PoWER: an innovative Photon Detection System for DUNE Phase II

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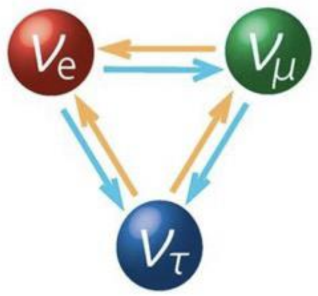
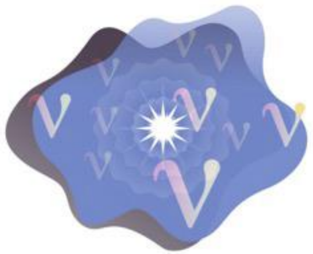
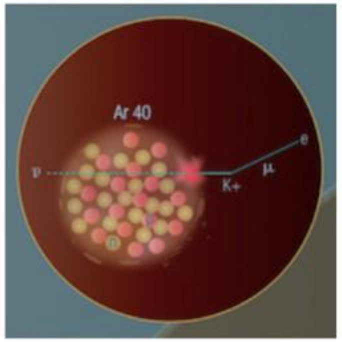
on behalf of the DUNE Collaboration

LIDINE, Hong Kong 22/10/2025

DUNE: a broad physics program

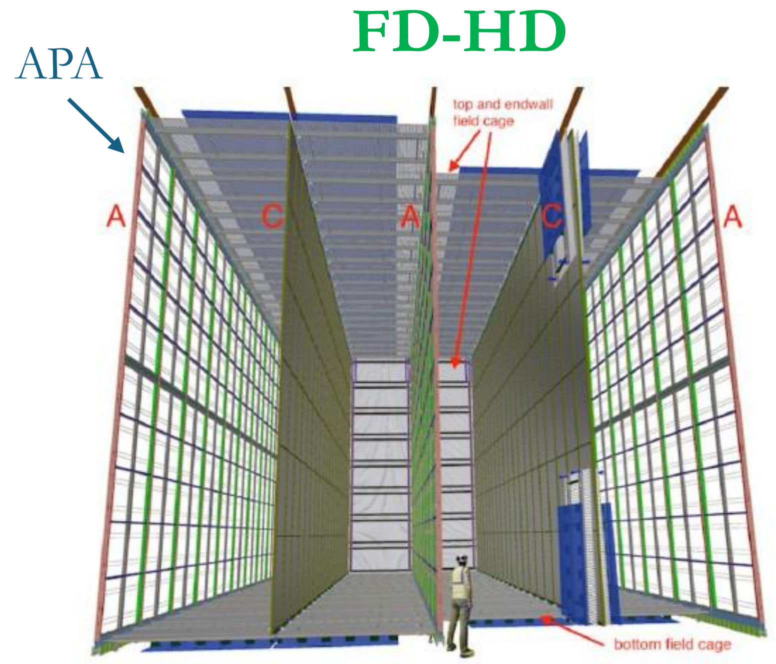


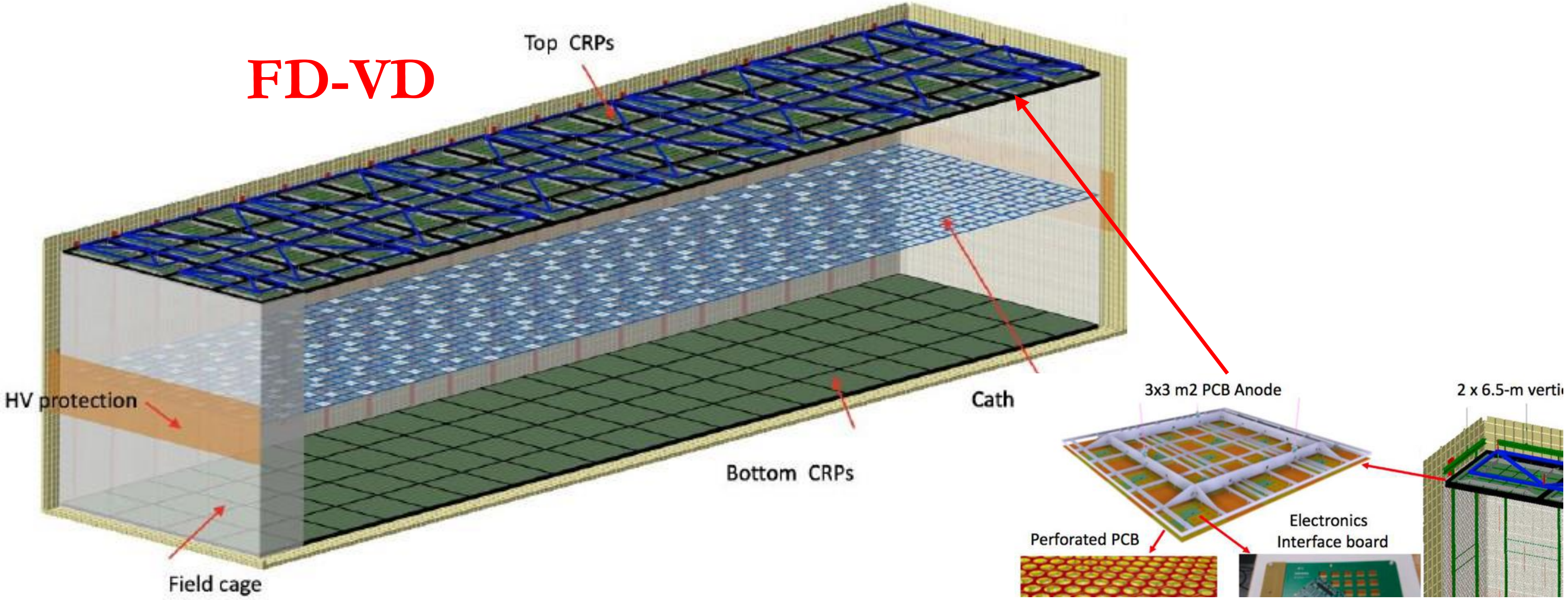




- **Long-baseline wide-band neutrino beam**
  - Measurement of CP violation phase and determination of neutrino mass ordering in a single experiment with spectral information
- **Underground location (1600 m) →Access to astrophysical neutrinos**
  - Supernova neutrino burst detection → sensitive to ν_e component
  - Atmospheric neutrino → capability of ν_τ identification
  - Solar neutrinos → potential detection of hep flux
- **Massive detector with excellent tracking and calorimetric information**
  - Search for nucleon decay like the baryon number violating channel $p \rightarrow \nu\, k^+$
  - Initially, two 17 kton LArTPC modules
- **Intense beam (initially 1.2 MW) and capable Near Detector Complex**
  - Precise neutrino physics
  - Movable LArTPC ND+muon spectrometer, SAND
  - BSM search

Phase I Far detector: two different readout technologies

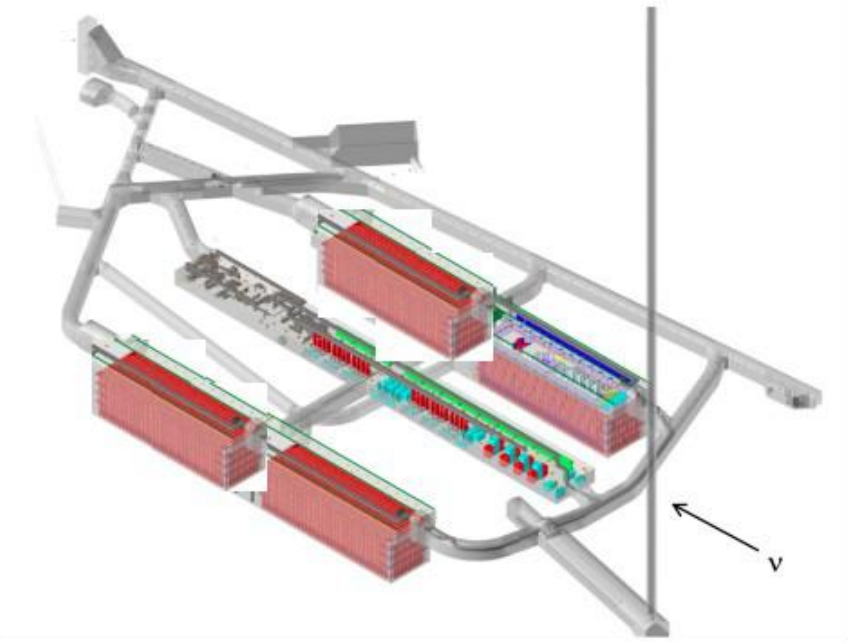




- **FD-HD module** will use Horizontal Drift technology: four **3.5 m drift** regions (3.5 m x 12 m x 58 m), charge readout with **348,000** wires in **150** Anode Planes Assembly (APA). Similar to ICARUS, MicrobooNE, SBND. Photon detection: X-Arapuca module (SiPM based light trap), about 300,000 SiPM
- **FD-VD module** will use Vertical Drift technology (two volumes 13.5 m x **6.5 m drift** x 60 m), charge readout with strips (**perforated PCB**). Photon detection on the field cage walls and on the cathode@300 kV; decoupling from HV achieved with optical fibers for power and signal transmission. Larger active volume, cheaper than FD1 and similar performances

DUNE Phase II

- Two additional Far Detector modules (on overall fiducial ≥40 kt)
- Beamline upgrade to > 2 MW
- More capable Near Detector (ND-GAr)
- Vertical Drift module is the baseline design for Phase II FD modules
- Several proposal to improve light collection (FD3): Aluminum Profiles with Embedded X-Arapuca (APEX) and PoWER (POlymer Wavelenght shifter e Enhanched Reflection)
- Improve PDS enhance light detection capabilities: improve energy resolutio boost low energy physics program
- Recent studies reveal high low-energy background level at SURF site: shielding/implementation of an active VETO are under investigation
- The phased construction program allows the development of the technolog to expand the DUNE physics scope ($0\nu\beta\beta$), dark matter…)
- FD4 is the «Module of Opportunity», more ambitious design are being considered, including pixel readout, integrated charge-light readout, low-background modules and non-LAr technologies



The key role of the Photon Detection System

PDS provides:

