Advanced Photon Detection in ANNIE for Next Generation Neutrino Experiments

Emrah Tiras

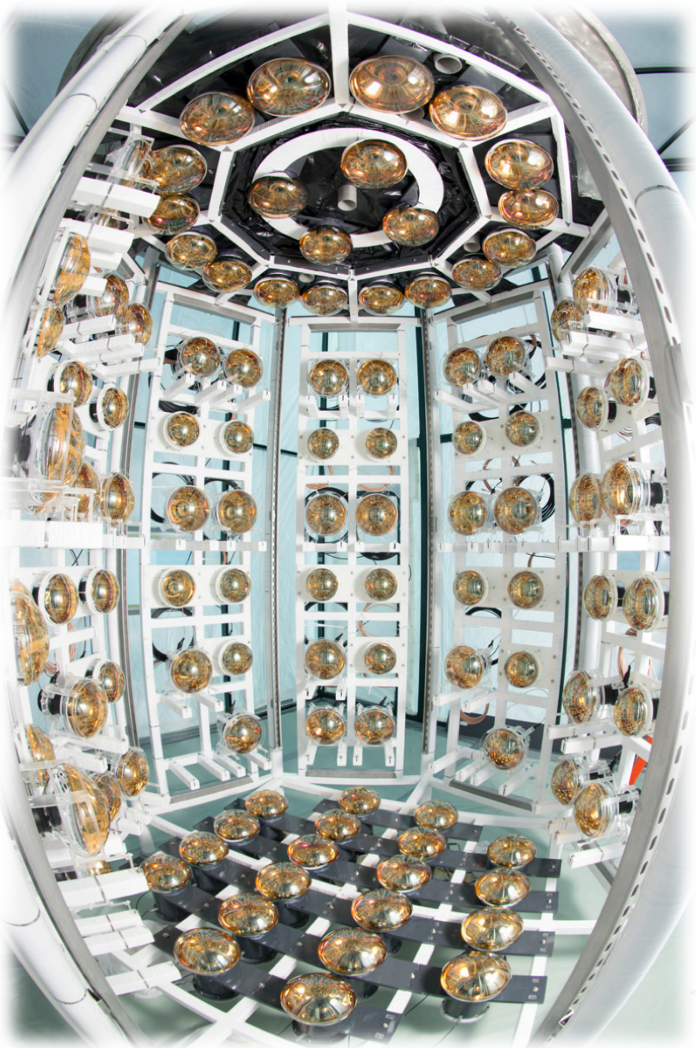
on behalf of ANNIE collaboration

Iowa State University

CPAD Workshop, Madison, WI

December 8-10, 2019

ANNIE: The Accelerator Neutrino Neutron Interaction Experiment



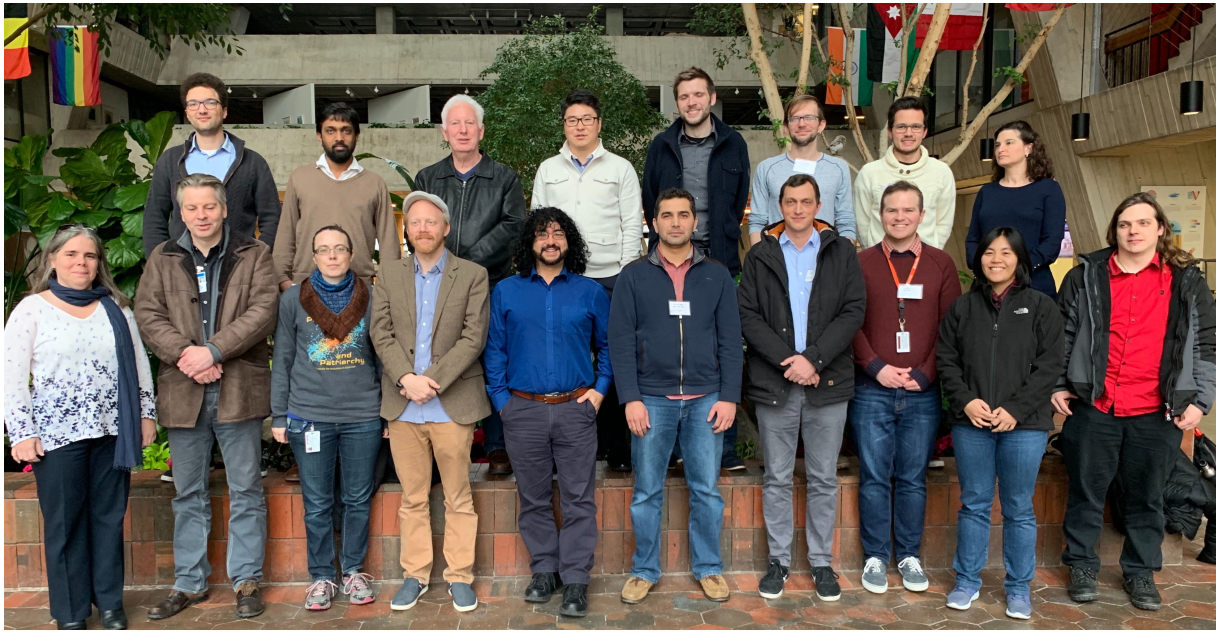
- 26-ton **Gadolinium (Gd)-loaded water Cherenkov Detector**.
- Located 100 m downstream from the target of the Booster Neutrino Beam (BNB) at Fermilab.
- Main goals:
  - Measure the beam induced final state neutron multiplicity & CC inclusive cross section on water.
  - Demonstrate new detection technologies:
    - Large Area Picosecond Photodetectors (LAPPDs)
    - Neutron tagging in Gd-loaded water.
    - Possible addition of WbLS

ANNIE Collaboration

- 30+ Collaborators from 13 institutions in 3 countries (🇺🇸 🇩🇪 🇬🇧) work together to achieve the goals of ANNIE.

- Fermi National Accelerator Laboratory
- Iowa State University
- Johannes Gutenberg University Mainz
- Kings College London
- Lawrence Livermore National Laboratory
- The Ohio State University
- The University of Sheffield
- University of California, Davis
- University of California, Irvine
- University of Chicago
- University of Edinburgh
- University of Hamburg
- University of Warwick

Spring 2019 Collaboration Meeting at Fermilab



Timeline of ANNIE

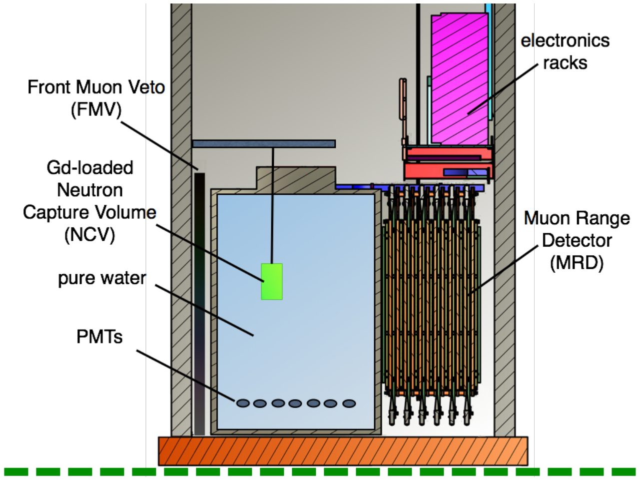
June 2016

Sept 2017

Background Measurements

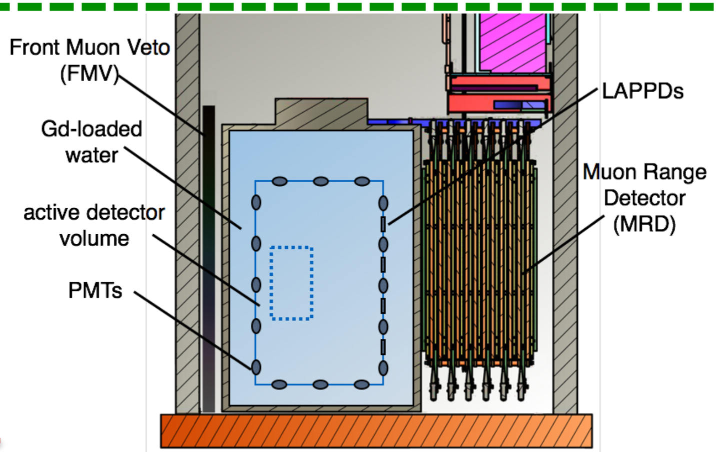
(arXiv:1912.03186 and submitted to JINST)

- Partially instrumented detector
- Feasibility demonstration
- Beam induced background neutron flux was measured to be <0.02 neutrons/ beam-spill/m^3.



Fall 2019

2021



Physics Phase

- First Gd-doped water Cherenkov detector in a neutrino beam.
- Neutron multiplicity and CC-inclusive meas.
- First LAPPD deployment in a neutrino beam.

