Система считывания света в жидком аргоне модульной TPC ближнего детектора эксперимента DUNE

Научно-методический семинар ЛЯП

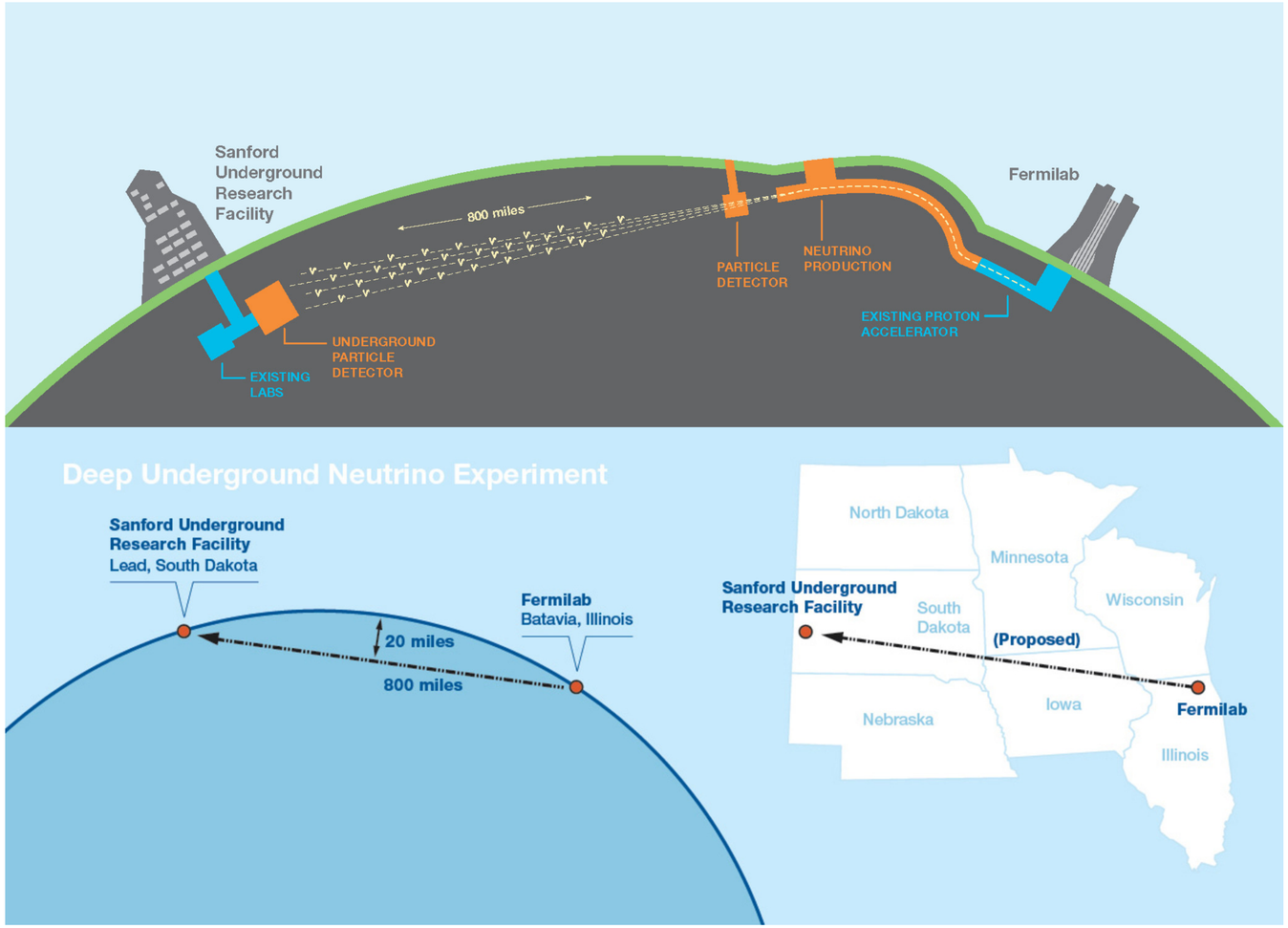
Селюнин Александр Сергеевич, 09.03.2023

Содержание

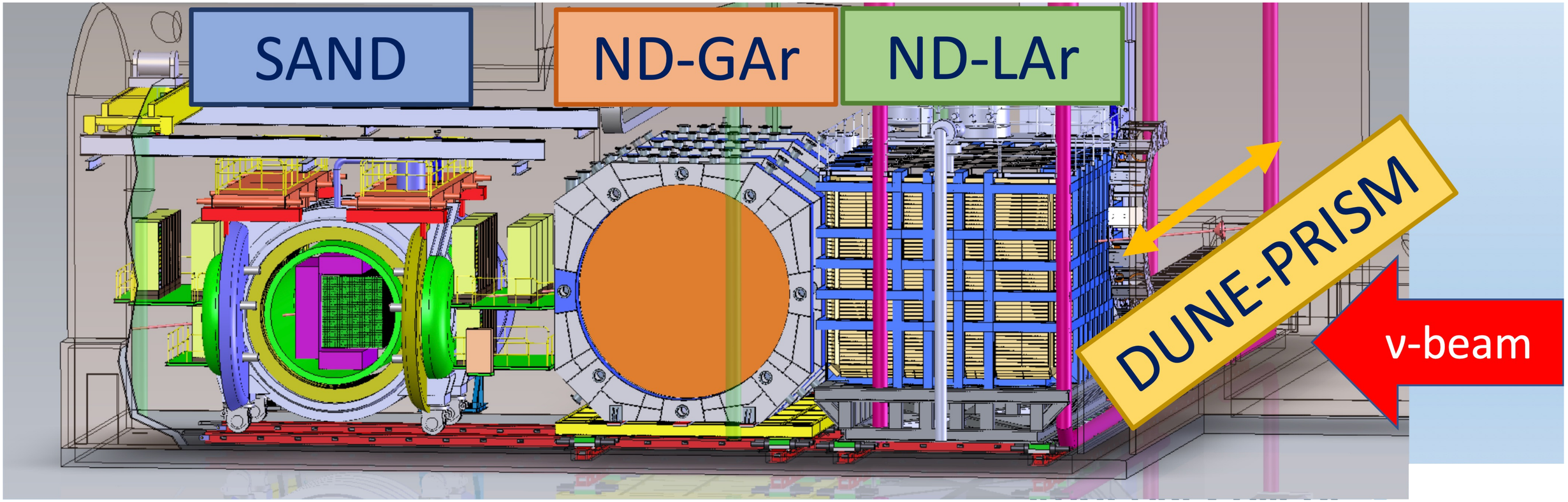
- Вступление:
  - эксперимент DUNE
  - Ближний детектор DUNE
  - Жидкоаргоновая ВПК
  - Зарядовая и световая системы
- Компоненты световой системы
- Прототип 2x2. Результаты испытаний в Берне. Подготовка 2x2 для тестов на пучке нейтрино.
- Подготовка к испытаниям полноразмерного модуля ВПК
- Планы на 2024-2026 гг.

Эксперимент DUNE

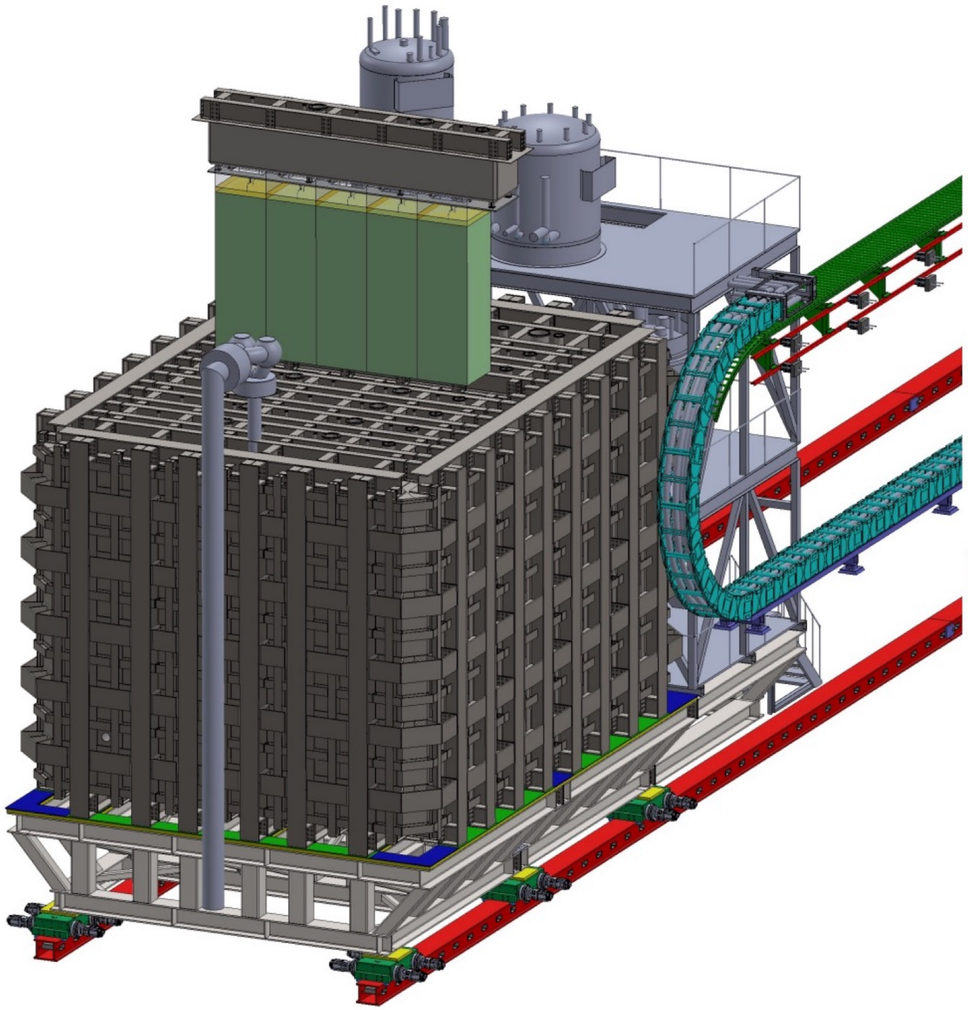
- Ускорительный нейтринный эксперимент с длинной базой (1300 км)
- Последователь эксперимента NOVA
- Два детекторных комплекса: ближний и дальний детектор
- Нацелен на изучение параметров осцилляции нейтрино, иерархии масс нейтрино, фазы нарушения CP инвариантности