- **Determination of the event starting time (t0):** essential for accurate energy reconstruction in the LArTPC
- **Triggering capability for non-beam events** (solar and atmospheric neutrinos, SBN and BSM searches)
- **Calorimetric energy measurement:** complementary to charge-based measurement

Minimal requirements from Far Detector TDR (Phase I) are:

- >0.5 PE/MeV set to have >99% t_0 ID efficiency for events with visible energy >200 MeV (**nucleon decay**)
- > 20 PE/MeV (**calorimetric energy measurement for beam and supernova neutrinos**)

Enhanced light detection and VETO capabilities:

- Higher energy resolution to improve experiment sensitivity: 2nd oscillation peak
- Expected to boost low energy physics program (solar neutrino, diffuse supernovae, boosted dark matter)
- Tag neutrons with TOF
- identification of low energy μ/π

Polymer Wavelength shifter and Enhanced Reflection

PoWER

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COLORADO STATE UNIVERSITY

Nikhef

SLAC NATIONAL ACCELERATOR LABORATORY

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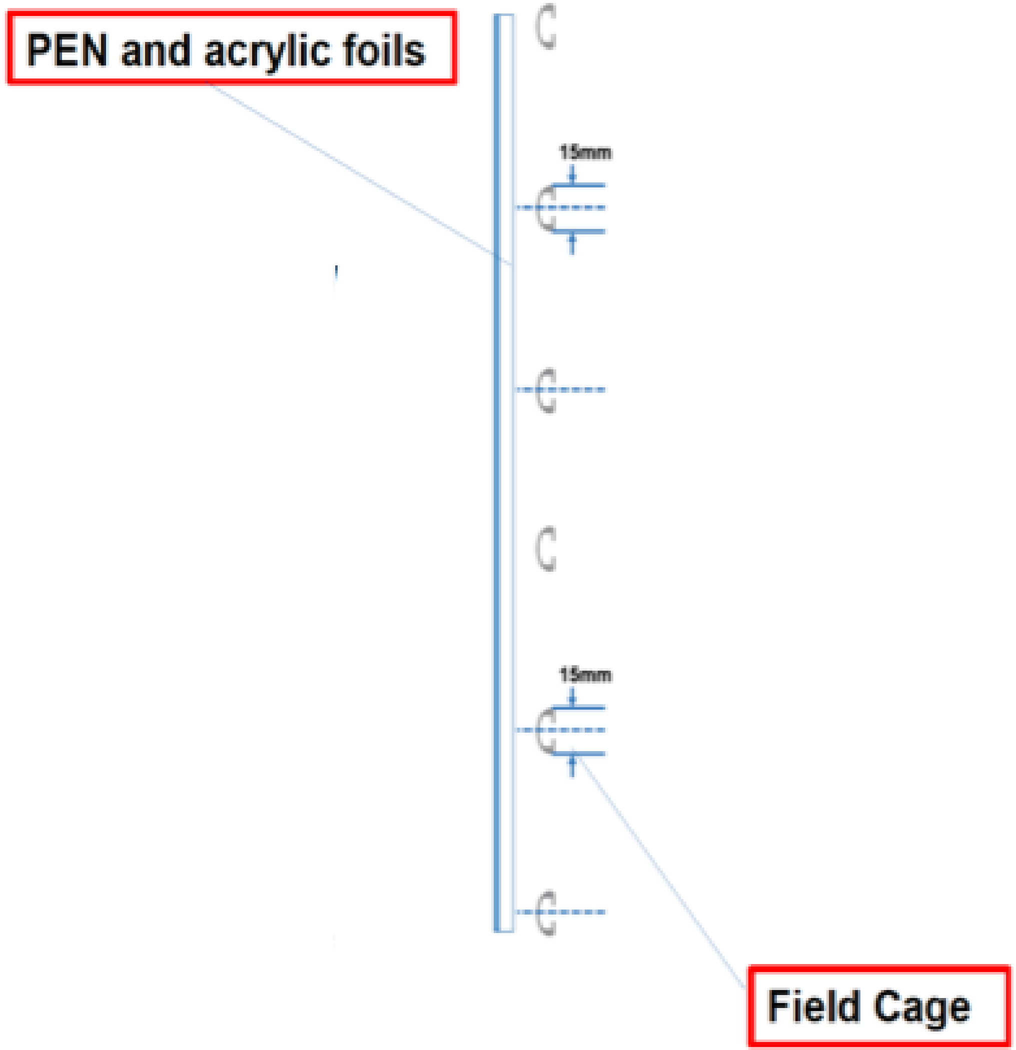
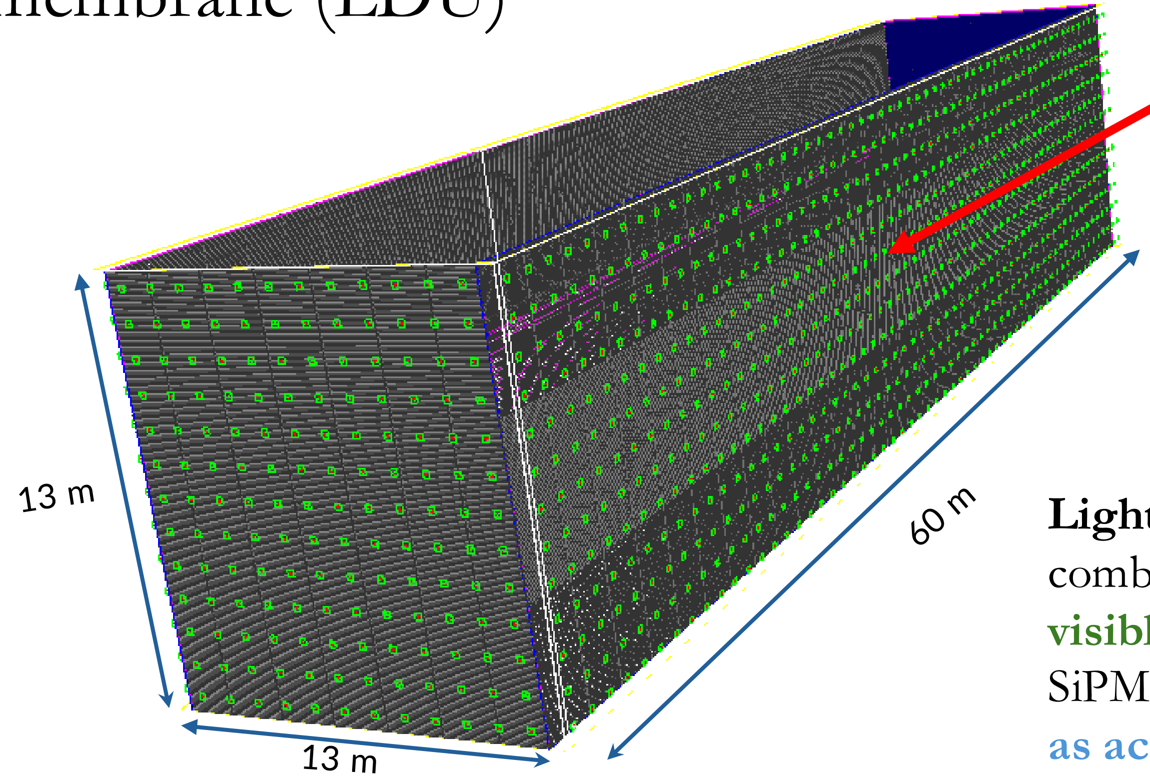
PoWER concept and design

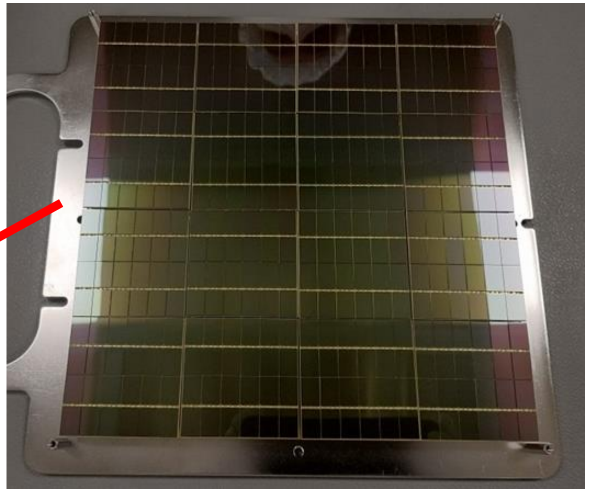
- Full coverage of the field cage with PEN foils



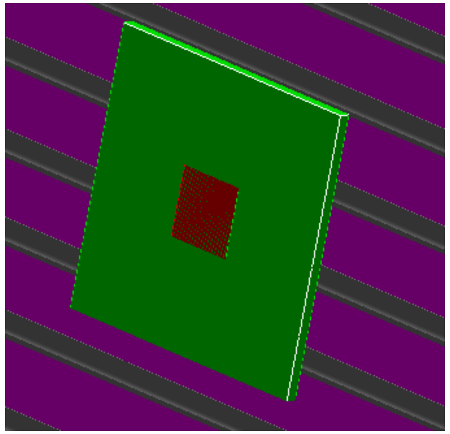
PoWER concept and design

- Full coverage of the field cage with PEN foils
- Large array of SiPM optical modules mounted on the membrane (LDU)