202X

Testing new tech for future experiments

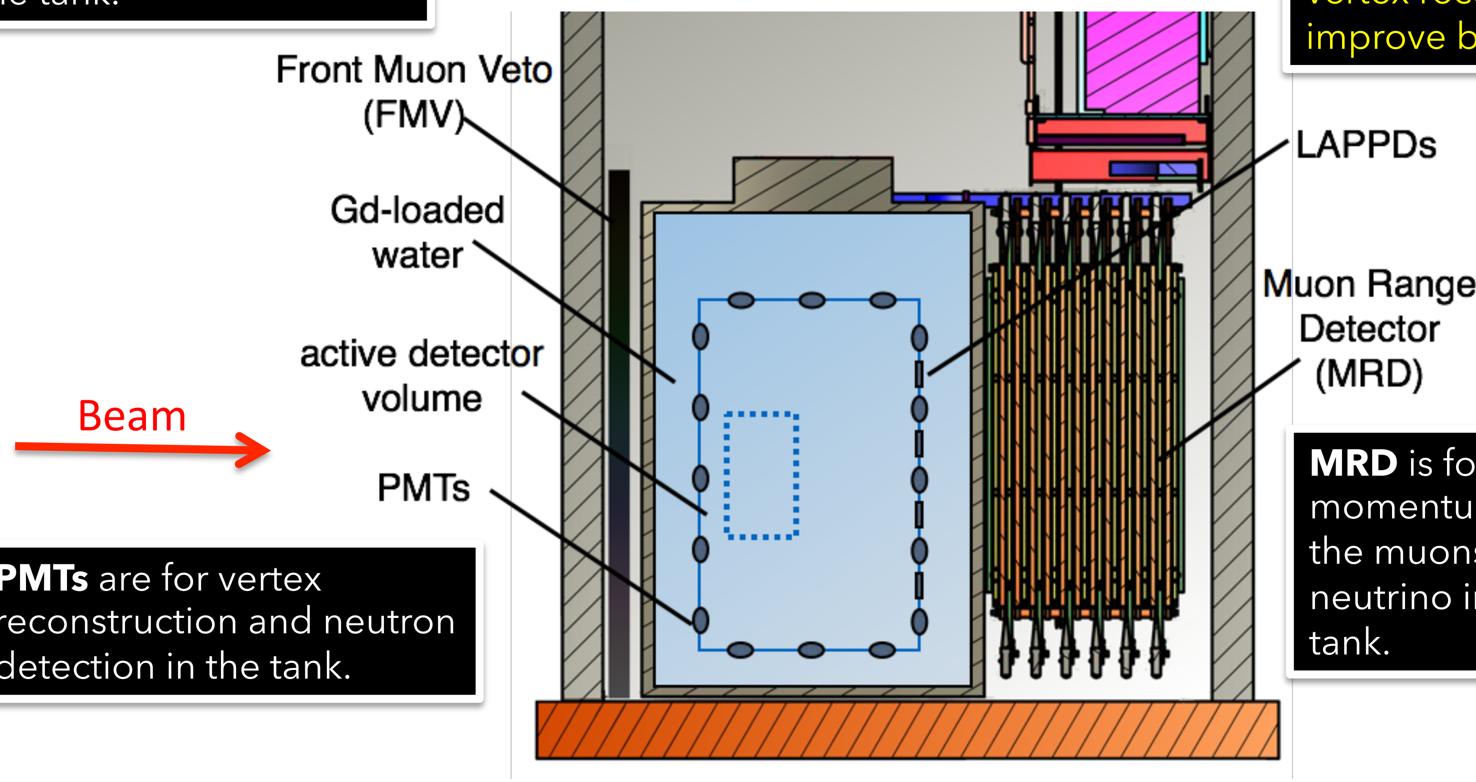
- Testbed for a new active medium (WbLS), LAPPDs and other technologies.

ANNIE Detector Components

- 26 tons of de-ionized water loaded with 0.2% Gadolinium sulfate (50 kg) as an active medium to capture neutrons and study charged current neutrino interactions.

FMV is used to veto muons not originating in the tank.

LAPPDs are used for better vertex reconstruction and to improve background rejection.



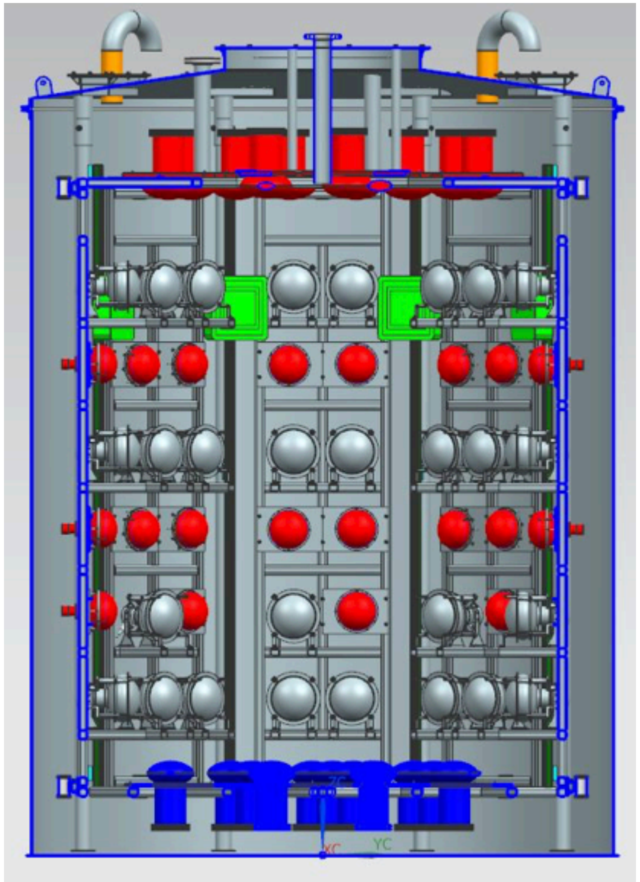
PMTs are for vertex reconstruction and neutron detection in the tank.

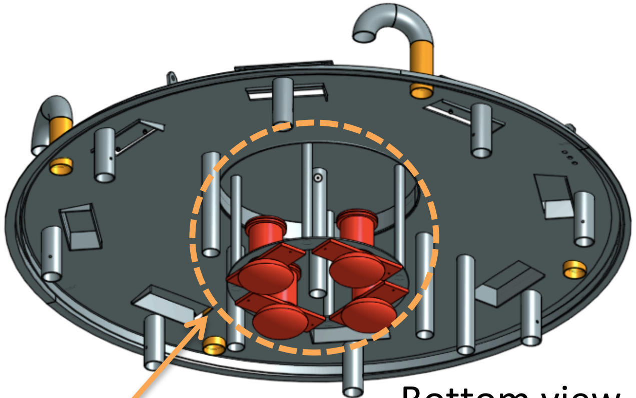
MRD is for measuring the momentum and direction of the muons coming from the neutrino interactions in the tank.

Flexible, Portable Detector Design

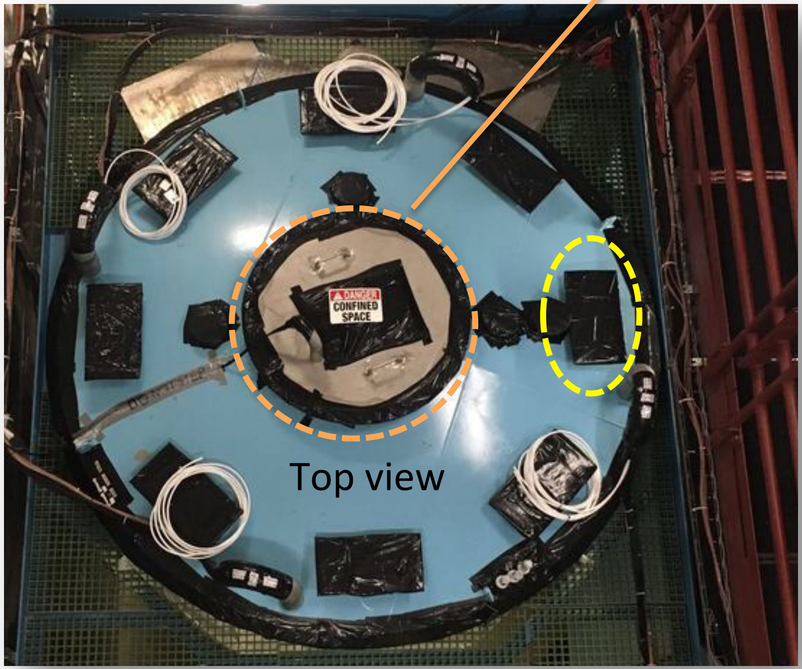
LAPPDs deployable in-situ

- The inner frame attached to the tank lid is an octagonal structure.
- It was designed for 132 PMTs and ~40 LAPPDs which are deployable in-situ
- A unistrut as an LAPPD tracker was mounted at each corner (vertex).




Bottom view

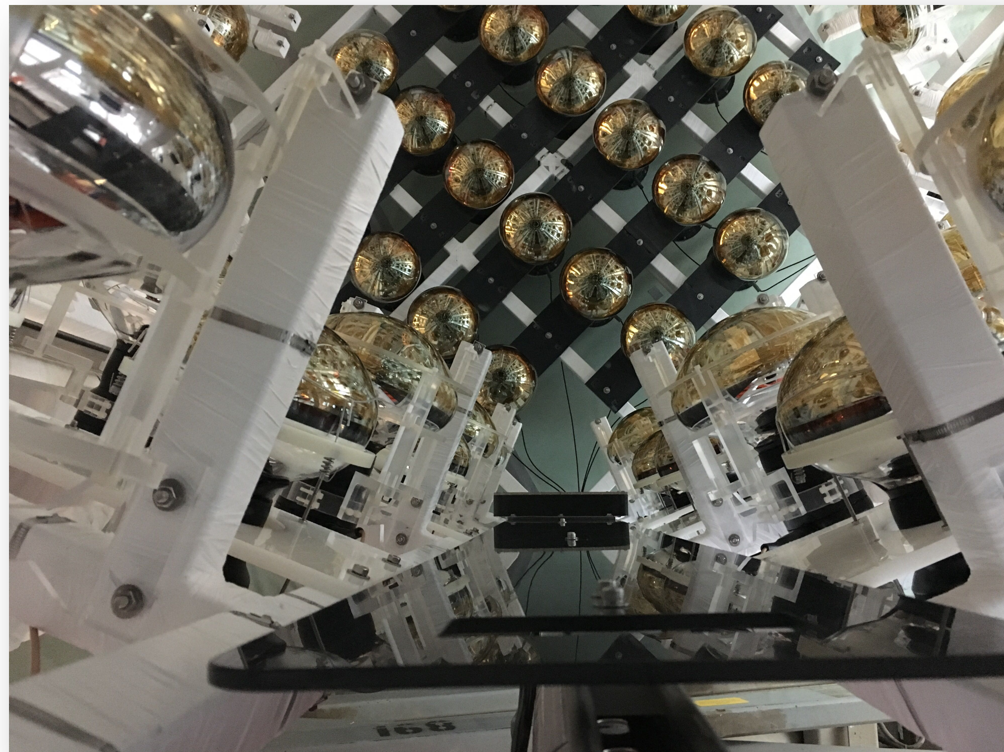
ANNIE Detector in the hall



Top view

LAPPD Deployment

- The LAPPD housing is mounted on ¼ inch PVC panel and it slides on the track with Polypropylene sliders screwed on the back of the panels.
- Deployment was successfully tested before the ANNIE detector was installed.

