The TORCH PMT: A close packing, long life MCP-PMT for Cherenkov applications with a novel high granularity multi-anode

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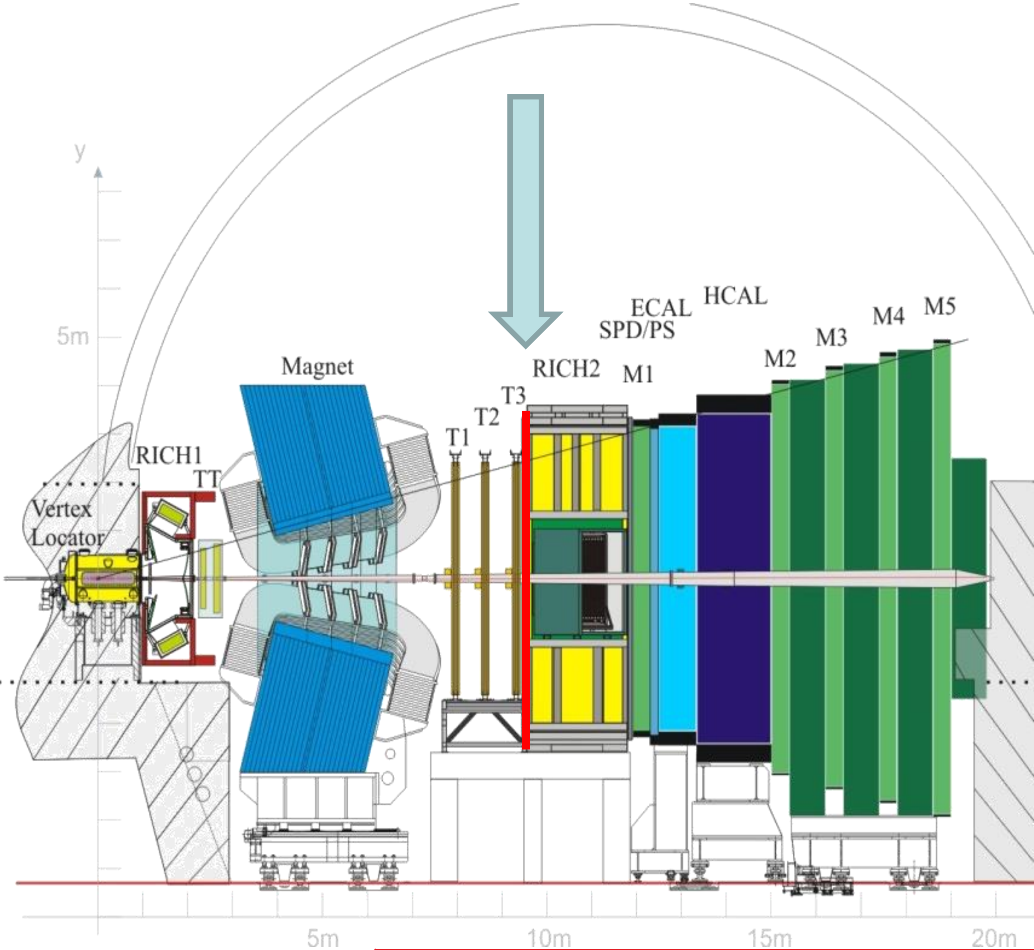
TORCH - Motivation

- TORCH is an ERC funded R&D project
- Proposal to upgrade LHCb Particle ID capabilities in 2-10 GeV/c region
- See talk by Thierry Gys



The TORCH PMT

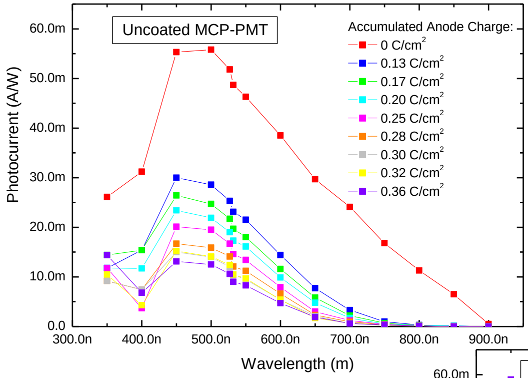
- In November 2012 Photek started the development of the TORCH (Timing Of internally Reflected CHerenkov photons) PMT
- A collaboration with CERN and the Universities of Oxford and Bristol for the LHCb upgrade due around 2023
- Technical aims:
  - A lifetime of 5 C/cm^2 of accumulated anode charge or better
  - A multi-anode readout of 8 x 128 pixels
    - Fine pitch resolution target 0.41 mm
  - Close packing on two apposing sides with a fill factor of 88% or better
    - 53 mm working width within a 60 mm envelope

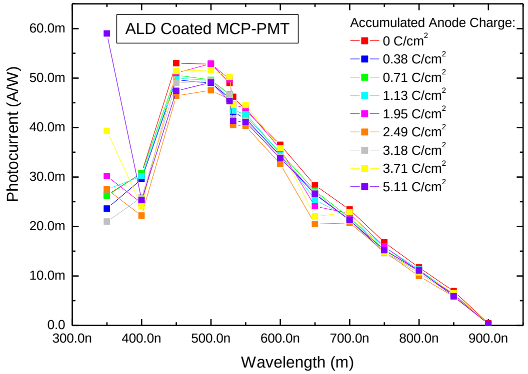
MCP-PMT Lifetime

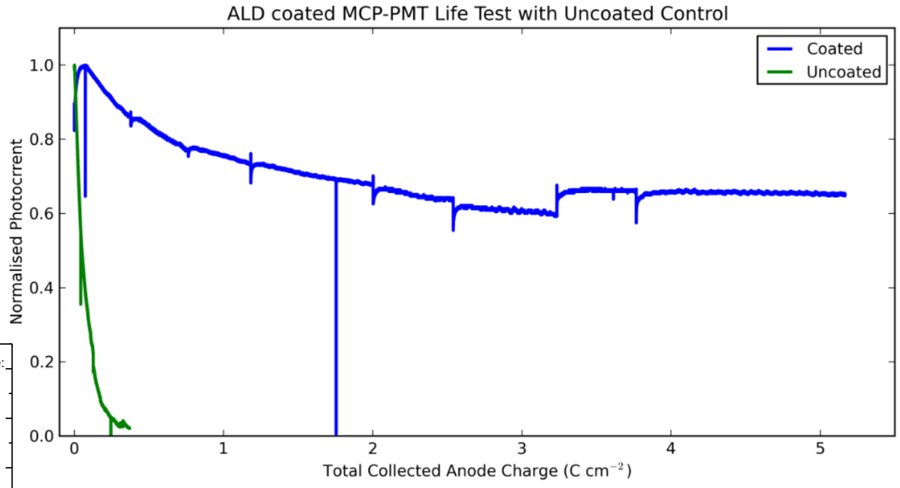
- Standard MCP detectors suffer from sensitivity loss after prolonged exposure:
  - An MCP has a very large surface area
  - Prolonged electron bombardment of this surface releases material that is ionised
  - These ions are drawn back to the photocathode and reduce sensitivity
  - *See talk by Albert Lehmann earlier today for full description*

MCP-PMT Lifetime

- Photek had already achieved the life time aim in previous work
- Two PMT samples produced in 2011: Double-MCP 10 mm diameter working area
  - One with ALD coated MCPs, One control with standard MCPs
  - Accelerated test: ~ 800 nA / cm^2 for ~ 14 weeks over small area