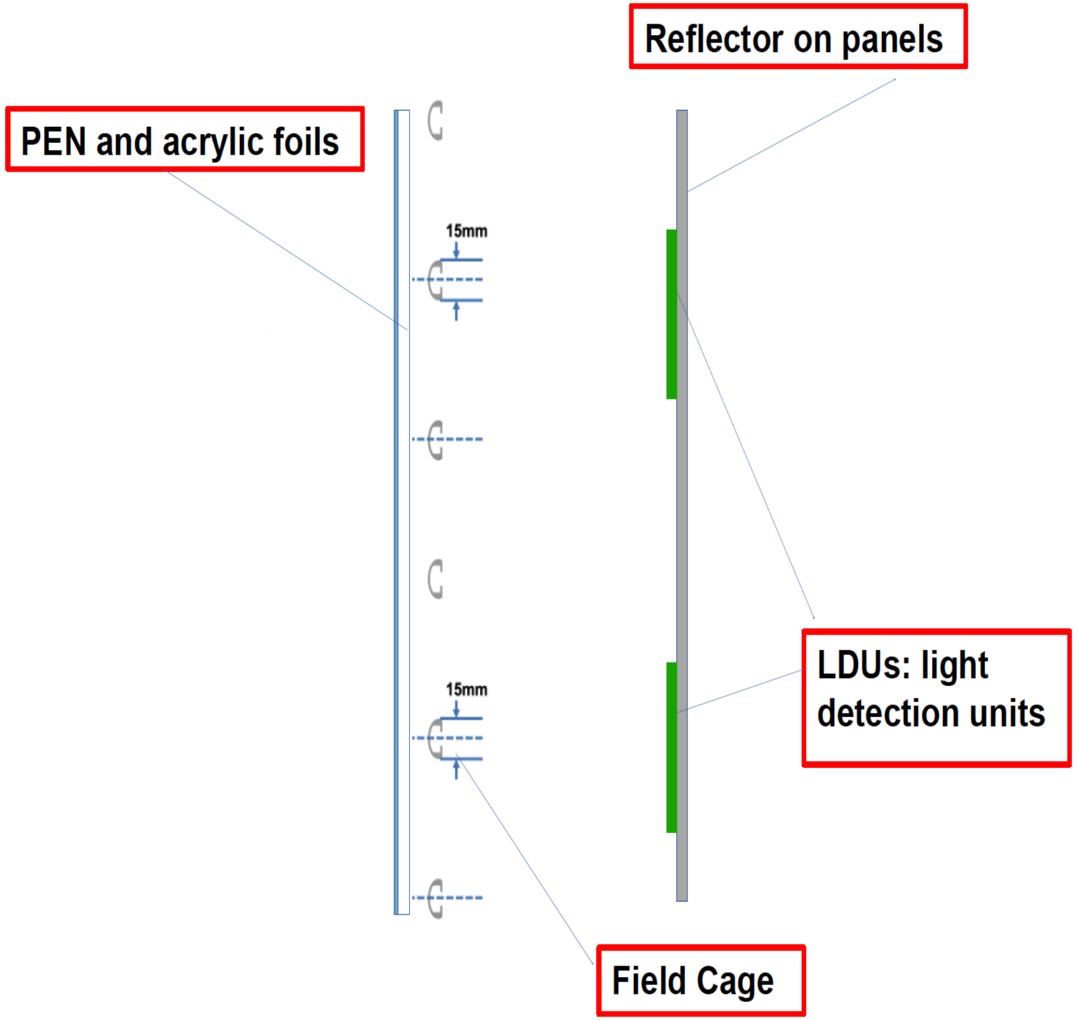
DS-like optical module 20 cm × 20 cm
(Image courtesely of L. Consiglio)



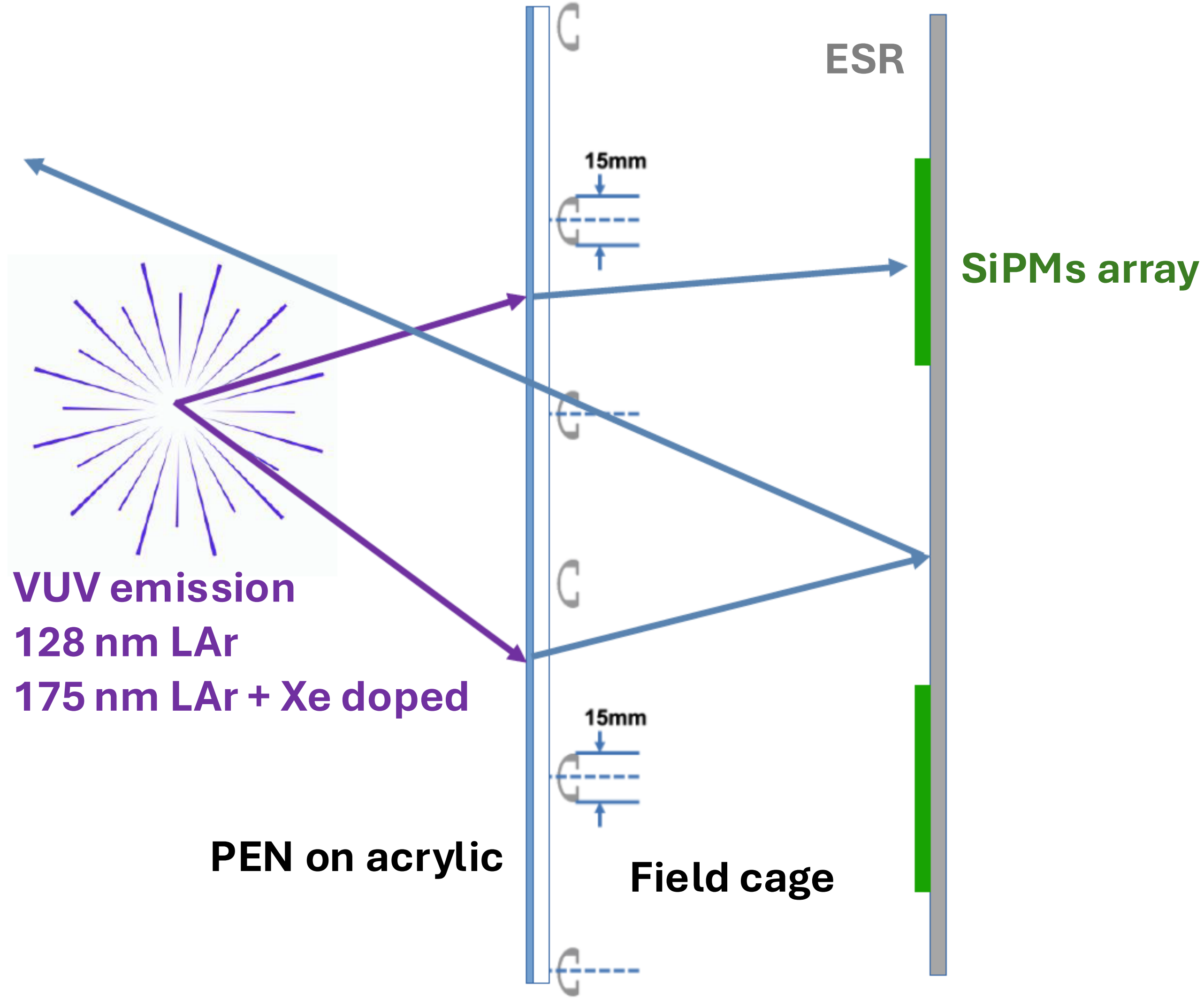
Light Detection Unit: combination of standard **visible** with **VUV** sensitive SiPMs: **LAr buffer used as active VETO**

PoWER concept and design

- Full coverage of the field cage with PEN foils
- Large array of SiPM optical modules mounted the membrane
- Combination of standard visible with VUV sensitive SiPMs: LAr buffer used as active VET
- Large plastic panels lined with ESR reflectors (>98% reflectivity of the visible light) on membrane to enhance the detection probability the visible-shifted photons.



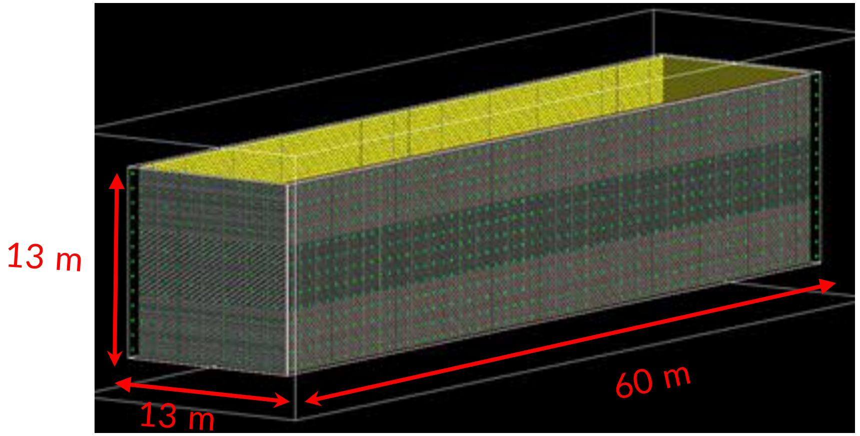
PoWER detection principle



- Scintillation VUV photons converted by PEN wavelength shifters
- 420 nm photons will pass through acrylic and can reach LDU on which are detected with a PDE of about 50%
- 420 nm photons alterntively can reach ESR and are bunched back in the active volume to possibly be detected by another LDU on the opposite side