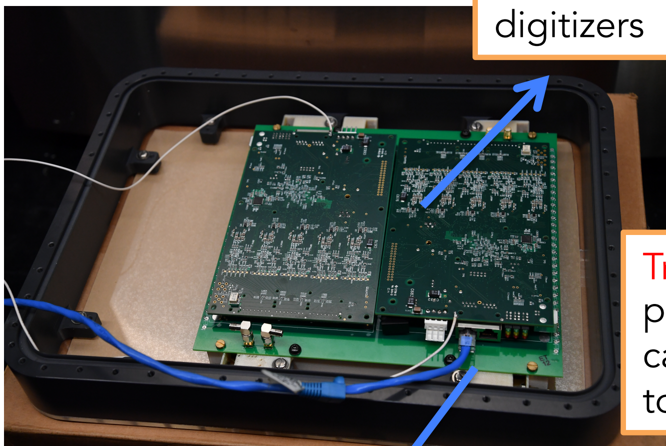


LAPPD panel on a track.

LAPPD Housing Design

- The housing was designed at UC-Davis.
- It was made of 2-inch thick PVC frame with a ¼ inch UVT acrylic window and thin SS back plate.
- Enough space for LV-HV board, fan, humidity and temperature sensors etc.
- O-rings on both sides of the housing provide water-tightness.
- Water-tightness tests and electronics integration are underway.

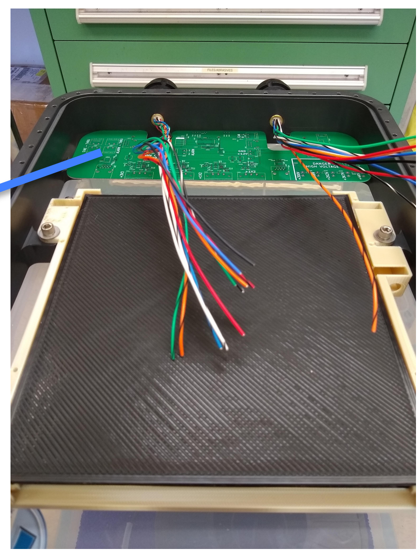
LAPPD Housing Design with Electronics



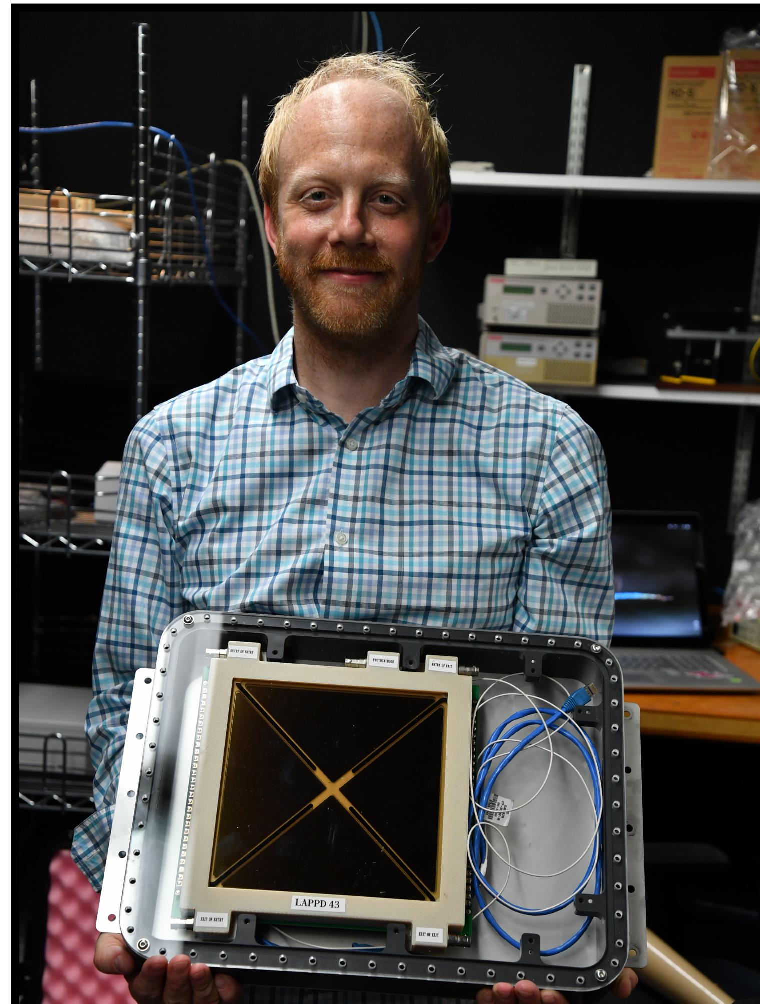
2 ACDC Cards as waveform digitizers

Trigger card in between pickup board and ACDC cards to provide trigger to the ACDCs.

Analog pickup board



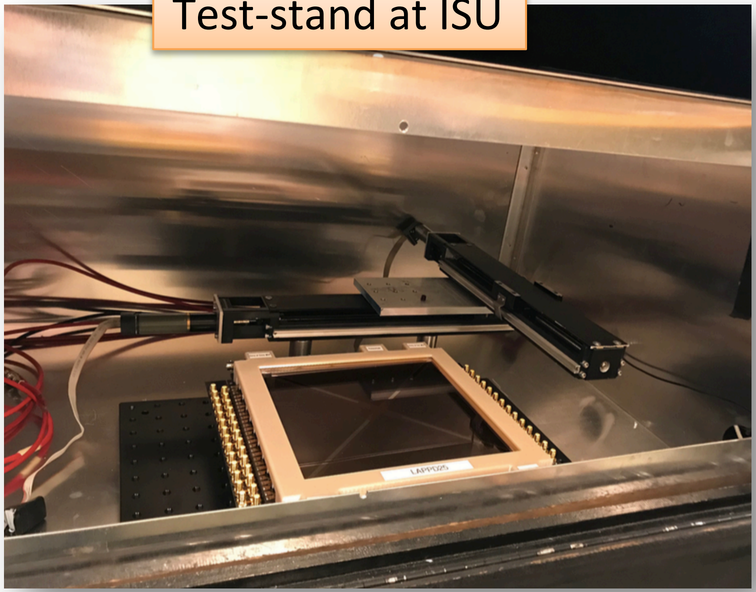
LV-HV board to provide power and slow controls



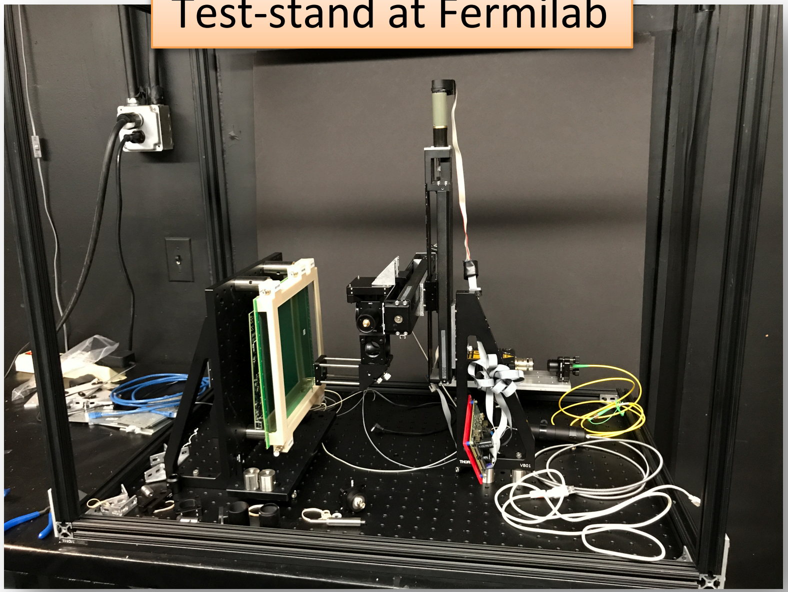
LAPPD housing and electronics integration
Matt Wetstein, ISU

