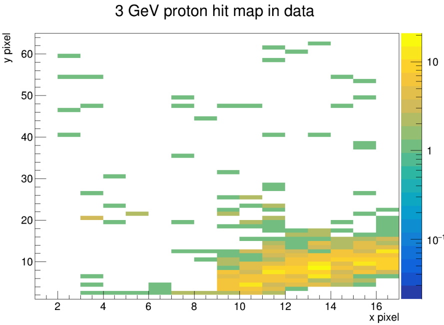


(b) Geant4 simulation

Different y-position $\implies$ Separation in Cherenkov angle

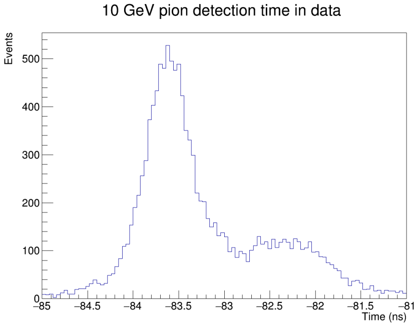


(a) Pions



(b) Protons

What about timing information? First look at 10 GeV/c pions and protons



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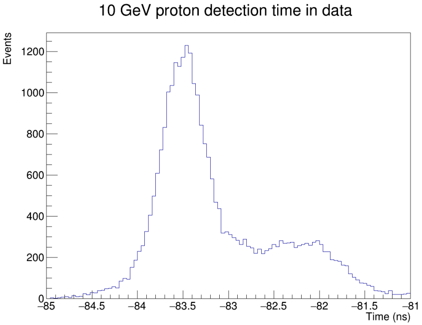
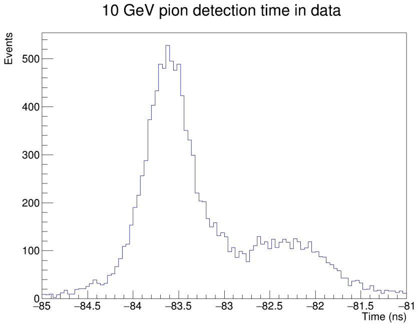


(b) Protons

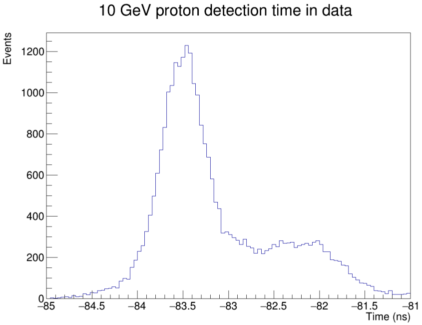
Small (0.15 ns) separation, as expected

2022 test beam analysis

What about timing information? First look at 10 GeV pions and protons



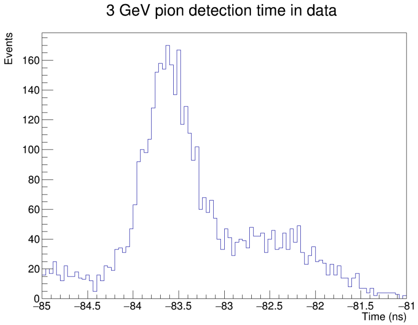
(a) Pions



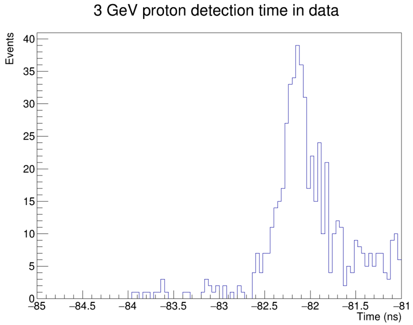
(b) Protons

Additional "reflection", which arrives ~ 1 ns later, is currently under study

Then consider the 3 GeV/c pions and protons, where a clear separation in arrival time is seen



(a) Pions



(b) Protons

Additional reflection also arrives later for protons

PID algorithm

- Long term goal: Demonstrate separation between pions and protons using a PID algorithm
- PID algorithm presented by Tom Jones last year:

$$P(E_\gamma, \phi_c, t_0) = P(E_\gamma) \times P(\phi_c) \times P(t_0)$$

1. $P(E_\gamma)$: Frank-Tamm distribution $\circledast$ Efficiency effects
2. $P(\phi_c)$: Uniform distribution
3. $P(t_0)$: Gaussian smearing due to electronics and photon reconstruction (pixel size and emission point assumptions)

