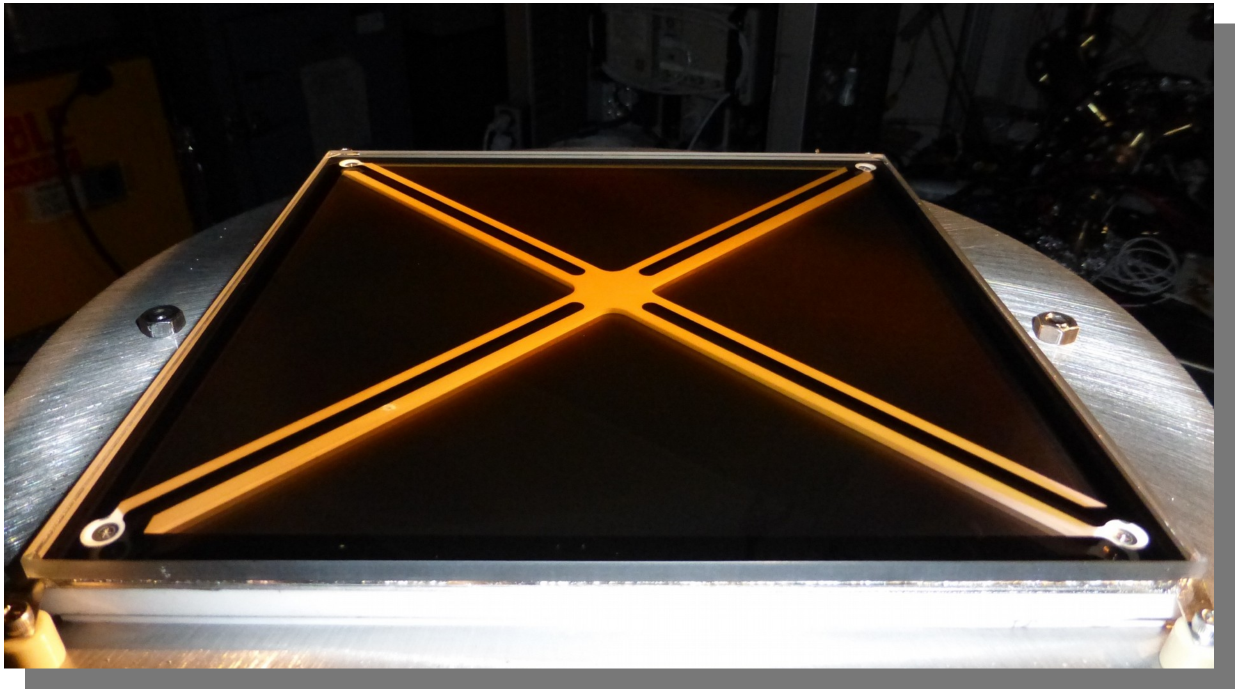
Large Area Picosecond Photo-Detectors



Matthew Malek

University of Birmingham Particle Physics Seminar

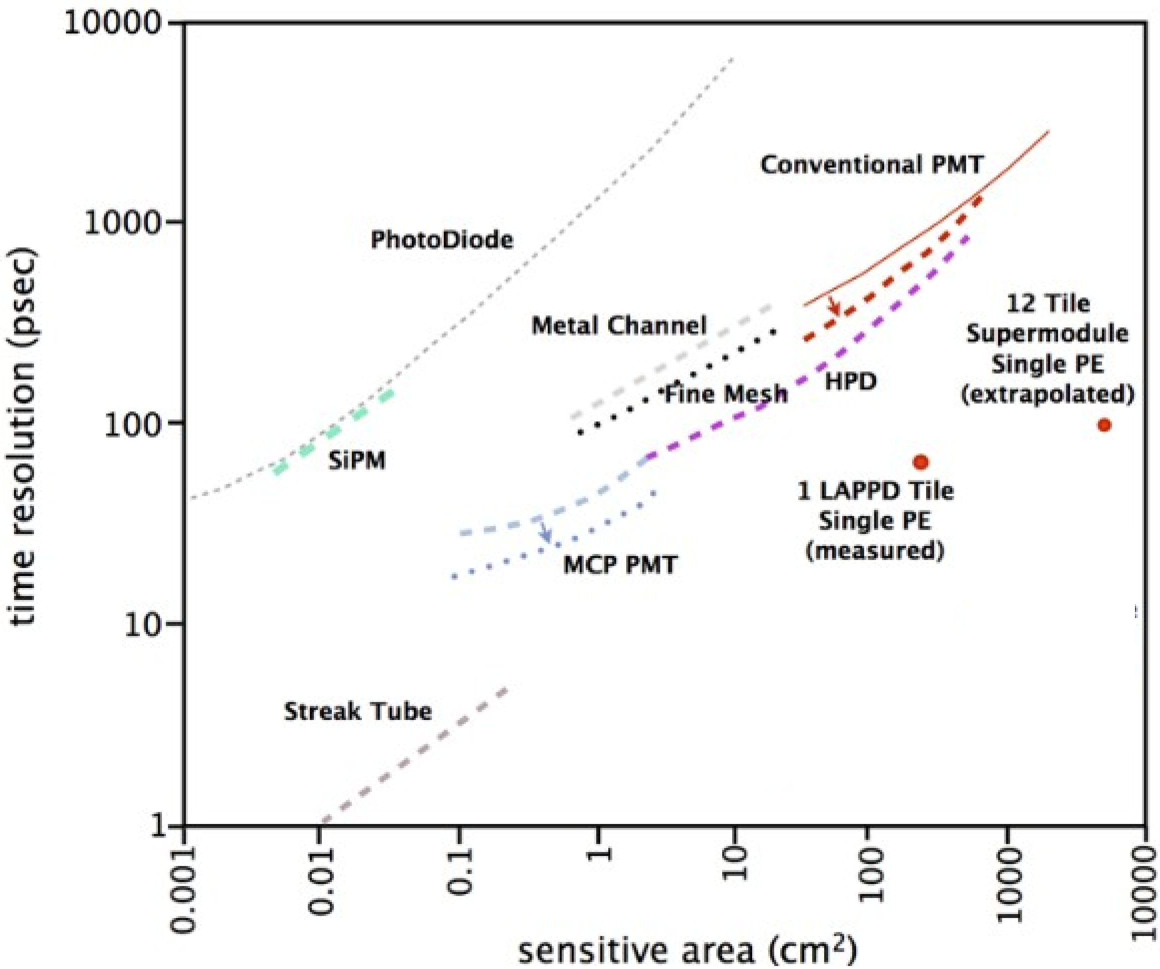
9th March 2022

Introduction

Photodetectors have been a staple of particle physics for decades, with the conventional PMT a stalwart ‘workhorse’ of the field.

Photodetection will continue to play a critical role in particle detectors but…

Next-generation experiments have challenges of size & cost.



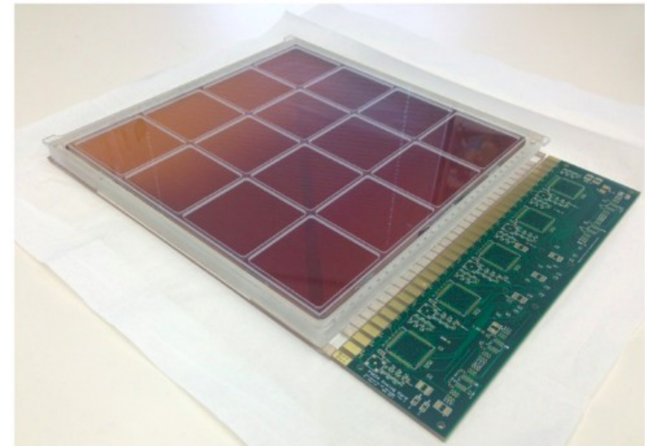
Advancing photosensor technology is a high-impact means of expanding our physics reach; many efforts on this front (*e.g.*, high-QE PMTs, hybrid photosensors). This talk focuses on one particular effort – **LAPPDs**.

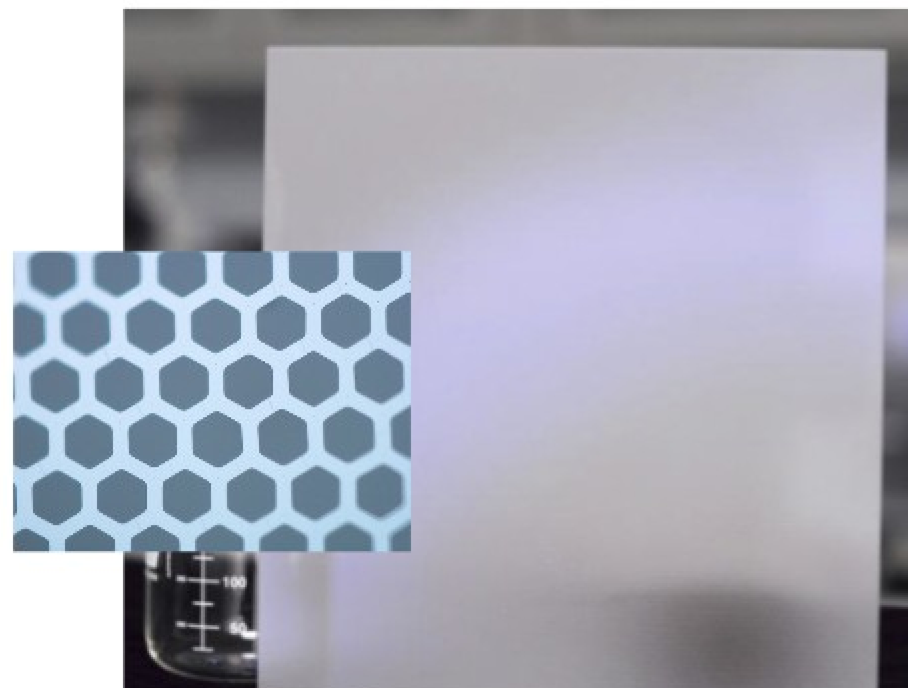
LAPPD Overview

- Overview of **L**arge **A**rea **P**icosecond **P**hoto-**D**etectors:

LAPPDs are:

- 400 cm^2 sensors (20cm x 20 cm)
- Based on microchannel plate technology (MCPs) [see next slide]
- Excellent resolutions:
  - Spatial: < 1 cm
  - Timing: < 100 ps (TTS)
- Capable of imaging single photons

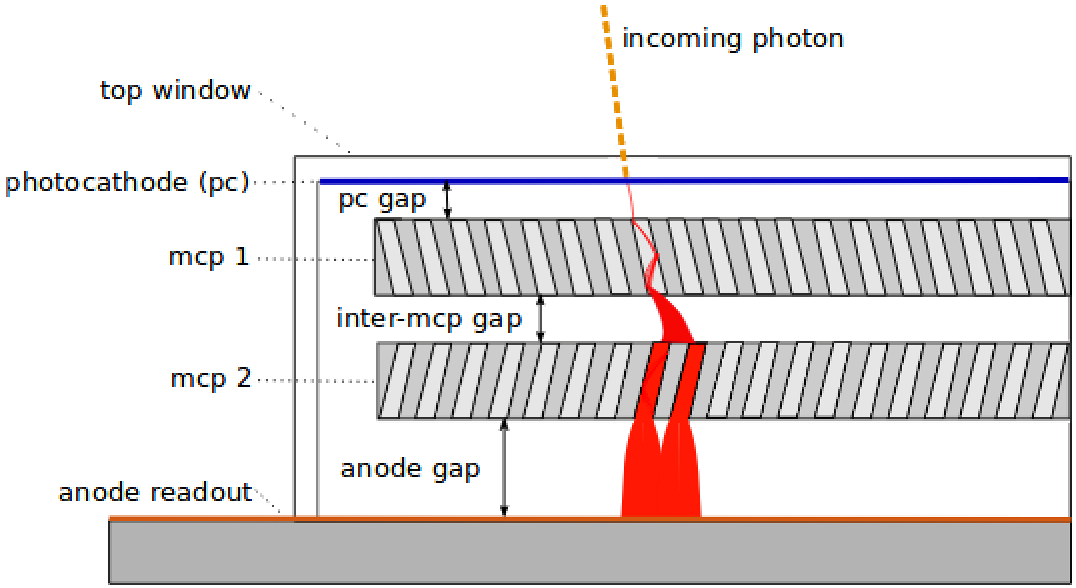




Microchannel Plate PMTs

Microchannel plates themselves are not new technology
- Example: Used in night vision goggles since 1970s

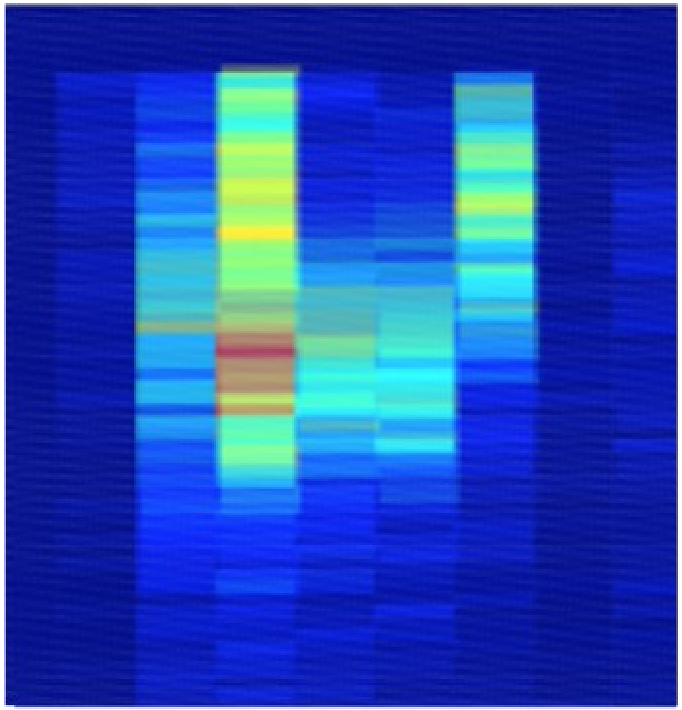
MCP PMTs are also not new
- Photonis Planacon has been in production for many years
- Limitations:
  - Small (~5cm x 5cm)
  - Expensive (~$10k)

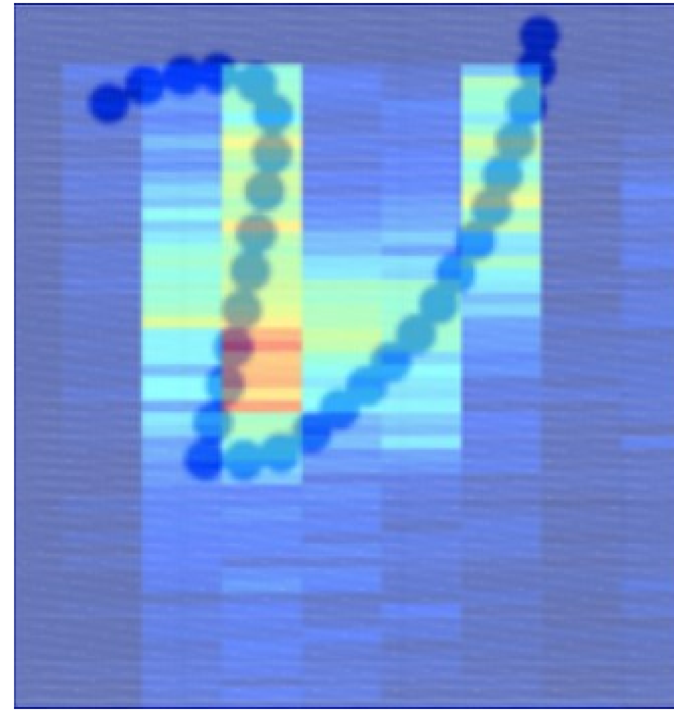


The LAPPD project was formed in 2009 to make this technology practical for particle physics experiments!

MCP-PMT Imaging

The University Of Sheffield.