Full Geant4 optical simulation of PoWER design

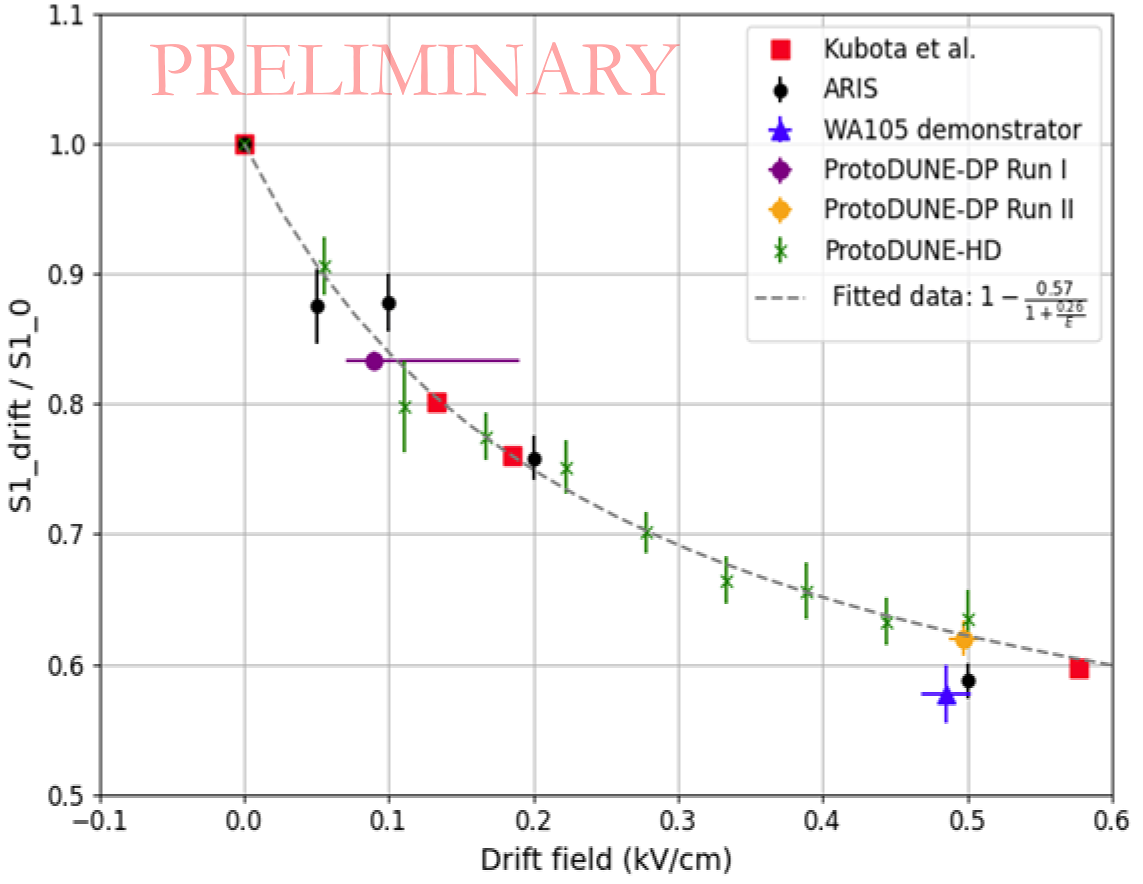
Optical Parameter	Value
Photon Yield @0.5 kV/cm	25,000 photons/MeV
Xe doping	10 ppm
Light fraction@128 nm	30%
Light fraction@175 nm	70%
PEN conversion (@128 nm and 175 nm)	50%
PEN Coverage	FC+50% cathode
Raylegh scatttering @128 nm	1 m
Raylegh scattering @175 nm	8.5 m
Absorption lenght @128 nm	20 m
Absorption lenght @175 nm	80 m
Reflectivity Anode	30%
Reflectivity ESR planes	98%



A central slice of the detector has been divided in voxels of 0.5 m× 0.5 m depositing 1 MeV energy in each voxel and propagating scintillation photons

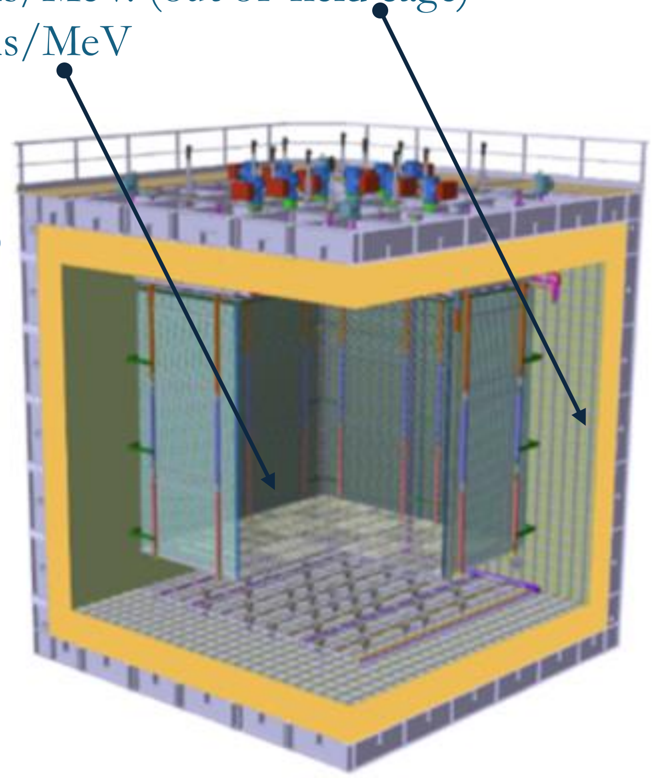
LArTPC light yield: photon generation

LAr Light yield is ~40000 photons/MeV. But this value changes with applied Electric Field



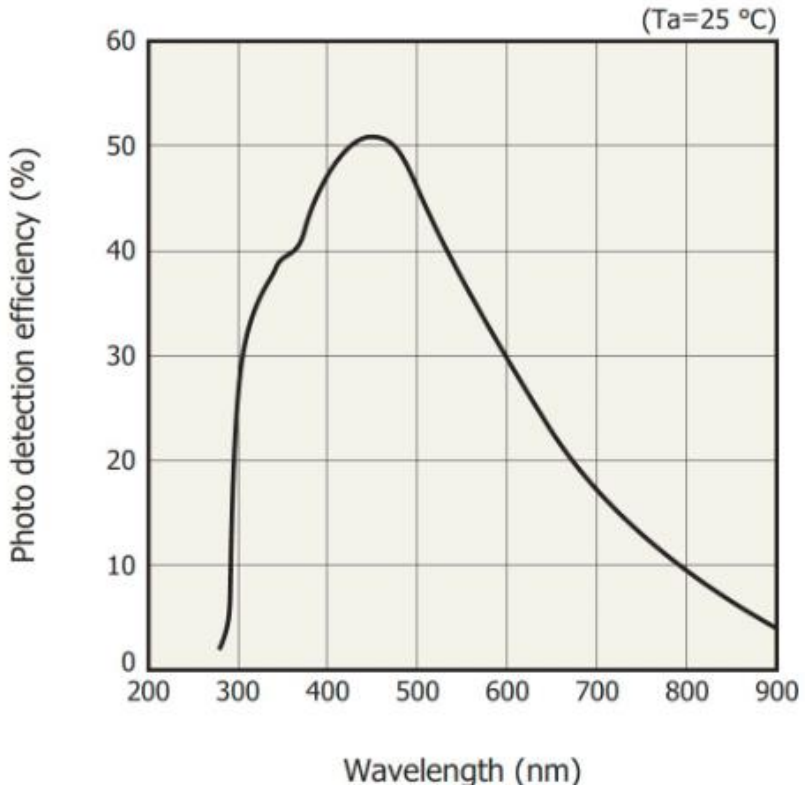
At 0.5kV/cm electric field there is a decrease of scintillation photons due to escaping electrons.
LY @0.0kV/cm = 40000 photons/MeV. (out of field cage)
LY @0.5kV/cm = 25000 photons/MeV

As measured in ProtoDUNE-HD the large prototype of the FD technology running at CERN in 2024