PID algorithm

- Long term goal: Demonstrate separation between pions and protons using a PID algorithm
- PID algorithm presented by Tom Jones last year:

$$P(E_\gamma, \phi_c, t_0) = P(E_\gamma) \times P(\phi_c) \times P(t_0)$$

- Convert (E_γ, ϕ_c) into detector hit position (x, y) using Jacobian J
- Each derivative in J is calculated by forward-propagating two photons
- Integrate over each pixel using 2D trapezium rule

$$P(x, y, t_0) = P(E_\gamma, \phi_c, t_0)/|J|$$

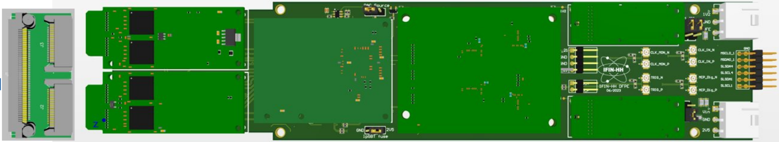
Future plans: Testbeam in 2025

2025 testbeam

- The TORCH collaboration is planning on going back to T9 in early 2025 with a 2.5 m length prototype TORCH module
- Completely new mechanical support structure, which will be discussed by Adam in the next talk!
- From our experience with the 2022 testbeam, we will be much better prepared for 2025:
  - More efficient data collection
  - Better quality data
  - First demonstration with full-size prototype

Future plans: New electronics

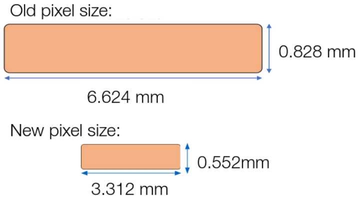
- New electronics: FastIC + PicoTDC + lpGBT developed by RICH
  - Only 2 sets available, which is insufficient for the next testbeam
  - Expected delivery at beginning of 2024
- FastIC chips will replace old NINO chips
  - 250 nm → 65 nm CMOS technology
- PicoTDC replace previous HPTDC chips
  - Time binning is improved from 100 ps to 12 ps
  - In the longer term, plan to use the FastRICH chip
- Testing with RICH carrier board and TORCH specific adaptor board

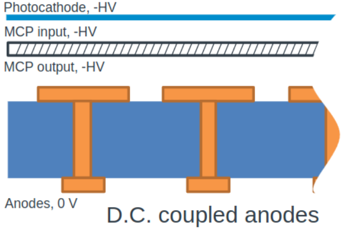


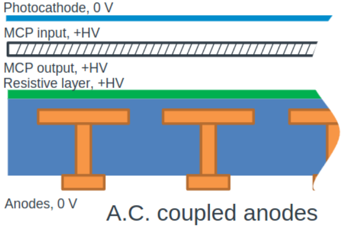
Dimensions of carrier board: 54mm X 250mm

Future plans: New MCP-PMT tubes

- Working with commerical partner, Photek Ltd, to develop MCP-PMTs suitable for HL-LHC
- From FTDR studies, we know centre module occupancy must be improved
- Increase granularity: $8 \times 64 \rightarrow 16 \times 96$
- AC coupled $\rightarrow$ DC coupled anode

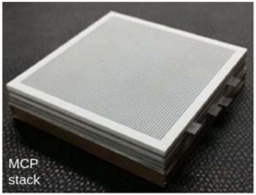


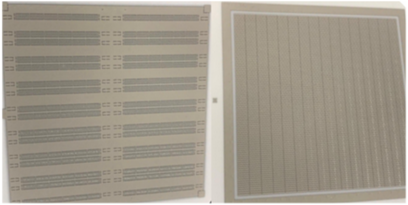




Future plans: New MCP-PMT tubes

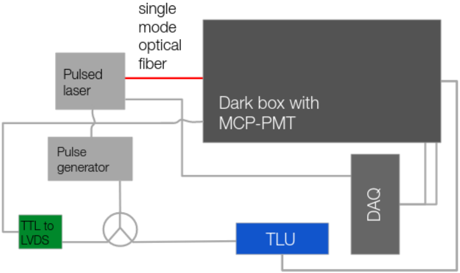
- New MCP-PMT has a ceramic anode with vias to route the signal to connectors on the back
- Connectors will be soldered with laser-jet soldering:
  - Required by the density of the readout
  - Needed to avoid heating the tube
- Expect delivery at end of February