For more information, please see:

A Brief Technical History of the Large-Area Picosecond Photodetector Collaboration (Adams *et al*, 2016) – https://arxiv.org/abs/1603.01843

LAPPDs Development

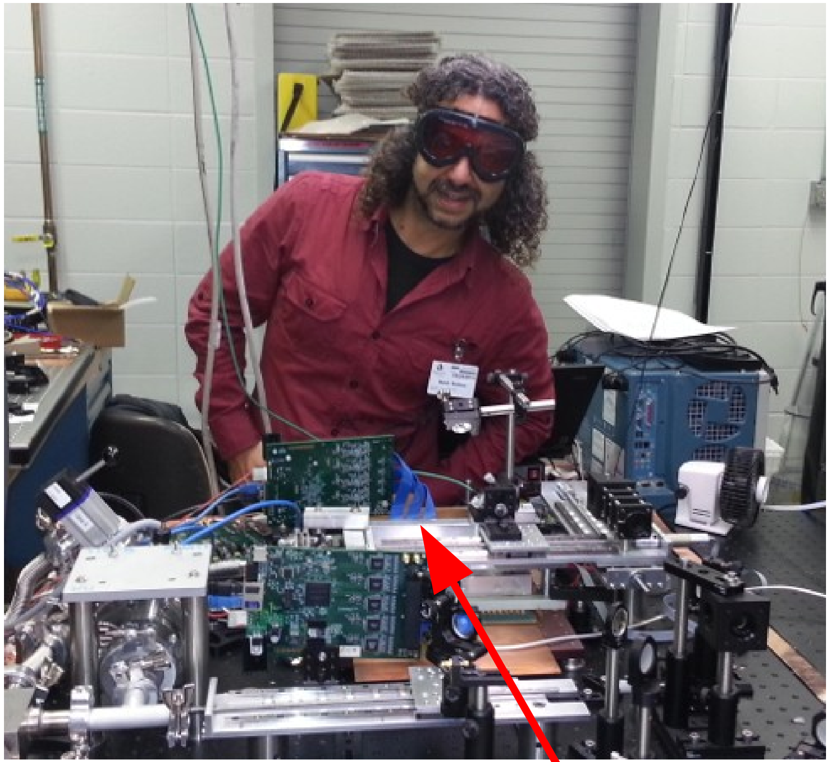
Areas targeted for improvement included:

- Microchannel plates:
  - Selection of substrates:
    Drawn glass capillaries, etched aluminium considered
  - Development of atomic layer deposition:
    Resistive coatings and secondary-emitting coatings
- Photocathodes:
  - Transfer of techniques for K_2NaSb photocathodes to 20cm square photocathodes on borosilicate glass
- Hermetic packaging:
  - Sealing of large tile <u>not</u> trivial! (see upcoming slide)
- Electronics readout:
  - Development of “PSEC” series of ASIC chips

LAPPDs Milestones

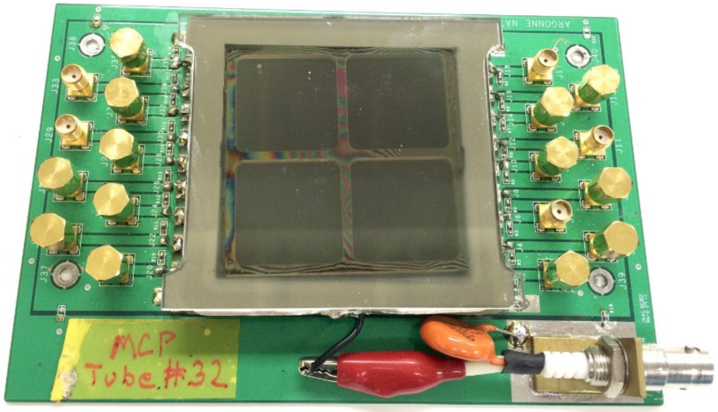
The University Of Sheffield.

Initial work focussed on advancing separate work packages



- Example: First “working” LAPPD had functional MCP… but needed to be continuously pumped <u>and</u> had a poor photocathode (aluminium)

- Small-scale (6cm x 6cm) prototype tiles were produced at Argonne National Lab to develop photocathode, electronics, etc.



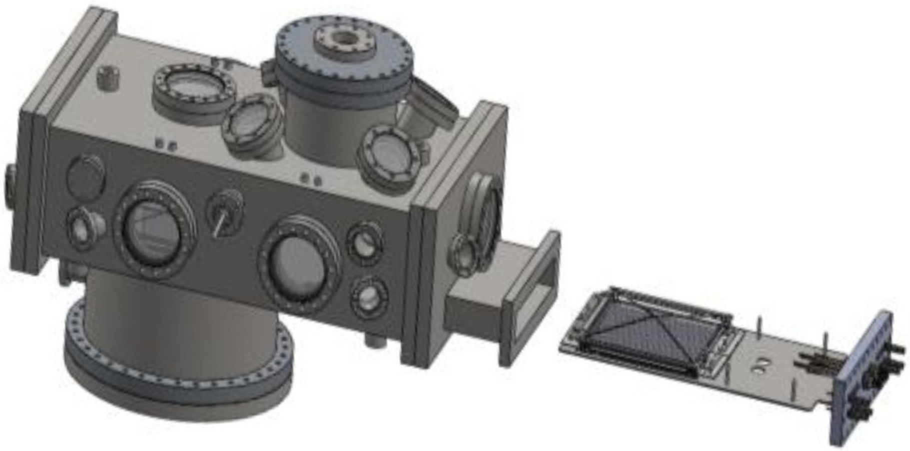
First working LAPPD! [not sealed; aluminium photocathode (QE = 10^{-7})]

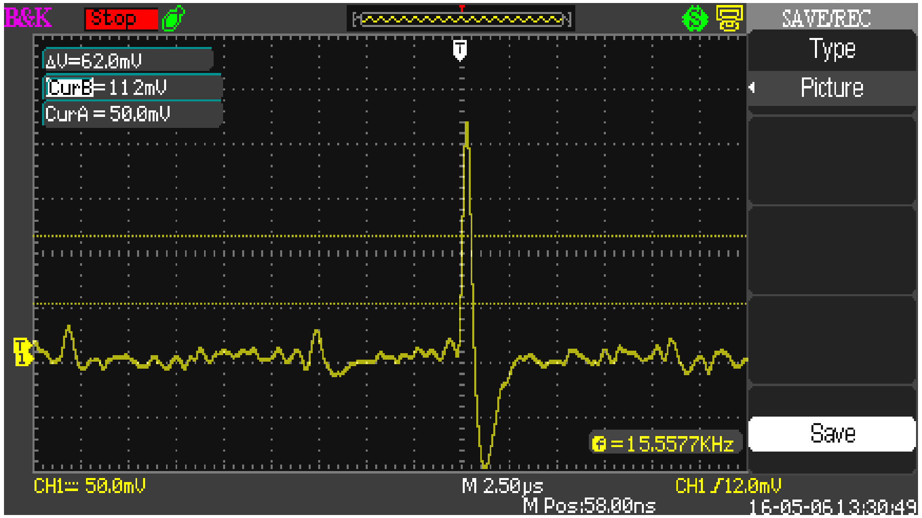
For UK-based tests with the Argonne MCP-PMT, see:

Characterisation and testing of a prototype 6 x 6 cm² Argonne MCP-PMT (G. A. Cowan *et al* 2016) https://arxiv.org/pdf/1611.00185.pdf

LAPPD Commercialisation

- Following R&D at US universities and national labs, commercialisation was transferred to a US-based company (Incom) and the design was refined.





LAPPD Commercialisation

The University Of Sheffield.

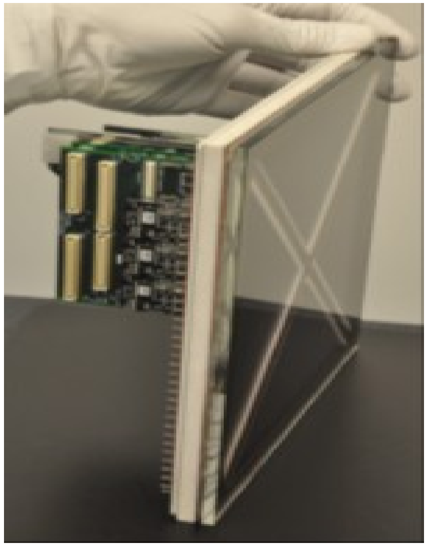
Incom production facilities in place by 2015:

1) Wafer Slice GCA

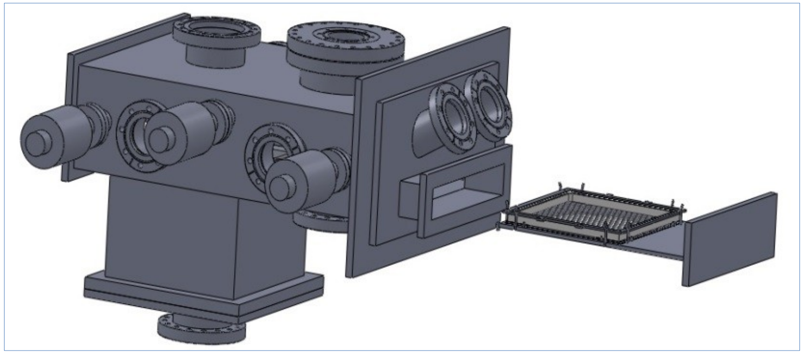
2) Apply Electrode

3) ALD Coat MCP

4) Measure & Test



5) LAPPDtm



6) Tile Integration & Seal

LAPPD Early Production

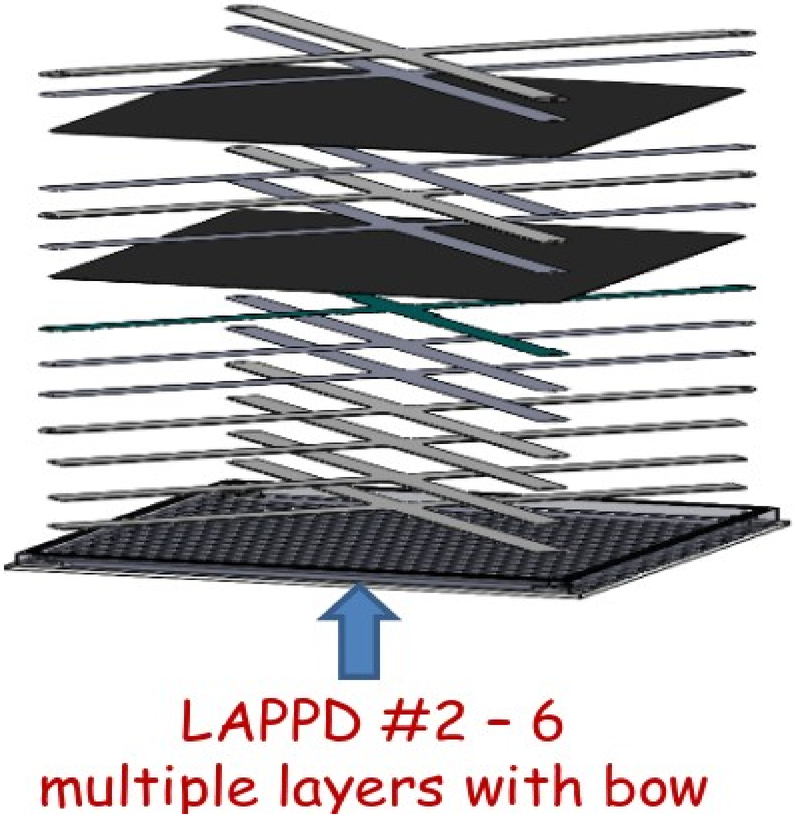
Performance Metric	LAPPD#1	LAPPD#2	LAPPD#3	LAPPD#4	LAPPD#5	LAPPD#6
Seal date	02/05/2016	02/22/2016	03/10/2015	04/28/2015	5/20/2016	06/08/16
Indium Seal	Excellent	Excellent	Excellent	Failed seal	Failed seal	Excellent
Vacuum Integrity	Excellent	Cracked window Low SH	Cracked window Low SH	High SH	High SH	Cracked window
PC QE @190C, @365 nm	1%	4%	1%	6%	9.4%	4.5%
Performance under Vacuum	Lost electrical connection to the top of entry MCP Contact failure	HV discharge problems Signal lost upon venting	☺ No HV problems Signal lost upon venting.	☺ No HV problems Dark pulses detected.	☺ No HV problems Dark pulses detected	☺ No HV problems Dark pulses detected

Tiles #2-6 (Feb – Aug) lost vacuum → hermetic sealing!

Tile #1 (Feb) had faulty electrical connection

LAPPD Redesign (2016)

- New, streamlined design has fewer spacer layers:



Stack Height - High	Stack Height - Low
Failed Seal	Cracked Window

More LAPPD production

Tile #7 (July 2016): Failed seal (window contamination?)
Tile #8 (Aug 2016): Electrical problems

Tile #9 (Sep 2016): First success!

On 14th September 2016, Incom achieved the first successful fabrication of a functioning LAPPD!

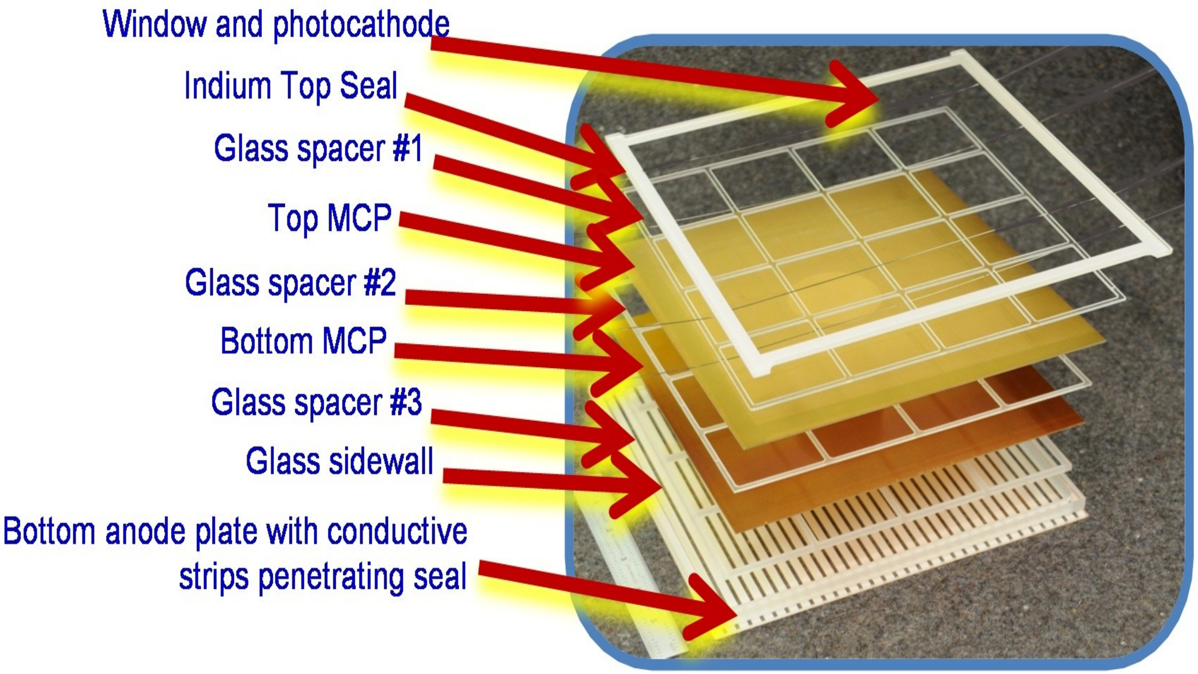
Caveat: Photocathode is aluminium (**extremely** low QE: 10^{-9})

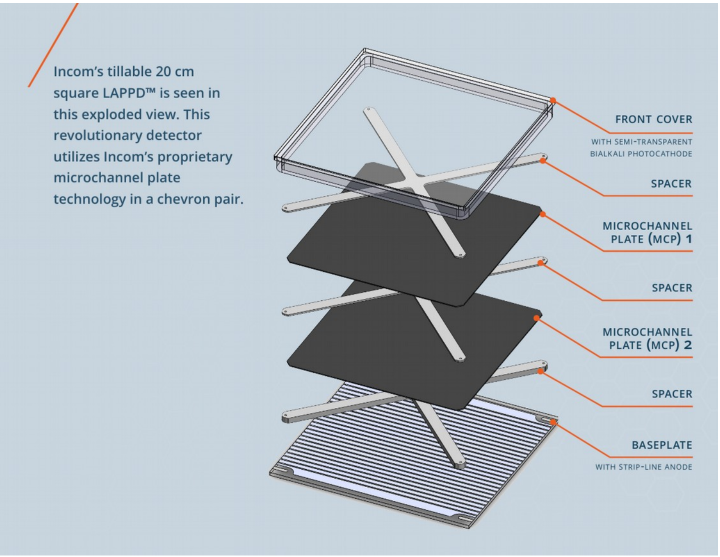
Usual bialkali photocathode (Na K Sb) had been replaced to check whether cathode deposits on the indium were contributing to poor seals.