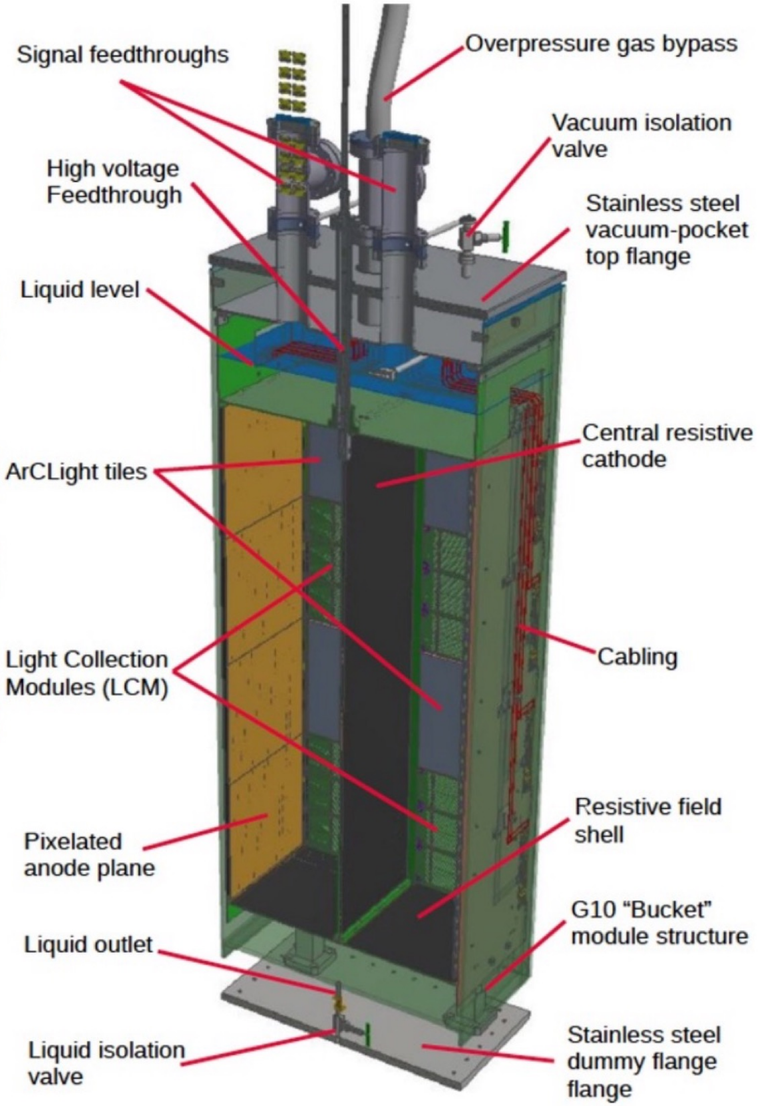
DUNE Near Detector



DUNE ND-LAr TPCs



5 x 7 = 35 TPC modules



ND module size – 1m x1m x 3m

Light detectors are along the electric field

Key Design Features:

Active size:

5m deep, 7m wide, 3m tall

→ For ν signal containment

Signal rate: ~10 M / yr

Modular design:

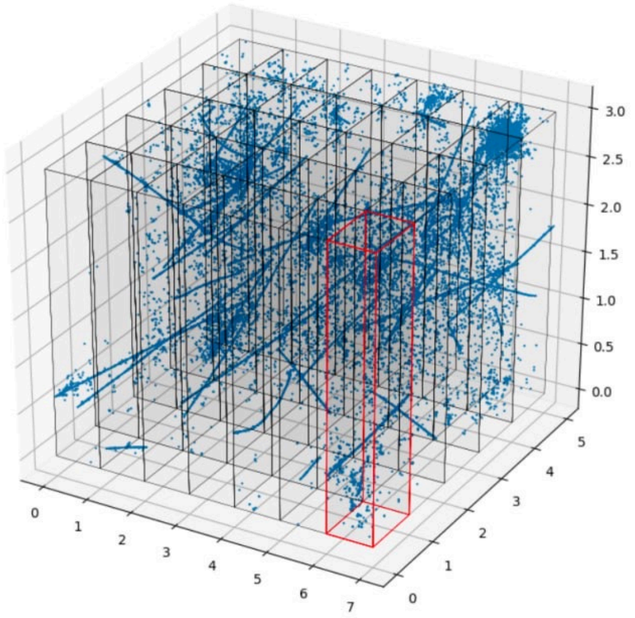
- 5 x 7 hermetic TPC modules
- 3m active height
- Minimal inactive material
- Material density (G10) similar to LAr
- Short drift (50 cm)
- Pixelated charge readout
- Optical segmentation
- High-performance light detection

→ *System reliability and capability to operate in high-rate environment*

By J. Raaf

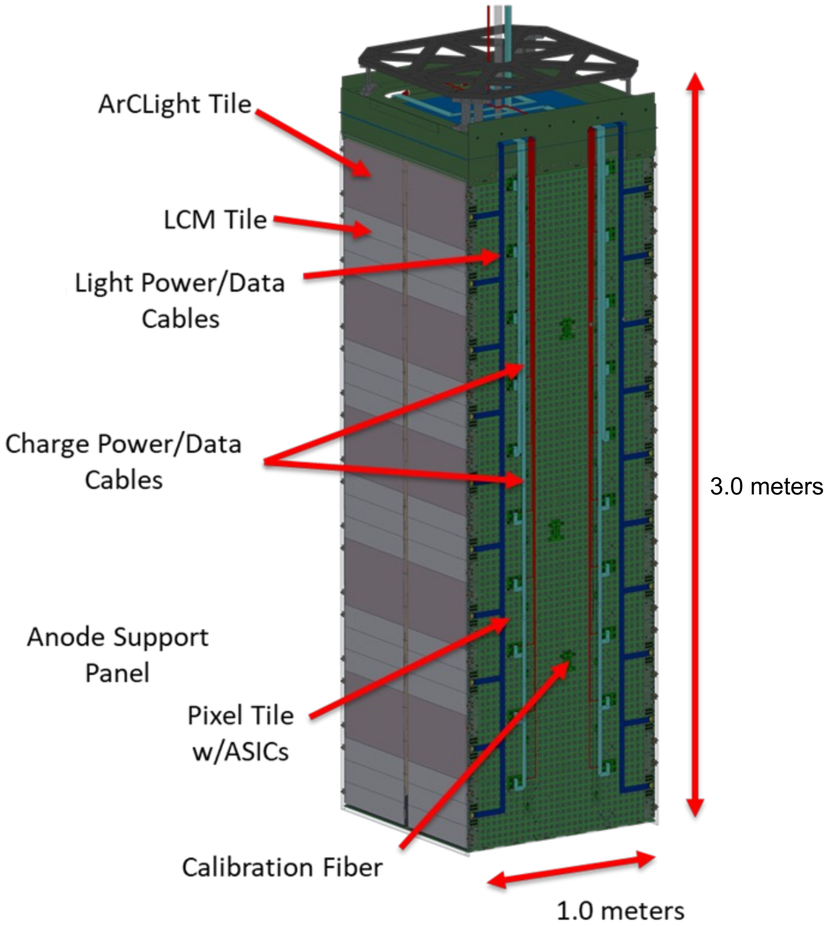
Intention of the Light detection system

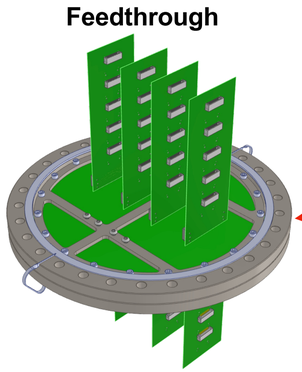
- Provide t0-trigger for track correction
- Resolve pile-ups and associate tracks in time
- Assign detached energy events (~ns)

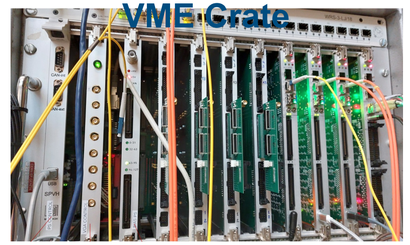


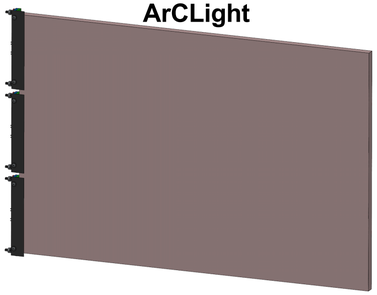
An event display of the visible energy for a typical spill from the 1.2 MW beam spill coming from the LBNF neutrino beam. The large number of crossing muons and multiple neutrino interactions can be seen along with the segmentation offered by the modular structure of the ND-LAr system