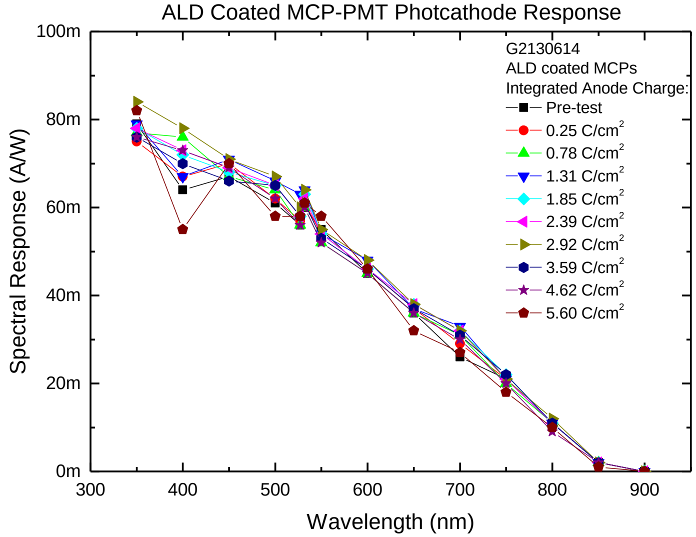


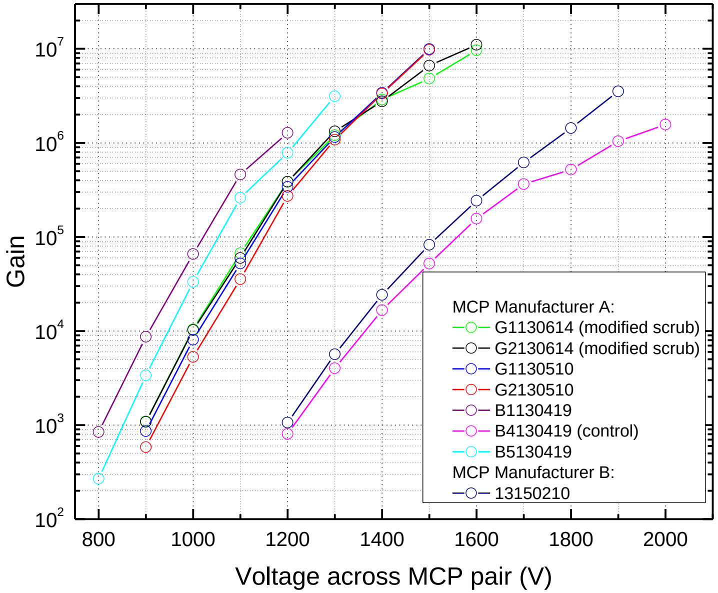


- Work presented by Conneely et al at VCI 2013

MCP-PMT Lifetime

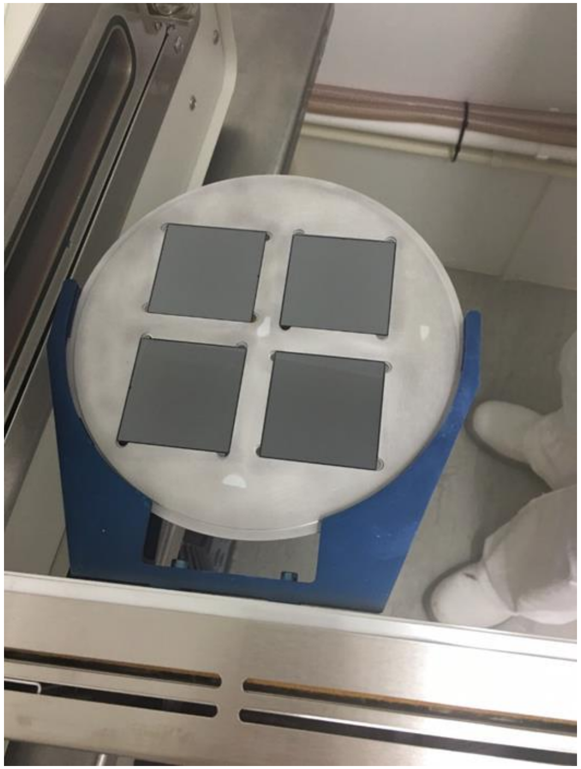
- In year 1 of the TORCH project we repeated these results
  - Same MCP manufacturer, ALD coating and testing method
  - Also confirmed by long term / full area life test at CERN from same batch (see talk by Thierry Gys)
- We have also looked at different MCP manufacturers with same ALD coating
  - Differing outcomes for gain enhancement
  - Extra gain not always wanted!
  - Also some different lifetime results, currently being explored
  - May need different surface preparation or modification of ALD process





MCP-PMT Lifetime

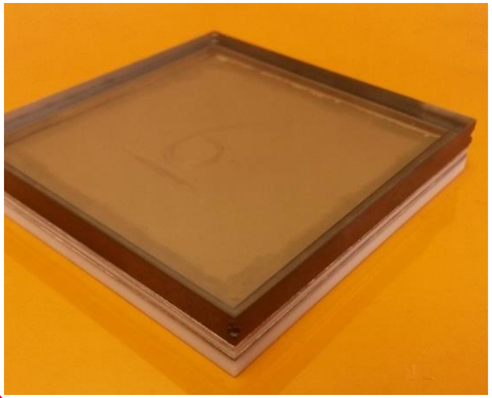
- Photek have licensed Arradiance ALD technology for in-house coating of MCP substrates
- We have started a KTP project in collaboration with the University of Liverpool ALD research group
  - Embed ALD process knowledge in Photek
  - Optimise process to improve MCP collection efficiency



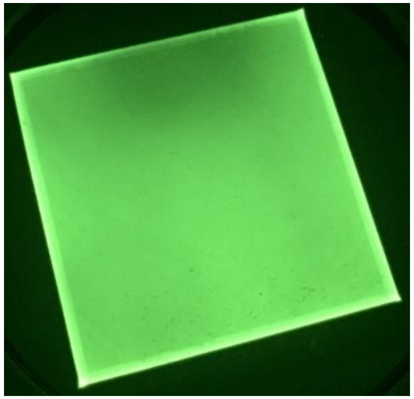
Square Tube Development

- At the beginning of the TORCH project square tube manufacturing was new to Photek
- We had to re-learn many processes:
  - Brazing
  - MCP location and electrical contact
    - Somehow possible to do one without the other!
  - Cathode Seal – still to be finalised
- New facilities built to handle large tube size

Successful square test cell



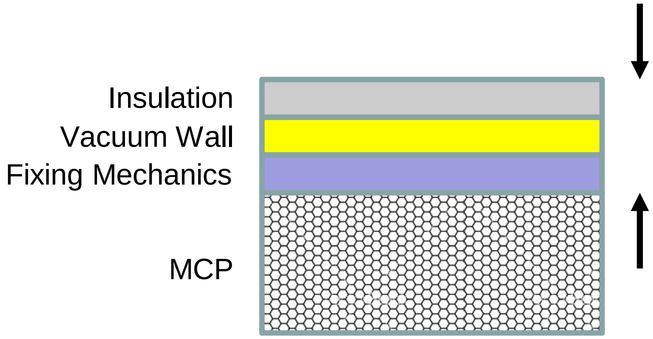
Assessment of square MCP with phosphor screen

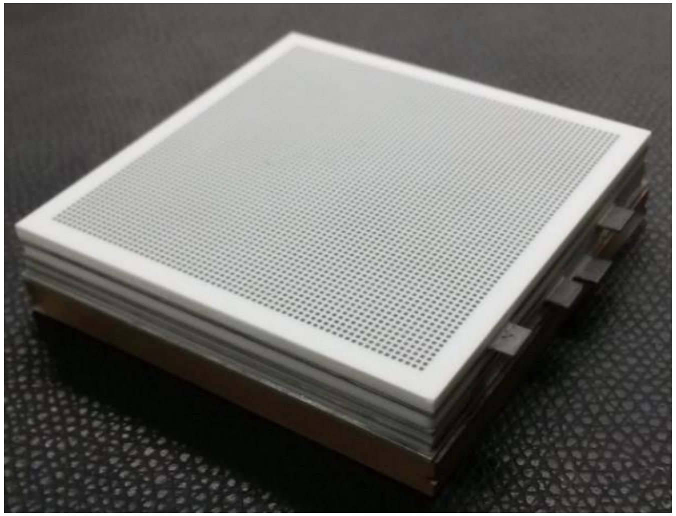


New process rig and oven to produce 3 square tubes

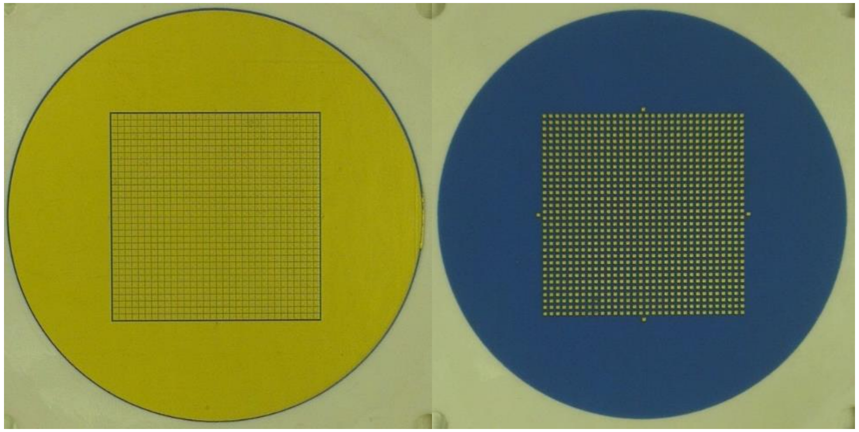
Square Tube Development

- The outside dimension needed to be 60 mm with a 53 mm working width
- This left 3.5 mm on either side for insulation, vacuum wall and MCP fixing
- The equivalent 40 mm round image intensifier has ~16 mm for the same task!
- Our novel MCP fixing method allows short gaps between photocathode, MCPs and anode
- Predicted gap between photocathode and MCP to be 1.5 – 2 mm
  - Measured at 1.8 mm on tube with unsuccessful seal
- Predicted MCP – anode gap is 2.5 – 3 mm