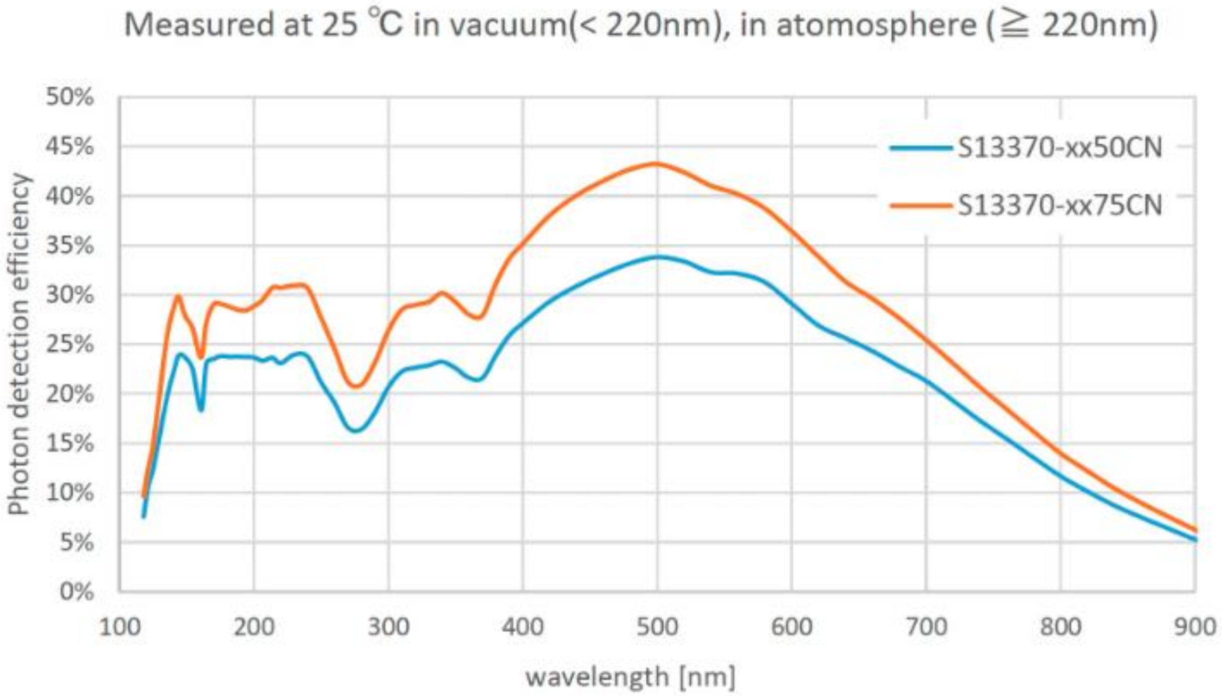


Photon Detection Efficiency for LDU

PDE of Hamamatsu Visible S14160 SiPMs



PDE of Hamamatsu S13370 VUV SiPMs

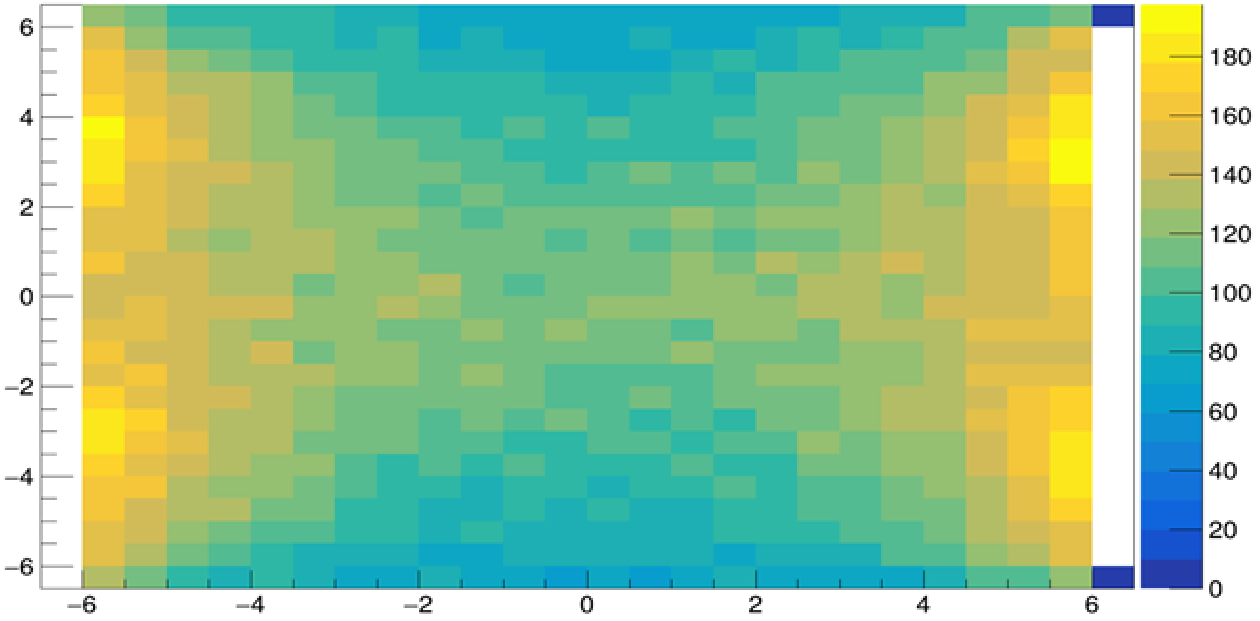


SiPM PDE implemented in simulation, based on the the Hamamatsu SiPM model specifications
SiPM surface reflectivity included in simulation

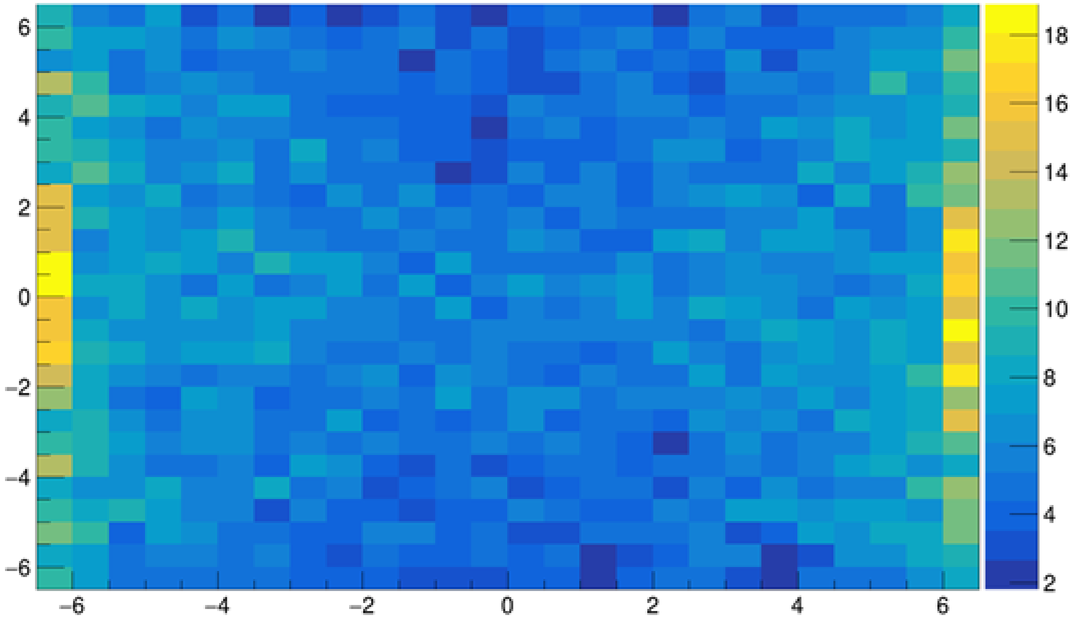
Light Yield map

Results obtained using 1872 light detection units spaced 1 meter apart (overall coverage 75 m^2)

LY map (visible SiPMs)



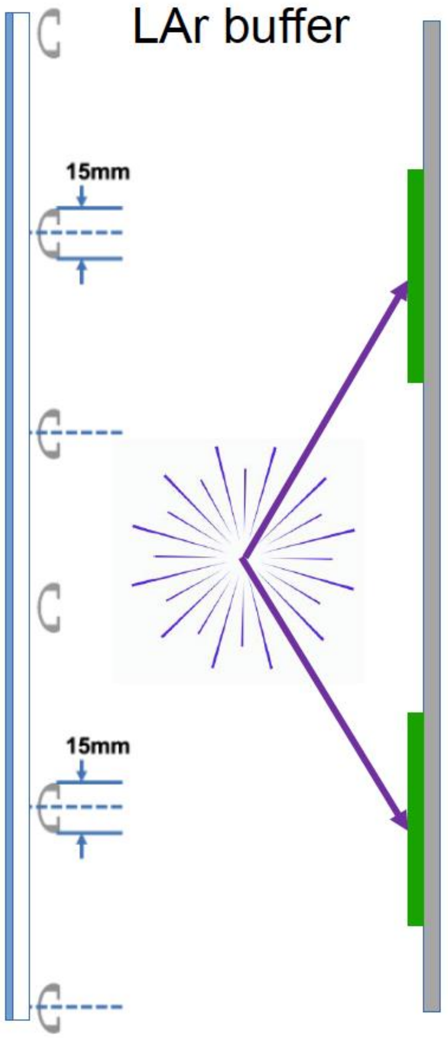
LY map (VUV SiPMs)



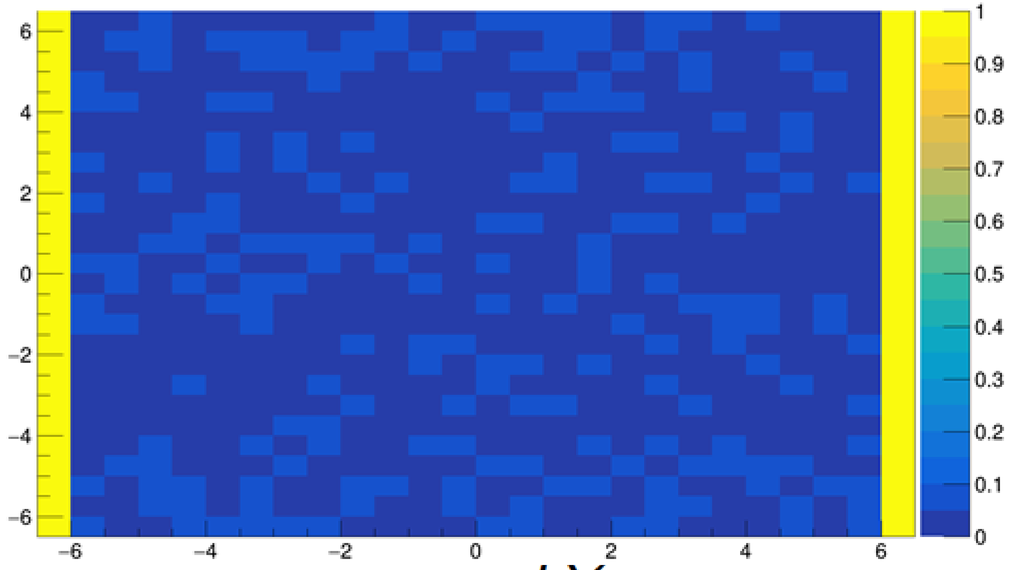
<LY> = 123 PE/MeV Minimum LY = 71 PE/MeV

Light yield enhanced by more than a factor of 3 with respect to Phase I VD design

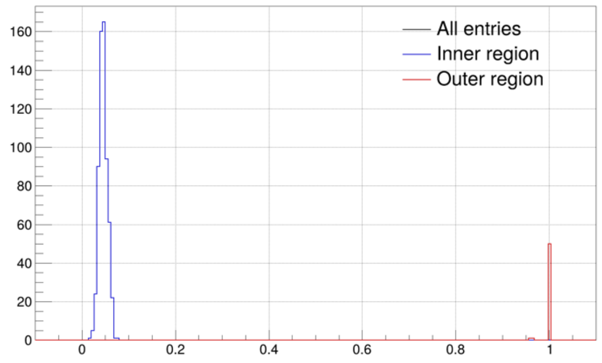
Events in LAr buffer



- Scintillation VUV photons are not converted by PEN since are blocked by acrylic
- Buffer events detected only by VUV sensitive SiPMs
- Events inside active volume produce signals from both Visible and VUV SiPMs
- Using signal unbalance to enable the buffer region as an active veto
- VUV/Total LY close to 1 in the buffer region and close to 0 in the active volume



$$r_{VUV} = \frac{LY_{VUV}}{LY_{VUV} + LY_{VIS}}$$

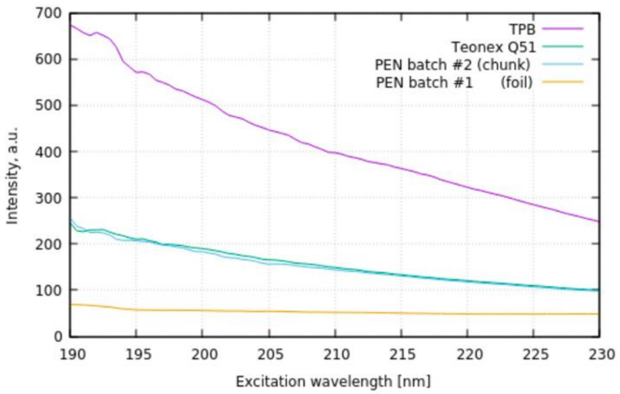


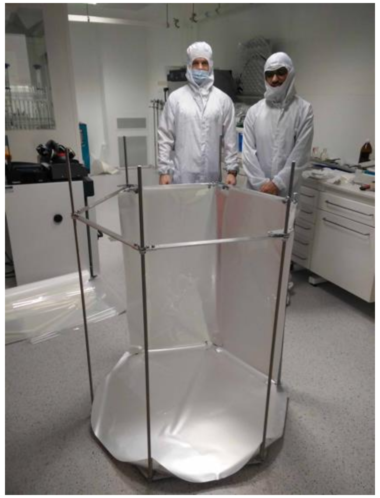
PEN studies

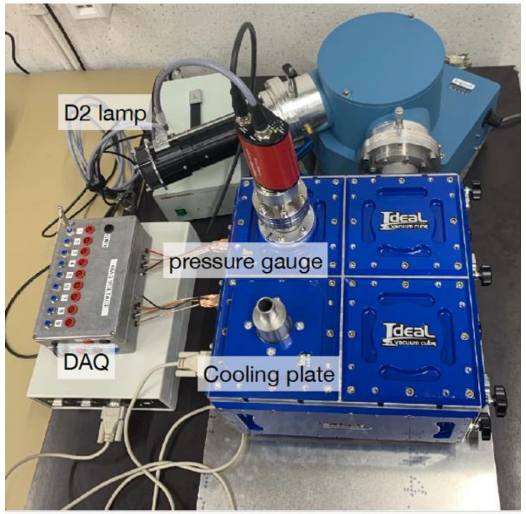
ASTROCENT

Nikhef

- **AstroCENT and Nikhef** groups gained large experience in PEN
- PEN WLSE measured with monochromator at cryogenic temperature
- Tests with additive-free bach of PEN succesfully synthesised matching the performance of commercial PEN (**AstroCENT**)
- PEN stability studies in tonne-scale LAr (**AstroCENT**)
- Synergy with LEGEND experiment: synthesised PEN under investigation (**Nikhef)**







