APEX: Scale up photodetectors for large area coverage

RDC2: Photodetectors
CPAD Workshop
SLAC, Nov 7

Wei Shi
on behalf of the APEX working group
Physics Cases

• Energy resolution is crucial for LAr experiments
  • Access second oscillation peak
  • Low energy physics (supernova $\nu$ bursts, solar $\nu$, and possible BSM): lower threshold & increase trigger efficiency (to ~100%) in the range $\geq$5 MeV deposited energy
  • Energy resolution w/ scintillation light better than charge/LArTPC (if high and uniform light yield is achieved)

• Scaling up photodetector coverage area is one of the most effective ways to improve energy resolution
  • Dual calorimetry: charge light anti-correlation (reduce electron recombination dispersion)
  • Improve PID/energy resolution via 6D-tracking: 3-D spacial trajectory, $dQ/dx$, time, and $dL/dx$ (from photodetector)
Photodetector: X-arapuca concept

- **A light trap**
  - Dichroic and pTP deposited on glass (1st wavelength shifting)
  - Bulk material is acrylic (PMMA) plate for 2nd wavelength shifting
- Widely used in LArTPC: MicroBooNE, ProtoDUNE-SP, SBND, DUNE FD1 & FD2
  - Average detector efficiency is 2-3%
  - Easy to scale up for large area coverage
  - Save space for more fiducial volume
Convert LArTPC Field Cage Structure into a Fully Active Photon Detection System

- Field cage is part of the high voltage system for LArTPCs and makes E-field uniform across large drift distance
- Light detectors in all existing LArTPCs located behind anode plane, or on cathode plane (DUNE FD2-VD)
- If located on all walls of the field cage around the LAr active volume, would naturally expand optical coverage up to $2000m^2$ (10x DUNE VD) ~ half of American football field!

$<LY> = 112.7 \frac{PE}{MeV}$

$LY_{min} = 66.7 \frac{PE}{MeV}$
A fully integrated FieldCage-Photodetector system for large volume LArTPC experiments
APEX Concept (Aluminum Profiles with Embedded X-Arapucas)

• Field cage modular unit 3m x 3.2m panel made of Al profiles, as in current DUNE FD modules

• We propose to retain the LArTPC field cage and integrate photodetector module into it
  • 0.5m x 0.5m PD module, 6 modules per row share power and readout
    • Granularity adjustable
  • Larger oval shaped FC profiles: keep the max E field small
  • Operate photodetectors on HV surface
    • Solution: PoF and SoF technologies (later slides)
  • Three FRP beams as structural support
    • Center beam also serves as cable conduits
A fully integrated FieldCage-Photodetector system for large volume LArTPC experiments
APEX Concept (Aluminum Profiles with Embedded X-Arapucas)

SiPMs at the center

SiPMs, electronics boards, and instrumentation housed inside Al profile (shielding and discharge protection)

Side view

50cm

0.5m

Mounting details

[Reflector - WLS2 - Dichroic - WLS1]

VIKUITI foil - PMMA - ALD - pTP film
View in DUNE VD-like LArTPC

3 m x 3.2 m module

4 modules/column

Interior view

Bird's-eye view
Charging up Test

- A bulk acrylic (insulating material) between FC metallic (conductive) profiles will charge up in $E$ field
  - Interest to reduce the number of FC profiles if charging up time is short

- Test shows this process is slow (~days) even on surface, still need extra field cage profiles

![Graph showing expected location of Bi-207 source under uniform E field](image1)

![Diagram showing PD surface charged up](image2)
Improve Dichroic Filter Coating

• Motivations
  • Explore possibility for high(er) rate industrial production, on large(r) dimension substrate of different type (from glass to acrylic)
  • Directly coat on acrylic WLS plates: lower weight on FC and simplify assembly

• Option 1: physical vapor deposition
  • Different techniques exist
    • Electron beam
    • Sputtering in a cylindrical chamber
    • Sputtering in a continuous In Line coater
  • Test production with PhotonExport

• Option 2: atomic layer deposition
  • State of the art: offer precise and easy thickness control, excellent uniformity (0.1-1%)
  • High quality control R&D needs project support
Solution for Detectors on HV Surface: Power over Fiber (PoF)