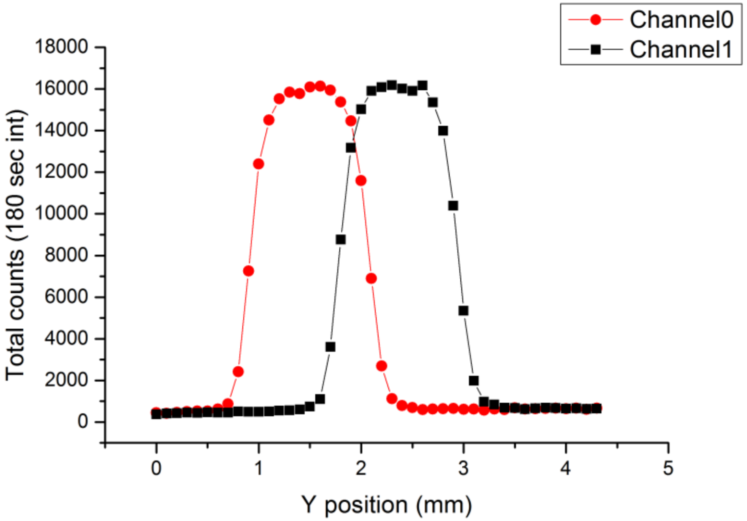


Multi-Anode - Heritage



Vacuum side *Air side*

- Previous project (*IRPics* with University of Leicester) had produced a 40 mm round PMT with 32 x 32 pads, 0.75 mm wide on a 0.88 mm pitch
- Multilayer ceramic with filled vias



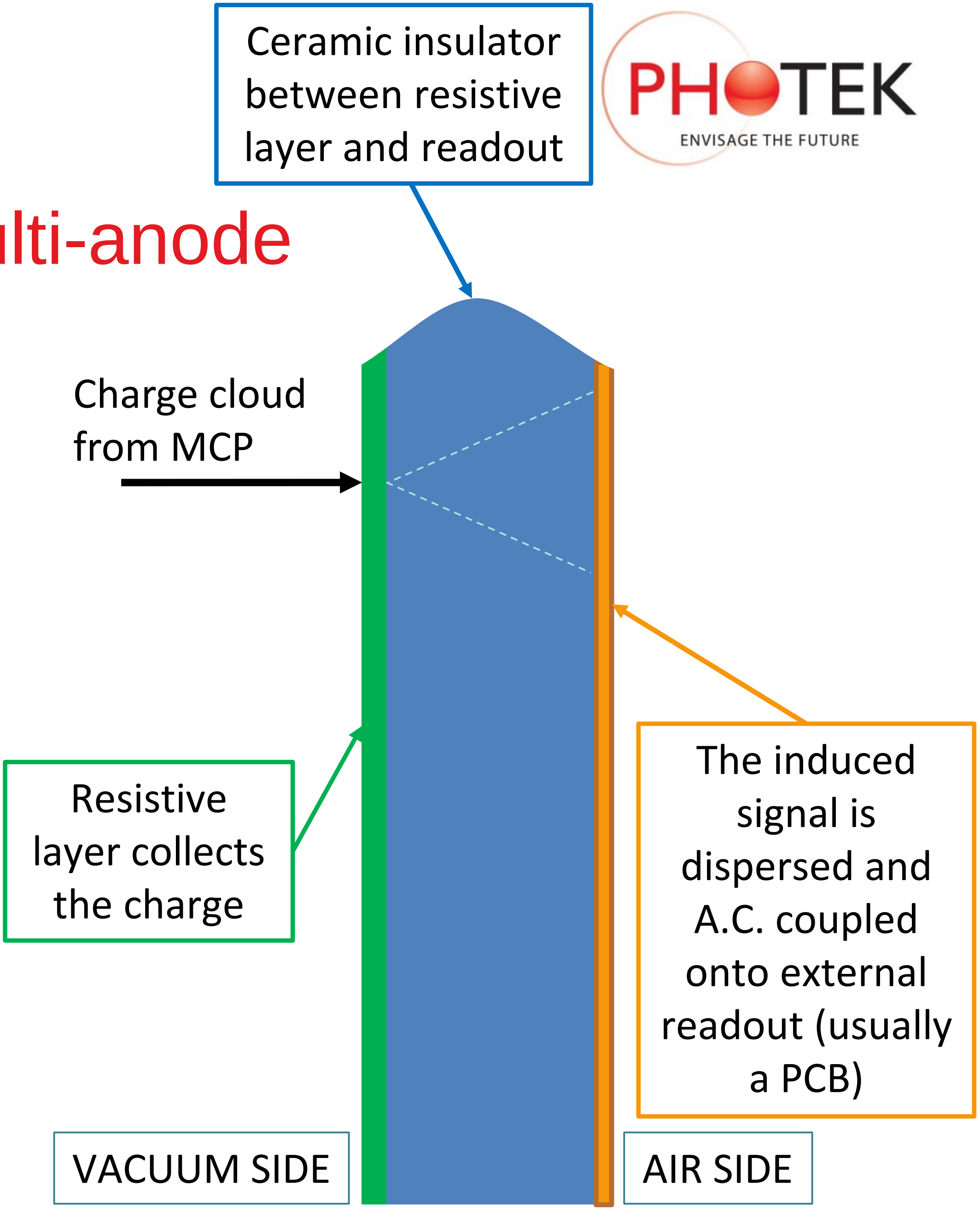
- Cross talk measured using single photon illumination at a gain of 5.5 × 10^6, 0.2 mm FWHM laser spot
- Roughly half the density required by TORCH
- Difficult to obtain higher density pads from known suppliers

High granularity multi-anode

- For the TORCH project, how do we obtain position resolution beyond the pitch of the pads? – Proposed idea of charge sharing:
  - Deliberately spread the charge footprint
  - Charge is shared over multiple pads
  - Charge is measured on each pad – needs charge measuring front-end
  - Simple algorithm calculates the interpolated position
  - *Reduces channel count – crucial factor!*
- Cannot share over too many pads without compromising the occupancy level
  - Important in a tube designed for high count rates
  - Ideally share over 2 – 3 pads

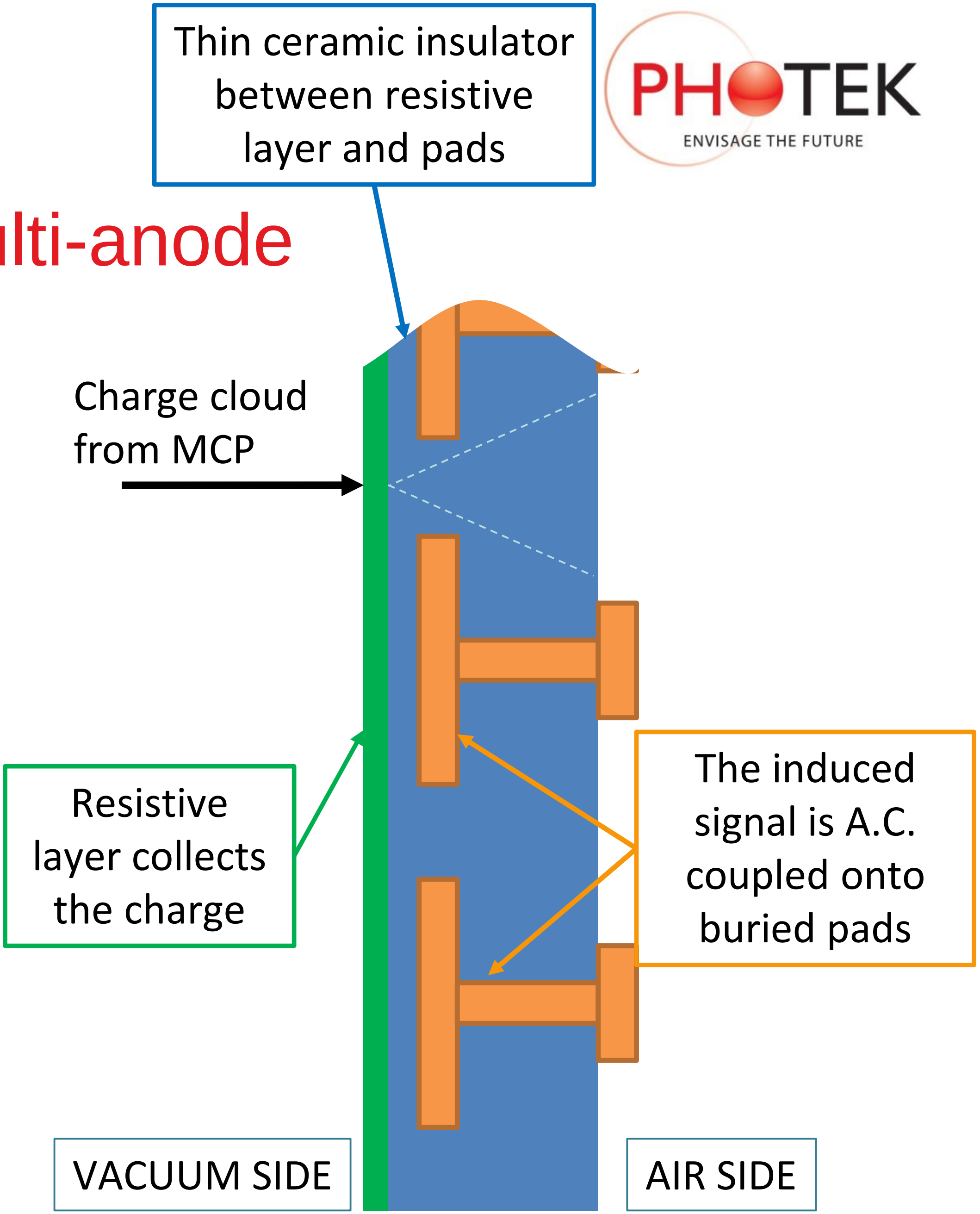
High granularity multi-anode

- Image Charge technique is recognised way of spreading charge footprint
- See Jagutzki et al, Proc. SPIE 3764
- Developed to increase charge spreading for position sensitive readouts that needed large charge footprints (Wedge & Strip, Delay Line)
- Charge footprint is typically 2 to 4 mm diameter once it reaches the external readout