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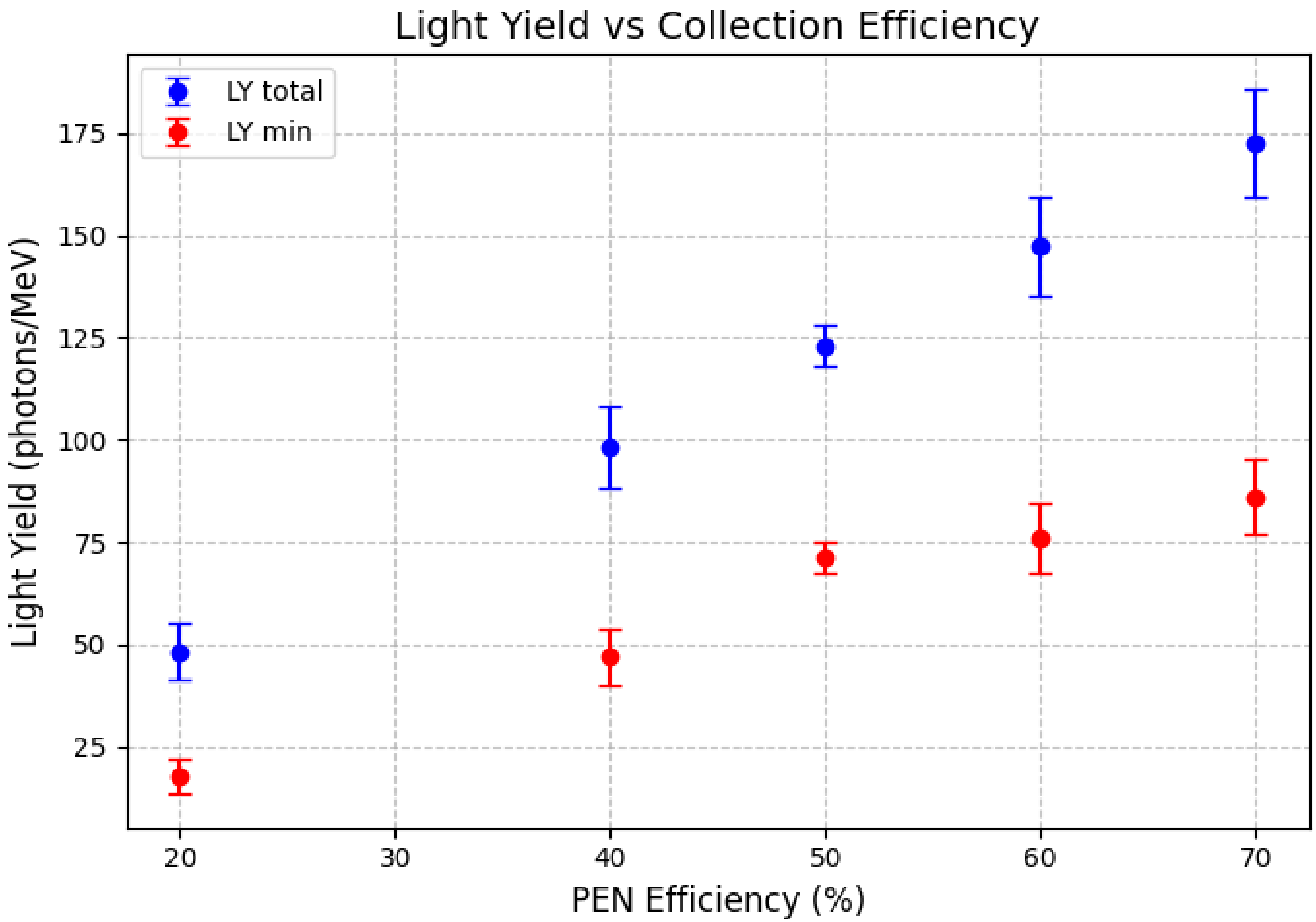
PoWER LY vs PEN WLSE



Small scale prototype

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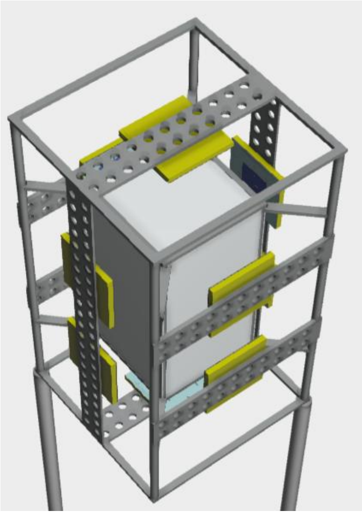
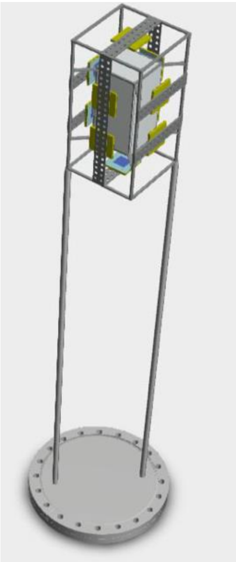
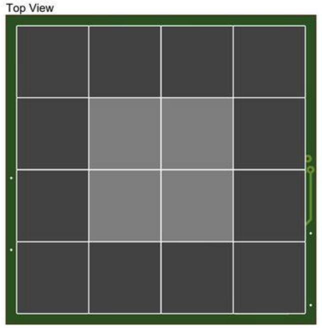
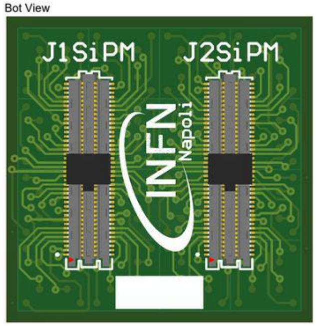
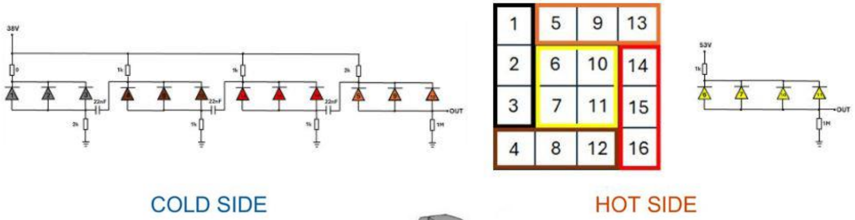


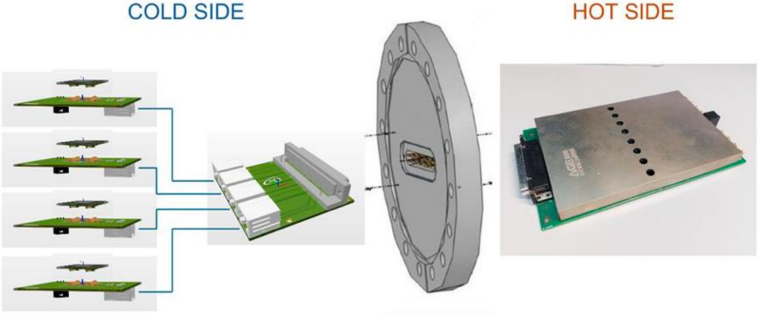


- Test stand at Campinas
- Test chamber is being assembled
- SiPM order placed
- 4 x 4 SiPM matrix will be used (Visible and VUV SiPMs)
- SiPM board+ganging board designed in production
- First tests in 2026









Conclusion

PoWER represents a simple and scalable design for DUNE Phase II:

- Light Yield performance largely satisfies physics requirements
- VETO capability is a highly attractive feature

Next analysis steps:

- Performance studies on low energy physics channels
- Veto studies with SURF background simulation

Small scale prototype test:

- design and part procurement in progress

Back-up slides

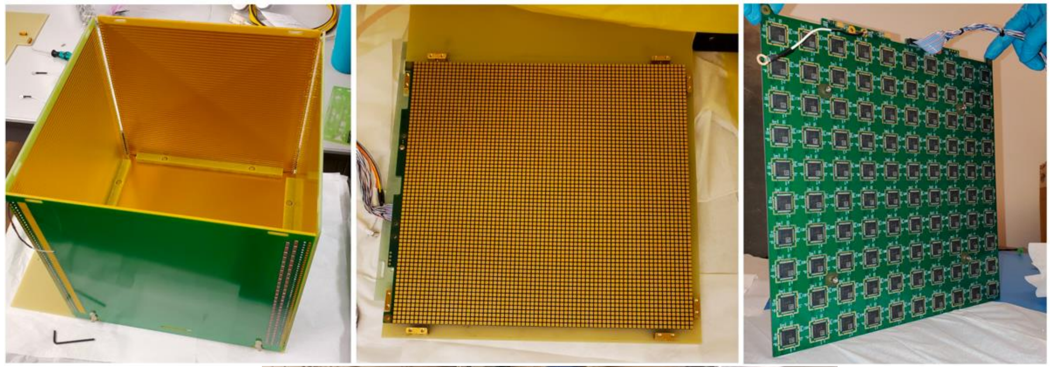
Building DUNE: construction schedule

- **Far site excavation is complete**
- Building and Site infrastructure ongoing
- Cryostat warm structure has been shipped from CERN to US, installation will start in 2026
- **Detector installation in 2026-27**
- Purge and fill with liquid argon in 2029
- **Physics by the end of 2029, early 2030:** Solar, atmospheric and astrophysical neutrinos
- **Beam physics with Near Detector by 2031**