Tile #10 produced in October 2016 with usual bialkali photocathode;
→ **Second success!**

Since then, production has been ongoing; tile count now in triple digits!

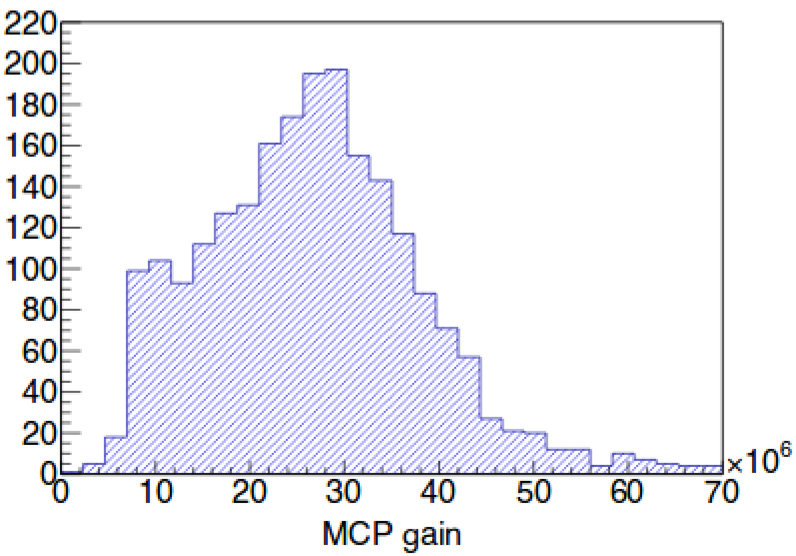
LAPPD: "Final" product





(Some) LAPPD properties:

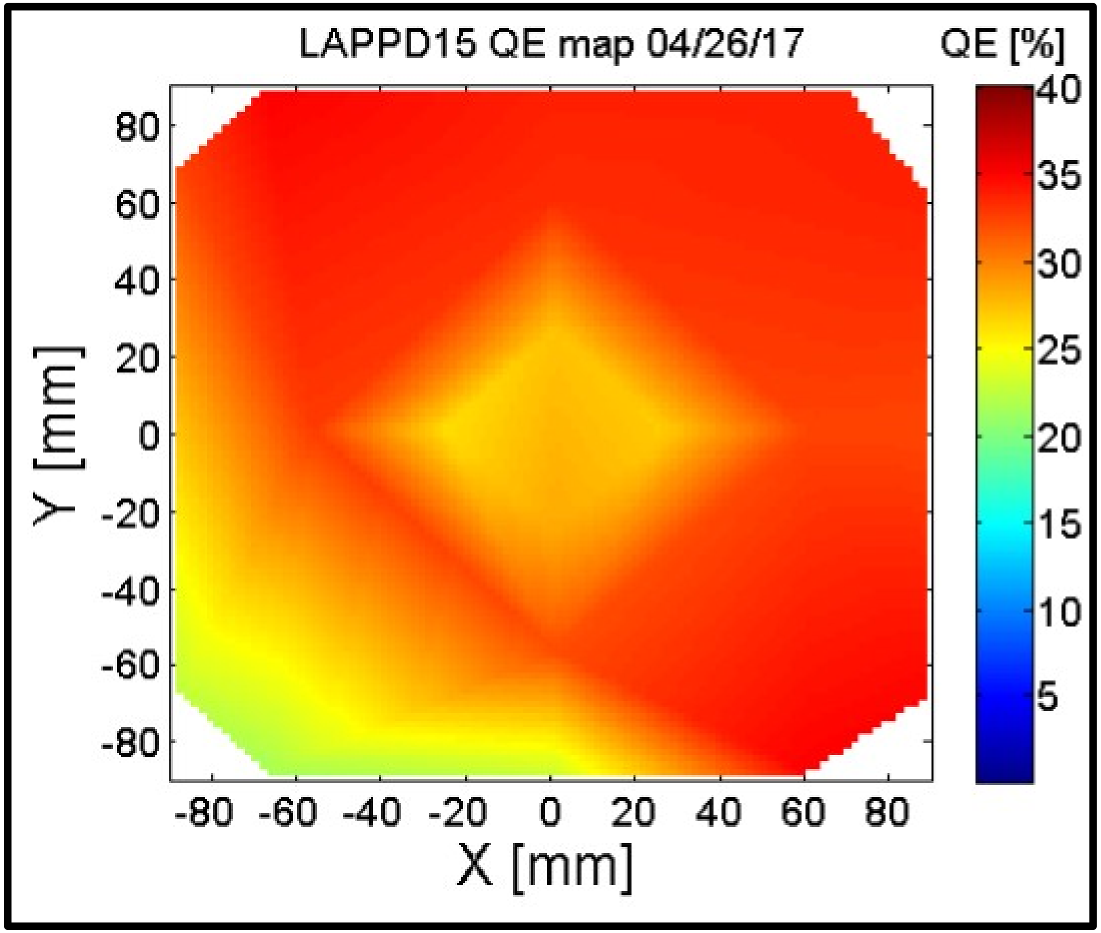
- Transit time spread (TTS) better than 60 picosec for single PE resolutions
- Gain > 10^7
- Readout via 28 striplines (Gen1) or 64 capacatively coupled "pixels" (Gen2)

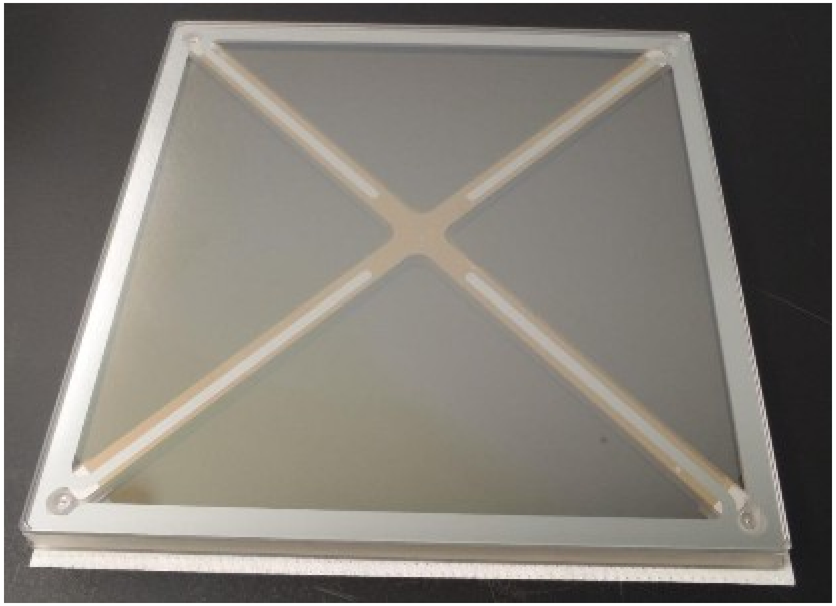


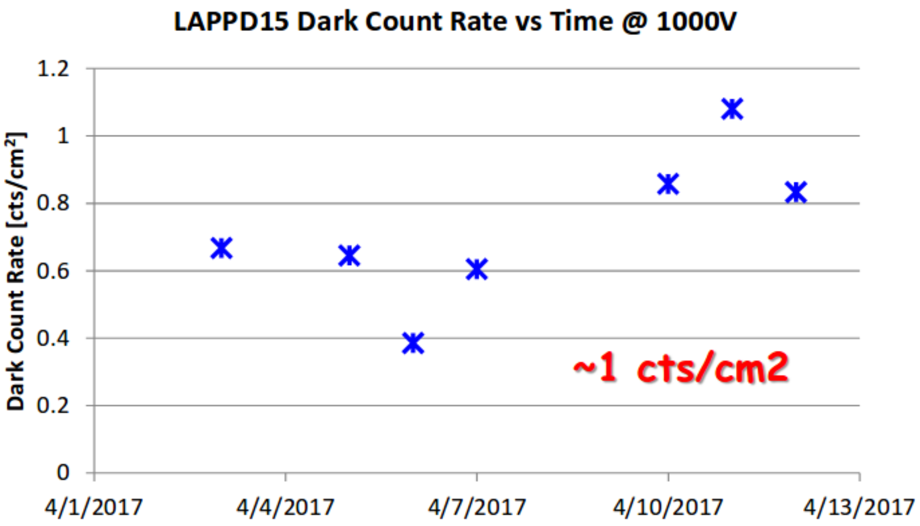
The University Of Sheffield.

Tile #15

Quantum Efficiency:

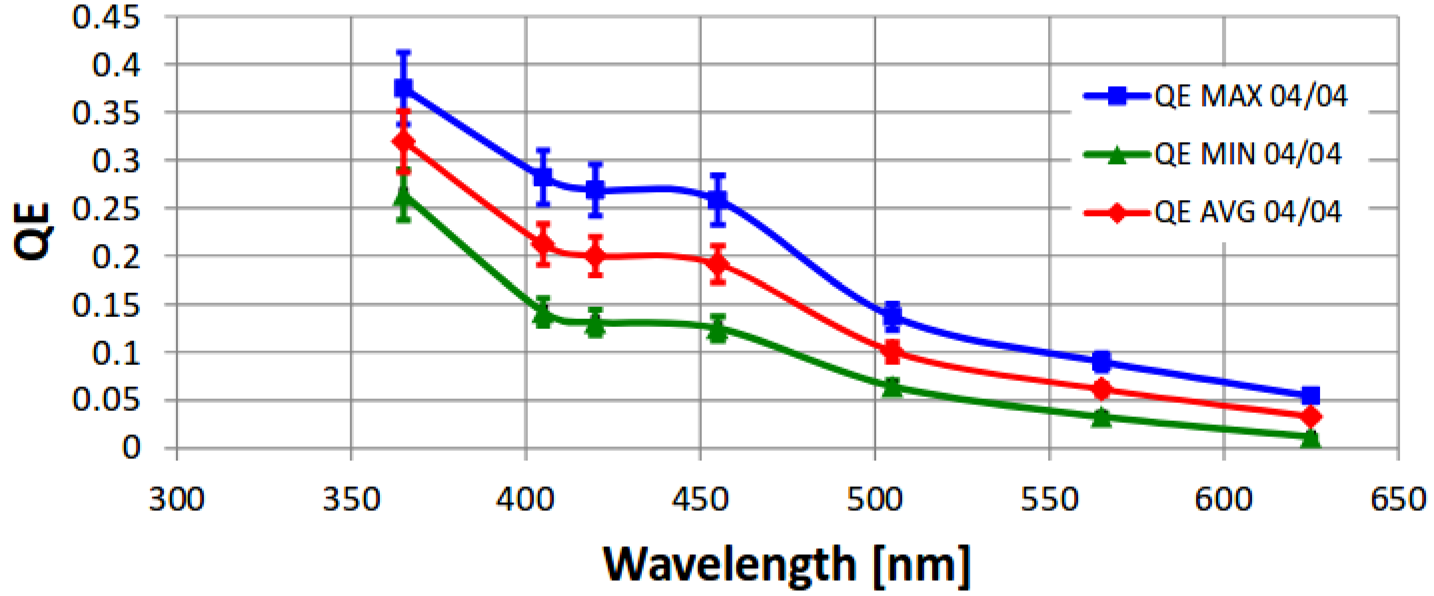


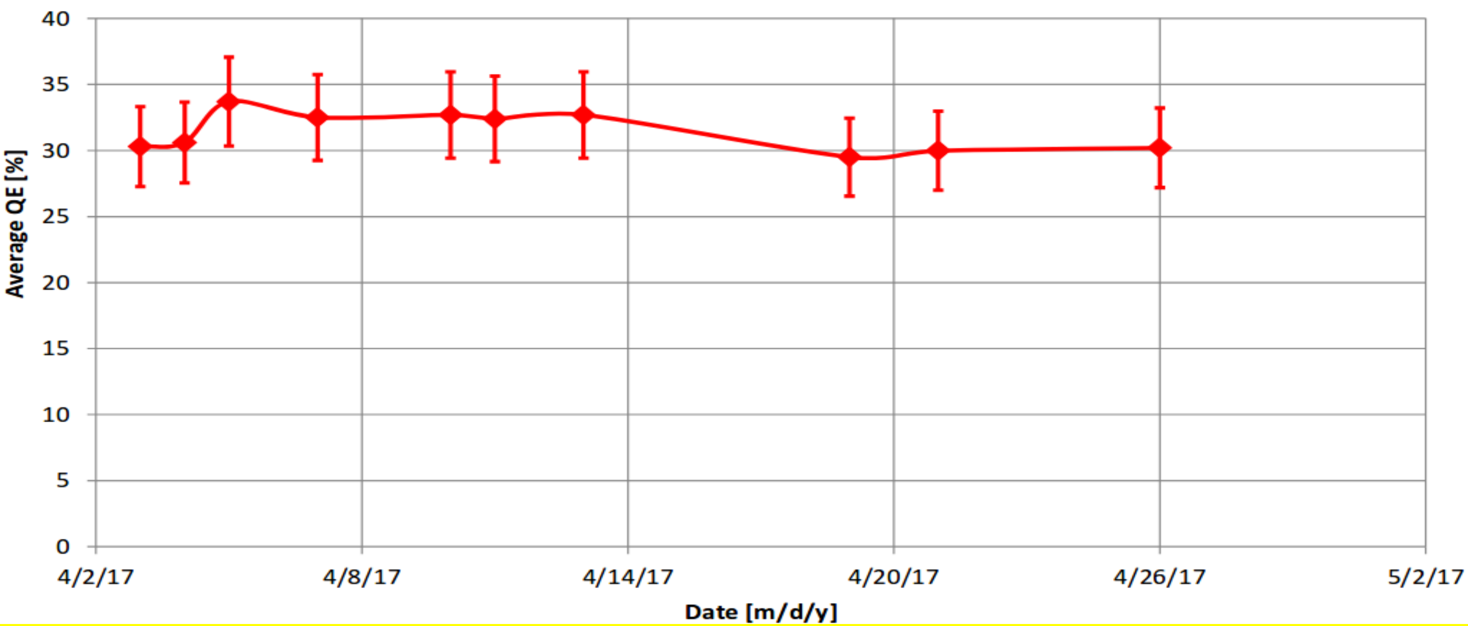




QE vs. Wavelength & Time

The University Of Sheffield.





