Next-Generation Photon Detection System for LArTPC Experiments

Principal Investigator: *Chao Zhang* (PO)

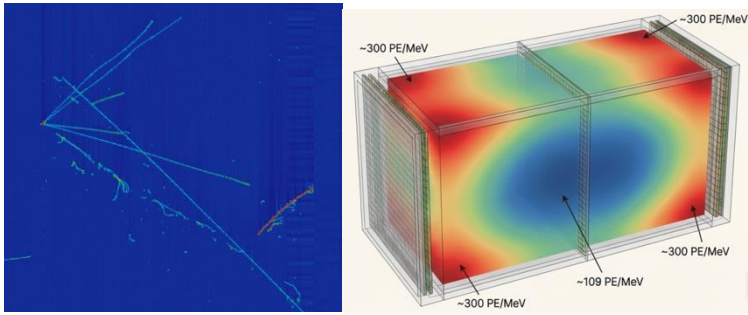
Other Investigators:
(PO): *Jay Hyun Jo, Yichen Li, Xuyang Ning, Gabor Galgoczi, Brett Viren, Xin Qian, Shanshan Gao, Volodya Tishchenko, Hucheng Chen, Steve Kettell*
(IO): *Prashansa Mukim, Bo Yu*

Proposal term from: FY27 **to**: FY29

Annual funding: FY27 $600K; FY28 $600K; FY29 $600K

Motivation

- Scintillation light signals in Liquid Argon TPCs provide a unique but currently under-utilized advantage in calorimetry
  - Self-compensation in light calorimetry mitigate one of the largest systematics in GeV neutrino physics: *Phys. Rev. D 111, 032007 (2025)*
  - High resolution and low threshold will unlock new discovery window for MeV neutrino physics: *Phys. Rev. D 112, 012019 (2025)*
  - Tremendous physics potential and new VUV photon detection technology will have broad applications beyond neutrino and high energy physics



Charge Imaging + Light Calorimetry

ultimate particle detector

- millimeter position resolution
- nanosecond time resolution
- precision energy measurement from sub-MeV to multi-GeV

- Challenges for large-area VUV (λ=128 nm) photon detection
  - Photon Detector: lack of economic and scalable methods for large area (O(1000 m^2)) coverage with high photon collection efficiency
  - Electronic readout: need new cryogenic readout with large dynamic range (sub-MeV to multi-GeV) and fast timing (ns) incorporating Signal over Fiber
  - Optical simulation: Massive detector size + high light yield (40k optical photons/MeV) makes precise photon propagation computationally prohibitive for high energy events
- This LDRD: R&D towards establishing a foundational, experiment-agnostic photon-detection platform applicable across future noble liquid detectors (with an emphasis on LArTPCs).

Proposed Research

❑ Photon Detector R&D

- Develop a cost-effective large-area photon detector solution to maximize VUV photon collection efficiency and light yield in liquid argon
- Establish a VUV photon detection R&D Facility
  - Upgrade existing spectrometer with cryogenic chamber for optical property measurements
  - Upgrade existing 260-liter LAr test stand for photon collection efficiency measurements

❑ Electronics readout & ASIC R&D

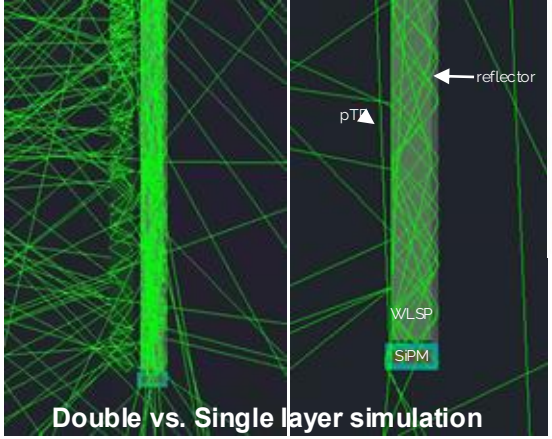
- Develop a cryogenic custom ASIC readout aiming for simultaneous improvement in
  - dynamic range (4-orders-of-magnitude, synergy with both DUNE Phase-II and FCC-ee ECAL R&D)
  - time resolution (sub-nanosecond)