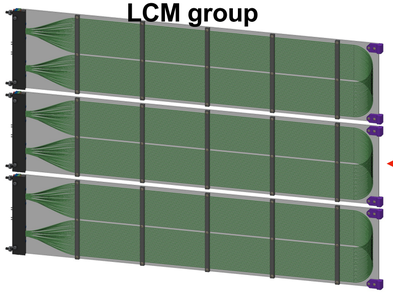
ND LArTPC Module Design

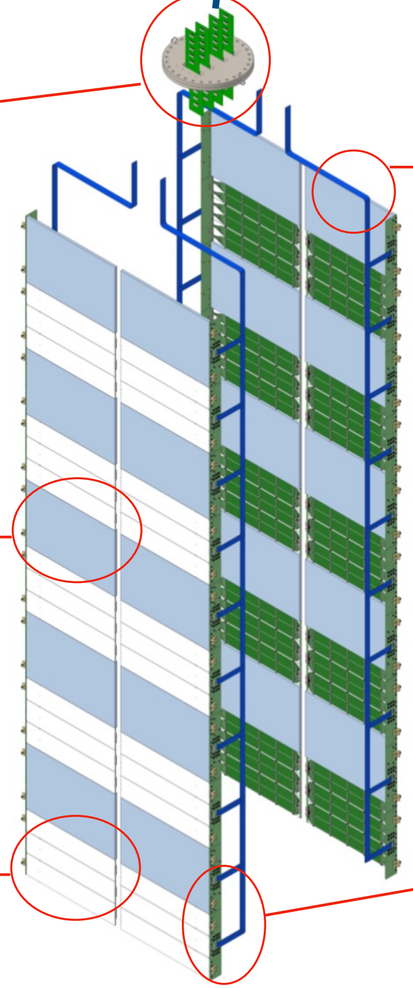


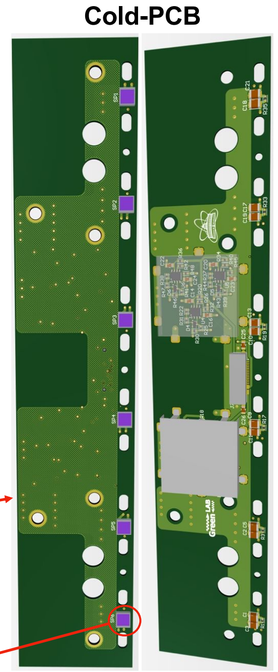






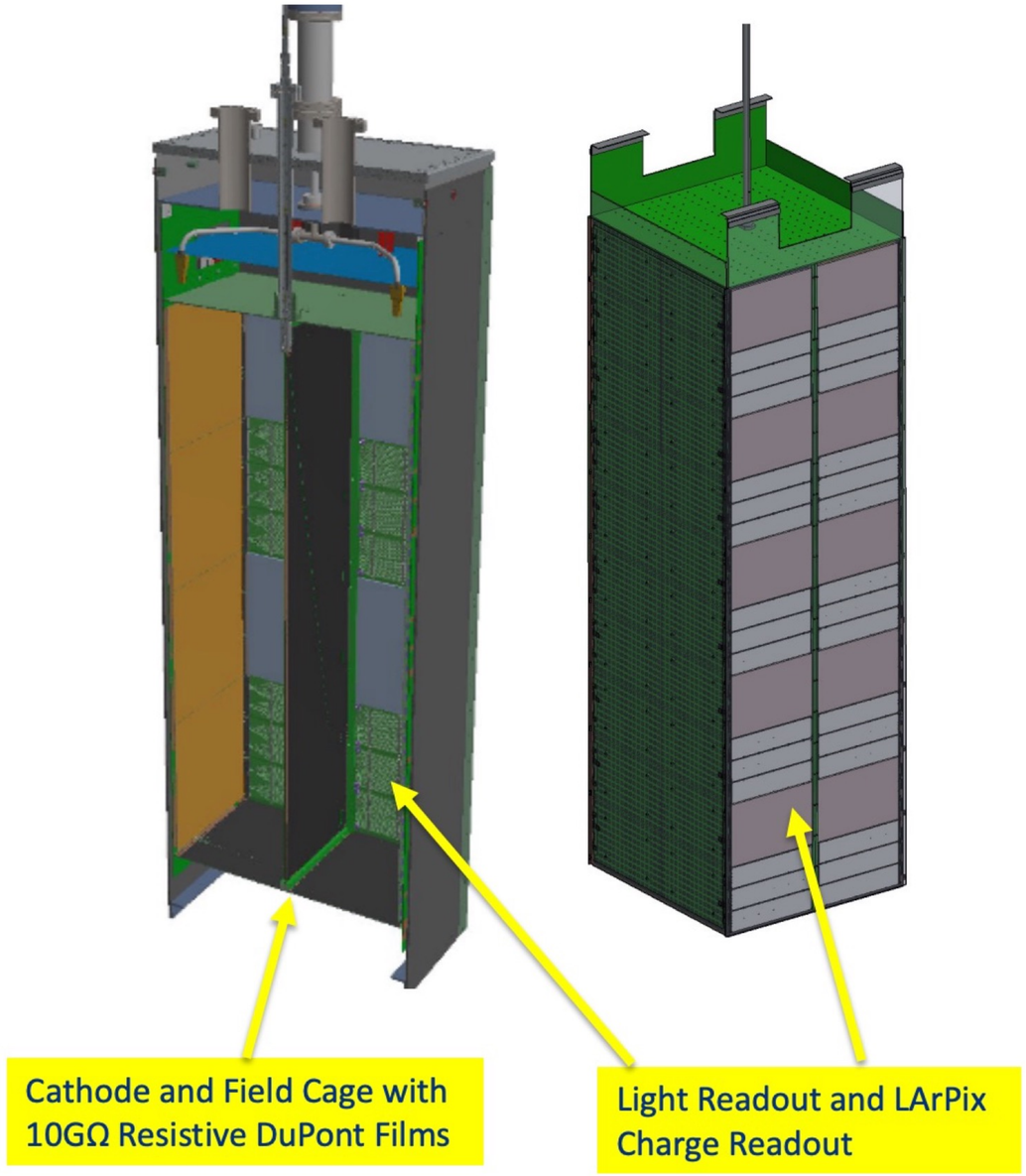


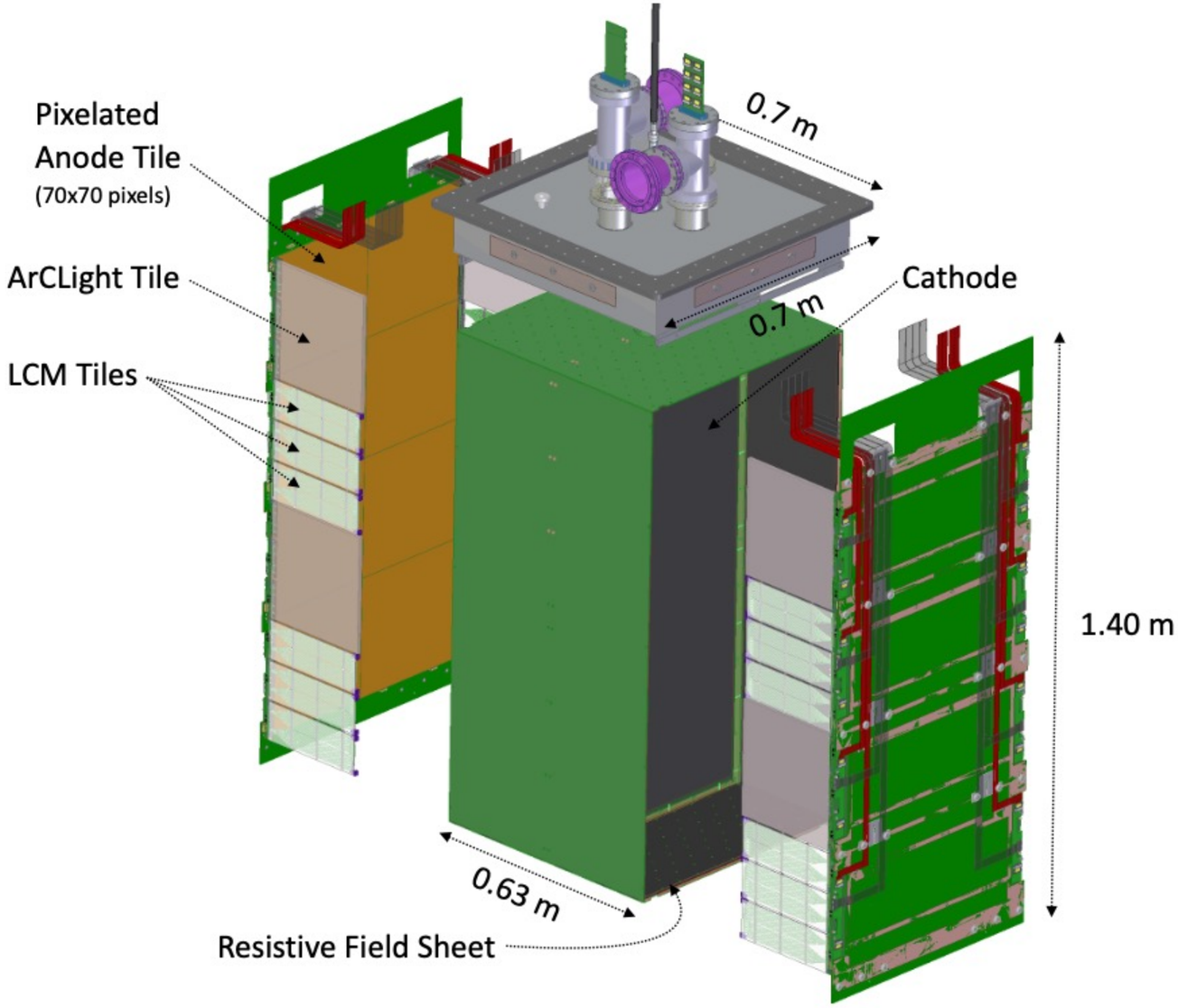




LCM group and ArCLight are fully interchangeable

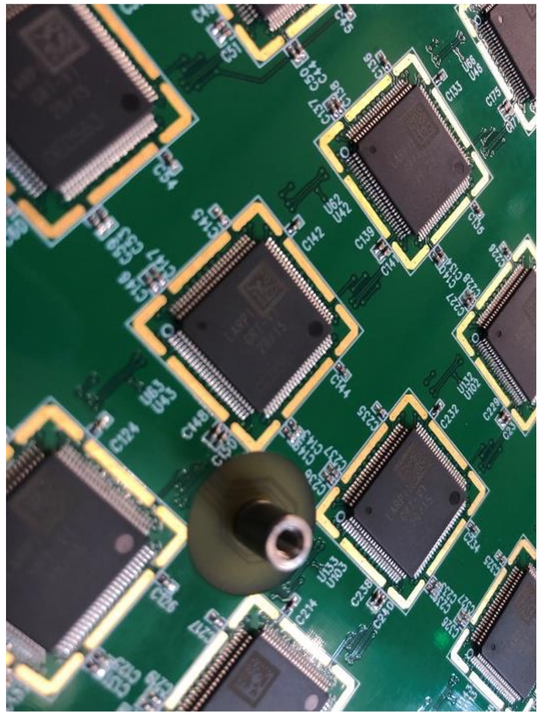
2x2 Modules: 0.75m x 0.75m x 1.6m

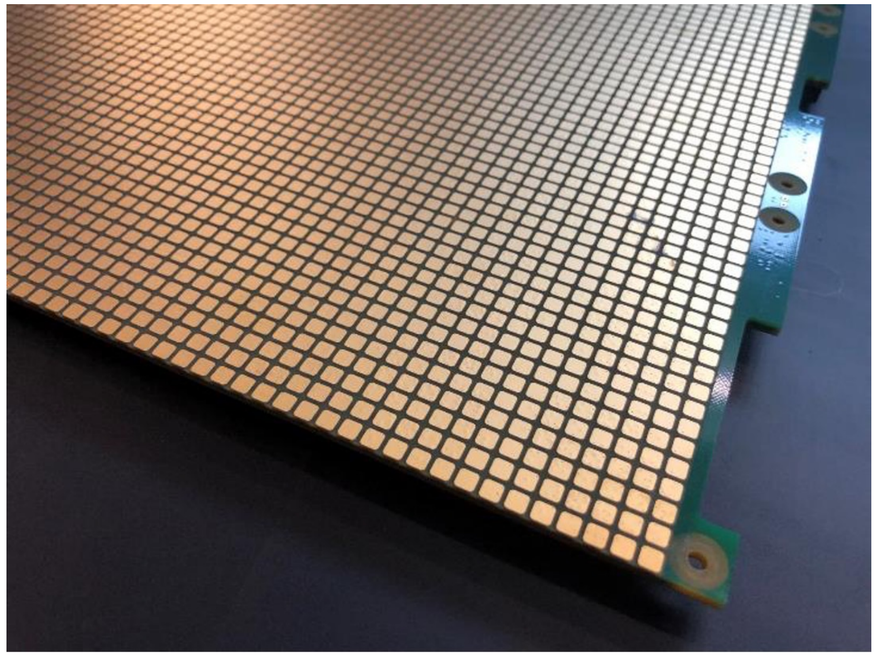




Charge readout

- Pixel Size - 4x4 mm^2, Pitch = 4.4 mm, 4900 pixels
- LArPix ASIC reads out up 64 pixels
- Pixel tile 300x300 mm (prototype), 100 ASICs
- Full Scale Demonstrator: ~ 300x500 mm