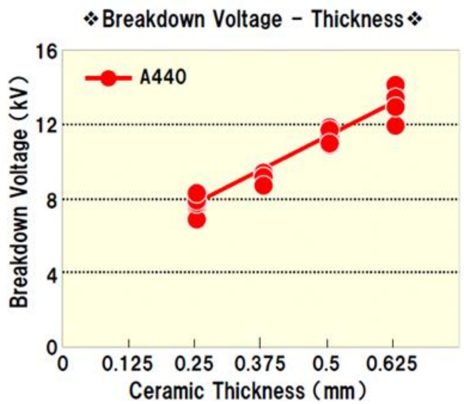
High granularity multi-anode

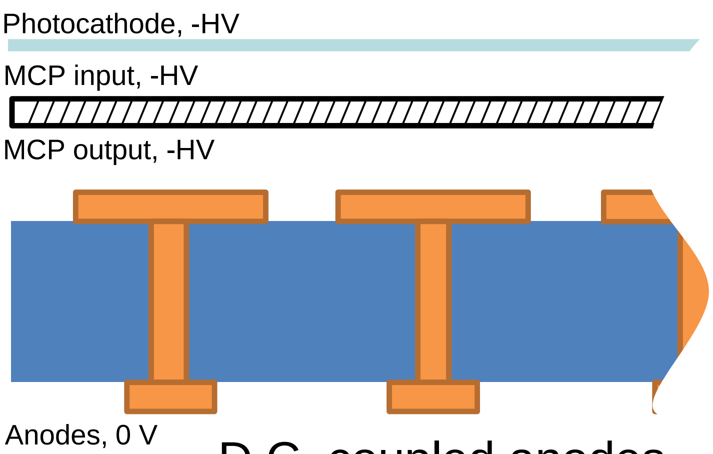
- Charge spread is too much for TORCH application
- Solution is to have buried pads – patented idea co-authored by Photek and Jon Lapington of the University of Leicester



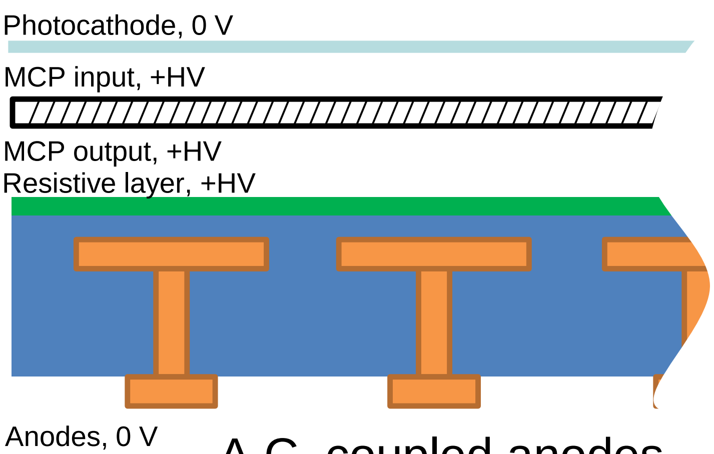
High granularity multi-anode

- Having A.C. coupled anodes allows the photocathode to be operated at 0 V
- This removes any issues with charge-up on the input window
- All year 2 prototypes (10 PMTs) were operated in this manner
- Requires thin ceramic insulator to hold off ~ 4 kV





D.C. coupled anodes



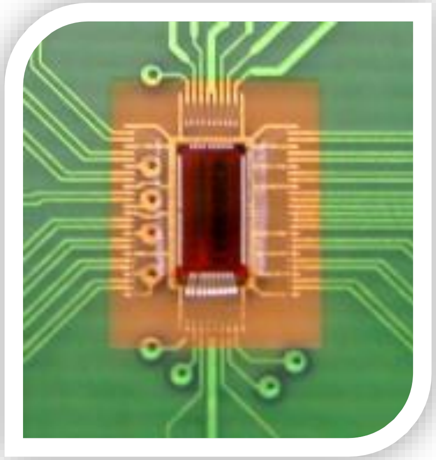
A.C. coupled anodes

High granularity multi-anode

- Needed software modelling to optimise anode geometry
- Model had to consider:
  - Dimension of the thin insulator between the resistive layer and the buried pads
  - Pulse Height Distribution (gain variation) and jitter of MCP charge cloud
  - Threshold and other characteristics of the front-end electronics
  - These factors are then applied to an imaging algorithm to produce a predicted resolution
- We used ANSYS Maxwell: *uses the accurate finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields*
- For more details see Conneely *et al* JINST 10 C05003 (2015)

High granularity multi-anode - readout

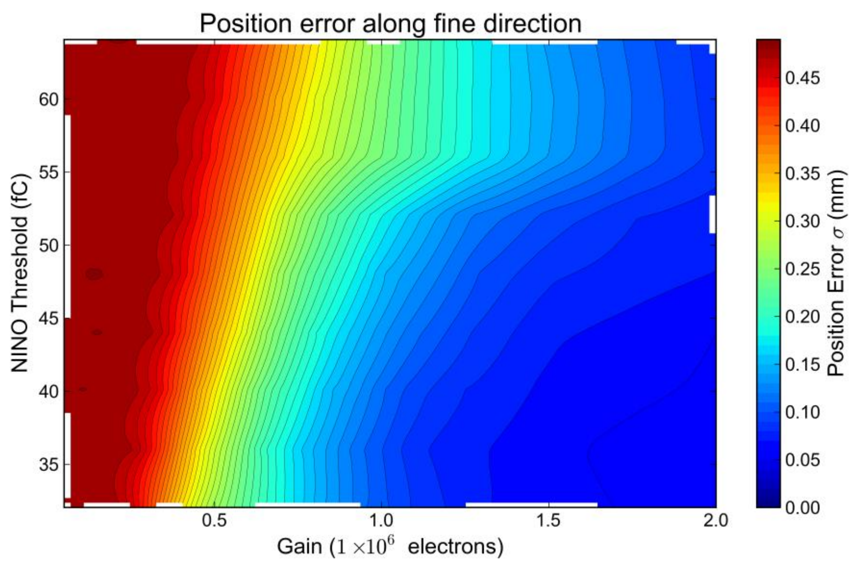
- NINO ASIC
- 32 channel differential amplifier /discriminator developed at CERN
- 10 ps RMS jitter on the leading edge
- >>10 MHz maximum rate
- The time-over-threshold technique uses the discriminator output pulse width to determine the event charge

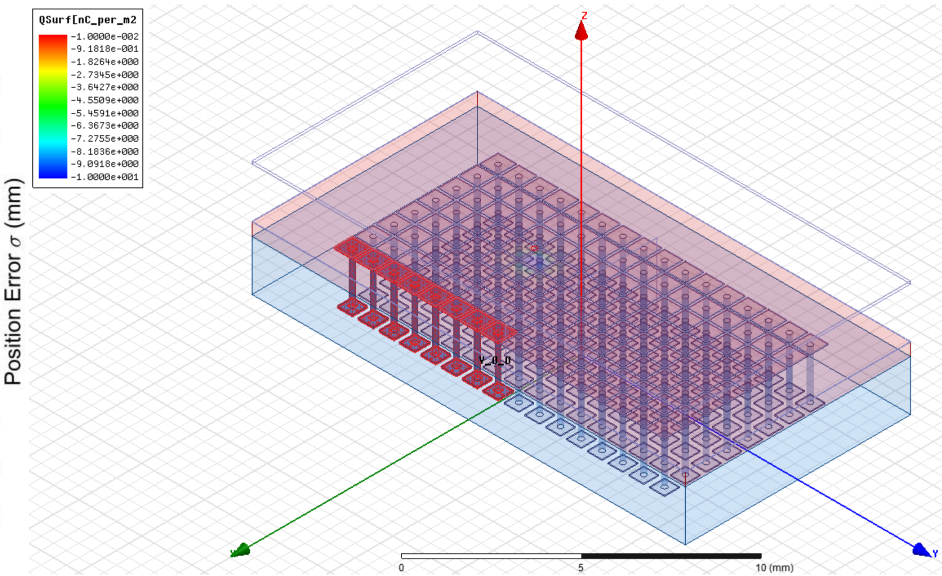


- High Performance Time-to-Digital Convertor (HPTDC)
- A programmable TDC developed for ALICE time-of-flight RPCs at the LHC
- Two modes of 100 ps LSB resolution with 32 channels, or 24.4 ps LSB resolution with 8 channels
- Default maximum rate is 2.5 MHz per channel, can be increased beyond 10 MHz using higher logic clock