Tile #15 Performace

Operating voltage:

- 1000 – 1100 V
- Positive or negative (usually run with negative HV)

Quantum efficiency:

- Max = 35% ; **Ave = 30%** ; Min = 21%

Dark noise:

- 258 Hz (at 1000 V)

Gain:

- 2.8×10^6

Readout speed:

- 1.8 ns (along the strip)

Saturation:

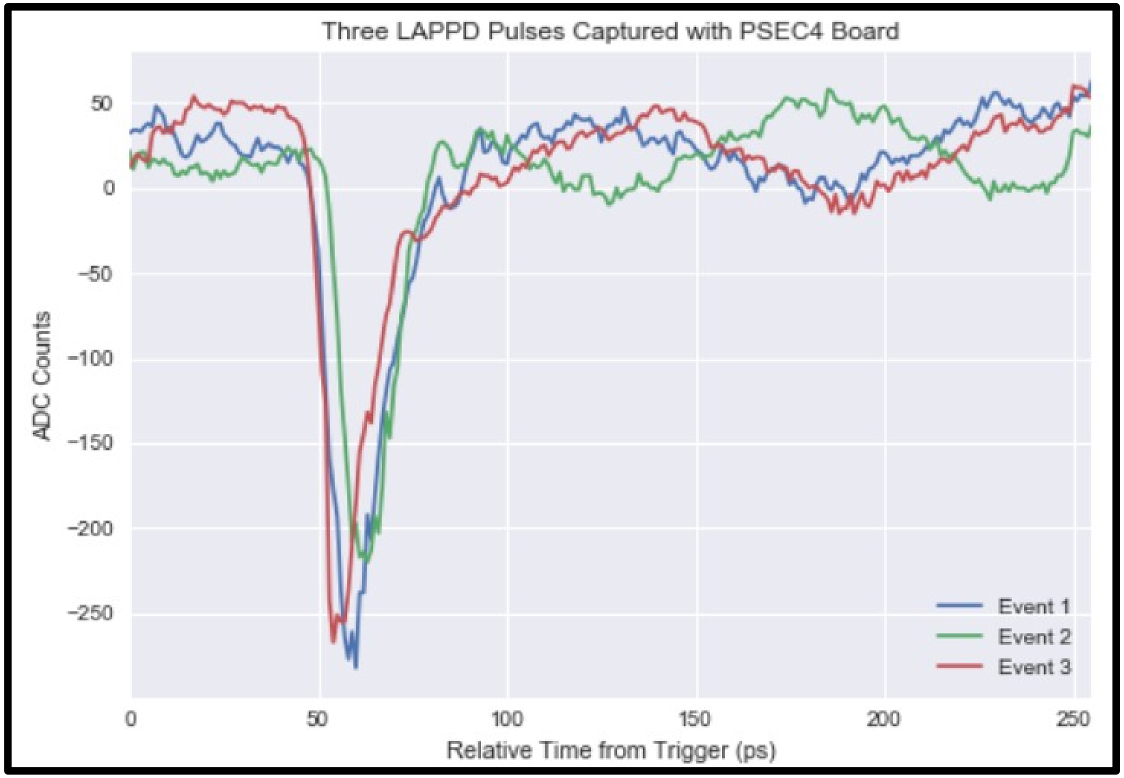
- None measured
- Tested w/ O(10k) photons

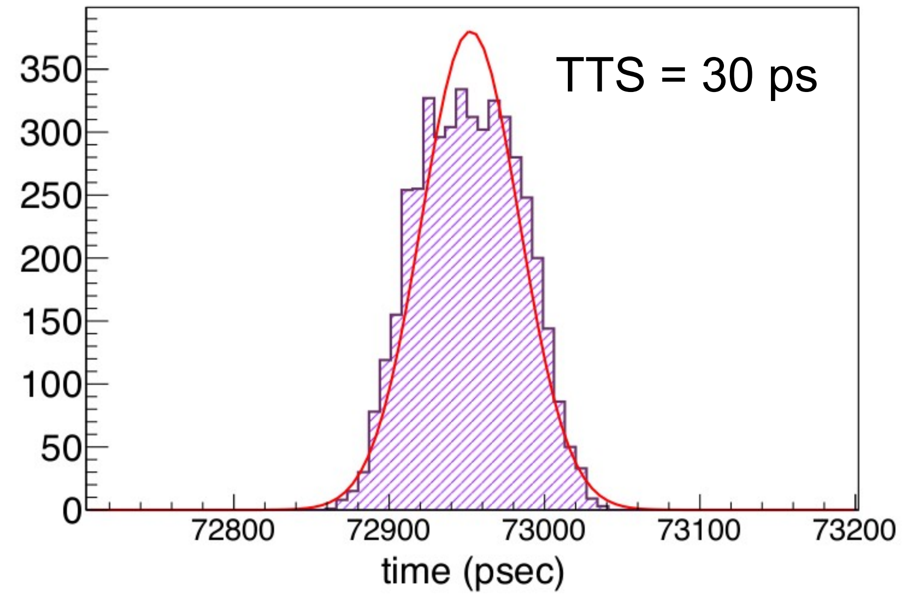
Dead space:

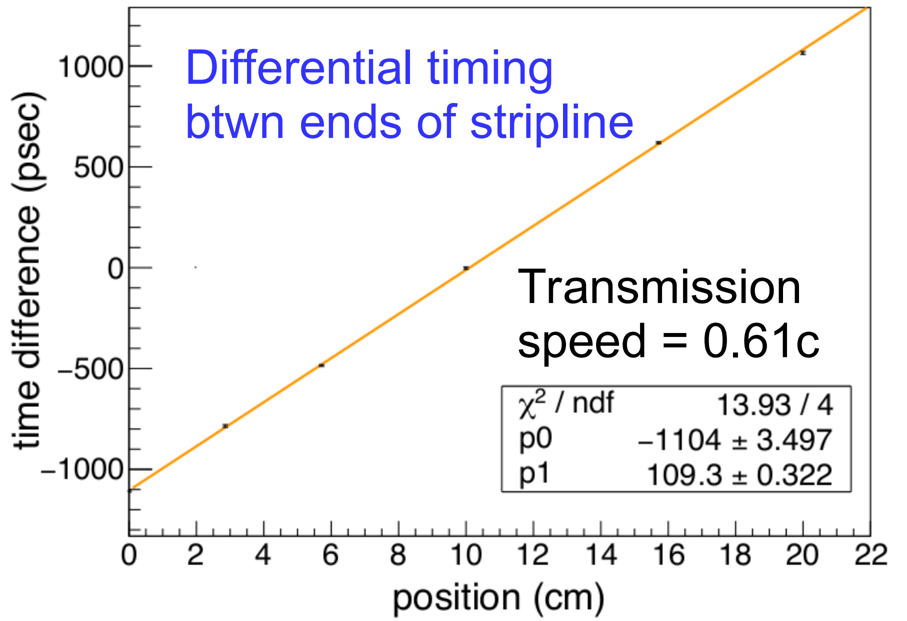
- Along cross spacers

Independent Tile Testing

As ‘early adopters’, a number of University groups are working with Incom to assist tasks like tile testing:







These tests performed on Tile #12 at Iowa State University; similar test setups now in place at UK Universities (Sheffield, Edinburgh)

→ See upcoming slides

LAPPDs in UK

The University Of Sheffield.

First **three** LAPPDs arrived in the UK in Autumn 2021:

- **Sheffield:**
  - 2x Gen1 LAPPDs
  - Stripline anode readout
  - LAPPDs #96 & #104
  - Ordered for WATCHMAN
- **Edinburgh:**
  - 1x Gen2 LAPPD
  - Pixel anode readout
  - Ordered for LHCb

Upcoming LAPPDs in the UK include:

- **Glasgow:**
  - 1x Gen2 LAPPD ordered
  - Expected in Spring 2022

Initial testing will involve basic characterisation (similar to tests at US universities), and developing UK expertise.

These include:

- Timing resolution
- Position resolution
- Basic QE
- QE vs. wavelength
- Dark count

More advanced follow-on tests in Sheffield test tank (2000 litres)

LAPPDs in UK

First **three** LAPPDs arrived in the UK in Autumn 2021:

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  - 2x Gen1 LAPPDs
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  - LAPPDs #96 & #104
  - O
- **Edir**
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Upcomir e:

- **Glas**
  - 1x
  - E

Initial testing will involve basic characterisation (similar to tests at US universities), and developing UK expertise.

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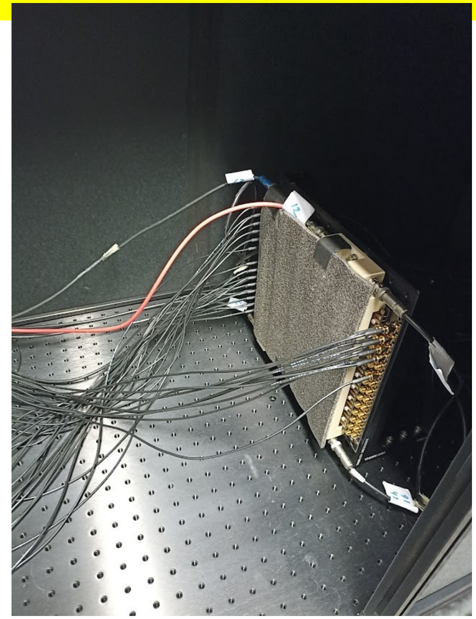
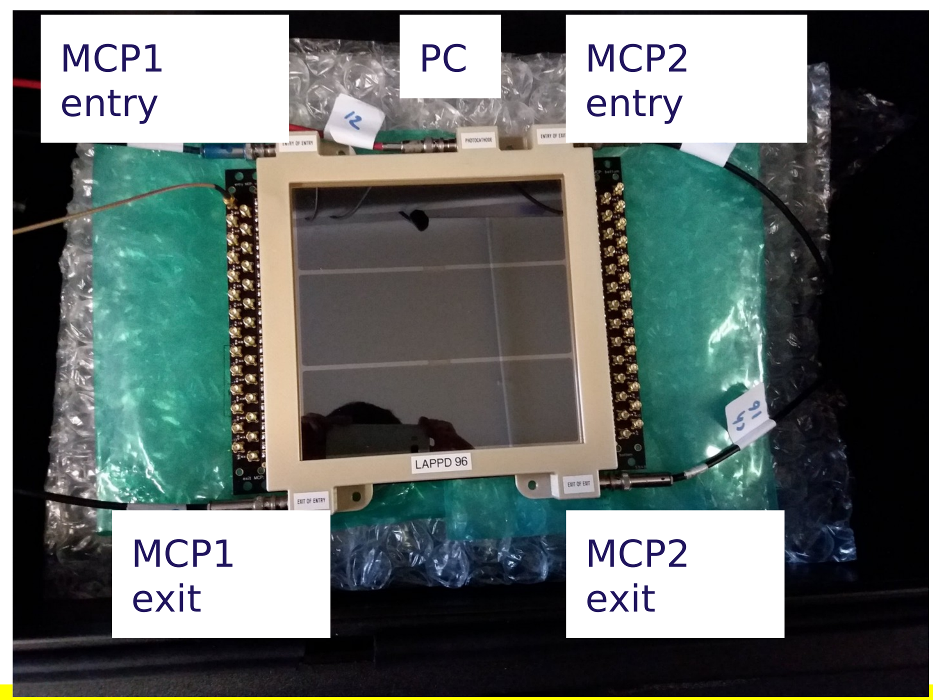
Initial Setup @ Sheffield

LAPPD 96 housed in custom dark box

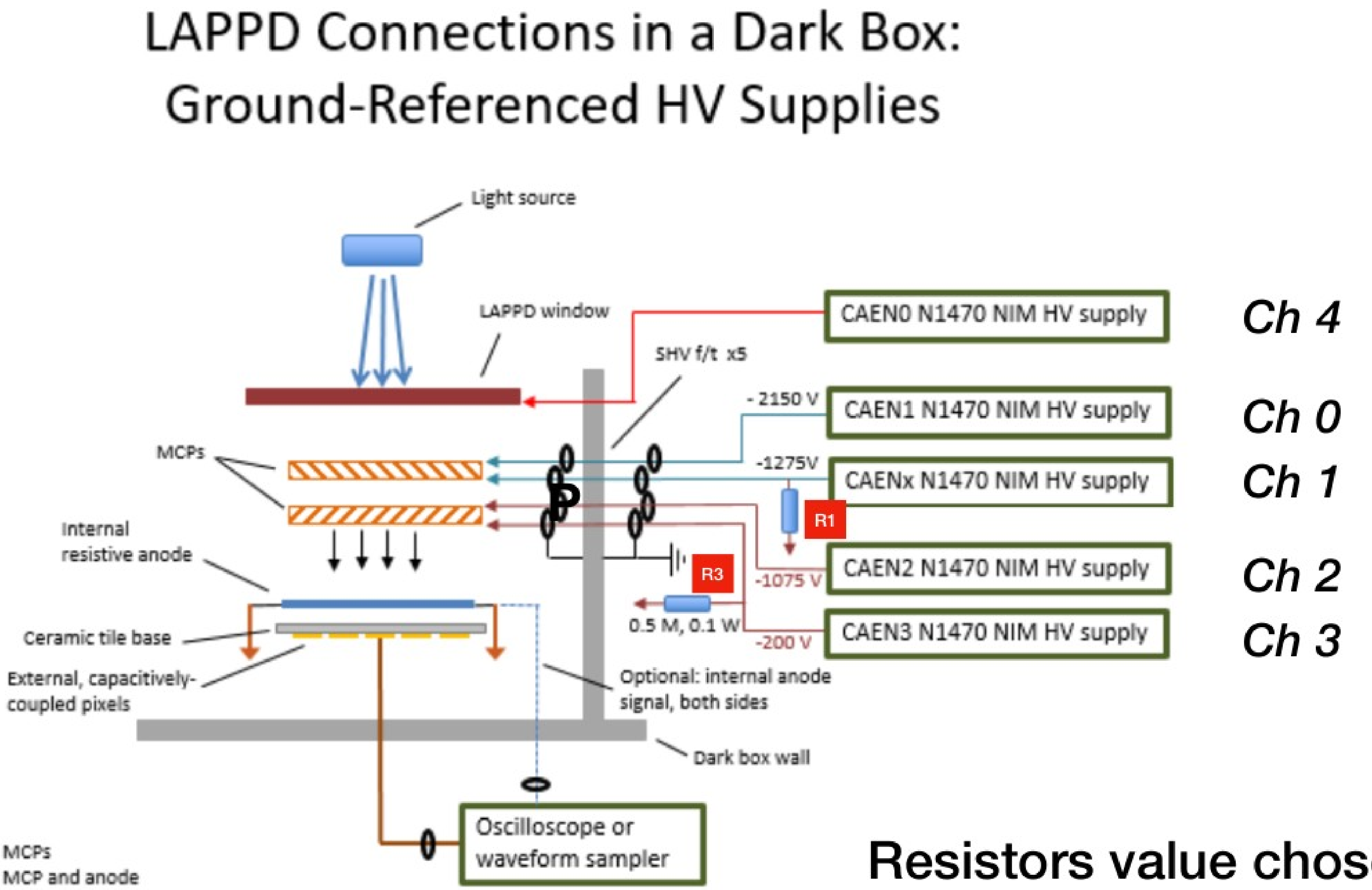
- 5 HV connections used
  - Each MCP needs for entry + exit
  - Reminder: 2 MCPs per LAPPD
  - Also apply HV to photocathode
  - Resistor chain added (see next slide)

- Readout:
  - Initially used commercial scope (Tektronix 6)
  - Now using 32-channel VME digitiser (5 GS/s) from CAEN
  - Will transition later to PSEC
  - Signals via Incom SMA pickup





Initial Setup



- 875 V/MCP
- 200 V between MCPs
- 200 V between MCP and anode
- 9.3 M entry MCP R
- 9.2 M exit MCP R