✦Drift velocity ~ 180 μs / 30 cm @ 0.5kV

✦MIP energy loss 2.1 MeV / cm

✦Electron-Ion pair energy 23.5 eV

✦Recombination ~0.6 @ 0.5kV

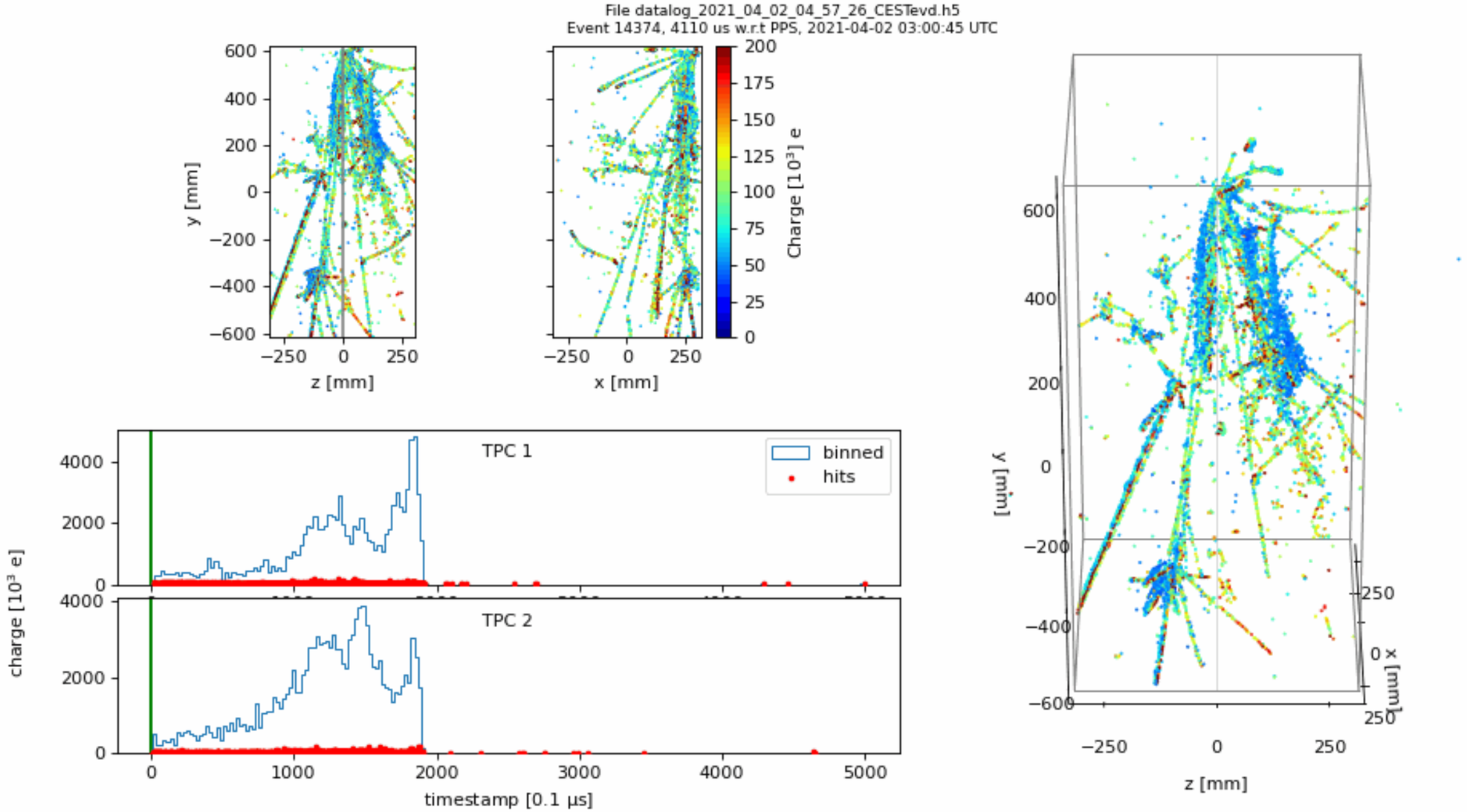
✦Pixel size ~ 4 mm -> $2 \cdot 10^4$ e^- per MIP

✦Resampling time 2.2 μs -> Time pixel ~ 4 mm

✦Hit time stamp ~ 100 ns -> Spacial resolution ~ 0.15 mm

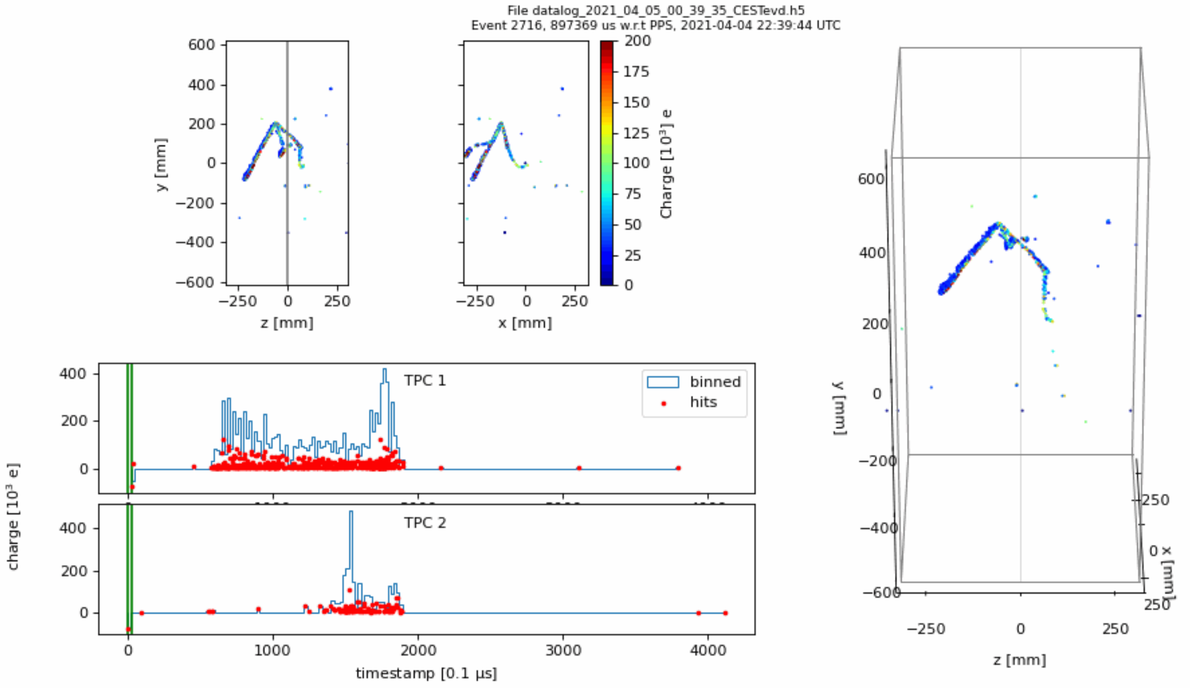
https://argoncube.org/tracks.html

Institutions: LBNL, Caltech, CSU, Rutgers, UC-Davis, UC-Irvine, UCSB, UPenn, UTA

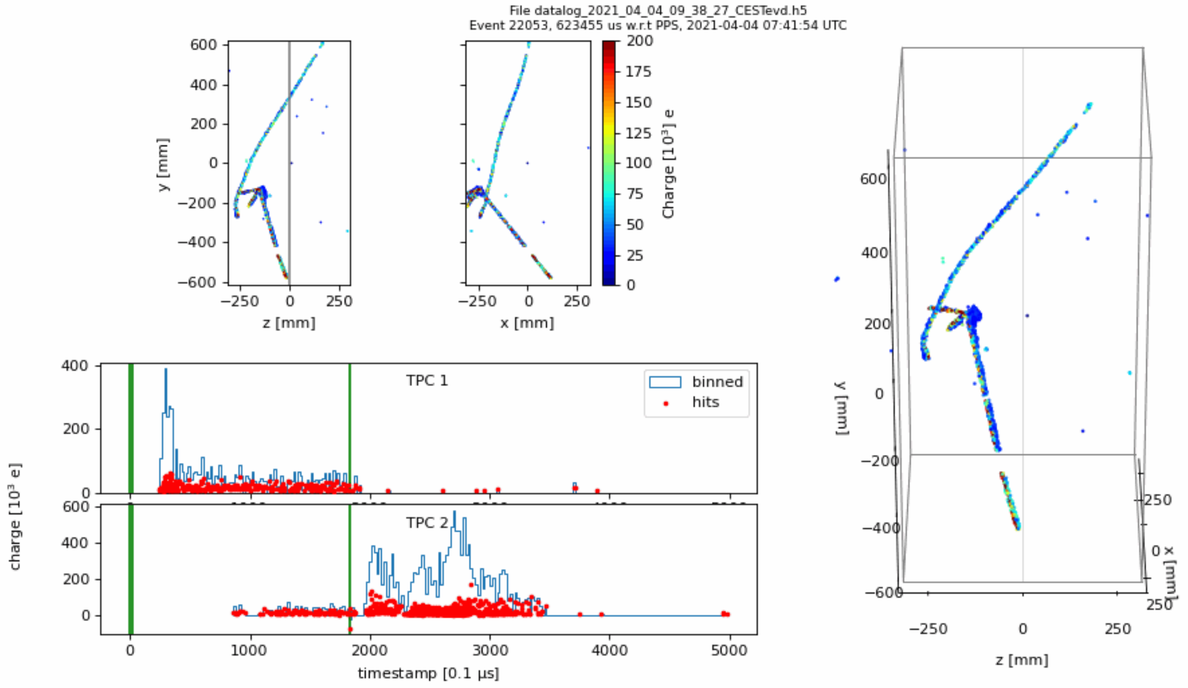


https://argoncube.org/tracks.html

Multi vertex interaction.



Neutrino like event with two pions and a proton.



Neutrino like event with a muon and three protons.

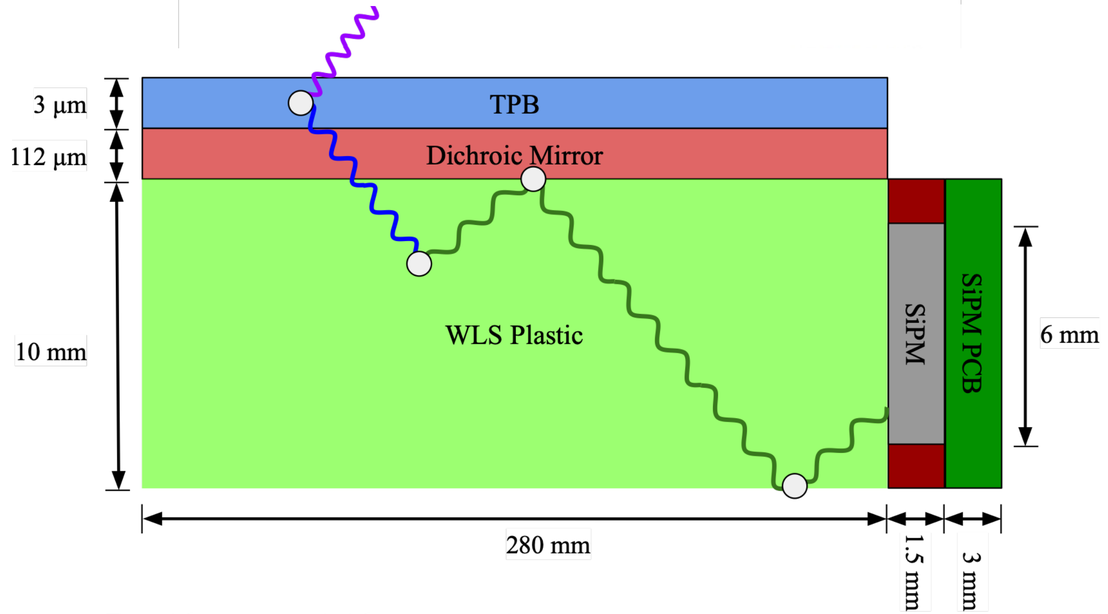
https://argoncube.org/tracks.html

Light detectors

Design drivers:
- Dielectric materials
- Large surface covering
- Relatively high PDE