LAPPD Characterization at ISU and Fermilab

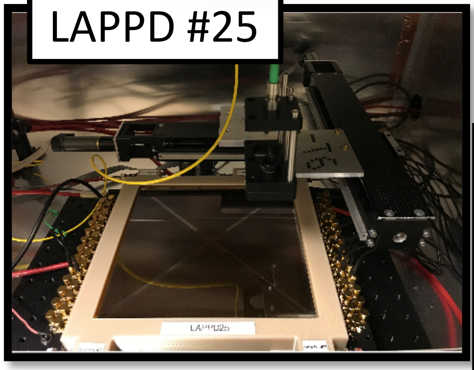
Test-stand at ISU



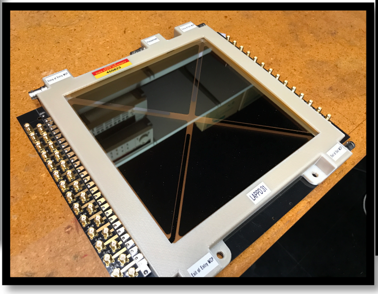
Test-stand at Fermilab



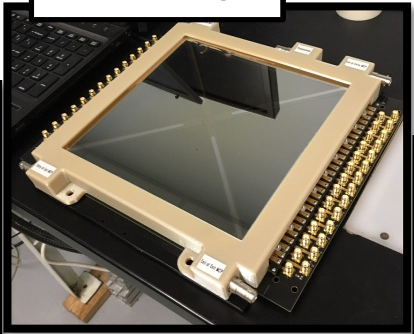
LAPPD #25



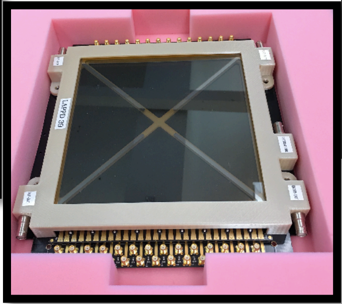
LAPPD #31



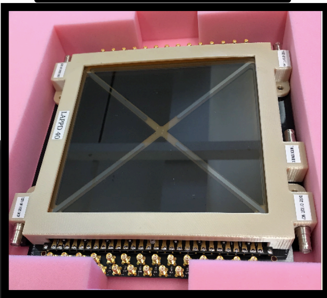
LAPPD #37



LAPPD #39

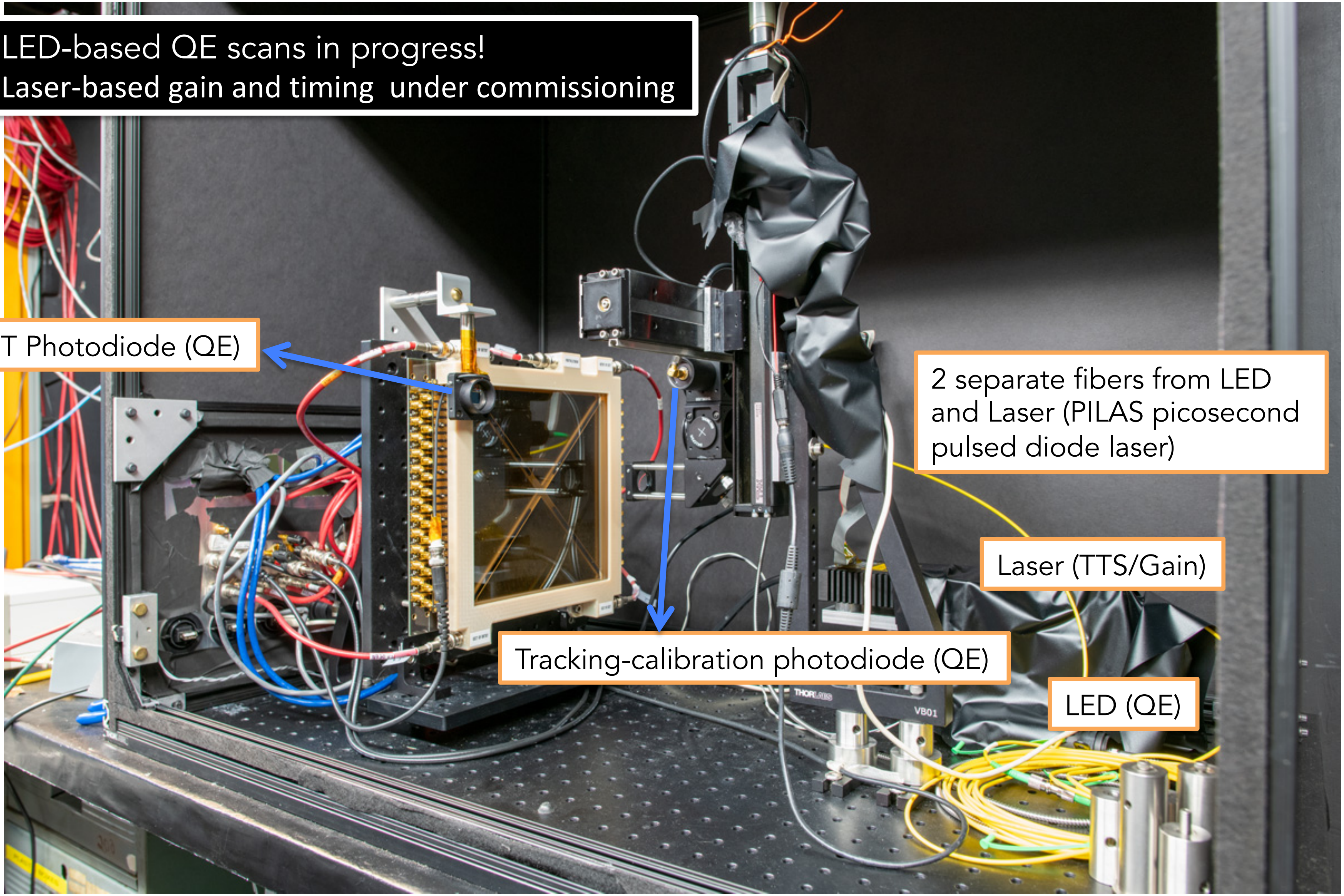


LAPPD #40

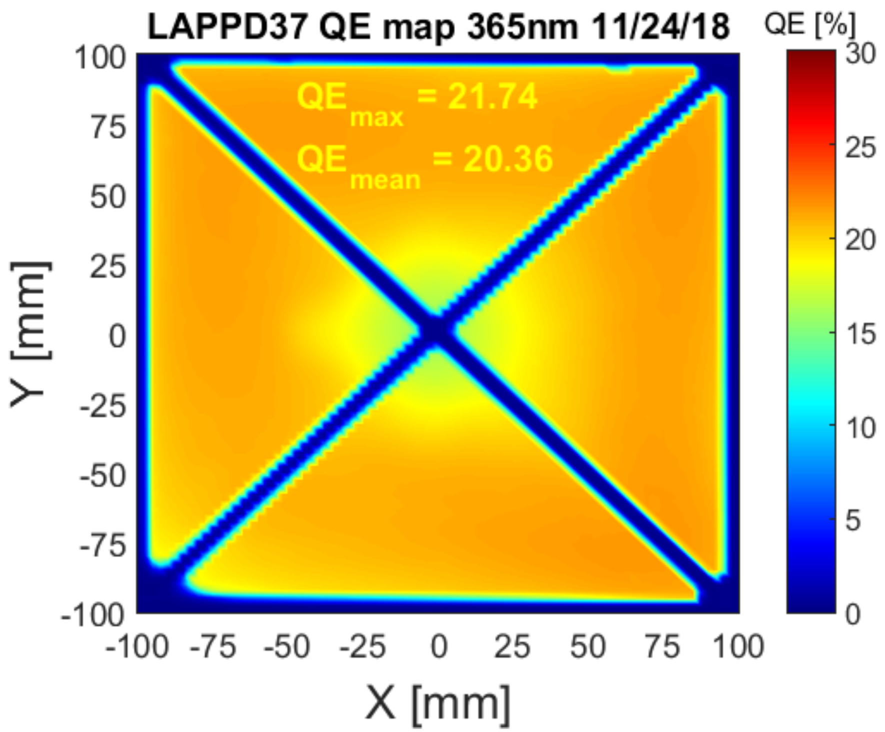


LAPPD Characterization at Fermilab

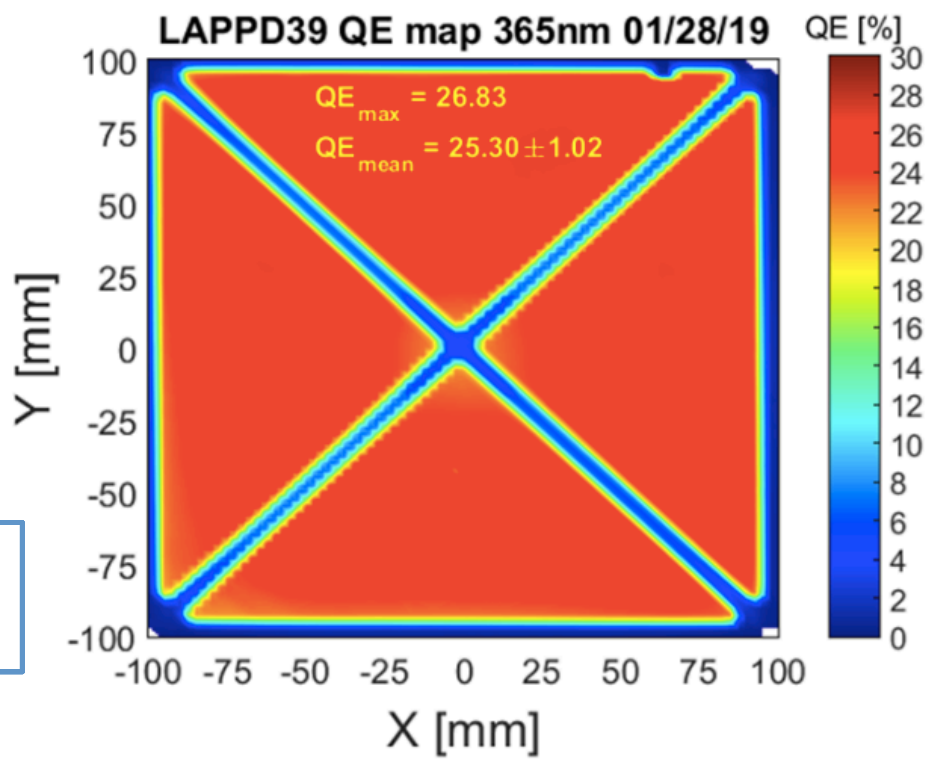
- LED-based QE scans in progress!
- Laser-based gain and timing under commissioning



QE of LAPPDs



- The QE results of 2 LAPPDs, #37 and #39
- QE characterization of other LAPPDs is in progress at Fermilab.