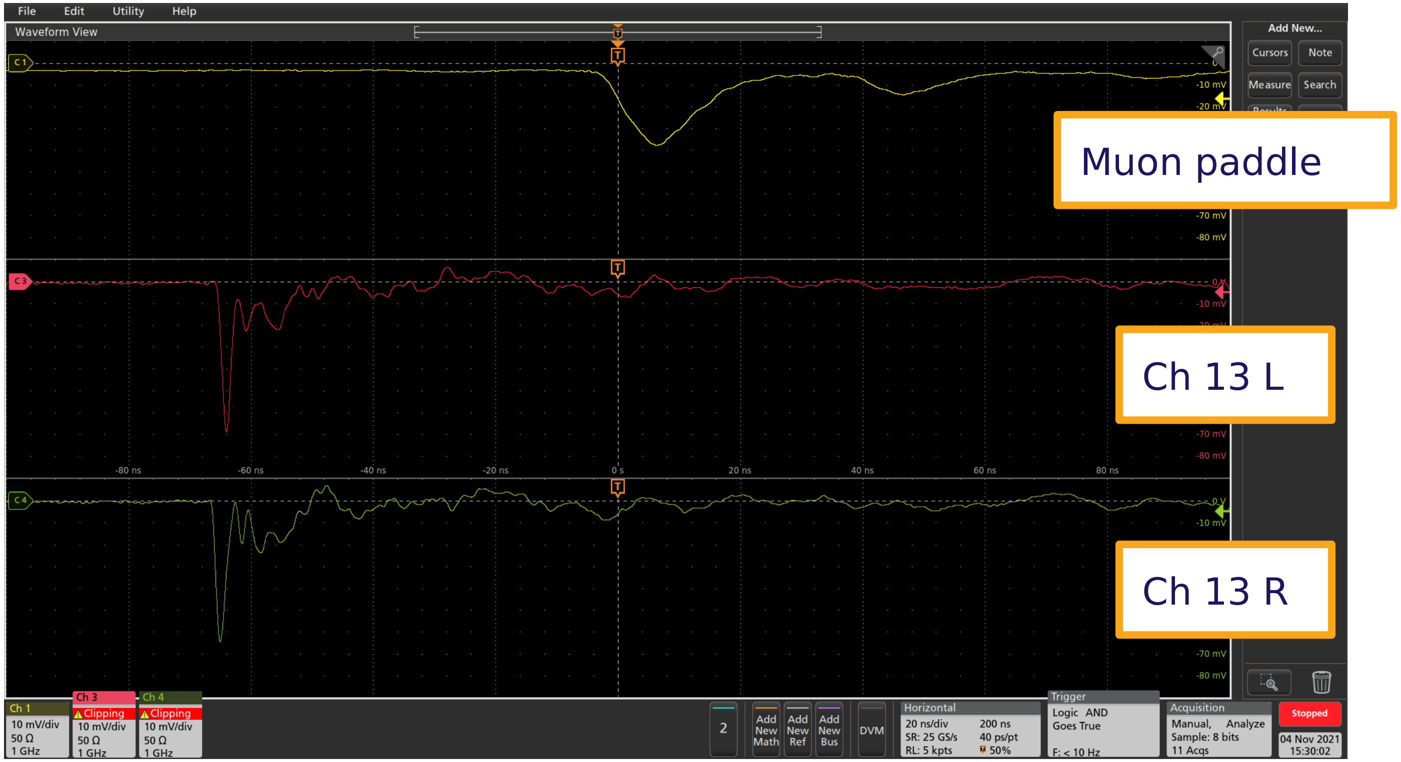
Resistors value chosen

R1 = 1 MΩ
R3 = 0.5 MΩ

Initial Measurements

Muon coincidence

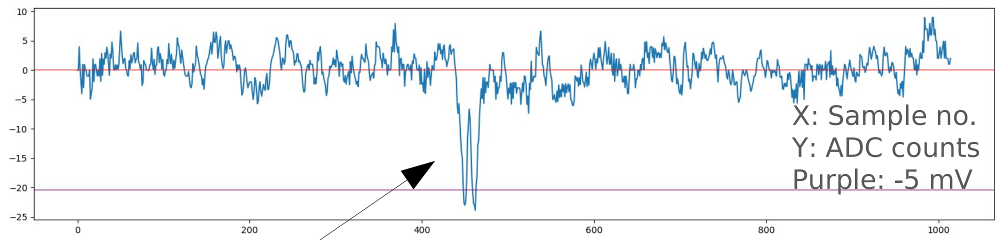
- **Motivation:** dark noise measurements distorted by large signals
  - Set up scintillator paddles to tag coincidences
  - Steady rate of muon events seen, with ~70 ns timing offset between the paddle and LAPPD #104



Initial Measurements

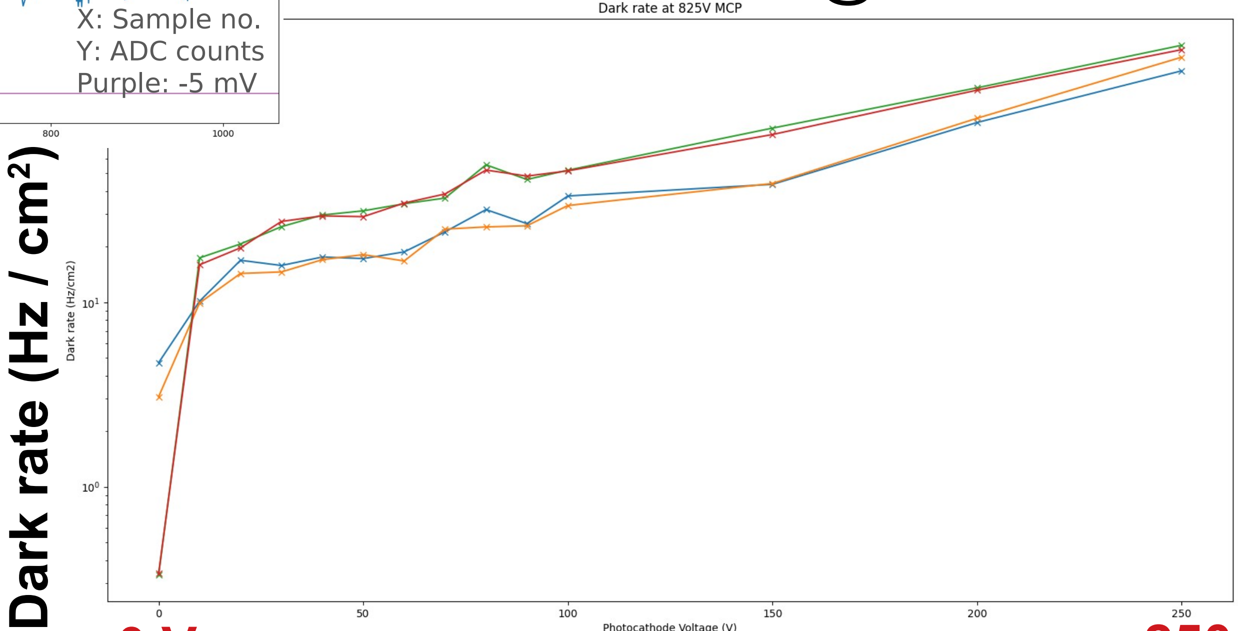
Dark noise rate measurement

- **Motivation:** Understanding dark noise rate critical for incorporating LAPPDs into event reconstruction
  - Tile left in the dark to “cool down” for one hour before testing
  - Photocathode voltage varied to gain broader understanding



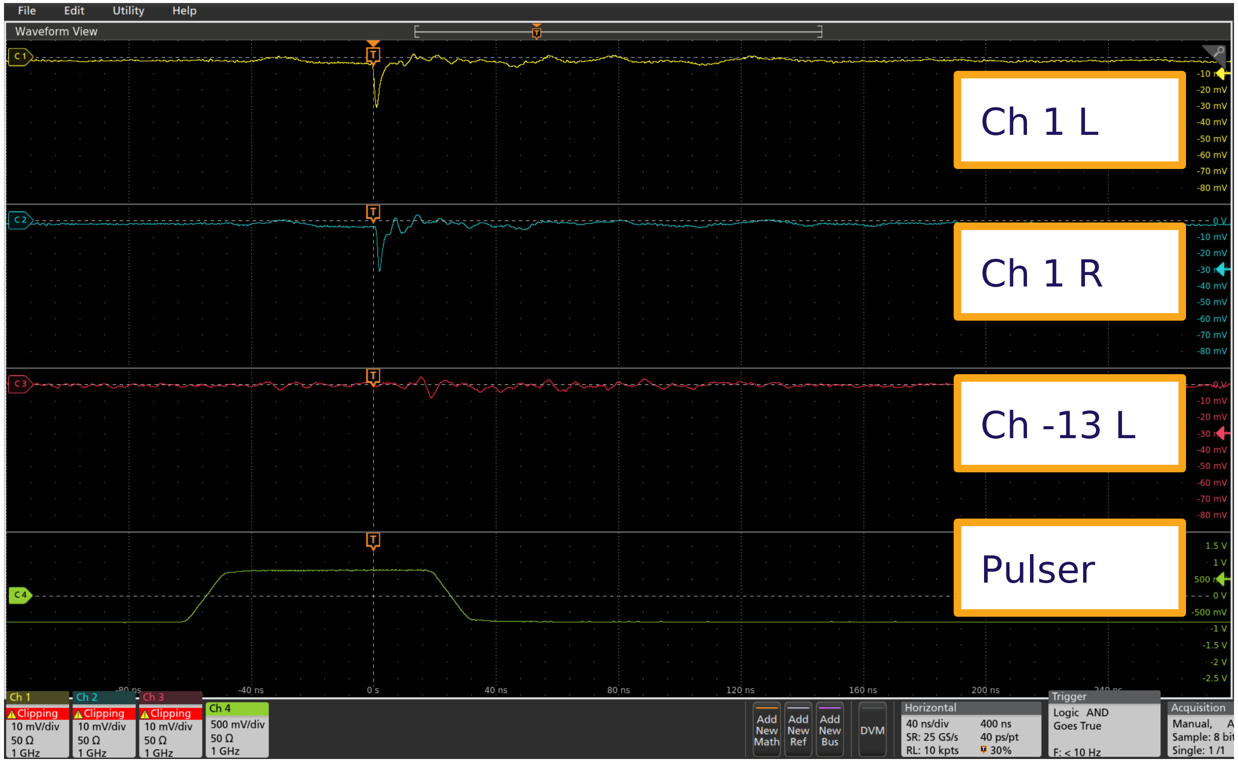
Typical dark pulse

Dark rate with MCP @ 825 V



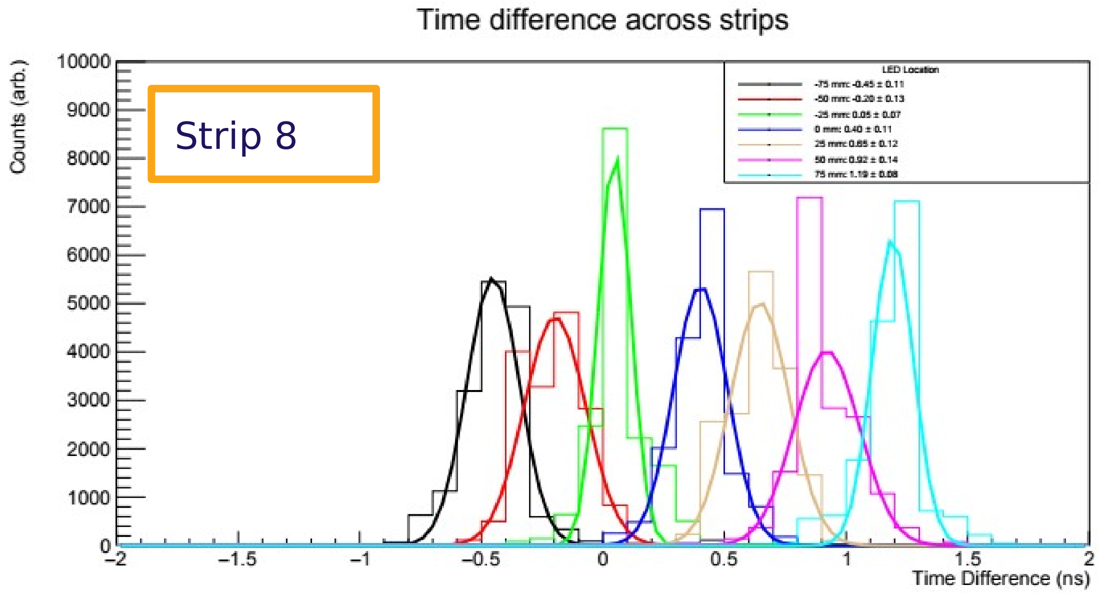
LED measurements

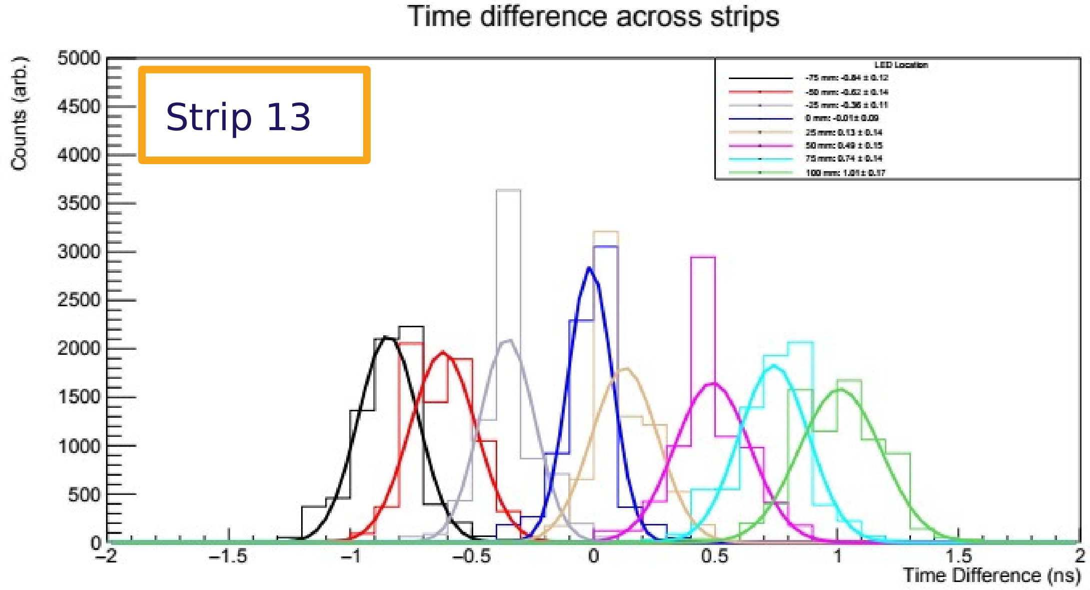
- **Motivation:** Study timing and position resolution via dual-ended readout of anode striplines
  - Fibre held over centre of channel 1
    - Centre of tile (numbering goes from -14 to + 14, w/o a “0”)
  - Coincidence can also be seen with pulser driving light source



Initial Measurements

Timing & position





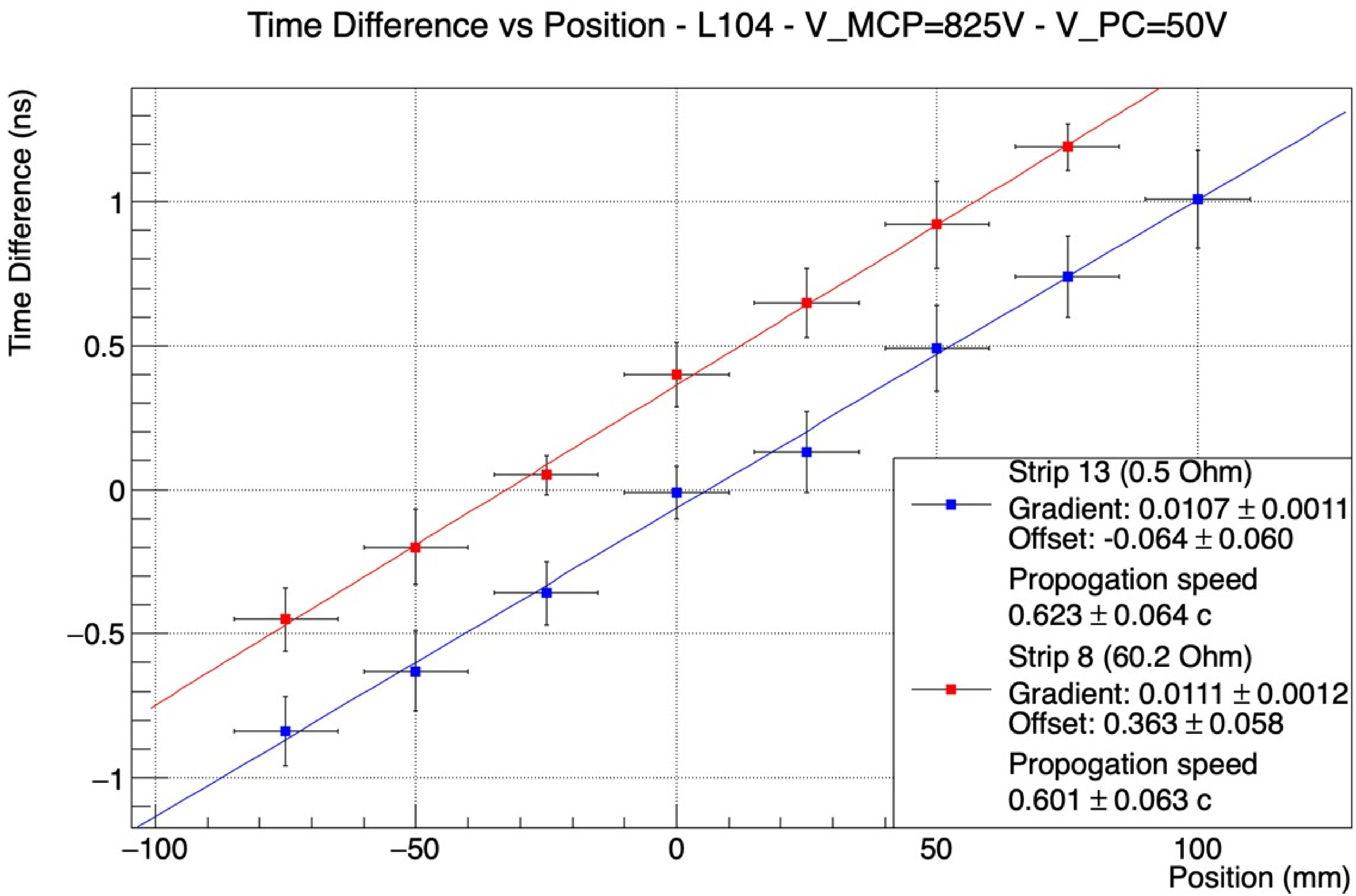
HOT OFF THE PRESS!
(Last week!)