Both approaches are based on shifting UV light (128 nm) into visible (425 nm) by TPB

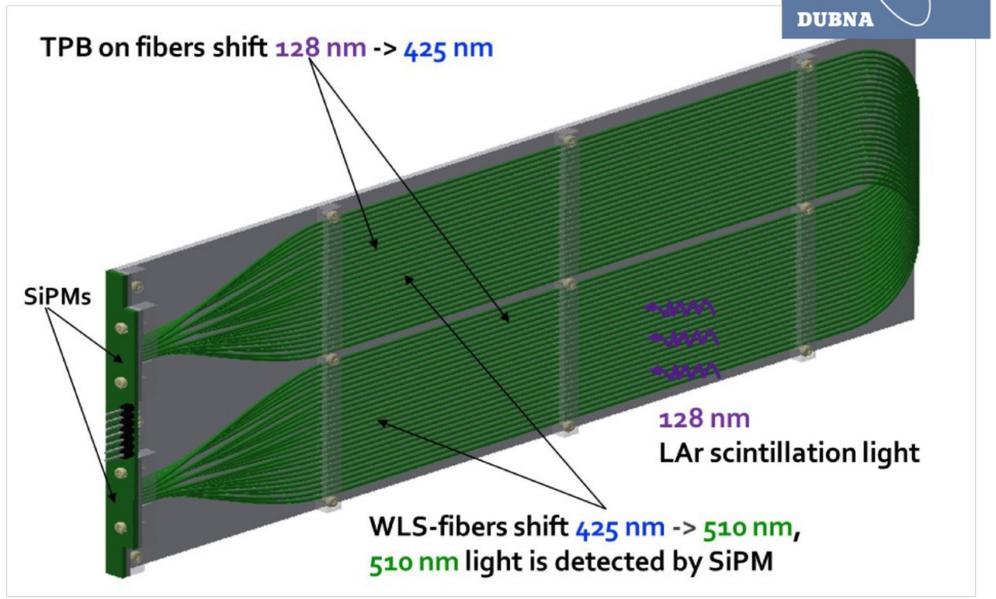
ArCLight Concept



+ Provides more rigid construction
+ Spacial resolution in depth.

- PDE ~ 0.2% (Currently)
- Heavier

LCM Concept

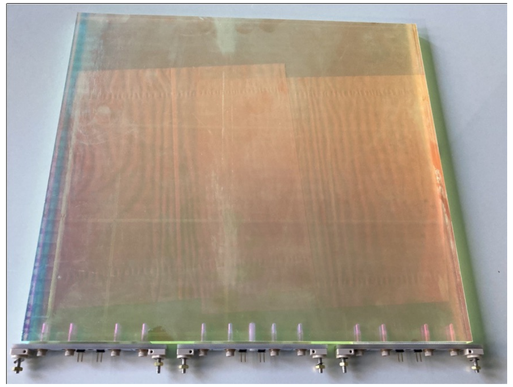


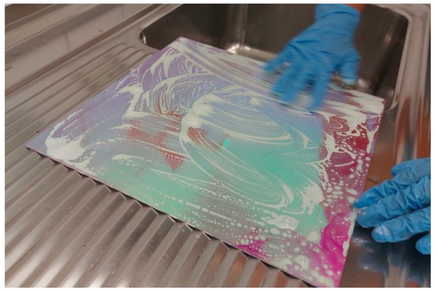
+ Easy to scale -> Fibers have long attenuation
+ Doesn't loose efficiency (PDE) with scaling up. PDE ~ 0.6%
+ Can be used as 1 DAQ channel

- Complex and flexible
- No spacial resolution in depth

Light detectors

ArCLight

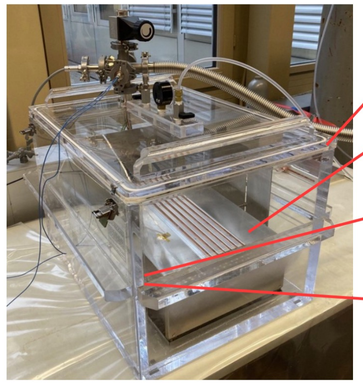




The film is cleaned with soap

The dichroic film is fixed on an aluminum plate

Module 0 and 1



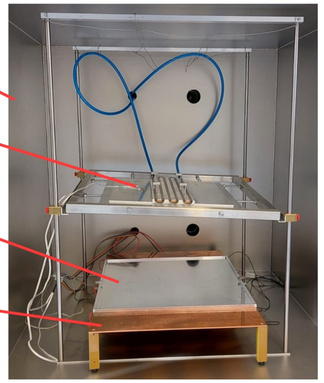
vacuum chamber
acrylic vs metal

cooling plate
identical

TPB tray
small vs big

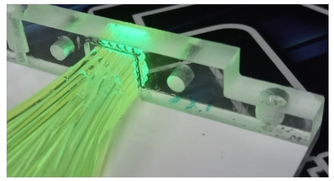
heating table
9 vs 24 resistance

Module 2

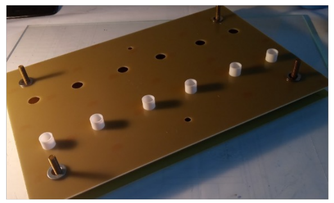


Coated film is removed from aluminum plate

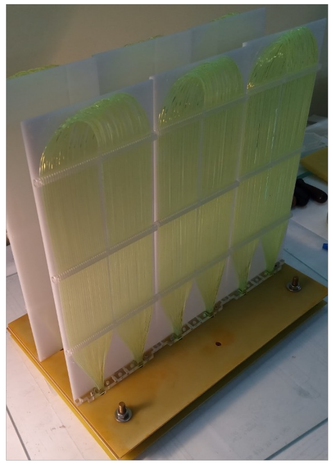
LCM

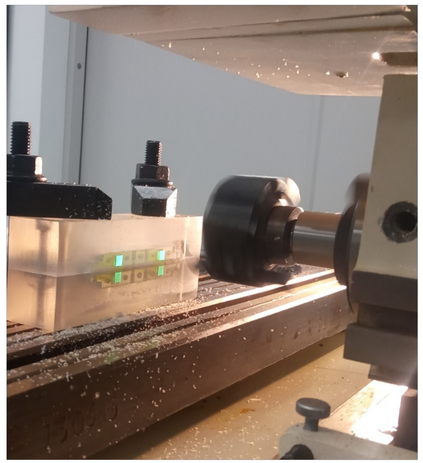


1x1mm groove for glue

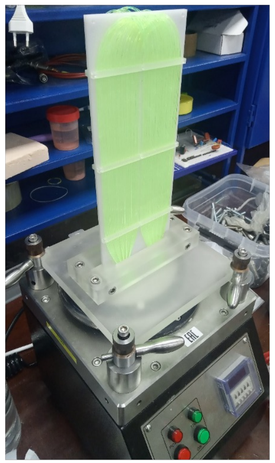


PTFE containers for bundle's fibers (capillary effect)

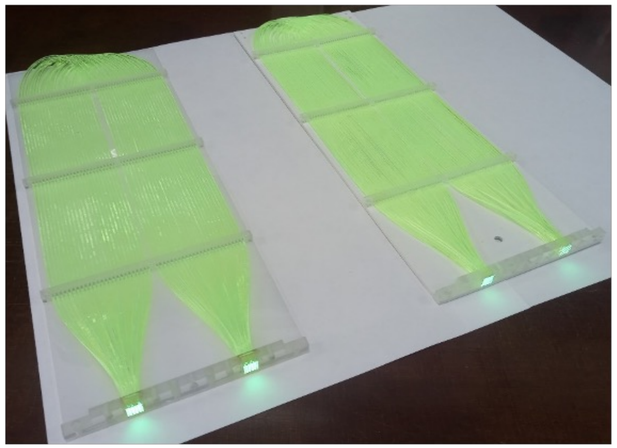




To process with MCD diamond tool



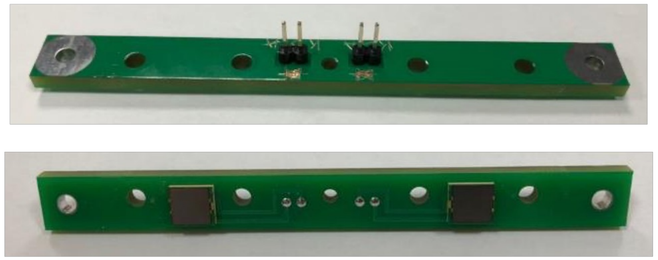
Apply polishing machine for fabric optical connectors

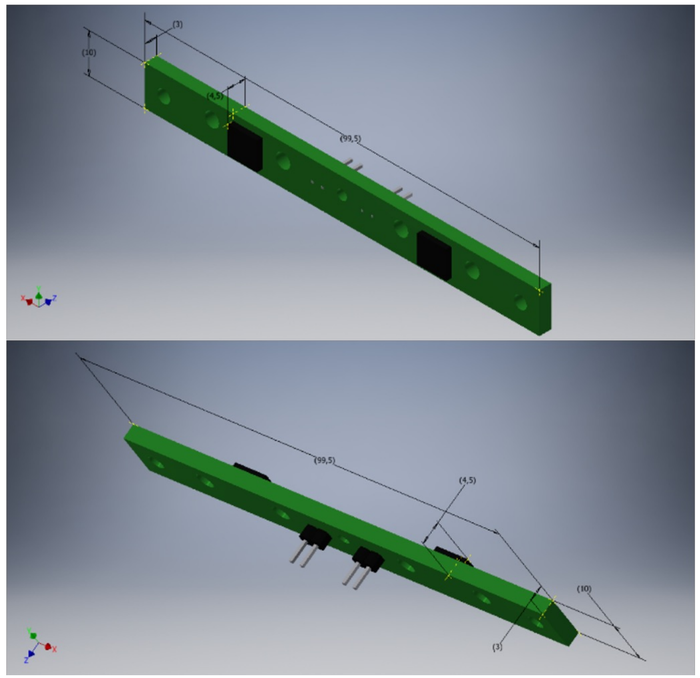


Change all the components to polycarbonate

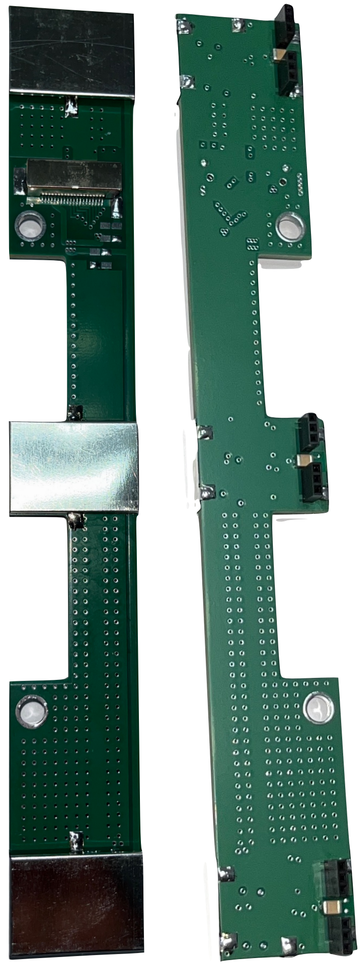
Cold electronics

- PCB with SiPMs is attached to the LCM
- PCB connected to E-pcb board with embedded pre-amps by means of pins