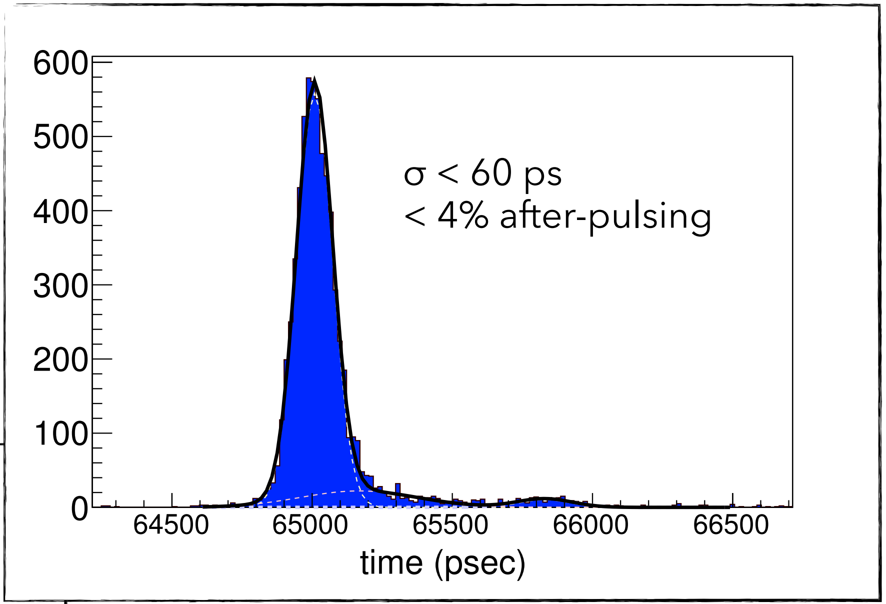


- Quantum Efficiency (QE) is more than 20%
- Nice uniform response from the LAPPDs

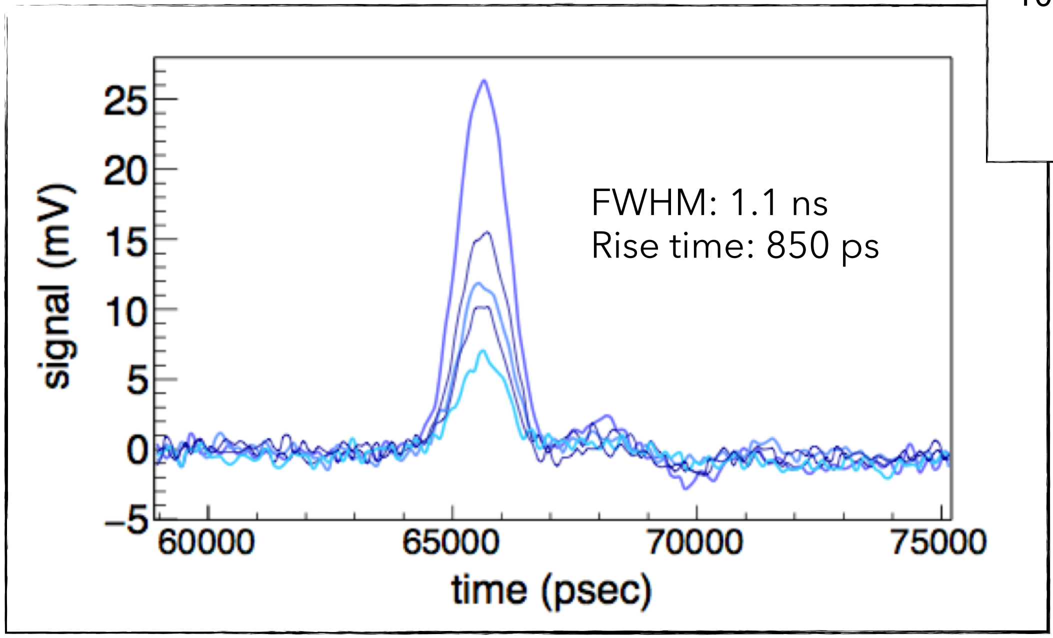
Timing Characteristics of LAPPDs

Timing resolution is less than 60 psec.

Transit Time Spread



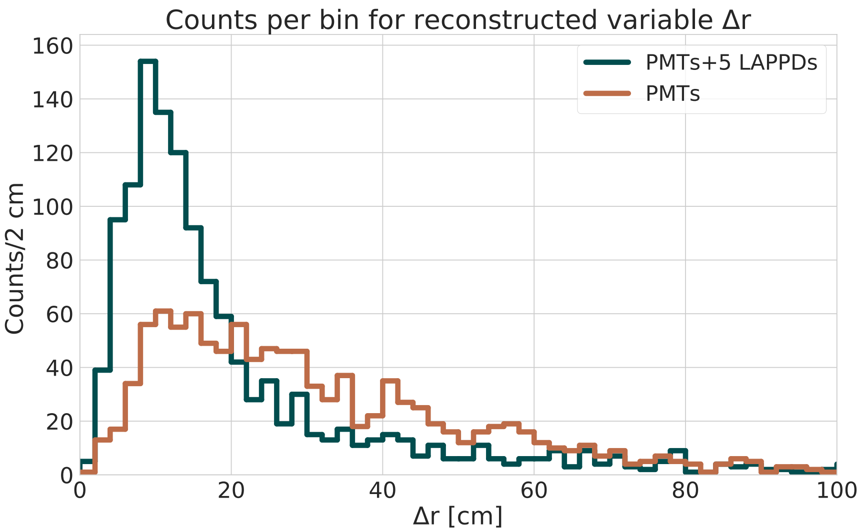
Typical Single-PE Pulses



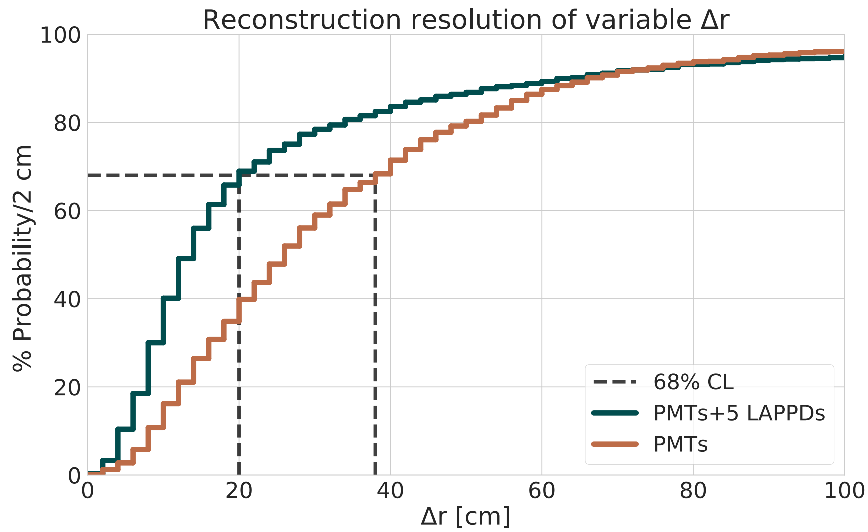
- Laser-based gain and timing characterization under commissioning.

Physics Benefits of LAPPDs in Neutrino Experiments

- The addition of 5 LAPPDs greatly improves reconstruction of muon track parameters.



Raw distribution



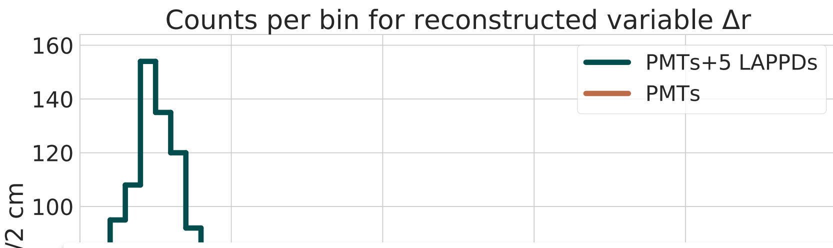
Cumulative distribution

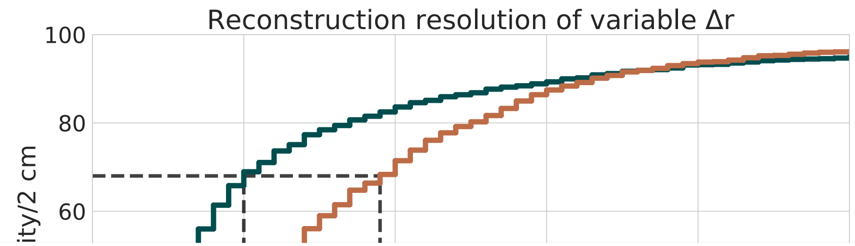
132 conventional PMTs (20%)	: 40 cm resolution
5 LAPPDs +132 PMTs	: 20 cm resolution (a factor of 2 improvement)

- They enable significant improvement for vertex and track reconstruction.
- They will improve energy resolution, background rejection and aid reconstruction of multi-track events.