Measurements made by stepping LED along the strip (parallel) in 25mm increments:

- -75 mm
- -50 mm
- -25 mm
- 0 mm
- +25 mm
- +50 mm
- +75 mm

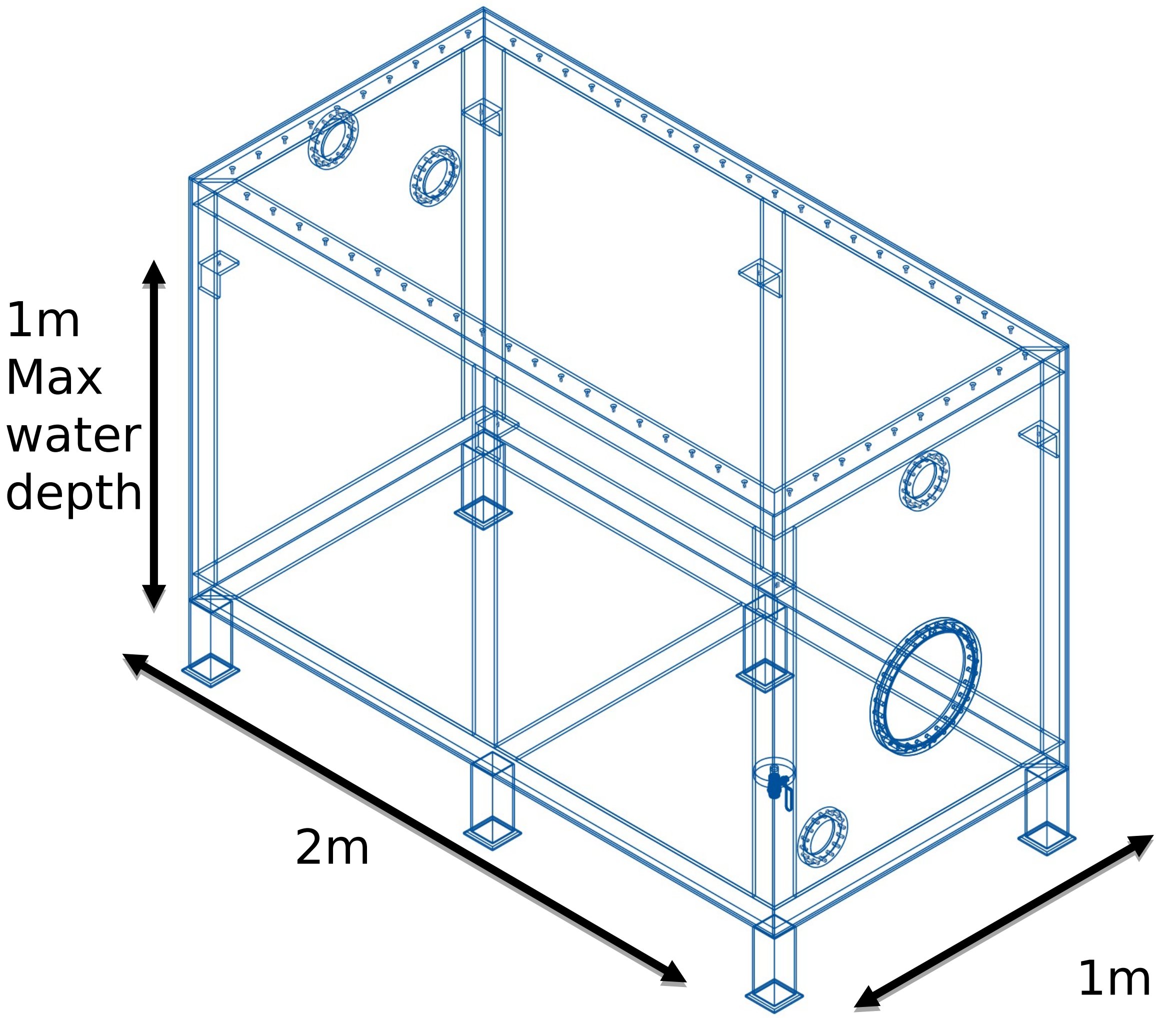
Strong position tracking is clearly visible (see next slide)

Initial Measurements



Next Steps

"PocketWATCH" is a 2000 litre (2 tonne) test tank facility at Sheffield



Construction from 316 SS is compatible with a variety of materials, including:

- Ultra-pure water,
- Gadolinium-loaded water,
- Liquid scintillator
- Gd-loaded liquid scintillator

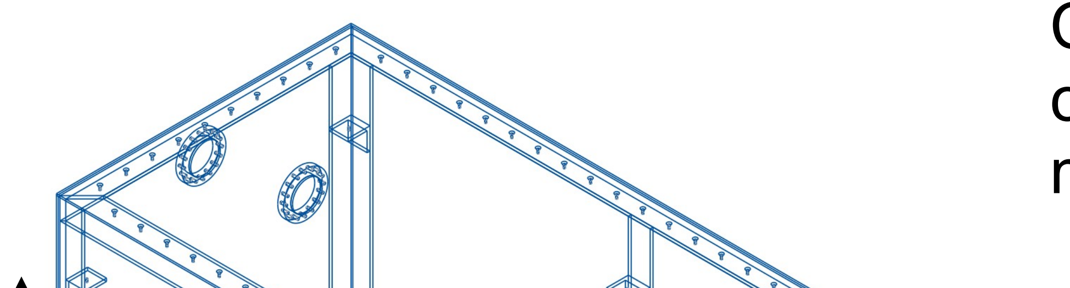
25 cm dry region allows for deployment of calibration systems via 5-dimensional gantry system

Water is purified and temperature controlled, settings from 5 – 35 C.

Next Steps

The University Of Sheffield.

“PocketWATCH” is a 2000 litre (2 tonne) te



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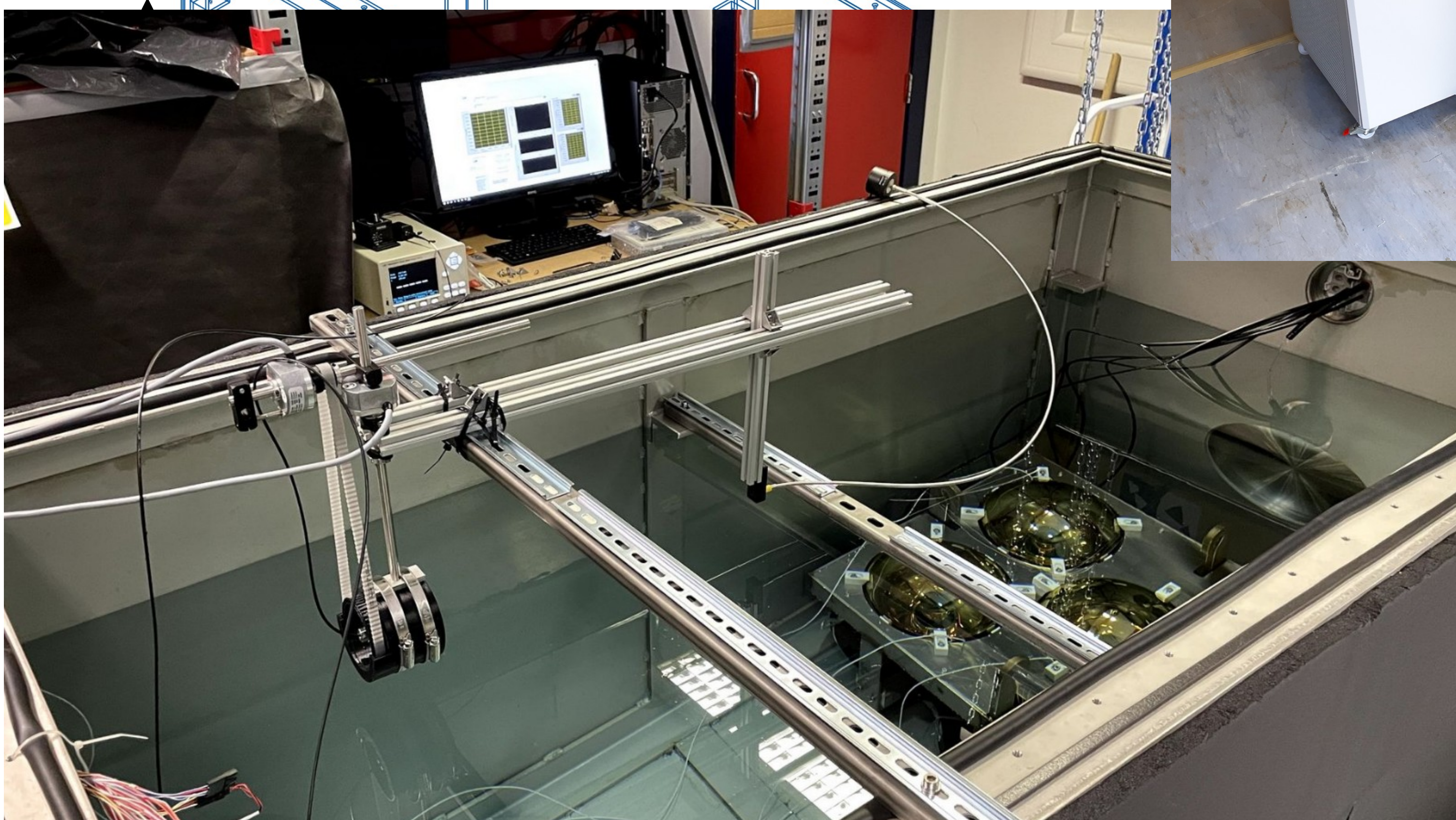

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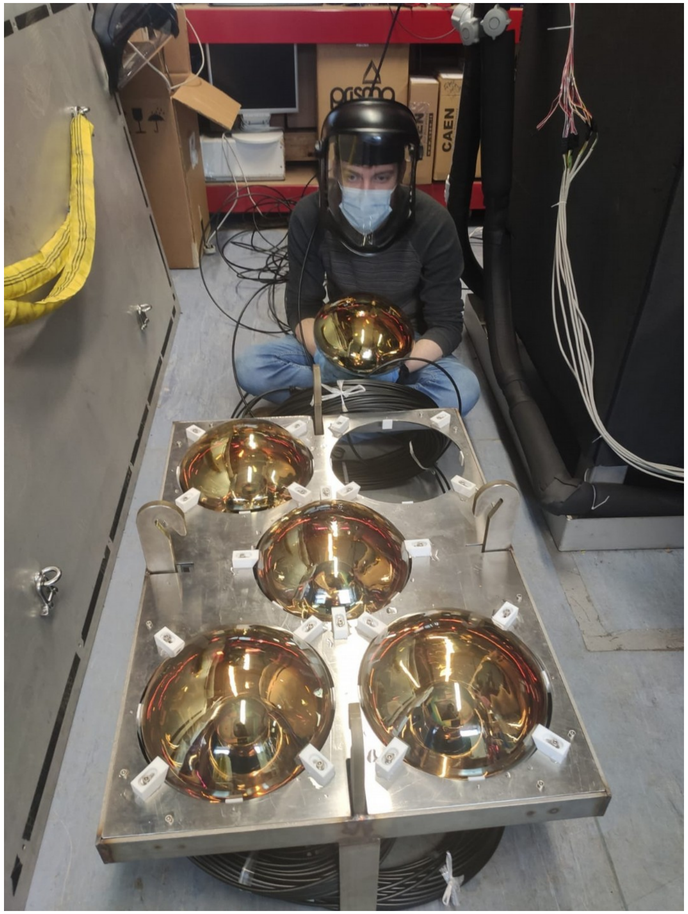
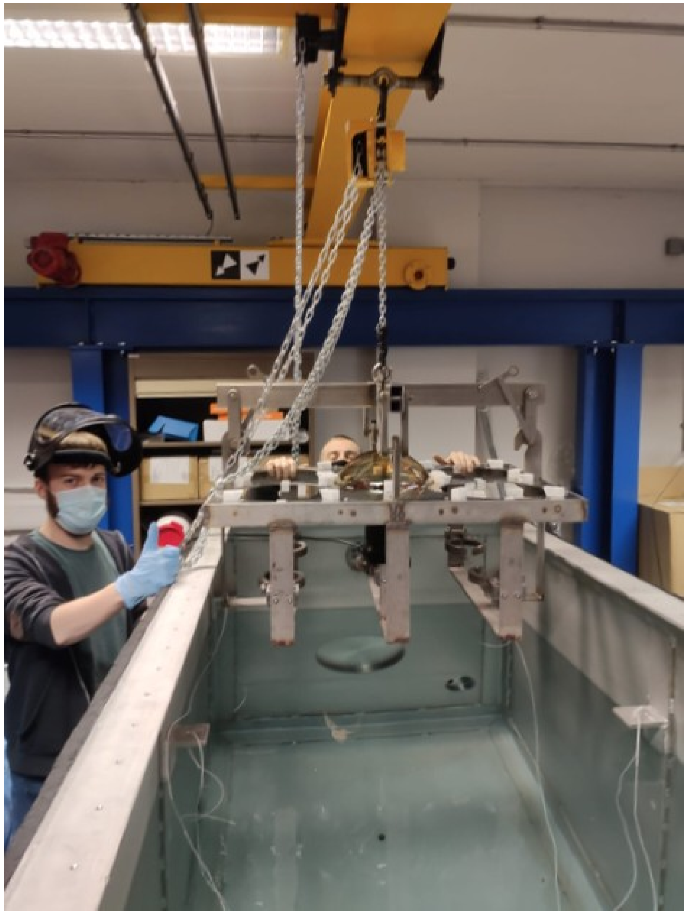
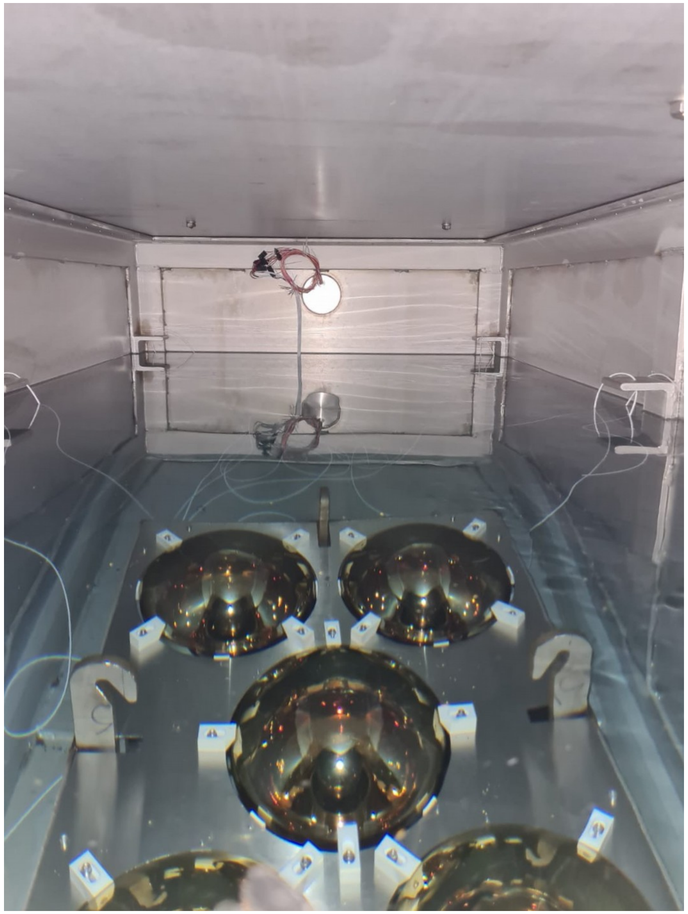
PocketWATCH Facility

The University Of Sheffield.

Currently operational for PMT testing; easy to add LAPPDs as well!