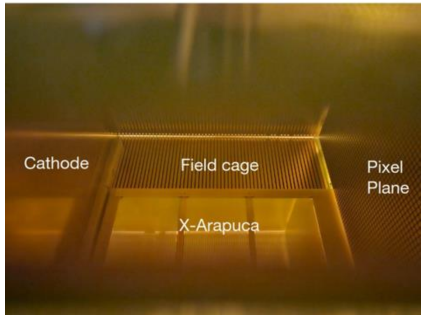
Medium scale facilities

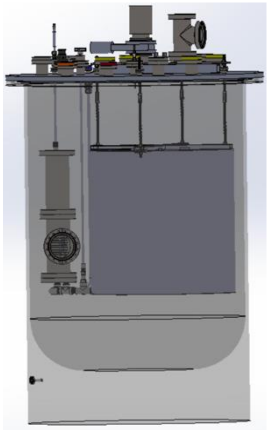
M. Mooney

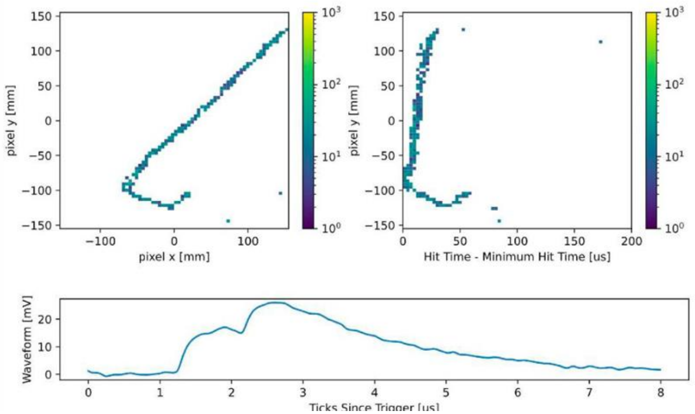
Yun-Tse Tsai

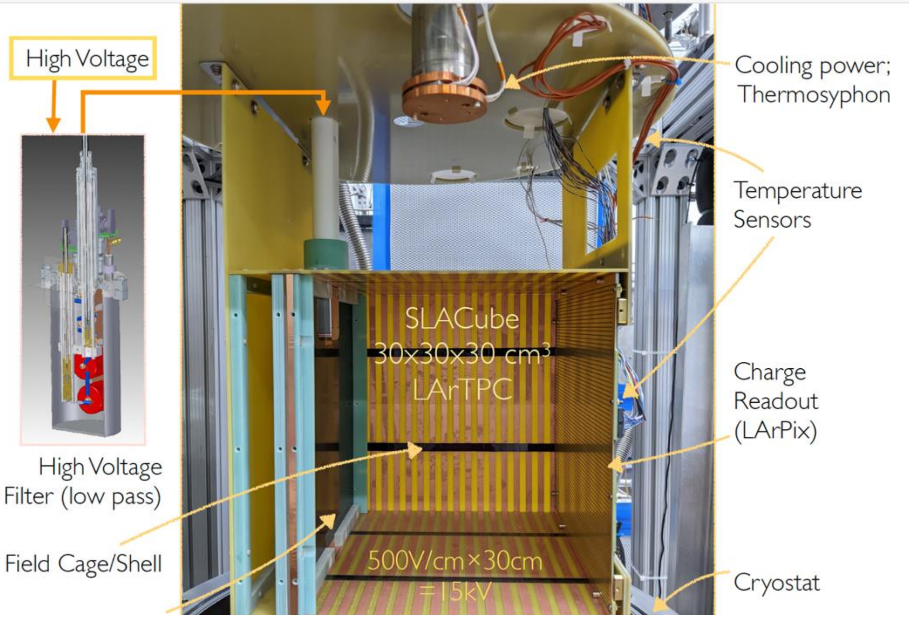


View inside TPC after installing light detector







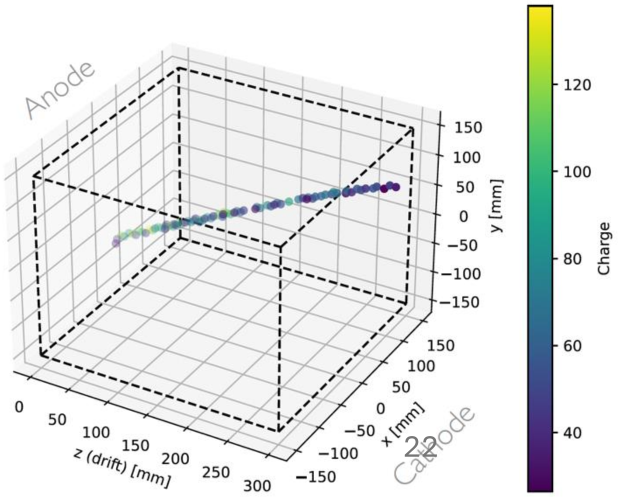


E = 500 V/cm

Electron lifetime (LAr purity) ~ 225 μs

Data taken on July 31st, 2022 (P.Tsang)

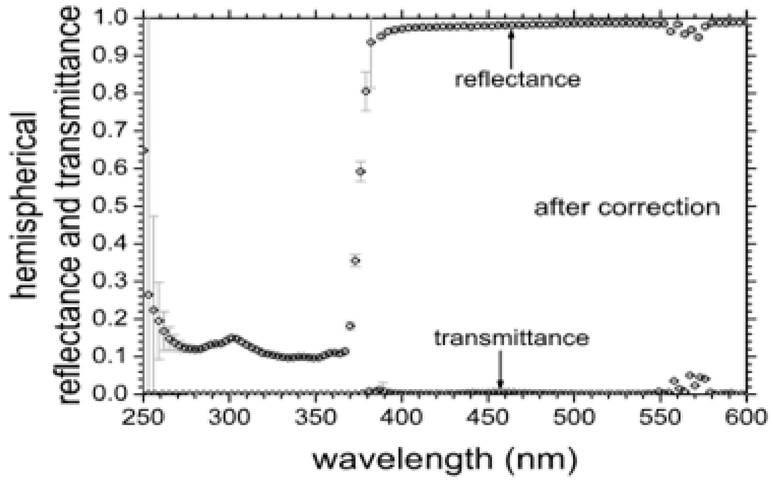
~1 cosmic ray track every 2 minutes

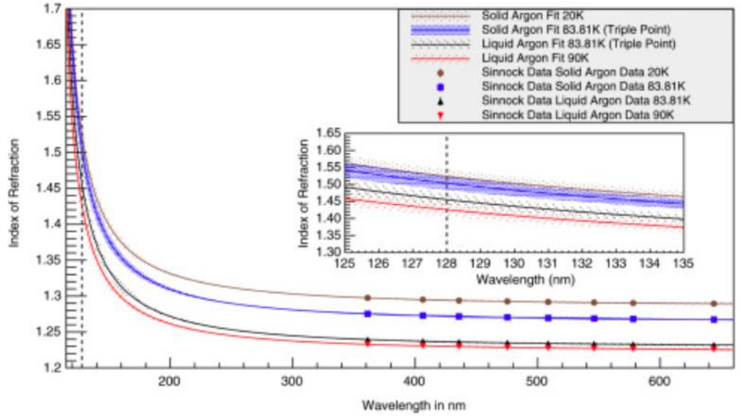


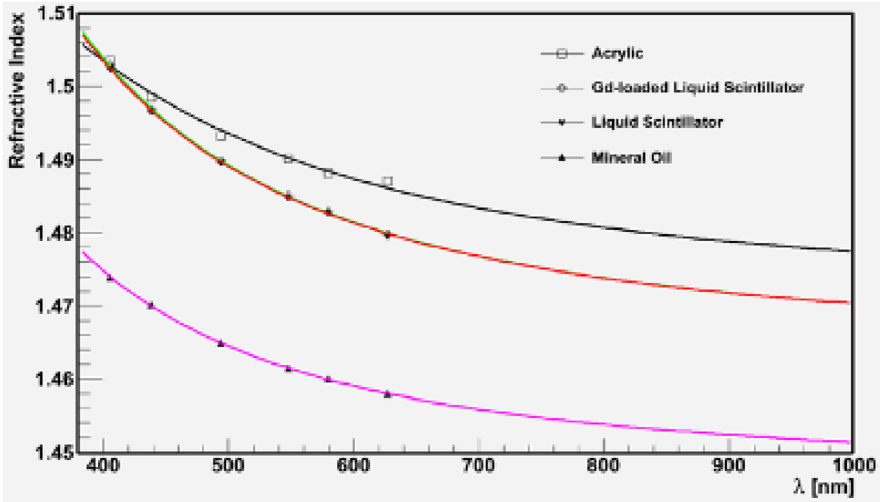
- CATS (Colorado Argon Test Stand), operating at CSU since 2021
- Pixellated charge readout with electron lifetime ~1 ms
- Light detector based on X-Arapuca (PoWER style can be implemented)

Material optical characteristics

- ESR reflectance vs wavelenght
- Acrylic optical characteristics
- PEN refractive index (1.65) and emission spectra
- ESR reflector and PEN also on cathode plane
- LAr refraction index vs wavelengh