Physics Benefits of LAPPDs in Neutrino Experiments

- The addition of 5 LAPPDs greatly improves reconstruction of muon track parameters.





Multi-track reconstruction, non-forward physics and addition of WbLS will require more LAPPDs spread isotropically.

Raw distribution

Cumulative distribution

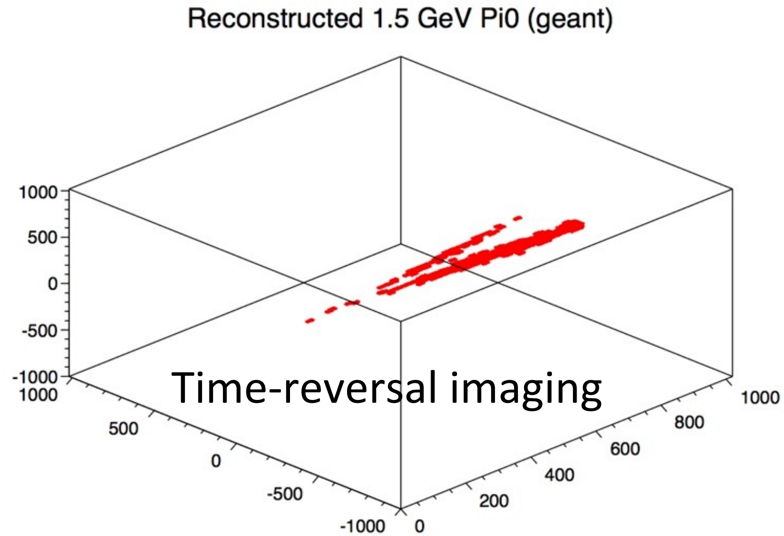
132 conventional PMTs (20%)	: 40 cm resolution
5 LAPPDs +132 PMTs	: 20 cm resolution (a factor of 2 improvement)

- They enable significant improvement for vertex and track reconstruction.
- They will improve energy resolution, background rejection and aid reconstruction of multi-track events.

LAPPD Applicability

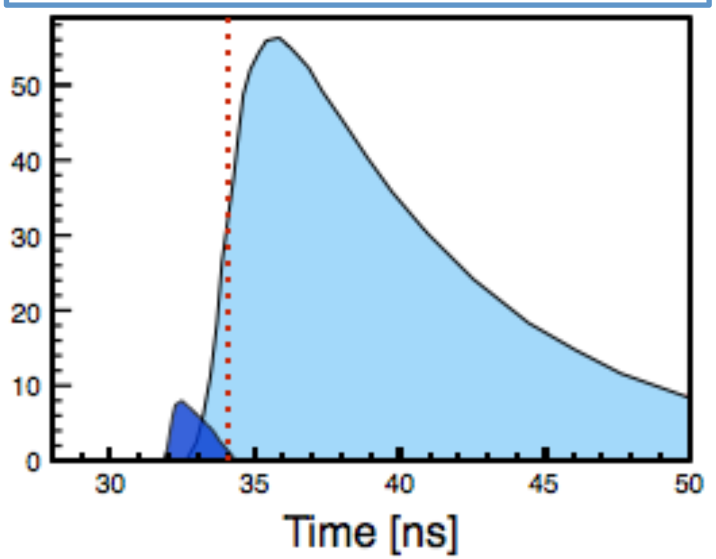
Fast timing

- better vertex reconstruction
- ability to reconstruct overlapping events and tracks
- better able to resolve structure of EM showers
- improved background rejection and energy reconstruction in higher energy beams



(from M Wetstein, talk at ANT2013)

C. Aberle et. al., 2013 arXiv: 1307.5813



Cherenkov and Scintillation Separation

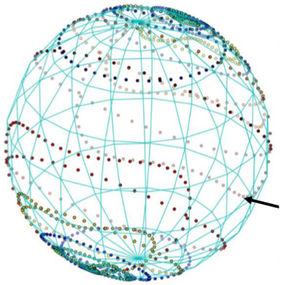
- Cherenkov light arrives earlier
- Timing information of photons makes the separation possible.

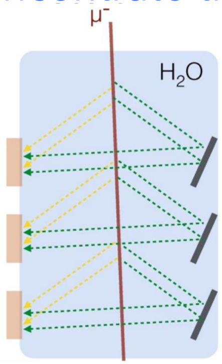
See also:
J.R. Alonso et. al., arXiv: 1409.5864
B. Wansak et. al., arXiv: 1803.08802

See talk by J. Caravaca in the Photodetectors session on Sunday.

LAPPD Applicability

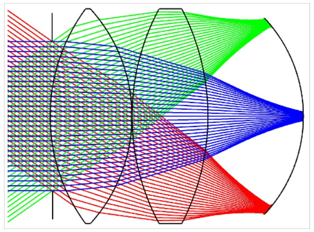
- **Imaging** is a powerful capability
- Because LAPPDs are imaging photodetectors, their marginal value increases with more dense occupancy. Could we develop interesting schemes to better concentrate the light?





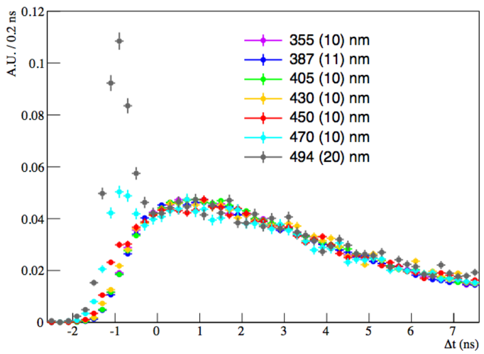
① Multi-bounce optics (UChicago - Oberla, Frisch, Angelico, Elagin)

https://arxiv.org/abs/1510.00947



② Plenoptic imaging (intensity, color and directional information) (J. Dalmasson et. al.)

https://arxiv.org/abs/1711.09851



③ Chromatic Separation (by using dichoric filters) (U Penn - Kaptanoglu, Luo, Klein): Dichroicons

https://arxiv.org/abs/1811.11587

See talk by Tanner Kaptanoglu in the Plenary session on Monday.

- Timing + Imaging photosensors could enable a very different kind of Cherenkov/scintillator detector with the advantage that it can be used to view all different fluxes in same detector.

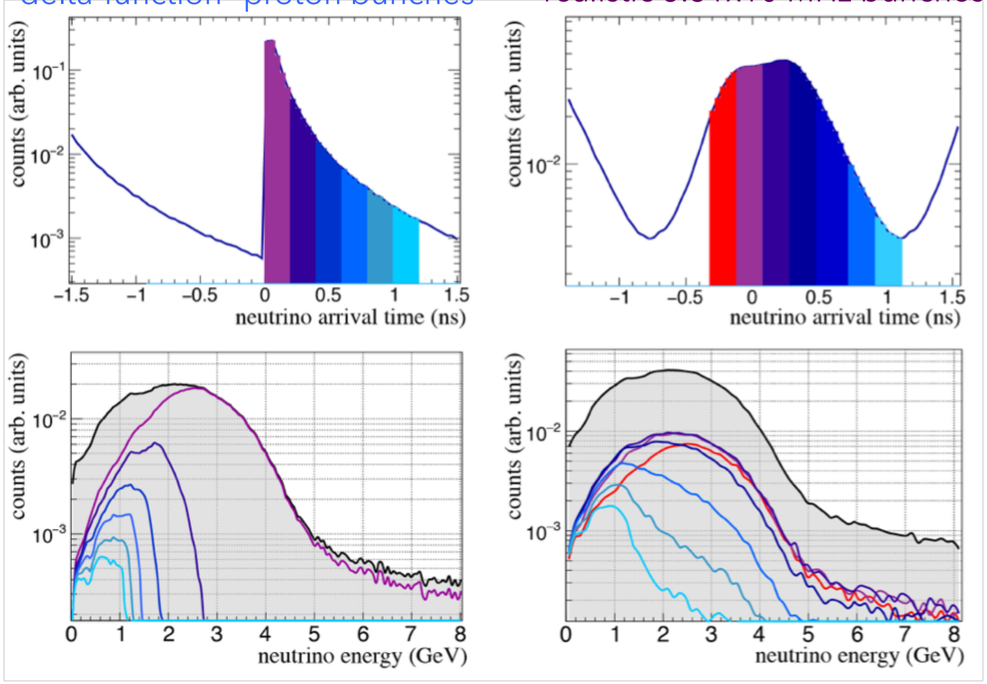
Beam Timing

- Timing can be used to select different energy fluxes from a wide-band neutrino beam.
- Lower energy neutrinos come from slower pions and arrive later.
- Will require precision time stamping O(100) ps.

- ANNIE might be able to provide a first demonstration of this approach, albeit on wide (1 nsec) bunches.
- It will be more visible in small bunch sizes.

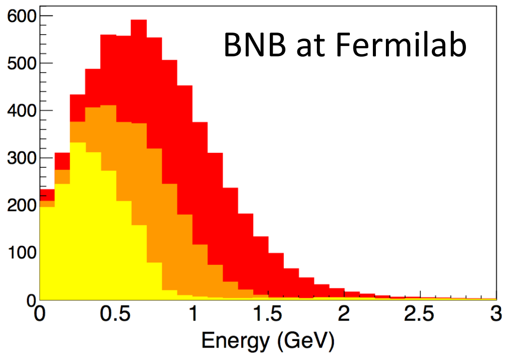
"delta-function" proton bunches

realistic 5.31x10 MHz bunches

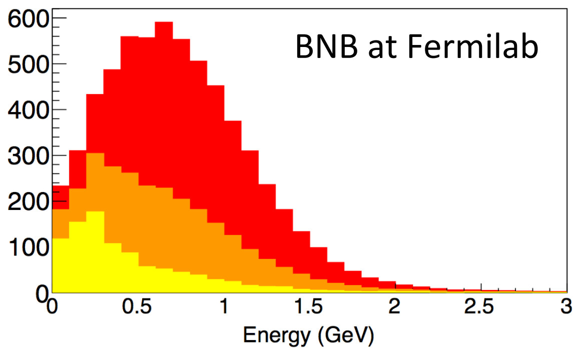


https://arxiv.org/abs/1904.01611

"delta-function" proton bunches



realistic bunches spread out in time



See talk by Evan Angelico in the Diverse Detector session on Sunday.