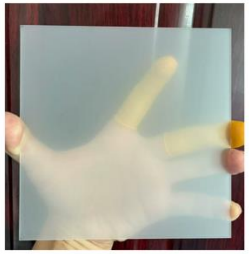
  for precision calorimetry and timing

❑ Physics simulation & AI/ML computing

- Develop a fast, GPU-accelerated optical simulation framework utilizing AI/ML algorithms to optimize detector design and reconstruction performance
  - Leveraging *EIC-opticks* software by NPPS
  - Validate Photon Detector R&D results
  - Provide guideline and physics requirements for ASIC/readout design
- Study light calorimetry in MeV – GeV Physics (ν oscillations, atmospheric ν, supernova ν, nucleon decay, and solar ν)

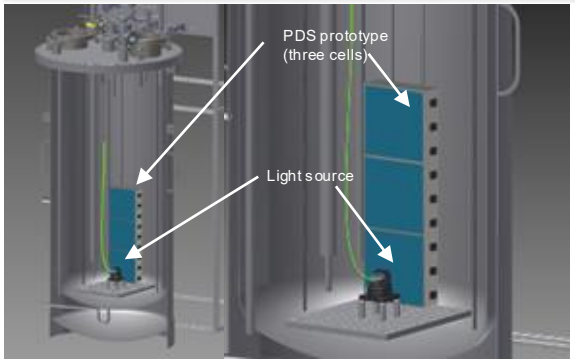
CHARMS250 (single channel prototype ASIC in 2025) demonstrates **very promising performance**: <10 mW per channel; works at 77K (-196 °C) – 300K; excellent noise performance at cold; good peaking time and linearity





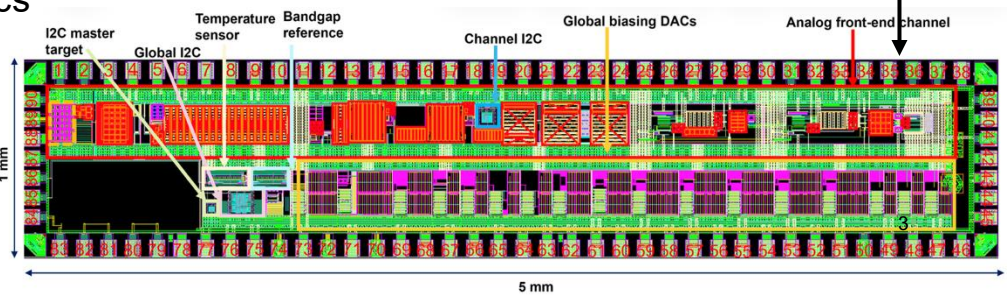
Uniform pTP film coated on a 14×14 cm B33 substrate

arXiv:2601.17161 (2026), submitted to JINST



LAr test stand upgrade plan for Photon Detector prototypes

CHARMS250 chip-layout (2025)



HOW DOES THE PROPOSED RESEARCH ENHANCE THE LAB STRATEGY

The proposed research aligns with BNL's strategic priority to understand the building blocks of the universe

- This generic R&D positions BNL as a leader in three critical frontiers:
  - **advanced instrumentation** (VUV optics)
  - **microelectronics** (ASIC)
  - **computing** (AI/ML & GPU acceleration)

  by establishing a foundational, experiment-agnostic photon-detection platform applicable across future noble-liquid detectors.
- Significantly advance the scientific potential of DUNE, a highest priority project recommended by the P5 panel for DOE and remains a priority in the 2025 updated of European Strategy for Particle Physics for CERN.
- Return on Investment
  - LArTPC Photon Detection System is a growth area for BNL (estimated ~$20M from new DUNE Phase-II PDS funds to BNL)
  - Ensure that BNL remains the central hub for future detector innovations, attracting significant future funding from DOE projects, and build a strong foundation for future detector R&D, AI/ML, ECA, and other DOE proposals

WHY BNL

BNL is uniquely qualified for the proposed research

- Long history of collective expertise in
  - LArTPC design, simulation and analysis
  - cryogenic electronics and ASIC design and testing
  - photon detector R&D (PMT, SiPM, wavelength shifter, etc.), simulation, and analysis
- Leveraging existing facilities necessary for validating the photon detector prototypes and ASIC performance.
  - 260-liter liquid argon test stand
  - McPherson monochromator + spectrometer with a high-intensity deuterium lamp
  - cryogenic electronics test stations
- Strong leadership in LArTPC Experiments
  - BNL is leading the DUNE Phase-I LArTPC Far Detector Projects
  - BNL is leading the early design of DUNE Phase-II Far Detectors with a substantially improved photon detector system

THE RESEARCH TEAM

We assembled a comprehensive team covering all aspects of the proposed R&D.