High granularity multi-anode

- Initial modelling showed strong dependence on detector gain and NINO threshold:

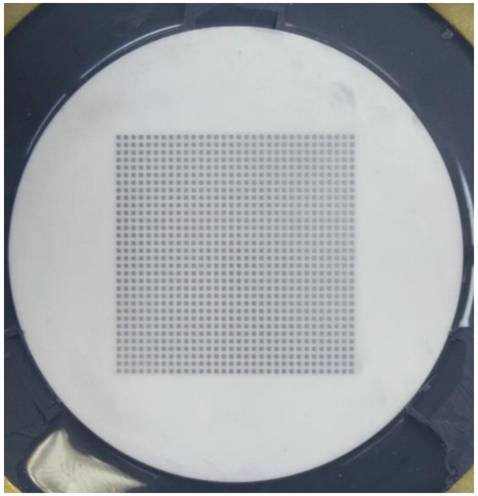


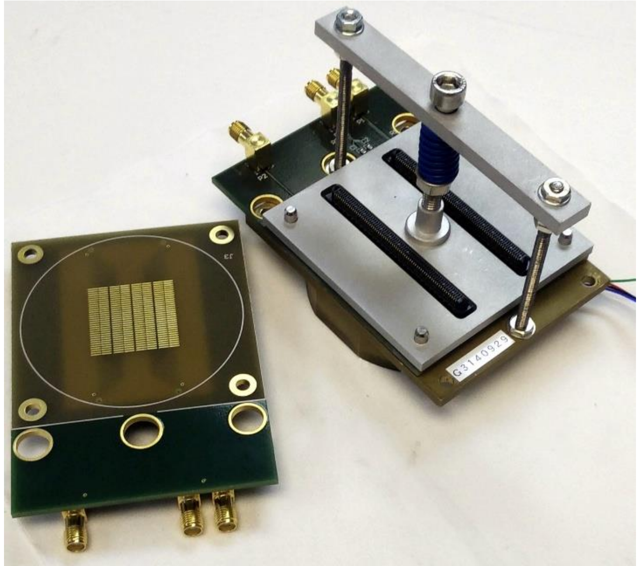


- Settled on 0.5 mm insulating gap for the first prototypes

High granularity multi-anode

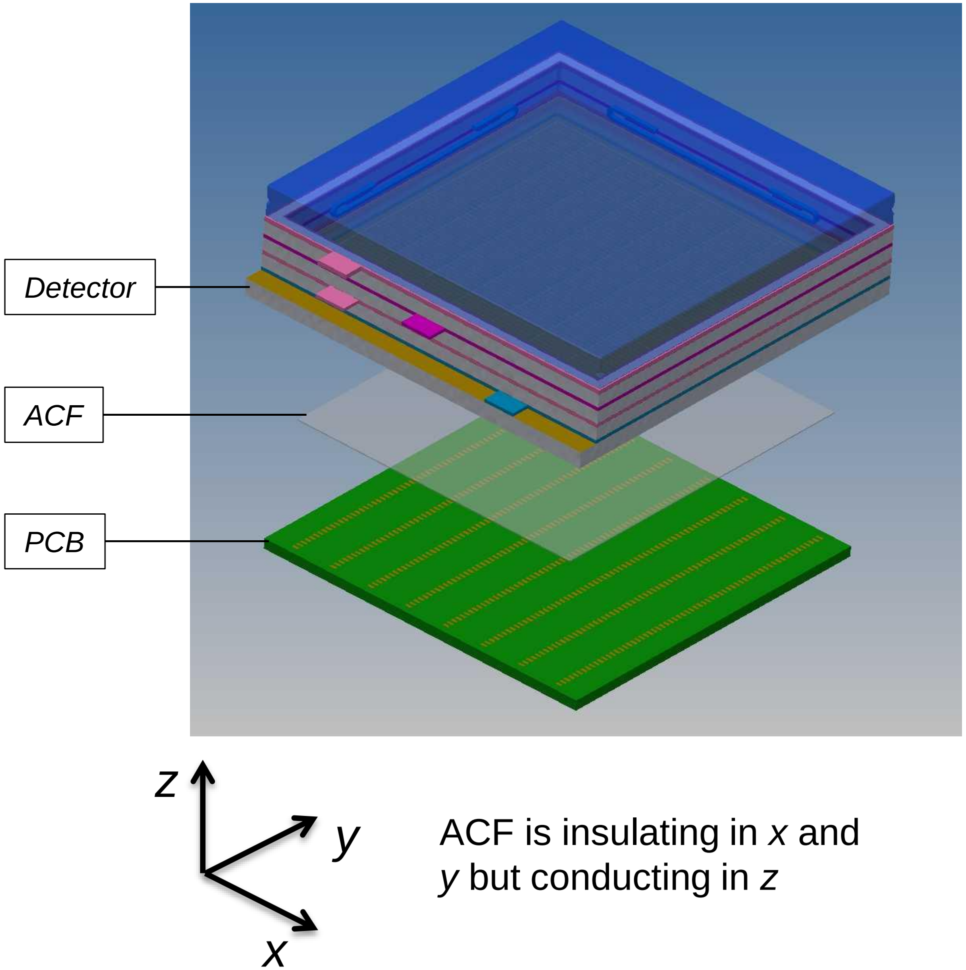
- First prototypes built with 32×32 multi-anode charge sharing anode in round format
- Internal pad width 0.73 mm, pitch 0.83 mm
- Year 2 deliverables for the TORCH project
- In one direction 8 pads ganged together to create 32×4 layout
- With charge sharing improve resolution to 64×4 pixel equivalent (or better)
- These represent ¼ size of final detector (target 128 x 8)
- Use mechanically applied Anisotropic Conductive Film (ACF) to connector detector output to readout PCB