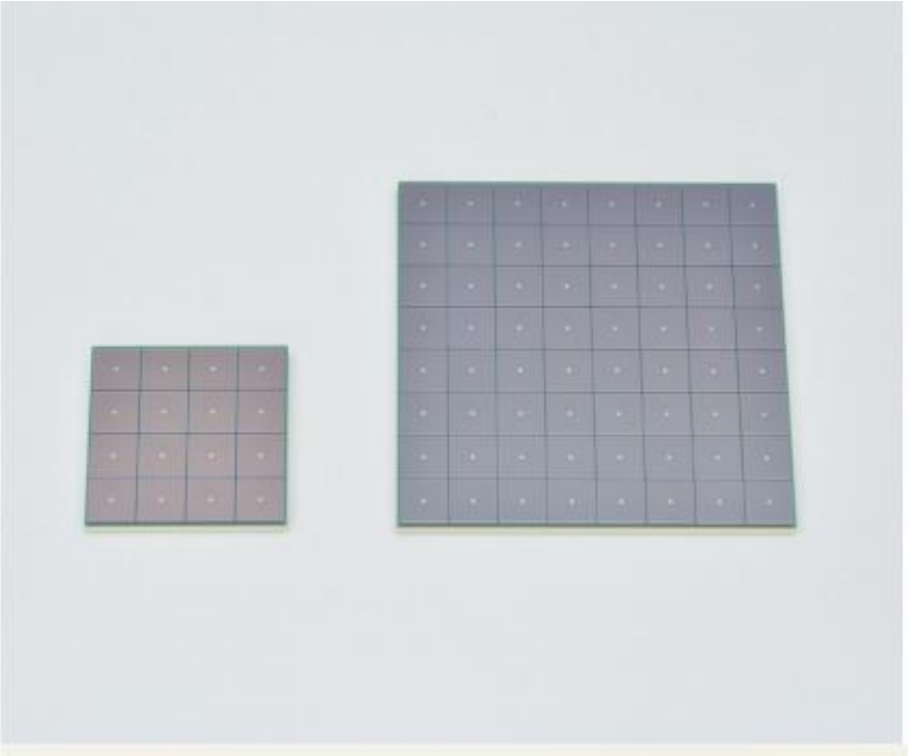




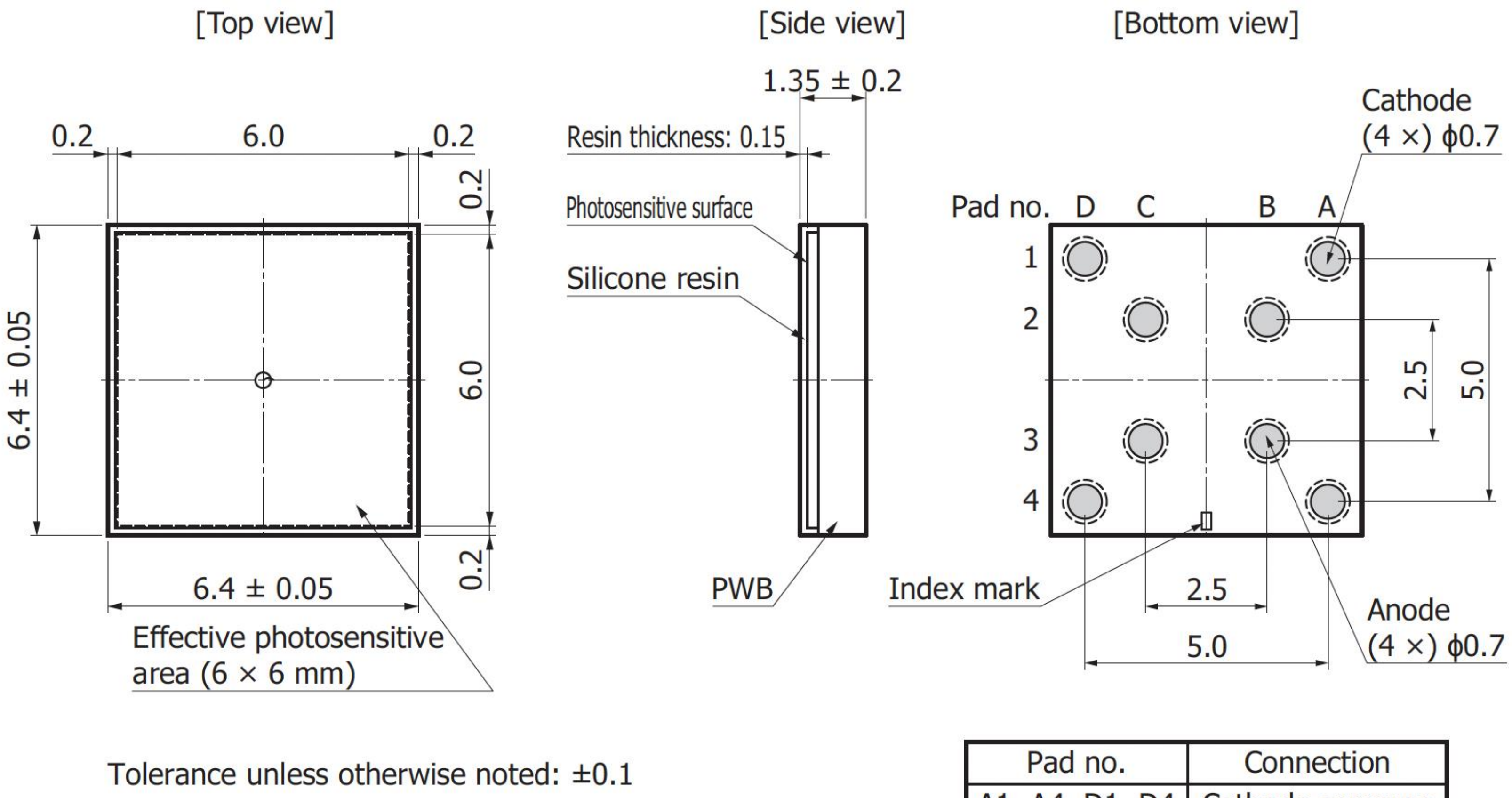


Hamamatsu SiPMs

- Matrices available: **S14161** model (4 ×4 and 8 ×8 arrays), standard visible light sensitive (up to 320 nm)
- **S14160** model: Single SiPMs with smd package (max dimension 6 mm × 6mm), the same used in DUNE for FD1 and FD2 in the Arapucas light collection systems
- VUV sensitive (**VUV4 – S13370 model**) – recently available in smd package and 6 mm × 6 mm sensitive area



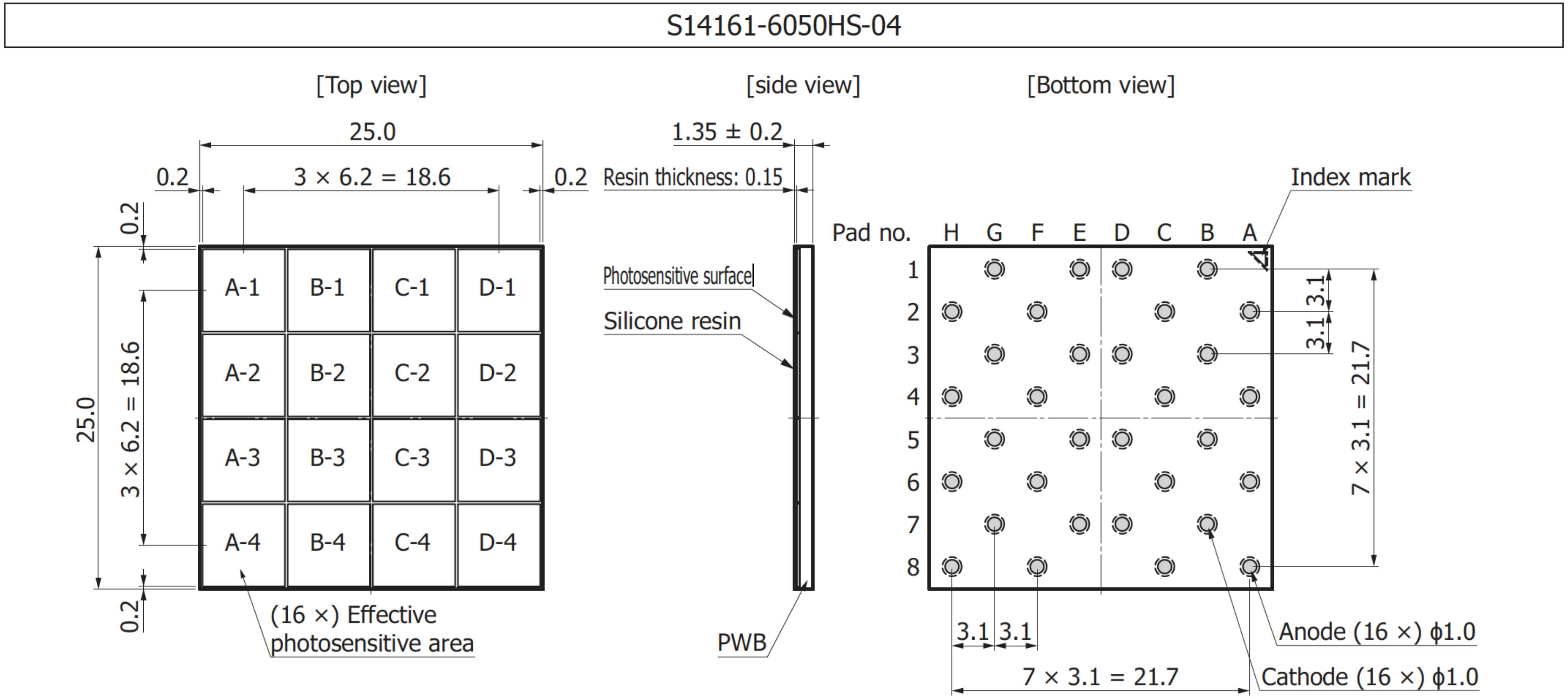
S14160-6050HS smd package



Pad no.	Connection
A1, A4, D1, D4	Cathode common
B2, B3, C2, C3	Anode common

- SiPMs anode and cathode pads can be directly soldered on properly developed PCB
- array of SiPMs with any dimension ans shape can be composed

4 x 4 matrix (S14161-6050HS-04)



LY map and Average LY

Distance between LDUs (m)	Number of LDUs	Area covered by the LDUs (m^2)	<LY>	LYmin
1.0	1872	75	124.83	56
0.9	2400	96	157.57	64
0.8	3060	122	196.42	86
0.7	3876	155	245.87	120