Water Based Neutrino Detectors (ANNIE, WATCHMAN, THEIA)

Fiducial Mass

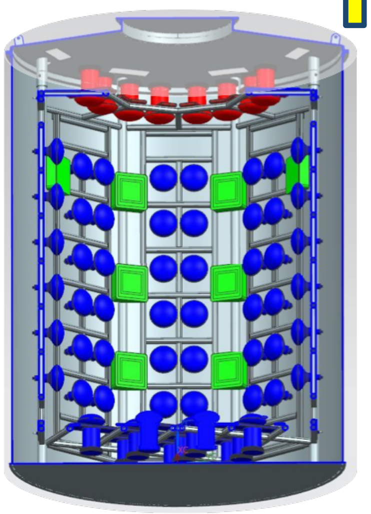
~50 ktons

~4 ktons

~30 tons

Potential future testbed for new technologies, WbLS and additional LAPPDs

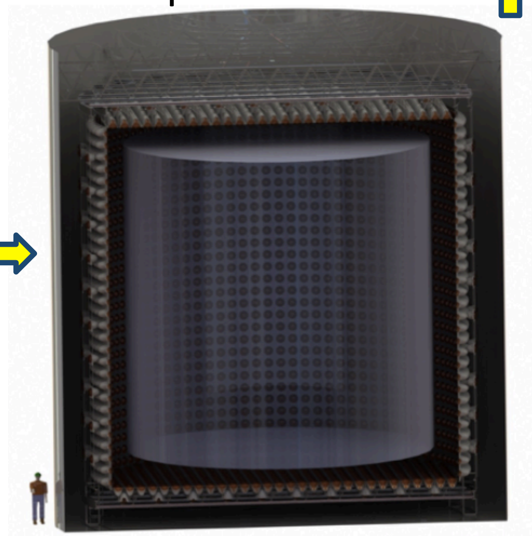
~ 150 photosensors



ANNIE

Gd in a large detector with possible LAPPDs

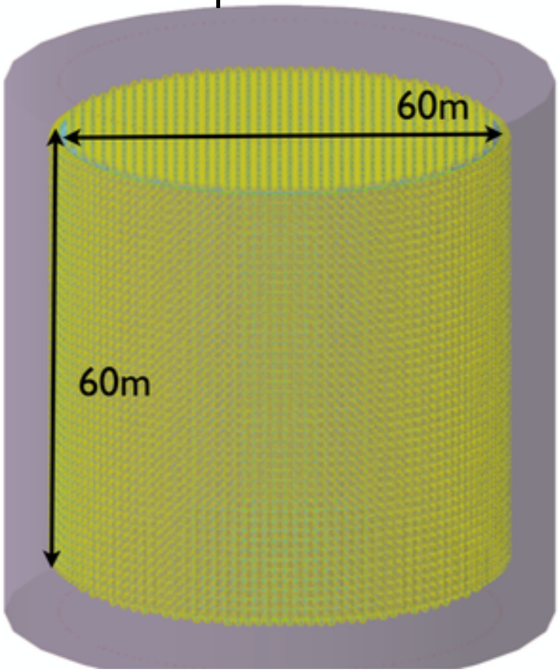
~ 5k photosensors



WATCHMAN

(AIT-WATCHMAN with WbLS)

~ 100k photosensors



THEIA

arXiv: 1911.03501

See talk by Bob Svoboda on Sunday

Directional (Cherenkov light), low-threshold, capable of flavor identification and signal-background separation detectors….

2019 +

2022 +

?

CONCLUSIONS

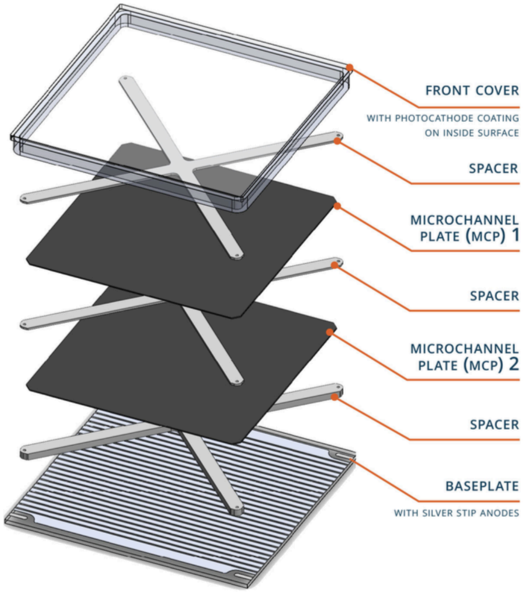
- Physics Phase detector installed and under commissioning
- ANNIE will measure the beam induced final state neutron multiplicity & CC inclusive cross section on water
- ANNIE is pioneering R&D of photodetection technologies/techniques:
    - Neutron tagging in Gd-loaded water
    - 5 LAPPDs characterized at FNAL being readied for installation
    - LAPPD coverage can be expanded in-situ to enable multi-track reconstruction and measurements of more exclusive final states.
    - Possible addition of WbLS to combine the tracking capabilities of Cherenkov reconstruction with the energy resolution and expanded sensitivity of scintillation light.
- Neutrino beam data taking to begin in January 2020.

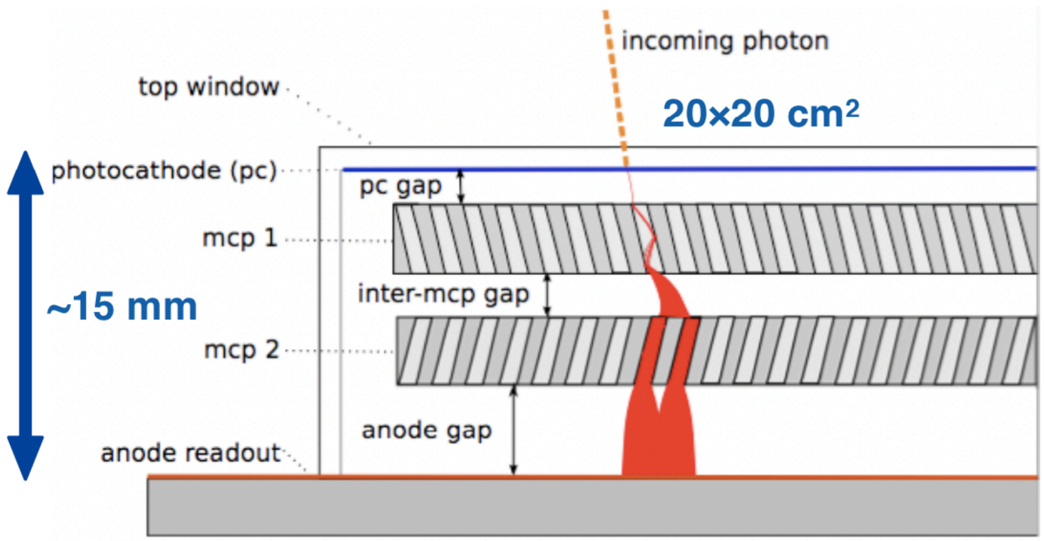
BACKUP SLIDES

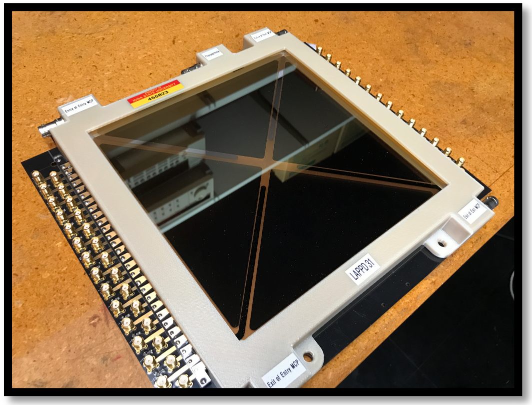
LAPPDs

- 20 cm x 20 cm flat panel, ALD* micro-channel plate (MCP) based photodetectors.
- Gain >10^6
- Spatial Resolution < 1 cm across strip and < 5 mm along strip (depending on the readout system)

- **ANNIE is an early adopter, building and developing new reconstruction techniques.**