- Team members have strong expertise on the assigned tasks. Members in red request funding from this LDRD (see the budget slide). Others will be consultants.

Tasks	People
Photon Detector R&D	Jay Hyun Jo, Yichen Li, Bo Yu (IO), Steve Kettell
Electronics readout & ASIC	Prashansa Mukim (IO), Shanshan Gao, Volodya Tishchenko, Hucheng Chen
Physics simulation & AI/ML computing	Chao Zhang, Gabor Galgoczi (PD, NPPS), Xuyang Ning (PD, EDG), Xin Qian, Brett Viren

Draft LDRD Funding Table

	Work	FTE FY27	FTE FY28	FTE FY29	Total FTE/y
Postdoc 1 (Xuyang Ning)	Detector simulation & optimization, physics study	0.5	0.5	0.5	1.0 (Postdoc)
Postdoc 2 (New hire)	Electronics and Photon Detector R&D, physics study	–	0.5	0.5	
Postdoc 3 (Gabor Galgoczi)	Lead GPU software R&D	0.5	–	–	
Chao Zhang (PI)	Overall management and lead physics studies	0.25	0.25	0.25	1.2 (Sci. Staff)
Jay Hyun Jo	Lead Photon Detector R&D	0.2	0.2	0.2	
Yichen Li	Lead PD test stand design	0.5	0.25	0.25	
Prashansa Mukim	Lead ASIC design	–	0.5	0.5	
Technician	Test stand setup	0.2	0.2	0.2	0.2 (tech.)
M&S	test stand material, travel	$100K	$100K	$100K	2.4 FTEs/y

Many opportunities to collaborate with students from SBU and other institutions.

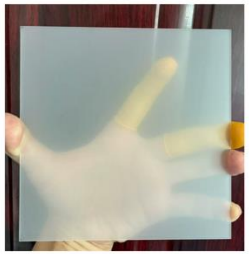
Backup Slides

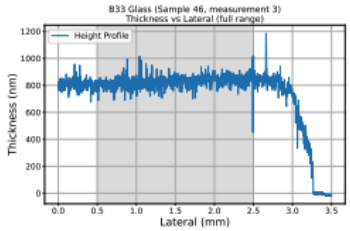
Related Publications in FY25

Industrial Deposition of Wavelength-Shifting Films for Liquid Argon Photon Detection Systems

Babak Azmoun, Aleksey Bolotnikov, Francesca Capocasa, Milind Diwan, Yimin Hu, Jay Hyun Jo, William Lenz, Yichen Li, Abdul Rumaiz, Vyara Tsvetkova, Matteo Vicenzi

arXiv:2601.17161 (2026), submitted to JINST





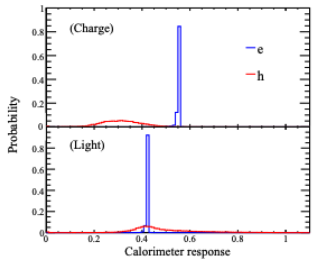
(a) Thickness vs. lateral distance (B33)

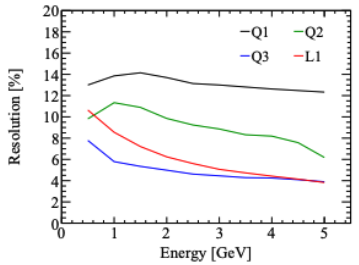
Uniform pTP film coated on a 14×14 cm B33 substrate

Self-compensating light calorimetry with liquid argon time projection chamber for GeV neutrino physics

Xuyang Ning [1], Wei Shi [2], Chao Zhang [1,*], Ciro Riccio [2], and Jay Hyun Jo [1]

Phys. Rev. D 111, 032007 (2025)





Physics prospects with MeV neutrino-argon charged current interactions using enhanced photon detection in future LArTPCs

Wei Shi [1,*], Xuyang Ning [2], Daniel Pershey [3,†], Franciole Marinho [4], Anjarazafy Fleuri [5], Ciro Riccio [1], Jay Hyun Jo [2], Chao Zhang [2], and Flavio Cavanna [6]

Phys. Rev. D 112, 012019 (2025)