This facility allows cross-testings of multiple photosensors, including:

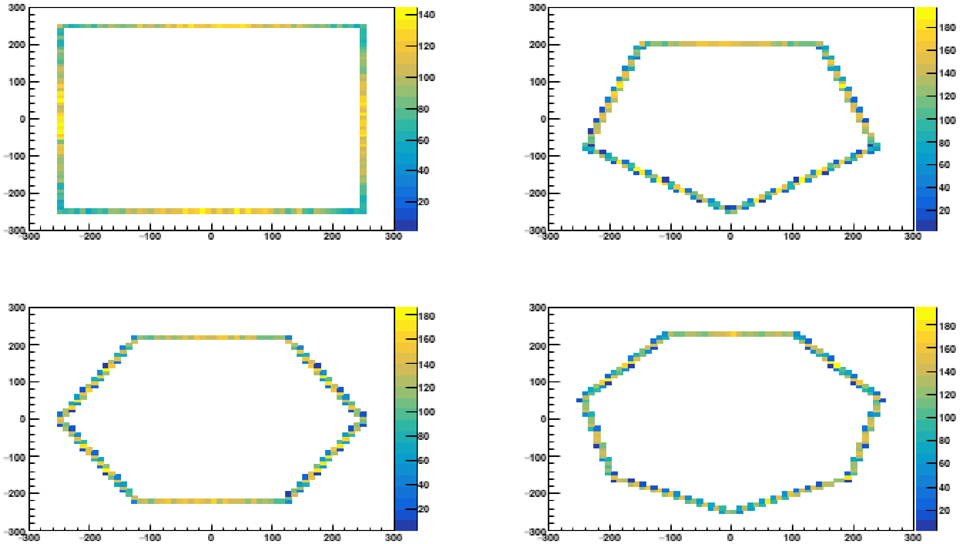
- Using PMTs & LAPPDs in water-based liquid scintillator to do Cherenkov / scintillation measurements with fast timing!

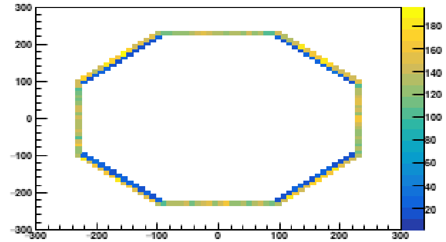
Further Tests

Other, more advanced UK tests being considered include:

- Measuring / comparing magnetic susceptibility (alongside PMTs) by using Helmholtz coils to induce a tunable **B** field.

- Joint characterisation with other novel photosensor ideas, such as wavelength shifting plates read out by SiPM strips along the edges:



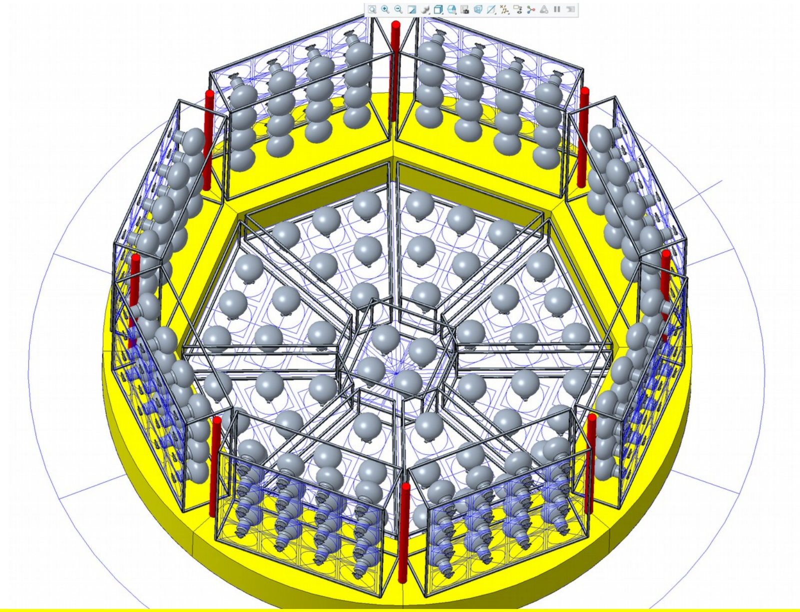


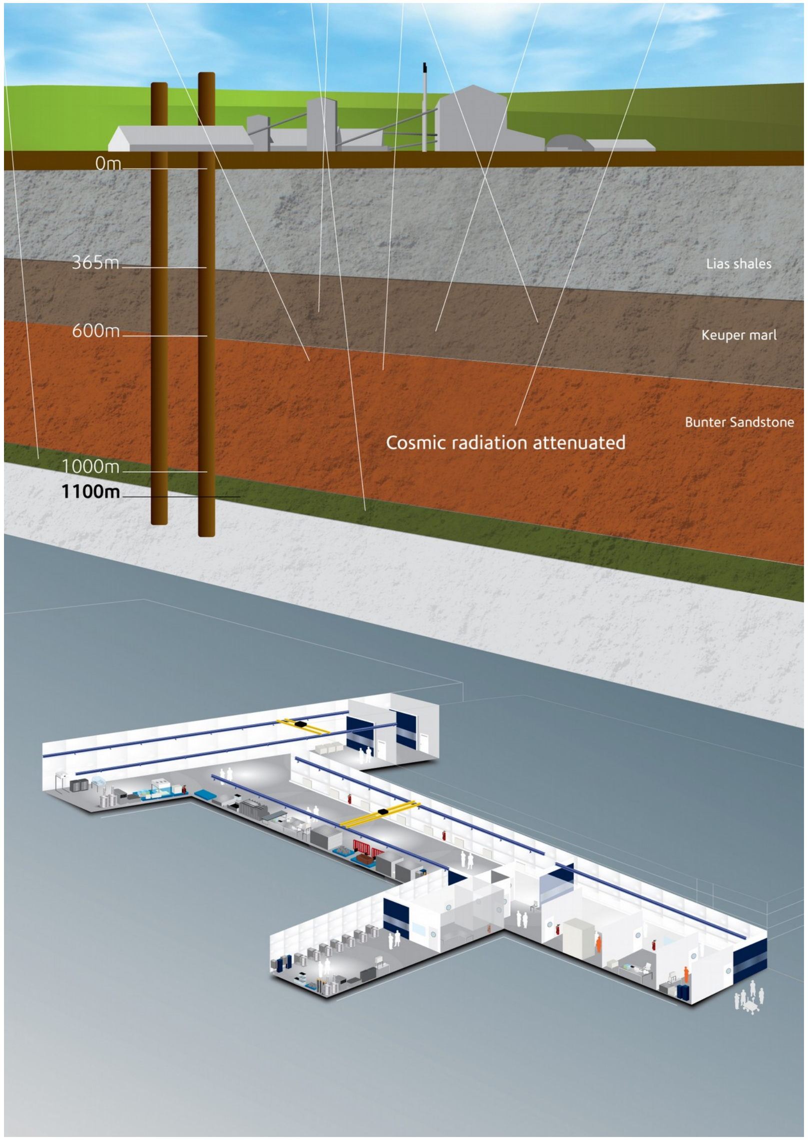
- R&D to adapt LAPPDs for use with other detectors
  Example: Replace glass window with MgF crystal and a CsI photo-cathode for use in VUV expts, such as LAr or LXe.

Introducing BOLEYN

BOLEYN is a ~25 tonne testbed being built at Boulby Underground Lab

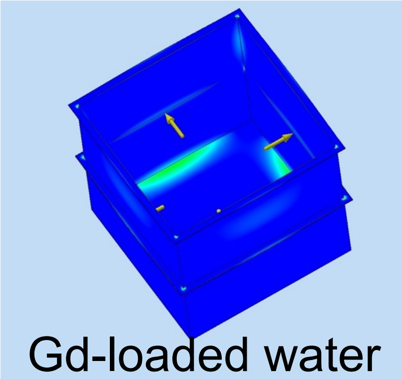
- When construction is completed in 2023, it will allow LAPPD tests in a quiet (low background) environment
- Initial instrumentation includes:
  - 90x 10" PMTs (Hamamatsu R7081)
  - 03x LAPPD (2x Gen1 + 1x Gen2)
  - 01x WLS plate w/ SiPM strip readout

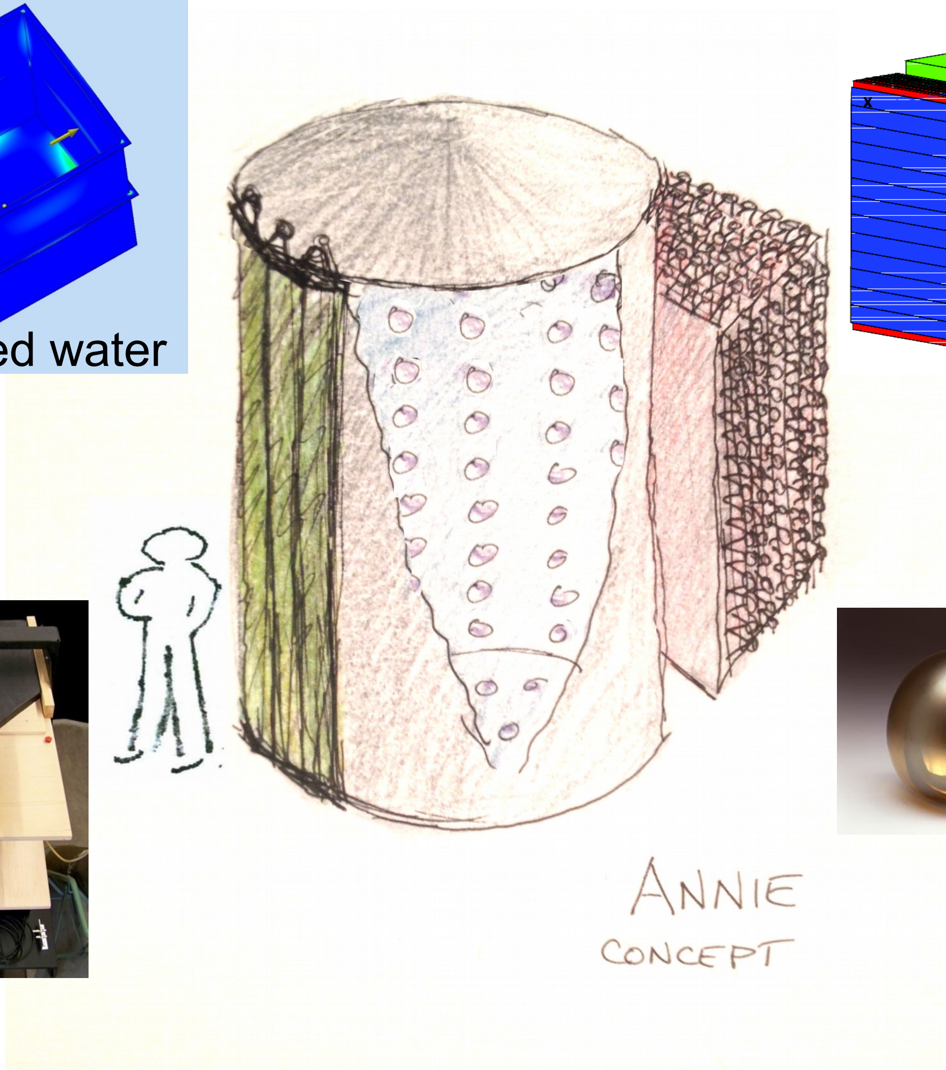


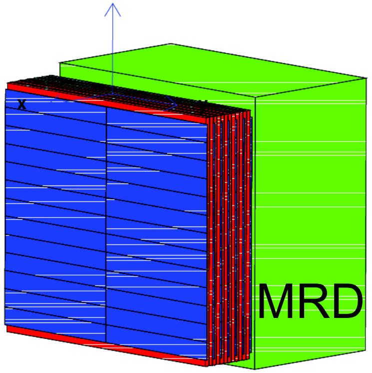


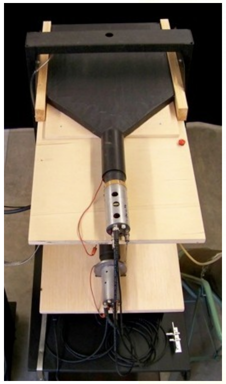
First Use in Expts: ANNIE

ANNIE: Accelerator Neutrino-Nucleus Interaction Experiment







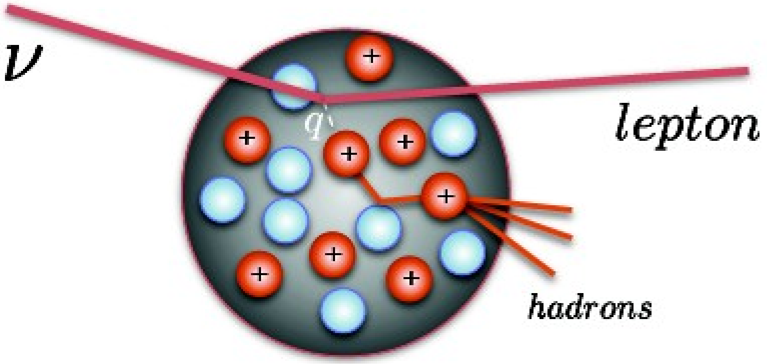


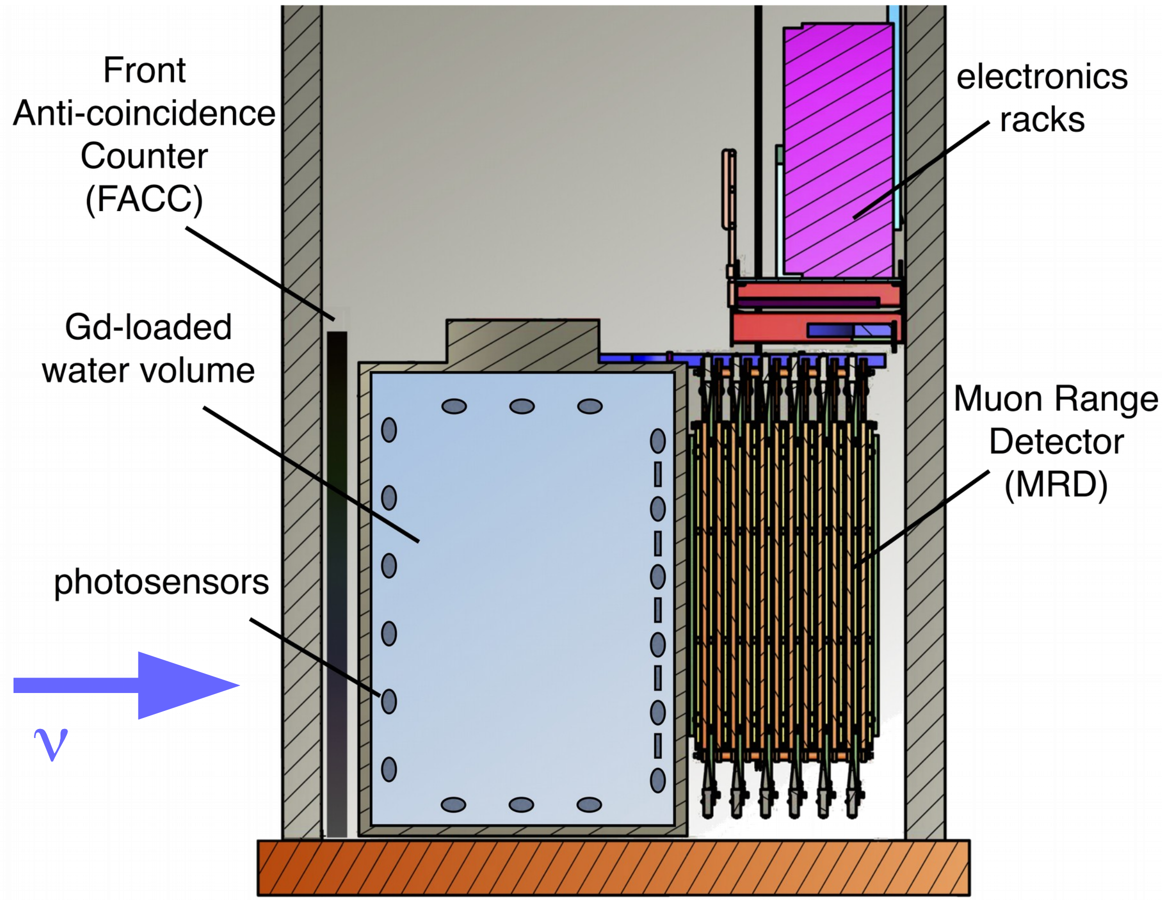
Upstream
μ veto

The ANNIE Experiment

Primary physics objective:

A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.