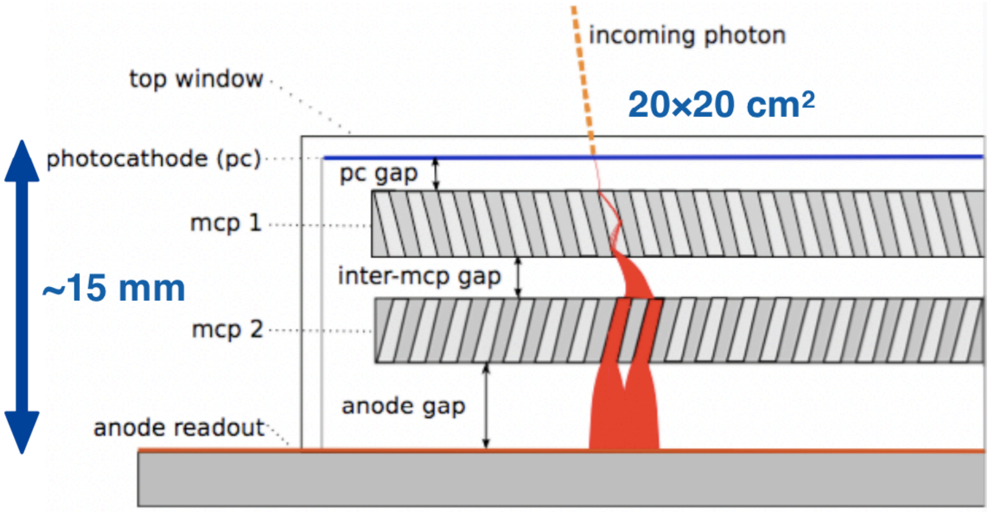




*ALD: Atomic Layer Deposition

Light Detection with an LAPPD

- Incoming photons produce electrons at the photocathode via the photoelectric effect
- Electrons enter microchannel plates (pore diamater ~10 micrometer)
- Collisions with the pore walls produce secondary electrons (Gain > 10^6)
- Signal collected on stripline anode
- Timing difference between strip ends used to recover longitudinal position



LAPPD General Characteristics

LAPPD #39 General Features and Parameters:

Feature	Parameter
Seal Date	1/17/2019
Photodetector Material	Borosilicate Glass
Window Material	Borosilicate Glass
Photocathode Material	Multi-Alkali (K_2NaSb)
Spectral Response (nm)	160-650
Wavelength – Maximum Sensitivity (nm)	≤ 365 nm
Photodetector Active Area Dimensions	195mm X 195mm
• Minimum Effective Area	34,989 mm^2 [(195*195)- {(2*265*6) – (6x6)}]
• Active fraction with Edge Frame X-Spacers	92% [(195*195)- {(2*265*6) – (6x6)}] / (195 * 195)
Anode Data Strip Configuration	28 silver strips, Width = 5.2 mm, gap 1.7 mm, nominal 50 Ω Impedance
Voltage Distribution	5 taps for independent control of voltage to the photocathode and entry and exit of MCP

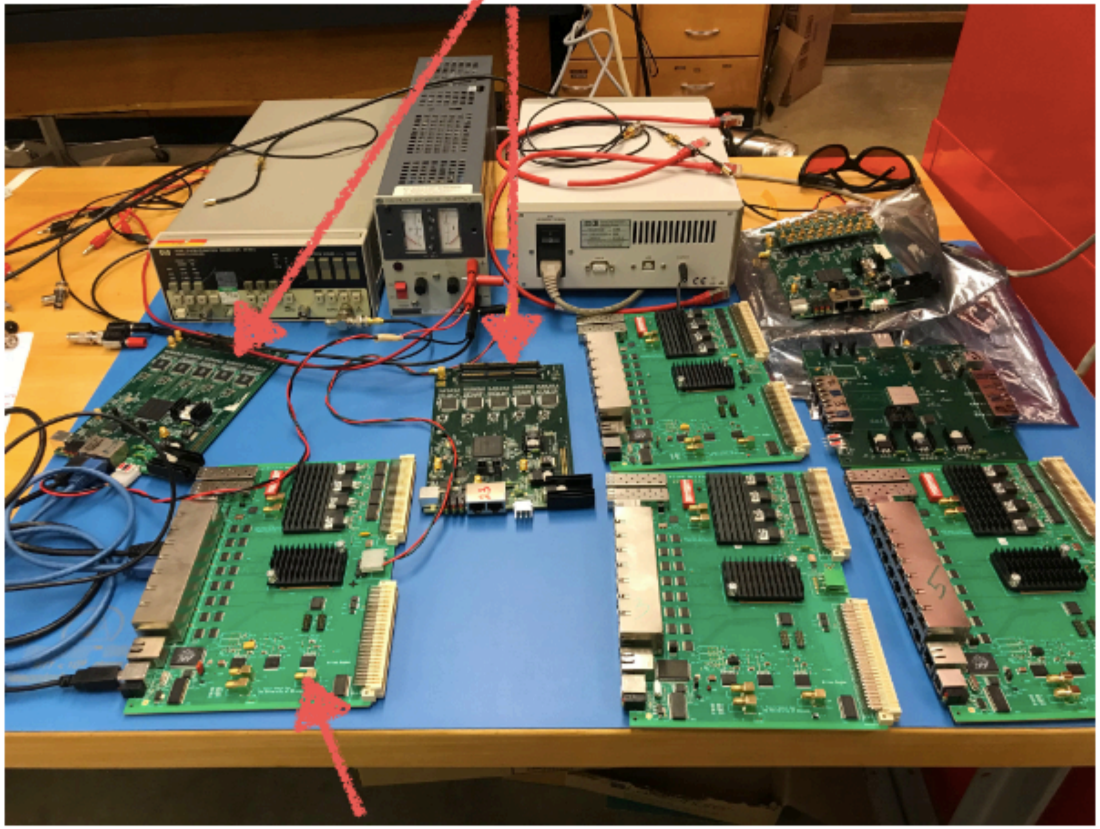
LAPPD #39 Operational Ratings

Parameter	Rating
Supply voltage Photocathode — Anode (Volts)	Typical: • 400 V between MCP and photocathode • 975 V/mcp • 200 V between MCPs • 200 V between MCP and anode • Photocathode voltage is -2750 V Maximum: Photocathode voltage at -2900 V
Operating ambient temperature °C	TBD (nominal room temperature)
Storage temperature °C	-12 to 50 (Avoid indium seal melt)

LAPPD Electronics

- LAPPDs with 10GHz digitization.
- ACDC cards attach to the analog pickup board on the back
- the slow controls card will go in the housing (which makes the low and high voltages and monitors everything)

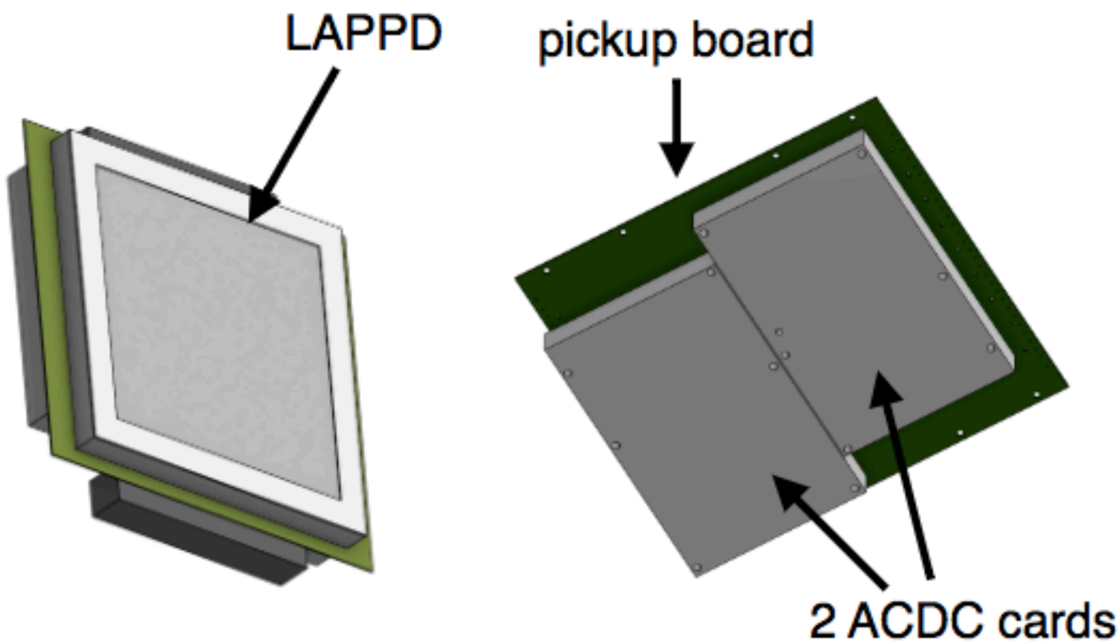
Two 30 channel ACDC cards - inside the housing



ANNE Central Card (ACC) - rack mounted

Electronics Design for LAPPDs

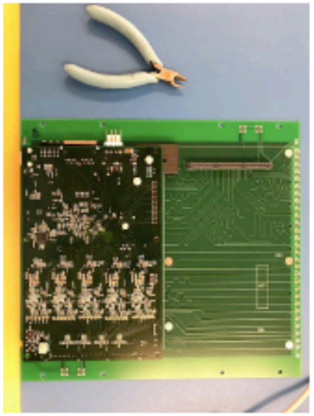
- ***Analog pickup board*** attaches to the back of the LAPPD and takes the signal from the silver anode microstriplines to Samtec connectors on the back
- Two ***ACDC*** mezzanine waveform digitizers attach to the *pickup board*
- ***Trigger board*** attaches at the bridge point between the LAPPD and pickup board and generates the trigger for the ACDC cards
- ***LV-HV board*** provides power and slow controls (not yet designed)
- ***Breakout boxes*** on the racks power and communicate with the LVHV boards convert to standard cabling from the high density.



ACC card

ACDC card

pickup board



Booster Neutrino Beam (BNB)

- The ANNIE detector is the closest experiment to the proton beam target on the BNB.
- 700 MeV peak energy.
- 93% ν_μ purity in the FHC mode.
- 4×10^{12} POT per spill at 5 Hz.
- One ν_μ charged-current interaction in the ANNIE fiducial volume in every 150 spills (~30 s).

Neutrino beams have a wide energy range.