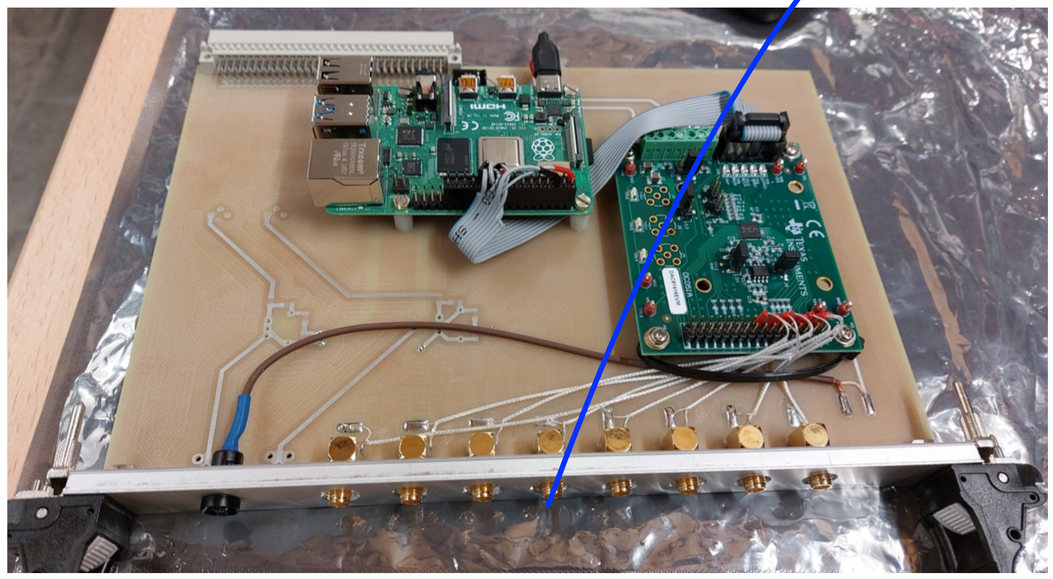
- E-PCB carrying 6 preamps
- Cold preamps (LMH6624) Gain ~ 5
- Power ~ 30-40~mW each @ BW of ~ 30MHZ (~10 ns rise time).
- Interface to 3 SiPM boards (3 LCMs or 1 ArCLight)
- Metal screens use to cancel clock pick up from Charge readout.
- Samtec connectors
- Left and right boards



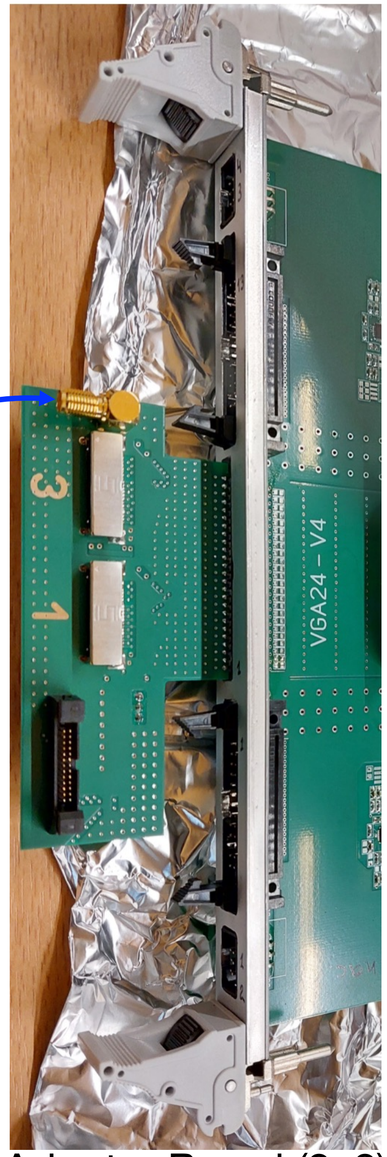
Samtec microcoax cable

Front-end electronics

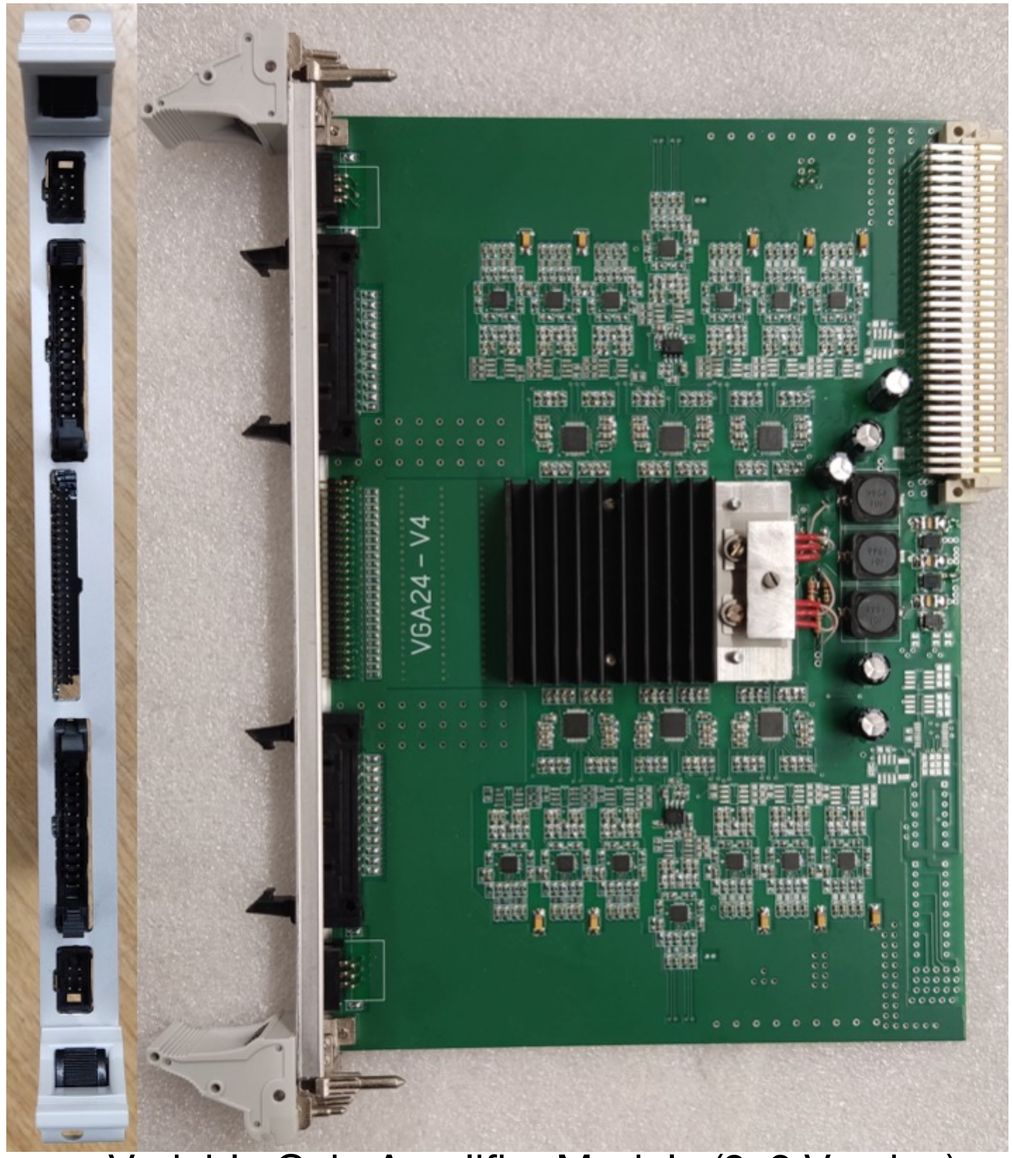
- Variable gain from 0 to 26 dB
- 2x2 Version - 24 channels/module. Drivers to long signal line
- **FSD Version - 60 channels/module. No long lines**
- Adapter board: Interface Microcoax cables to VGA and SiPM PS and Preamps power
- 2x2 Version - Controlled by means of external analogue signal (VGA control unit DAC+RPi)
- **FSD Version - Controlled via CAN-open (DAC onboard)**



VGA Control Unit (2x2)



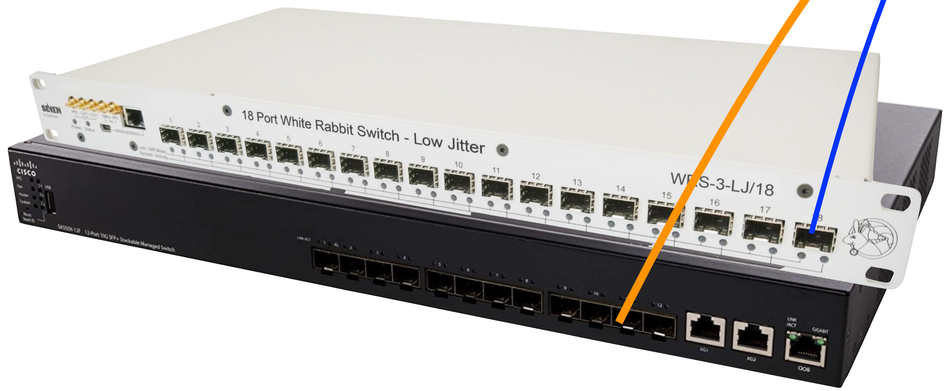
Adapter Board (2x2)



Variable Gain Amplifier Module (2x2 Version)

ADC

- **14-bit @ 62.5 MS/s (16 ns) - Buffer of 2 kSamples = 32 μsec, full range ± 1V**
- Analog inputs on **2x32 channel Diff-pairs connectors**
- Self-triggering mode by a digital threshold
- **64 channels**, 1-unit wide 6U VME64 module, standalone
- **VME64 VXS**
- **Optical link 10 Gbps**
- ADC stream UDP/TCP data packets via M-link MStream ADCs
- **White Rabbit protocol with 8 ns timestamp, <100 ps clock sync**
- Spill = 10 μsec, Light pulse ~ few μsec, ADC window ~ 32 μsec