- Power can’t transmit via conductive cables due to discharge risks (field cage at HV)
- PoF is a new technology to transmit power via optical fibers to detectors on HV surface, already applied in DUNE FD: developed over 3 years at Fermilab with industrial and university partners
- Laser power is converted to electrical power: efficiency already at ~55%, could reach 75% in theory
- Light noise from PoF system well understood and mitigation solutions are developed
New Development for APEX: PoF for SiPM Bias

- Earlier PoF system can only output lower voltage (~7V)
  - Need LDO + DC-DC step up for SiPM bias

- Latest PoF product can provide bias up to 36.9V
  - Higher output possible by improving the receiver design

- Demonstrated SiPM can be successfully biased from PoF and have good SNR

![Graph showing laser power vs. output voltage](image)

LN2

SNR = 4.47

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Solution for Detectors on HV Surface: Signal over Fiber (SoF)

- Use 1310 nm (room temperature) Fabry–Pérot laser diodes on front end cold electronics to convert SiPM electric signals to optical signals and transmit over fiber
- **A commercial laser diode with > 2 years of R&D to customize it for LAr application**
  - E.g.: customized defocused products solved power stability problem when immersed in >12” LAr
  - Demonstrated long term stability above 6m LAr hydrostatic pressure (~12psig)
PoF and SoF in APEX

- LV PoF for powering cold readout electronics
- Each row of 6 PD modules share HV PoF to bias all SiPMs, share ADC to single SoF fiber
- Digital SoF is widely implemented in HEP experiments, the challenge is to make it work in LAr
  - Wavelength division multiplexing for SoF can further reduce number of fibers (later slide shows some encouraging progress has been achieved already)
Signal Digitization and Transmission via Cryogenic Digital Optical Link
Baseline Solution

- Several prototypes tested at Fermilab
  - ADC chips: TI ADS52J90, ADI AD9656, TI ADS52J65 (to be tested)
  - Best efficiency when many channels can be utilized

- Slow control signals
  - Had issues with plastic optical fibers with LED transmitters
  - An onboard active controller device (ASIC, FPGA, Microcontroller) would greatly simplify the design, eliminating the need for most control
Advanced Solution:
Ring Resonator for Signal over Fiber

- Challenge of increasing readout channels and large bandwidth data transfer
  - 14(ADC-bits) x 67 MHz x 288 channel per FC ring x 24 rings ~ 6.5 Tbit/sec

- **Micro-ring modulators (MRM)** offers low power, low heat load solution
  - Signal bits modulates laser on and off
  - Wavelength division multiplexing can reduce number of fibers
  - Already used in LHC experiments, but need to be customized for 87K application
  - MRM’s tuning, optical packaging, integration with CMOS and detector
  - Has university partners, more R&D required
Digital SiPM

- One step further to reduce channel count, but is a well established concept
  - Could eliminate the scaling of noise with the number of pixels
  - Minimize power by eliminating cold ADC

- Single Photon Avalanche Diode
  - CMOS SPAD devices may allow a much larger active photo-detection area to be read out on a single channel with essentially zero noise
  - Limited in-pixel electronics: active or passive quenching circuit, comparator, and adder
  - In touch with industrial partners to discuss roadmap
Toward DUNE Phase II FD

DUNE FD3 Mini-Workshop Toward a Combined Photon Detection and Field Cage System

Jun 26 – 28, 2023
Stony Brook University Physics Building
US/Eastern timezone

> 60 participants!

- Kickoff workshop at Stony Brook
- Discussed items (detector & electronics) that can be further improved from VD
- Discussed synergies with other FD3 concepts (TPC charge readout)
- Made plans toward prototypes
Prototyping Stages

Table-top 50L TPC 2023

ProtoAPEX Ton-scale (CERN/FNAL) 2023-2024/5

ProtoDUNE 1kton-scale (CERN) 2025-2026

CERN 50L

ProtoAPEX TPC

CERN 2t

FNAL Iceberg 4.2t

FNAL IERC

APEX & ARIADNE+ 2025/26
Summary

• APEX is a proposed solution for a significant expansion of the active optical coverage area \(O(2000 m^2)\) for (future) large volume LArTPC experiments, toward \(4\pi\) light collection

• APEX would provide photo detection with very high and uniform light yield

• Many new ideas developed from DUNE VD R&D (See A. Paudel’s talk)

• Challenging but exciting: integration of PDS to the LArTPC field cage, power delivery and cold readout via fiber, and reducing channel count

• Prospects of improving energy resolution at GeV and MeV region by leveraging dual calorimetry and PDS timing