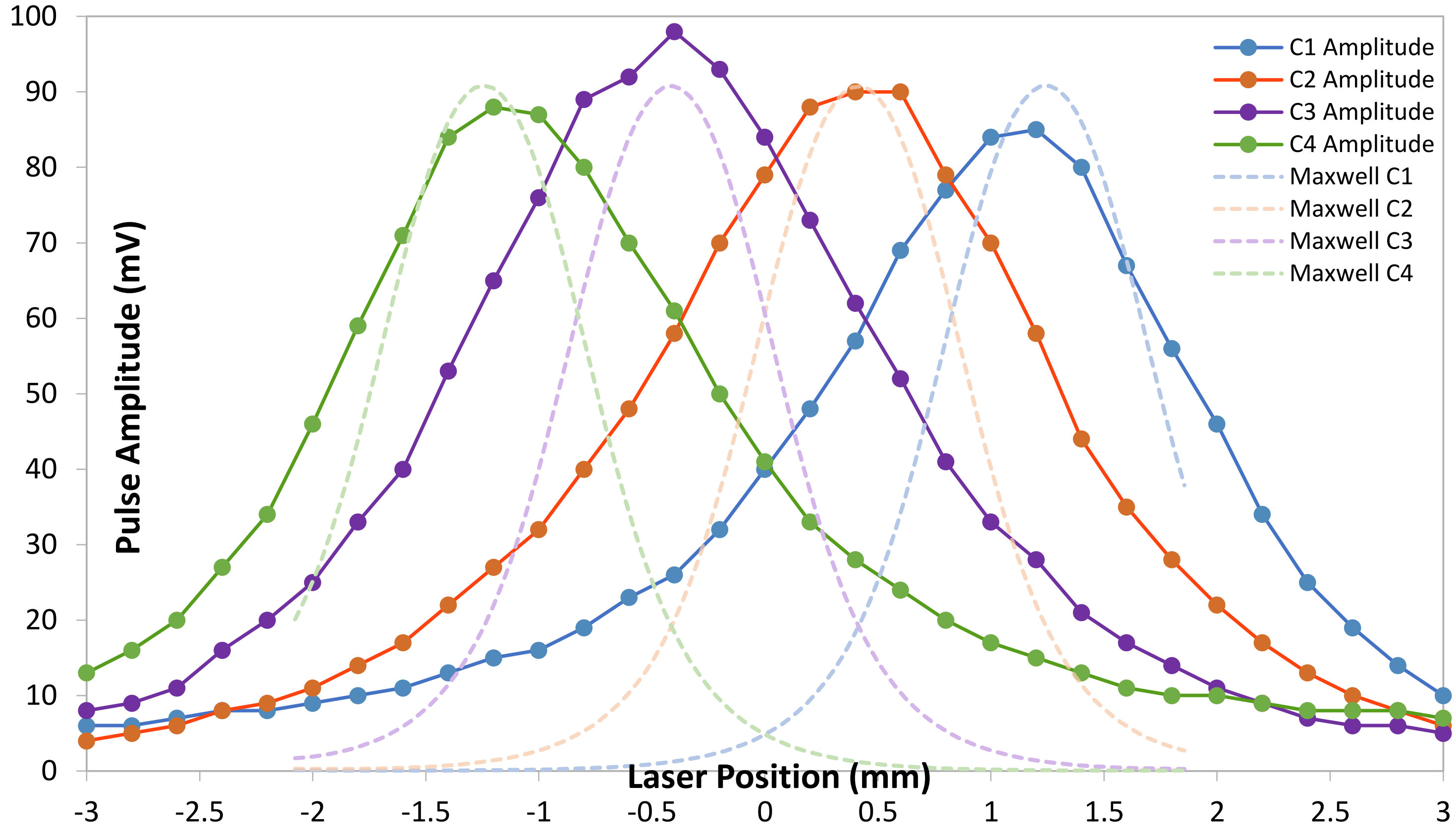
Anisotropic Conductive Film

- Contact made to anodes by Anisotropic Conductive Film (ACF)
  - Mechanically applied ACF used in circular prototypes
  - Thermally applied ACF to be used in square version
  - Thermal application still being perfected
  - Commonly used in mobile phone cameras



ACF is insulating in *x* and *y* but conducting in *z*

First Prototypes – Charge Spread



- Charge spread measured on oscilloscope – *this is not the position resolution*
- Maxwell curves show modelling results
- Why was the spreading greater than predicted?

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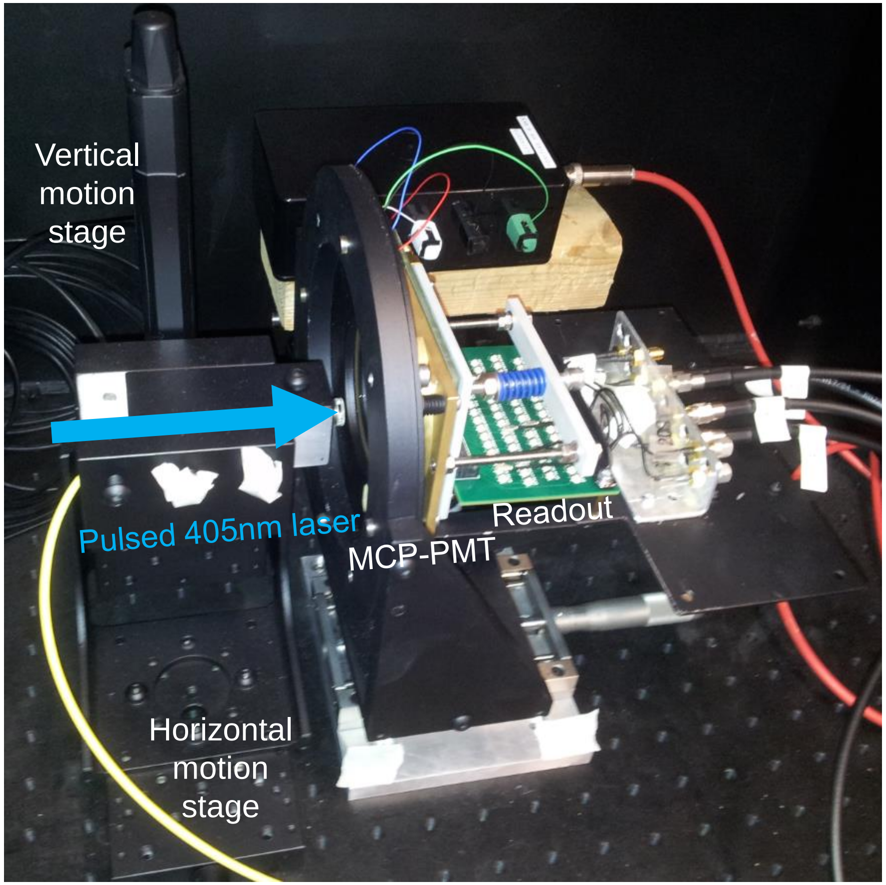
High granularity multi-anode

- We returned to the ANSYS Maxwell model and refined to include:
  - Temporal profile of the MCP cloud profile
  - The effect of the sheet resistance on charge footprint dispersion, and effects of electronics charge integration time
  - Previous model had effectively looked at static charge profile
- New model predicted ideal thickness to be 0.3 mm for the insulating gap
- The TORCH collaboration considered this a critical parameter for the PMT so we agreed to delay the square PMT development to produce more round prototypes with the new thickness

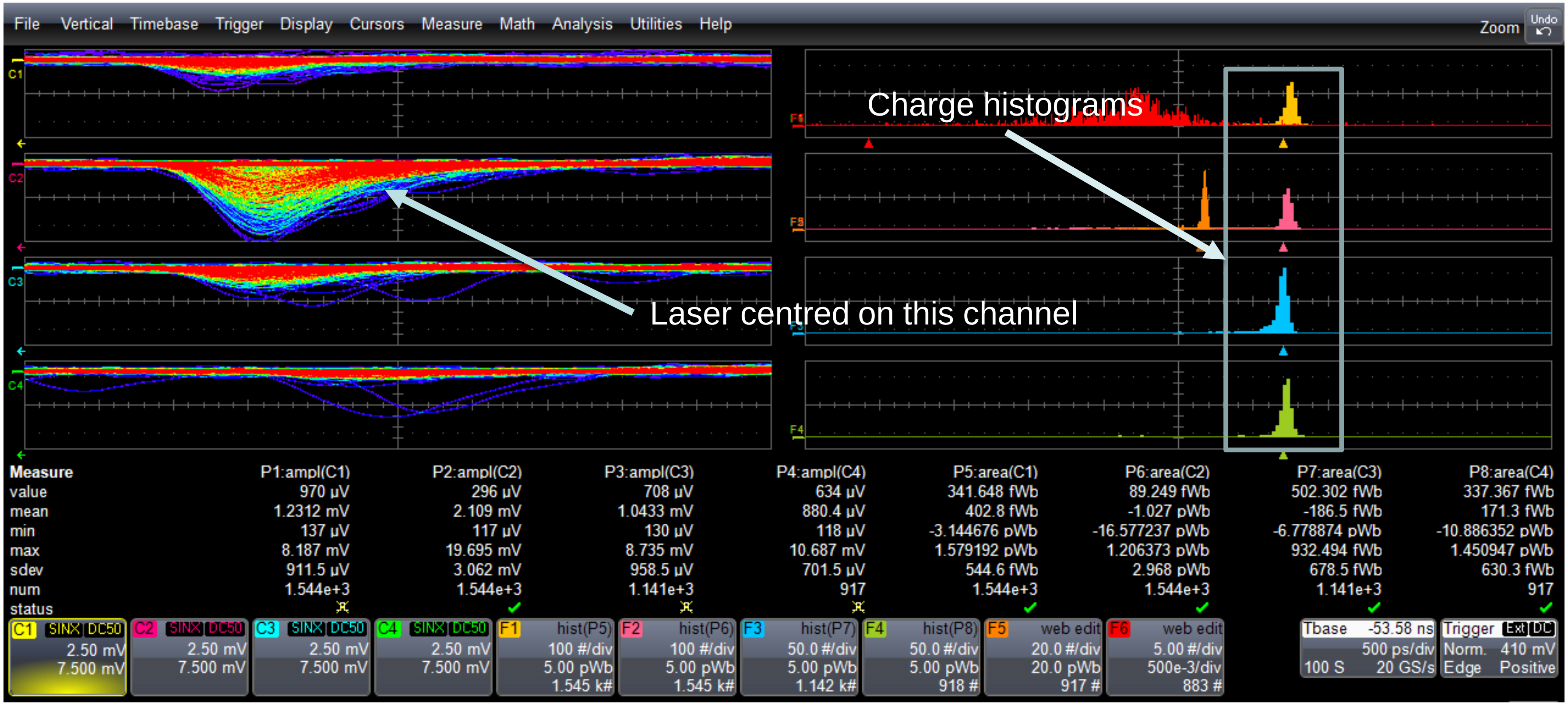
High granularity multi-anode

- Test performed on University of Bristol laser scanning setup
- >15 µm laser spot size
- Use a 5 GHz, 40 GS/sec scope to sample output for four channels
- Digitised pulse integrated to measure charge per pad



High granularity multi-anode

- Example of oscilloscope charge spread measurement:



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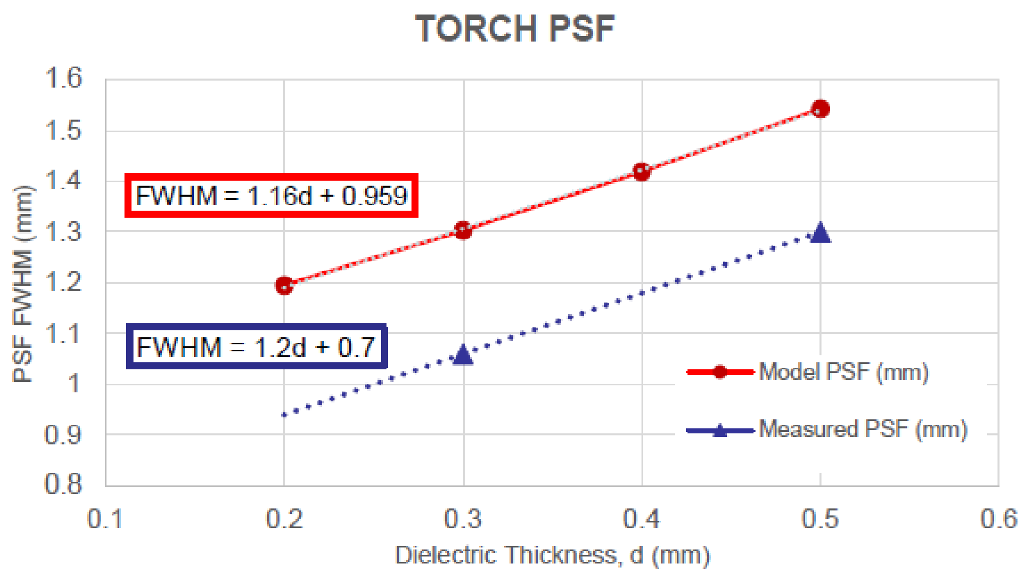
High granularity multi-anode

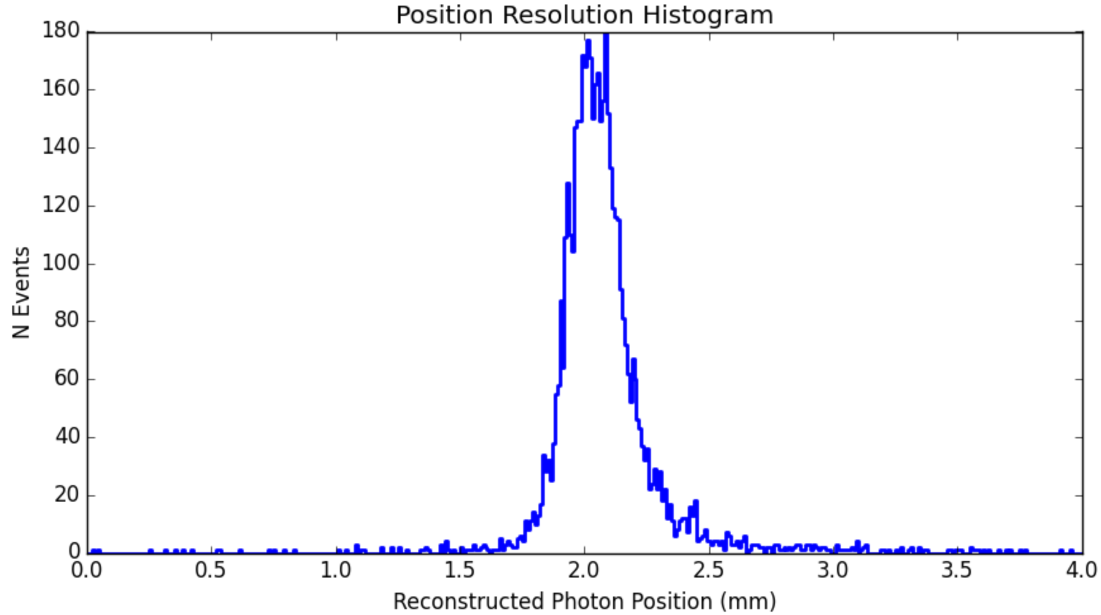
Phase	Dielectric Thickness	Model PSF	Mean Measurement PSF
2.1 old results	0.5 mm	1.54 mm	1.65 mm
2.1 new results	0.5 mm	1.54 mm	1.30 mm
2.3	0.3 mm	1.30 mm	1.06 mm



Questionable fit!!

Position Resolution – Early Result

- Applying imaging algorithm on event by event basis, with laser aligned in centre of 4 pixels
- TORCH target 0.12 mm rms
- 0.096 mm rms (0.225 mm FWHM) derived from pads on a 0.83 mm pitch
- Measured on 4-channel oscilloscope
- PMT had 0.5 mm insulating gap