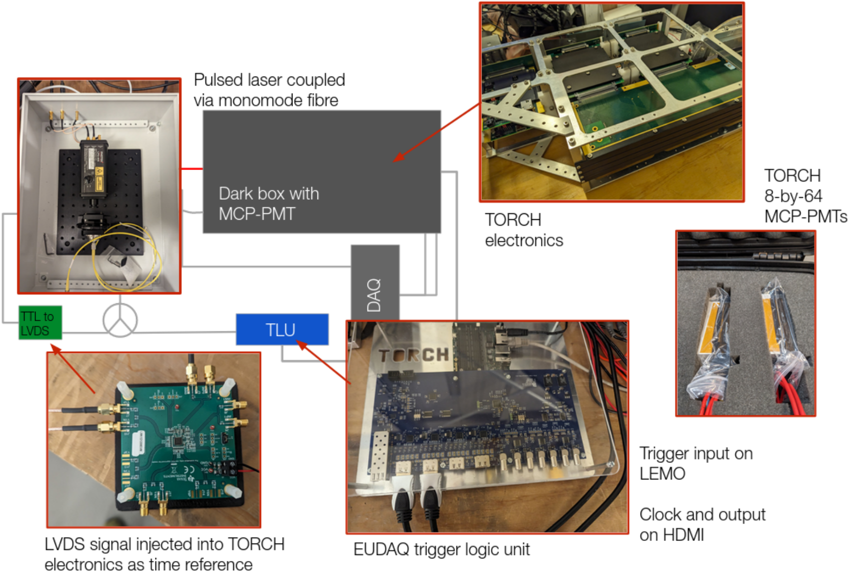
Photograph of the back and front of the new anode from AdTech

Future plans: Lab testing of new MCP-PMT tubes



- Lab setup at University of Warwick commissioned to qualify the MCP-PMT devices.
- Fast signal provided by picosecond pulsed 405 nm laser with 6μm spot size.
- Signal read out through standard TORCH DAQ or via analogue breakout board to oscilloscope.

Future plans: Lab testing of new MCP-PMT tubes



Summary and future prospects

Summary:

1. Test beam analysis progressing well
    - Hit patterns well understood
    - More detailed analysis of time information ongoing
    - Improved calibration is essential
2. We are acquiring new electronics and new MCP-PMTs
    - Lab testing of electronics ongoing
    - New electronics will replace legacy NINOs and HPTDCs
    - New MCP-MPTs have higher spatial resolution
    - Delivery of new MCP-PMT tubes expected at the end of February

Future prospects:

1. Finalise test beam analysis
   - Calibrations
   - Photon counting
   - Time resolution
   - PID performance
2. New test beam is planned for early 2025
   - Demonstration of full height quartz plate TORCH and mechanics

Thanks for your attention!

Backup slides

Backup: Reminder of Photek MCP-PMT

- Photon detector: MicroChannel Plate PhotoMultiplier Tube
  - T.M. Conneely *et al* 2016 *JINST* **10** C05003
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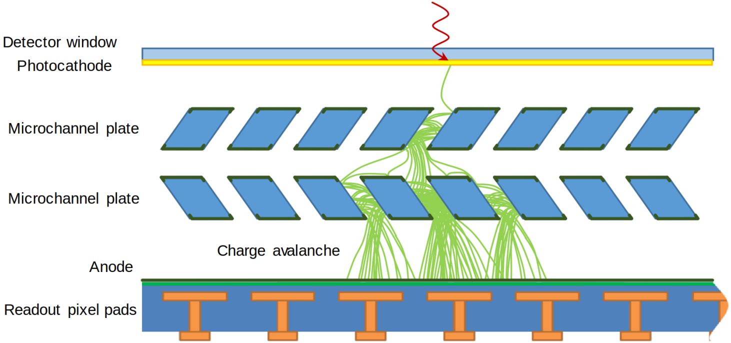

Backup: TORCH electronics

- NINO: Amplifier and discriminator
  - R. Gao *et al* 2022 *JINST* **17** C05015
- High Performance Time to Digital Converter: 100 ps bins
- Legacy electronics that will be replaced, more on this later!