Current status:

All PMTs installed

26 tonne water volume is fully loaded with Gadolinium

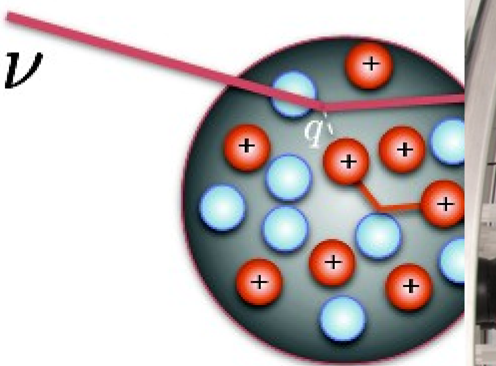
MRD completed
LAPPDs being prepared

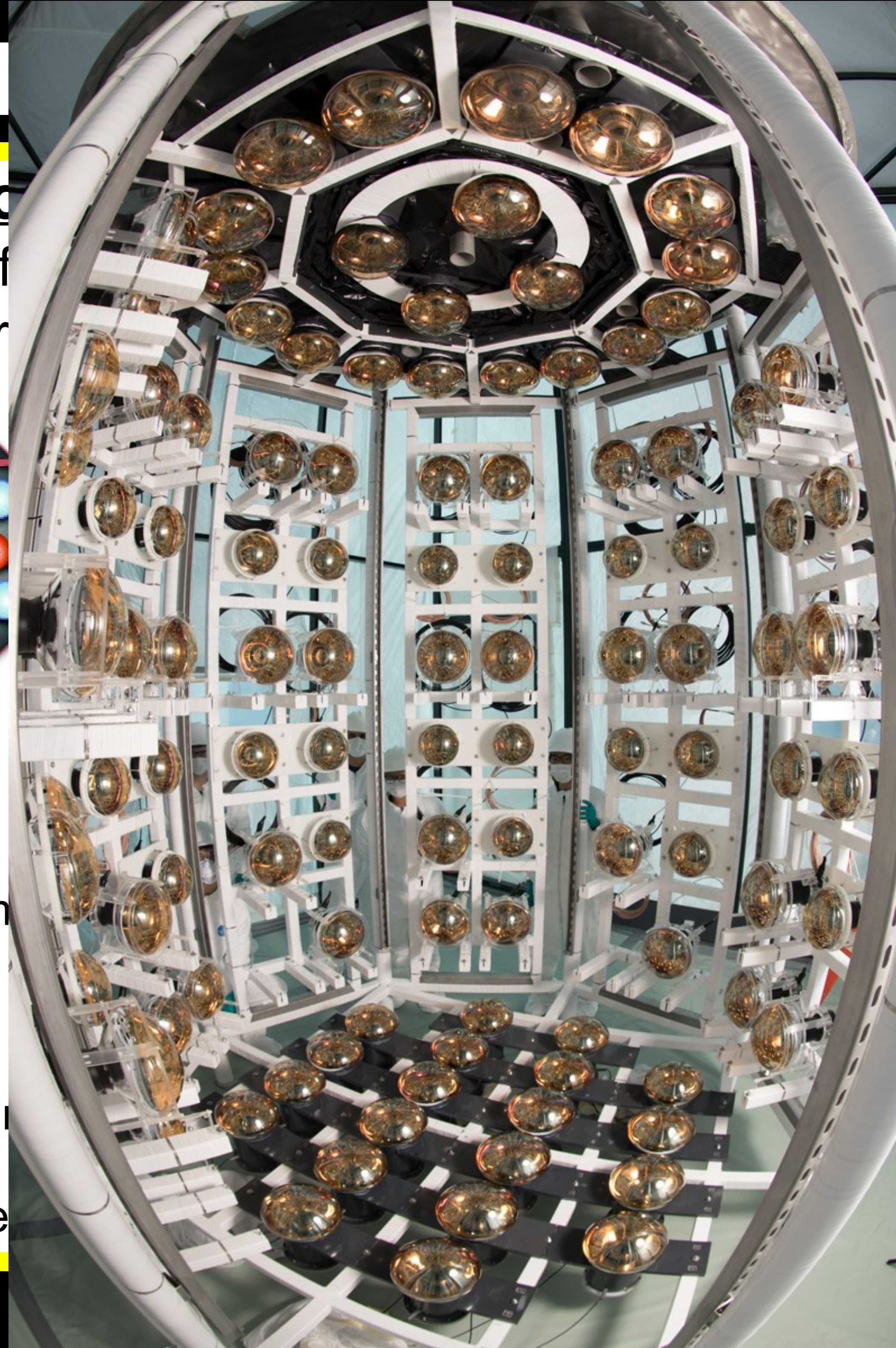
Commissioning w/ beam data NOW

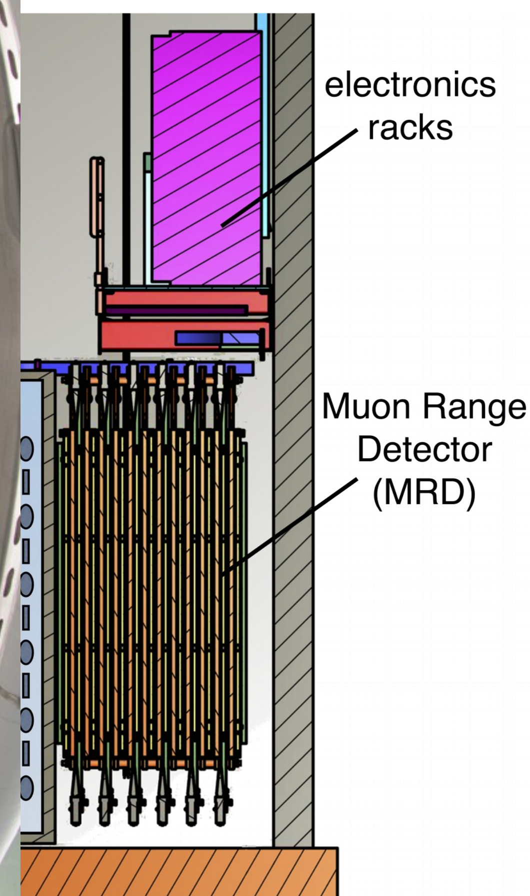
The ANI

Primary physic

A measurement of   s ("neutron yield")
from neutrino inter   gy.







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26 tonne water volum
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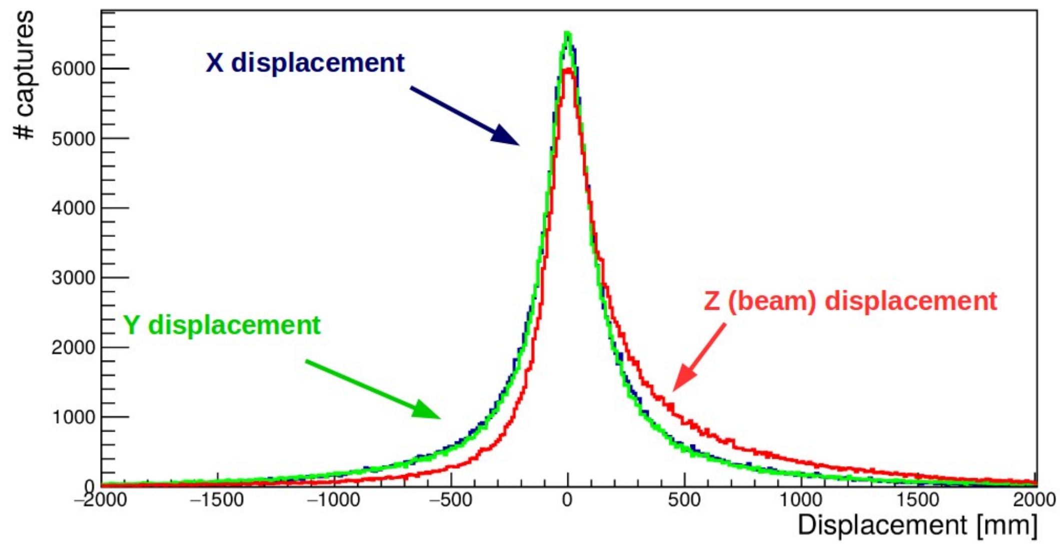
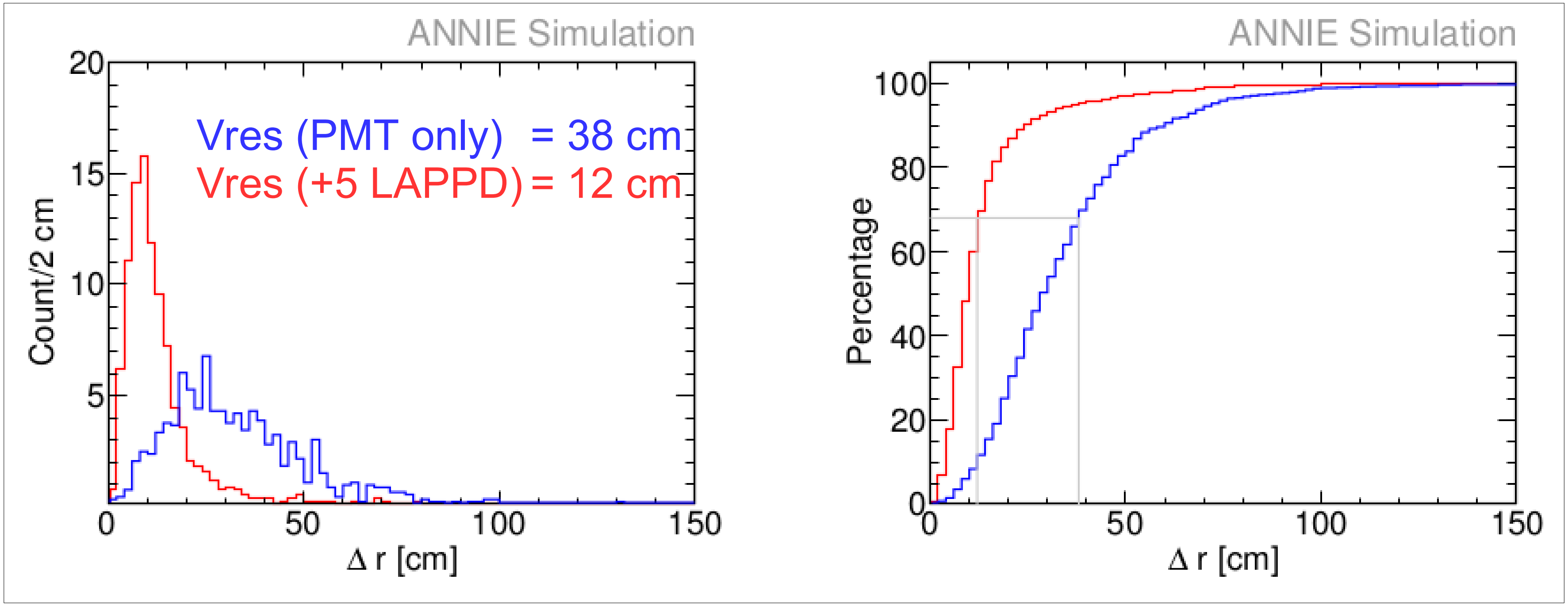
Commissioning w/ be

Motivation for LAPPDs

ANNIE is a small (3m ϕ, 4m h) water Cherenkov detector at Fermilab, requiring excellent V_{res} (~10cm).



First deployment of LAPPDs in ANNIE coming up **this year!**

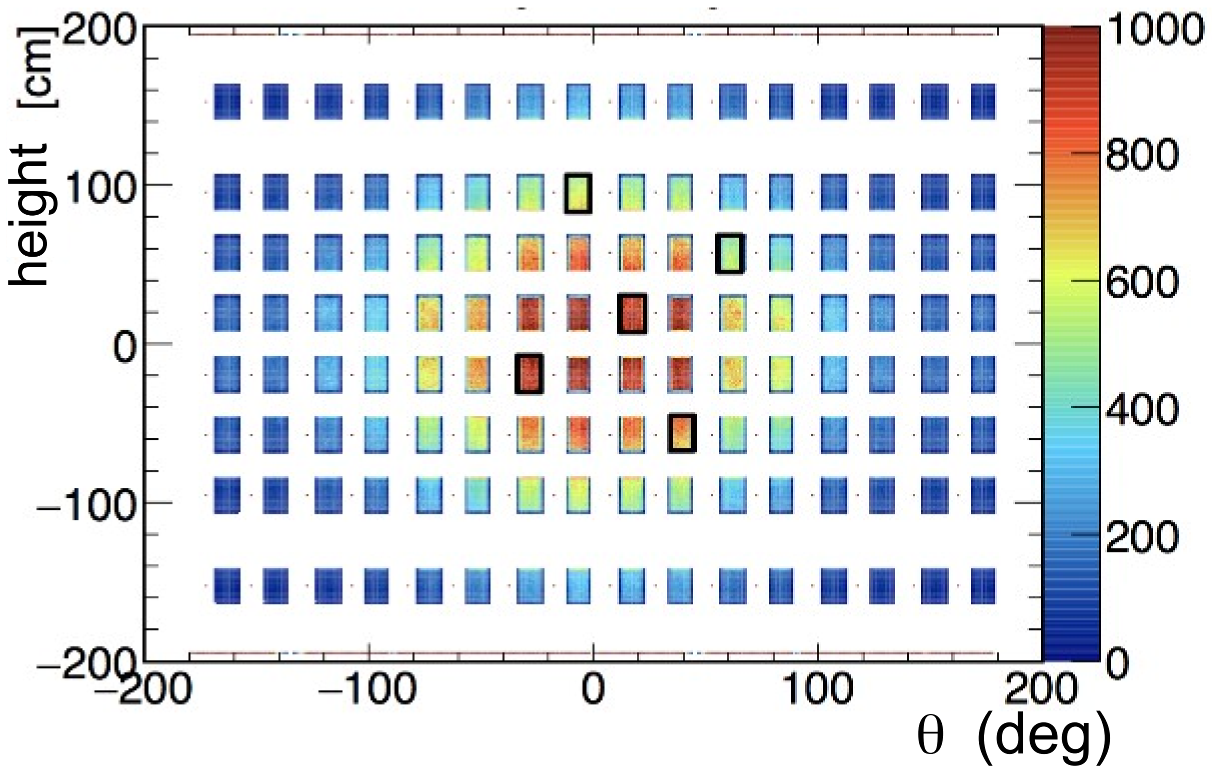


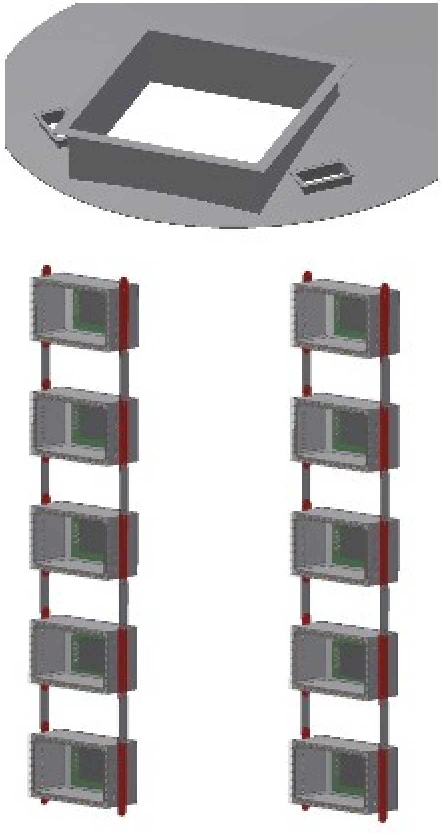
LAPPD Deployment

The University Of Sheffield.

Initial ANNIE running planned for 5 downstream LAPPDs

As more LAPPDs (and $£) becomes available, can actively deploy elsewhere in detector <u>without</u> major interruption in running...





Conclusions

- Improved photodetectors can optimise physics reach
  - *e.g.*, convert water Cherenkov to 'optical TPC'
- LAPPDs are one such type of new photosensor
  - Superior timing and position resolution
  - Imaging sensors
- **After many years, LAPPDs now exist!**
- In US, first deployment in ANNIE @ Fermilab imminent
- In UK, first LAPPDs have arrived, with more on the way
  - Above ground tests taking place at universities now
  - Underground tests @ BOLEYN planned for next year
- Exciting times ahead!

Thank you for listening!