$$x = \frac{\sum_{i=0}^{3} x_i q_i}{Q}$$

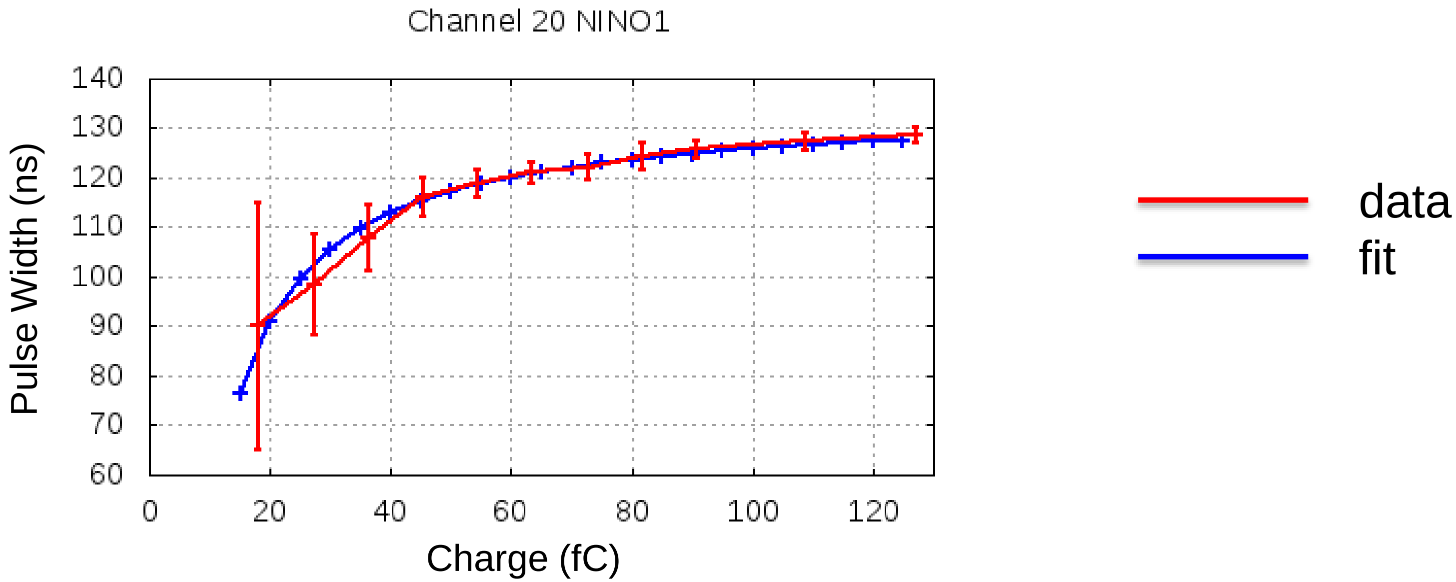
x_i is co-ordinate of pad

q_i is charge collected by pad i

Q is the sum of all charge collected

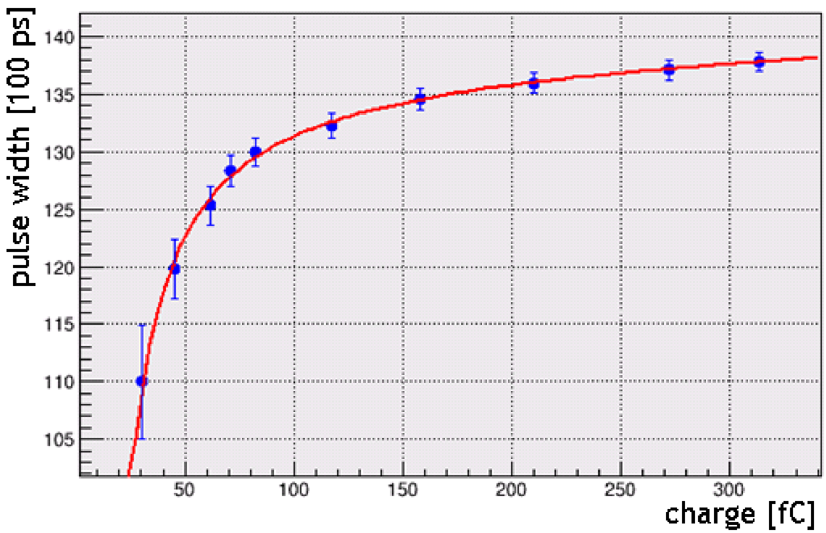
Position Resolution – NINO Measurement

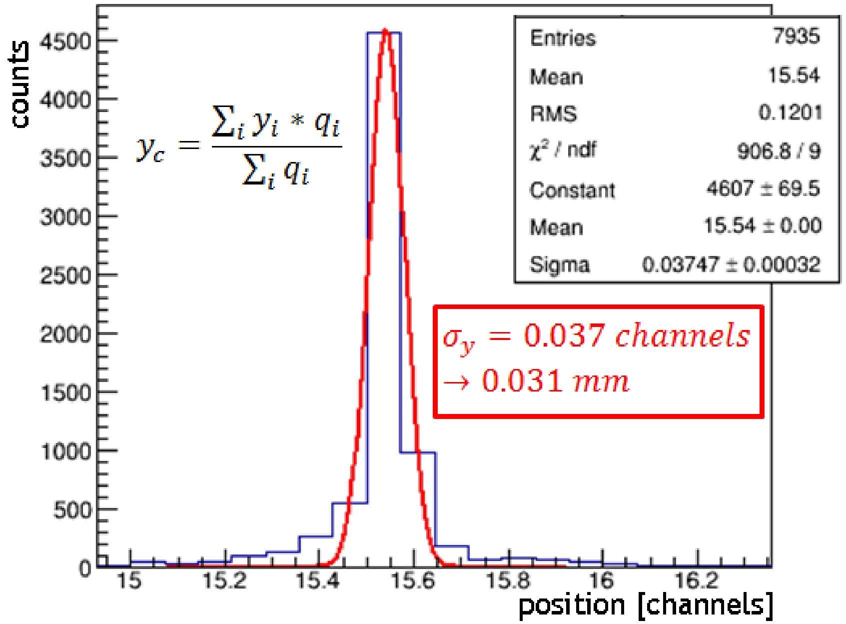
- Measurements using the NINO ASIC have proven difficult
  - Each channel needs individual calibration for charge input / pulse width output using the time-over-threshold technique – threshold dependant
  - Very susceptible to electronic noise
  - Odd / even channels can behave differently



Position Resolution – NINO Measurement

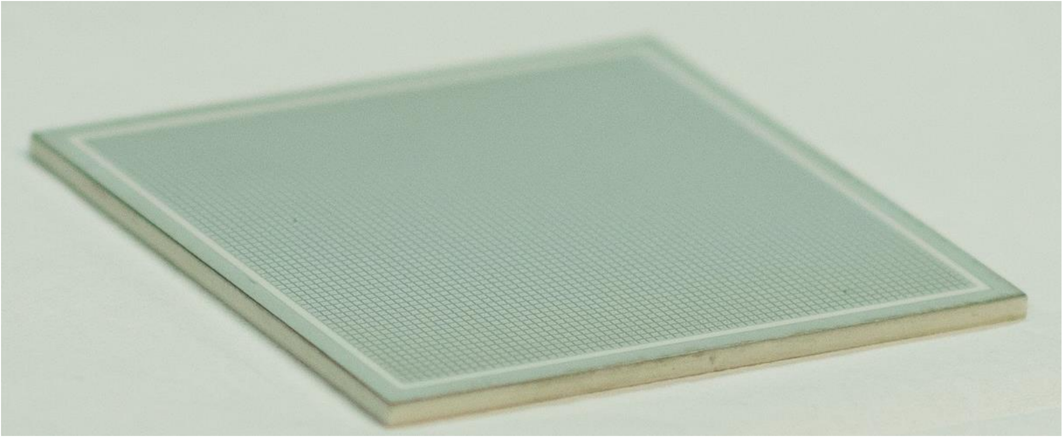
- Despite these issues, an excellent result was achieved:





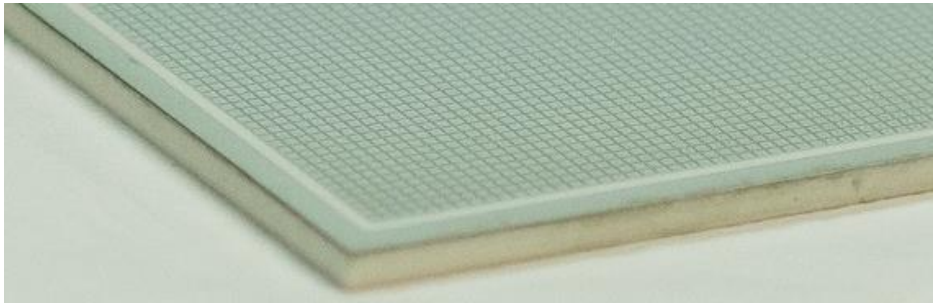
- See L. Castillo García et al *JINST 11 C05022 (2016)* also talk by Thierry Gys
- Still assessing data on different insulator thickness – we have both versions in the square 64 x 64 format ready to go

Commercial Square PMT

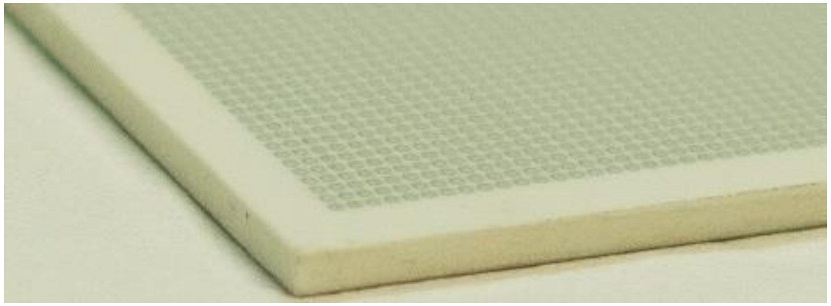


- Direct couple anodes
- Will be used on commercial Photek MA-PMT
- 64 x 64 array
- 0.73 mm pad width on a 0.83 mm pitch

Vacuum side



Air side



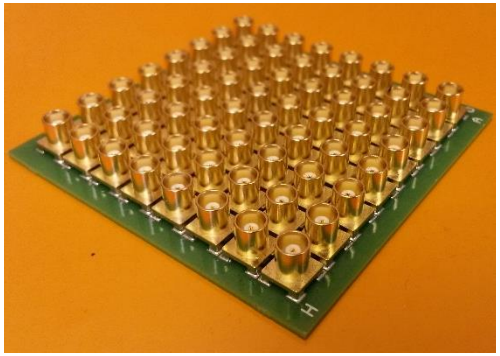
Commercial Square PMT

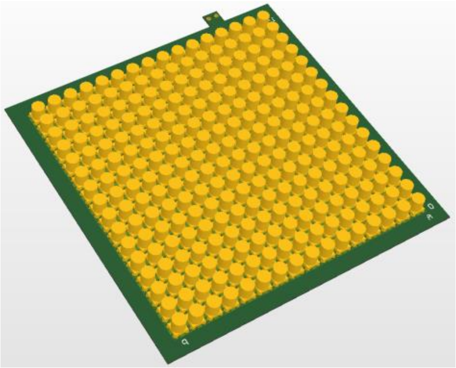
- Unrealistic to individually connect all 4096 connections in 64 x 64 array to front-end electronics
- However, this format gives flexibility to gang pads together:

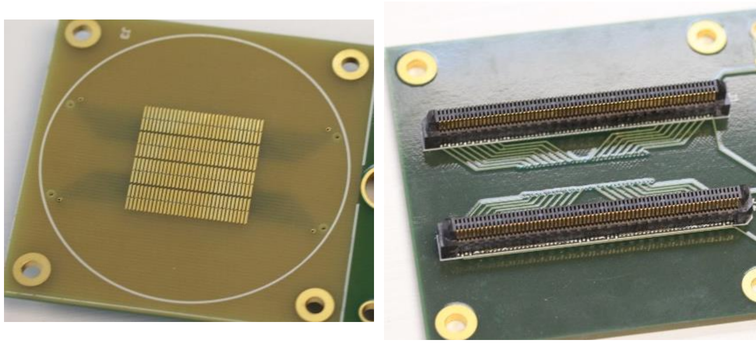
- Gang 8 x 8 pads together
- 8 x 8 array
- e.g. MCX co-ax

- Gang 4 x 4 pads together
- 16 x 16 array
- e.g. SSMCX co-ax

- Gang 8 x 1 pads together
- 8 x 64 array
- e.g. Samtec 140-pin multi-way







Summary

- TORCH PMT in development at Photek
- 3 year development aims to finish 2016
- 1st year task complete: To produce long-life demonstrators
- 2nd year task complete: To produce high-granularity multi-anode demonstrator
- Final year task: Fully functioning detector
- Also producing 64 x 64 direct coupled anode version

With thanks to…

The members of the TORCH collaboration at the University of Bristol, CERN and the University of Oxford

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Thank you for listening