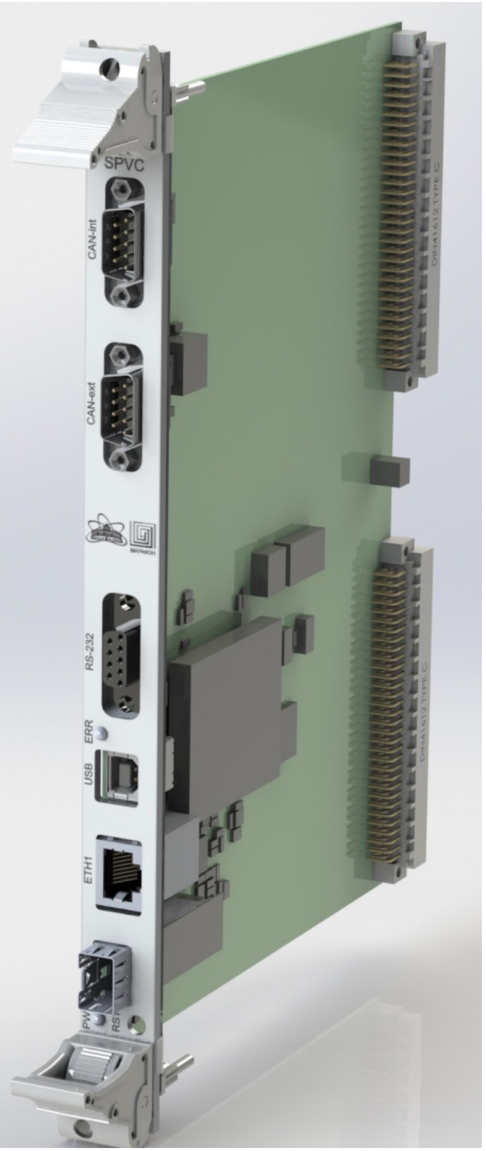


Synchronization with other subsystems by means of absolute time given by GPS

SiPM power supply

Main Features:

- VME mechanics
- Based on AD5535B chip
- Voltage up to 200 V, 14-bit
- Max current 500 μA/ch
- CAN-open protocol

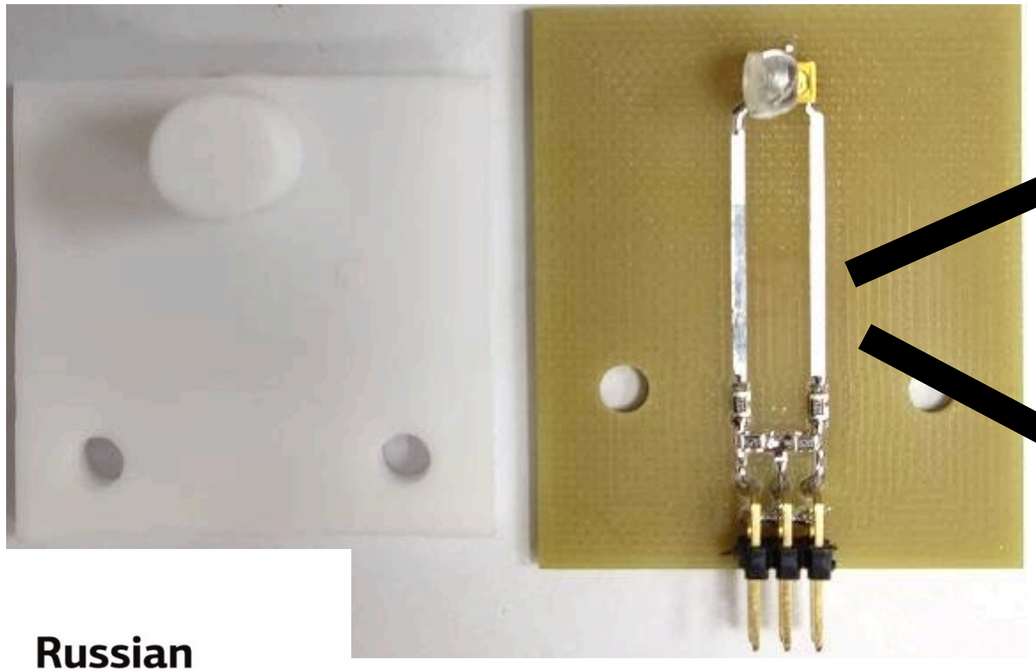


Design by Marathon Company (MSU)

JINR is the License owner

Calibration system

- LED unit on board: λ = 425 nm
- PTFE Diffuser - Unifies the light field
- 4 Calibration units per TPC: TOP & BOTTOM // LEFT & RIGHT
- 50Ω impedance matched



Supported by

RSF | Russian Science Foundation

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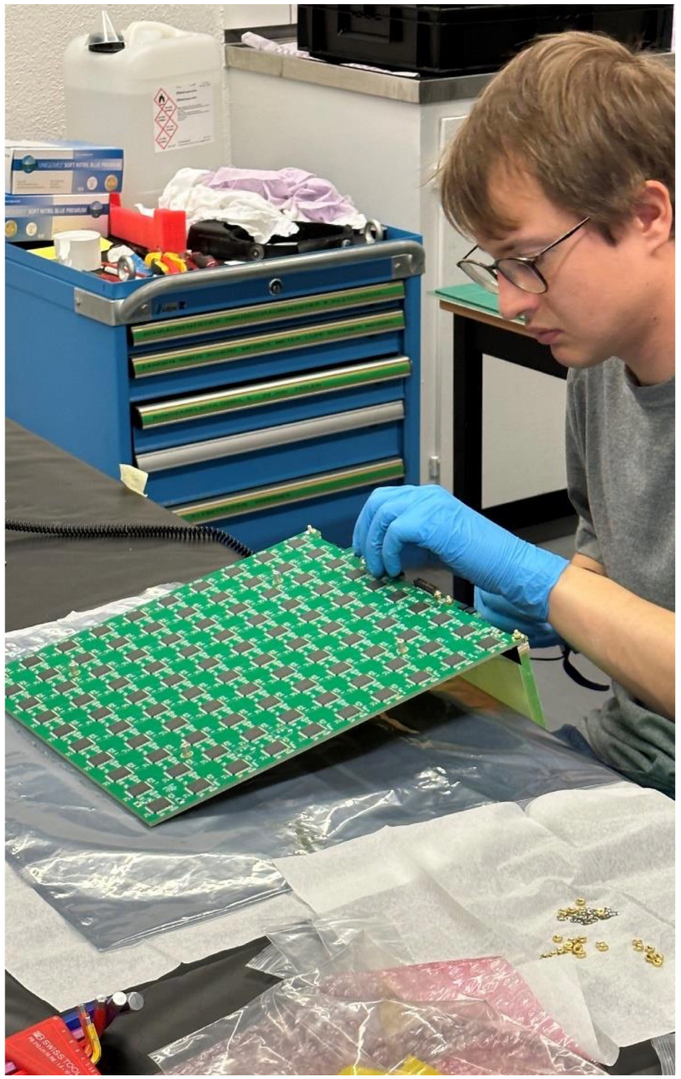
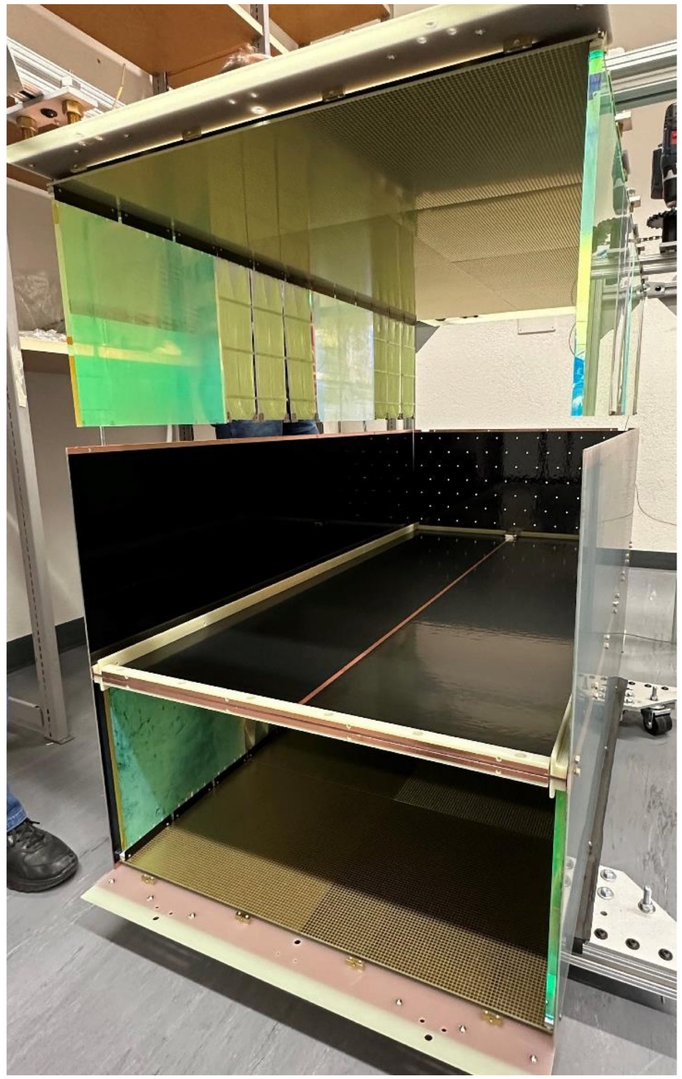
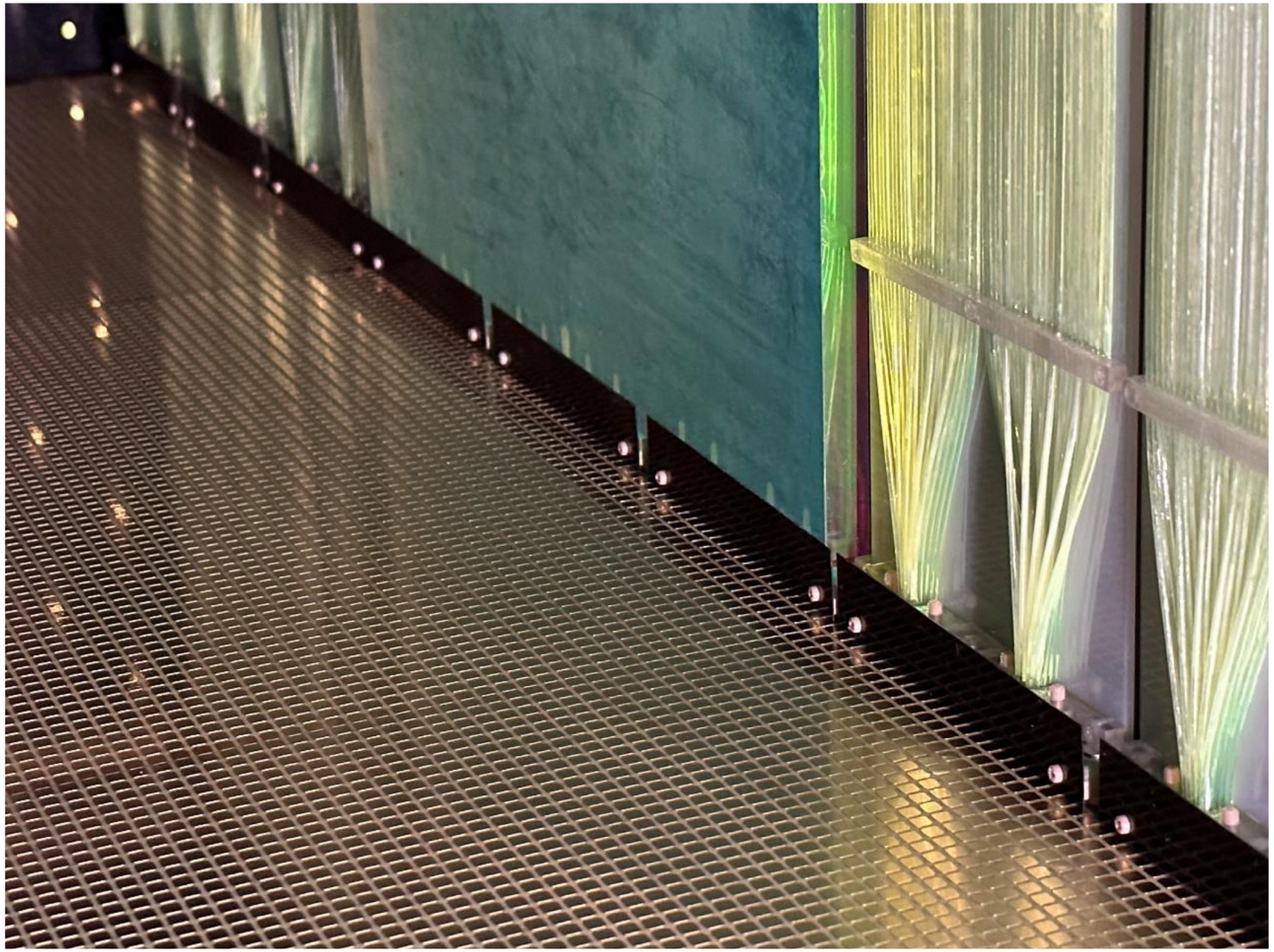
Module assembly at Bern