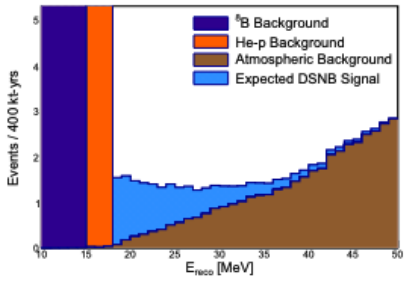
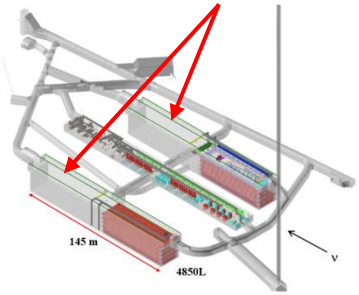


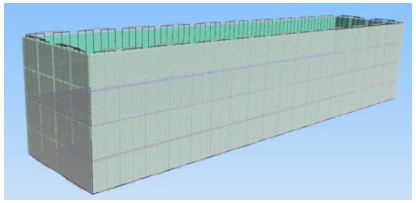
FIG. 13. Expected DSNB spectra with backgrounds at 400 kt-yrs exposure under the best energy reconstruction strategy of combined calorimetry at a $\overline{LY}$ of 180 PE/MeV, $E_{reco,\ Q_{75}\ +\ L_{180}}$, and exclusion of hadron tagged events.

DUNE Context

- One of the top recommendations in the 2023 P5 report is a re-envisioned second phase of DUNE with an early implementation a third far detector
- Phase I: two 10-kt LArTPC far detectors
  - FD1: horizontal drift (large BNL contribution)
  - FD2: vertical drift (BNL-led project)
- Phase II: two more 10-kt FDs
  - Required to fully reach the P5 goal with improved statistics, but also an opportunity to improve technology and expand physics reach
  - White paper in 2024: JINST 19, P12005 (2024)
- Our previous effort (facilitated by FY23-25 LDRD 23-058) has positioned BNL in leading positions for DUNE Phase II
  - BNL produced the first design of Phase II FD Photon Detector System (APEX), which is the FD3 reference design in the Phase-II white paper
  - BNL initiated the first design of 65-nm ASIC chips with 250ns timing (CHARMS) for DUNE optical readout
  - BNL produced the first physics studies motivating light calorimetry in DUNE phase II
    - Discovered self-compensation of light calorimetry to improve GeV neutrino physics (Phys. Rev. D 111, 032007, 2025), led by postdoc Xuyang Ning.
    - Improve MeV supernova/solar neutrino with light plus charge signals (Phys. Rev. D 112, 012019)
- This LDRD will significantly improve Phase II FDs' photon detector system to enable light calorimetry in LArTPC across a broad energy range from sub-MeV to multi-GeV
  - Expand DUNE physics potential in neutrino oscillations, atmospheric neutrinos, supernova neutrinos, nucleon decay, and solar neutrinos

Cavern for Far Detector 3 & 4





Proposed APEX design for FD3 Photon Detector System (Bo Yu)

Technology	Option for FD3	Option for FD4	Can integrate with
CRP (strip-based charge readout)	✓	✓	APEX
APEX (X-ARAPUCA light readout on field cage with SiPMs)	✓	✓	CRP, LArPix, Q-Pix, ARIADNE, SoLAr
LArPix, **LightPix** (pixel charge and light readout)		✓	APEX, SoLAr
Q-Pix, **Q-Pix-LILAr** (pixel charge and light readout)		✓	APEX, SoLAr
ARIADNE (dual-phase with optical readout of ionization signal)		✓	APEX
SoLAr (integrated charge and light pixel readout)		✓	APEX, LArPix, Q-Pix
Hybrid Cherenkov + scintillation		✓	N.A.

Many competitions exist for FD3 PDS designs. It's important to demonstrate APEX's advantage over other technologies in the next 2-3 years

DUNE Phase-II Timeline

- DUNE Phase II timeline
  - DUNE Phase II is one of the highest recommendations in the 2023 P5 report
  - DOE has indicated that Phase-II R&D funding will not be available until after FY26. We would think that to keep Phase-II viable, R&D funding would likely need to start by FY28 with the planned Phase-I project funding ramping down
  - Within DUNE, the management has expressed that decisions on the technology choices for FD3 and FD4 are expected no later than 2027 and 2028:
  - The timeline of this LDRD (FY27-29) is critical to make APEX, the BNL-led PDS design, into DUNE Phase II.