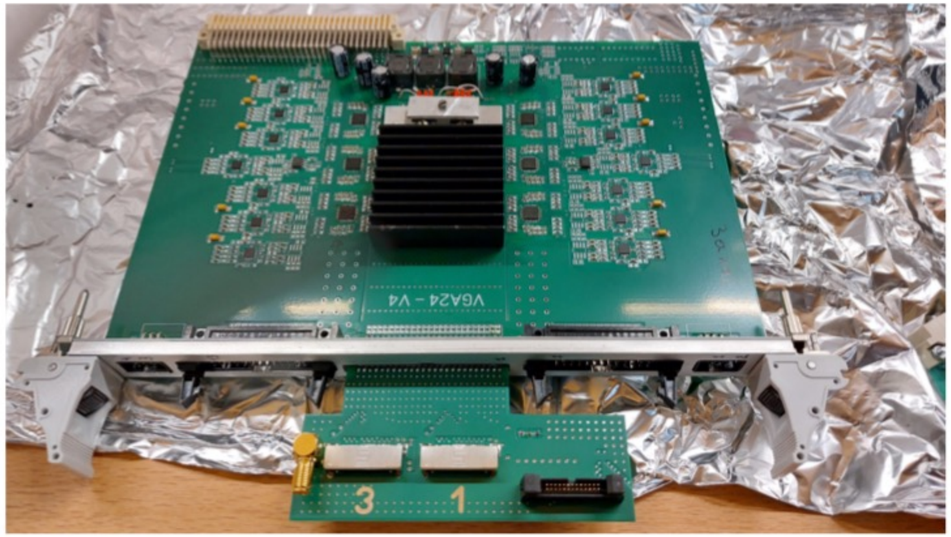




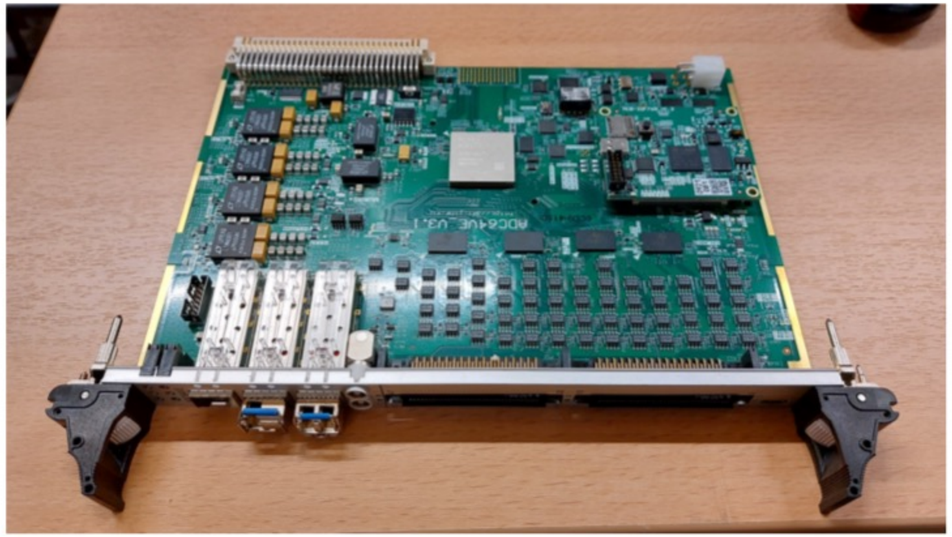
Module assembly at Bern



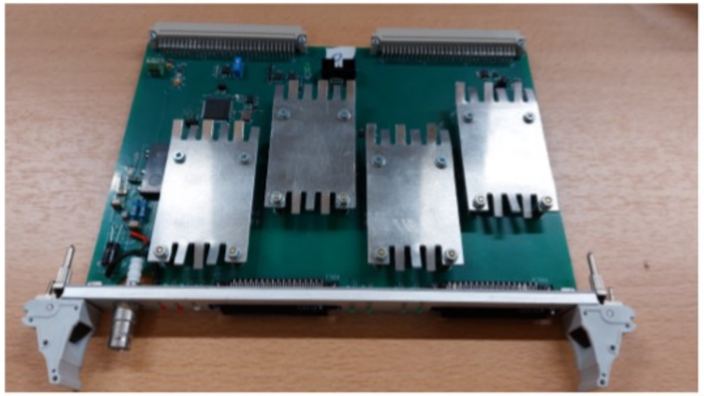
Light system electronics shipped to Bern



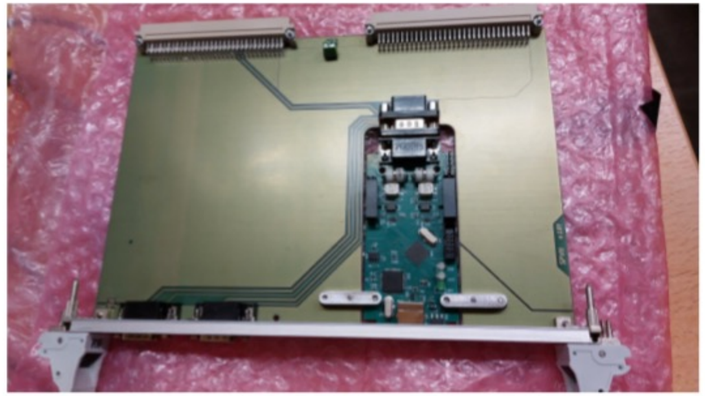
VGA board + Adaptor card for input micro coaxial cables



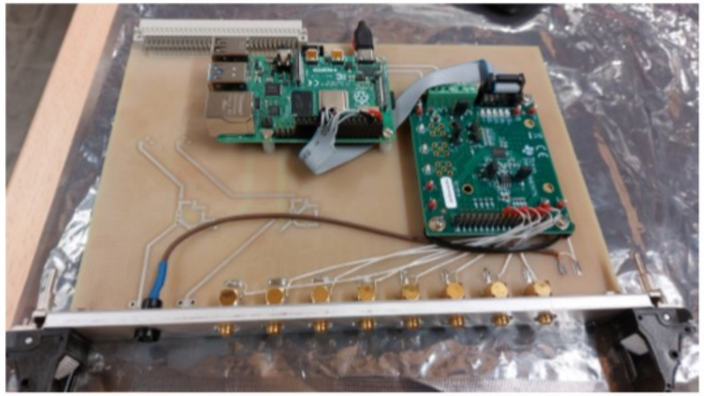
ADC board



Bias Power Supply



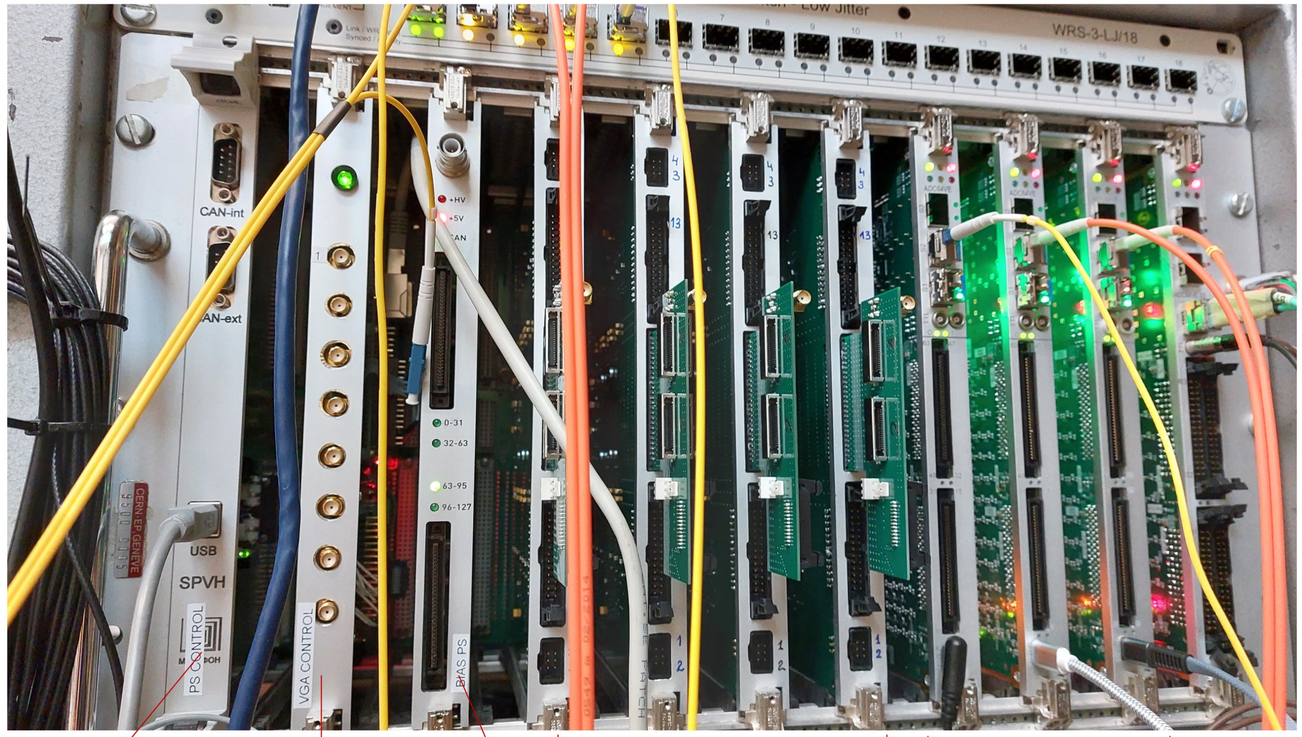
PS control unit



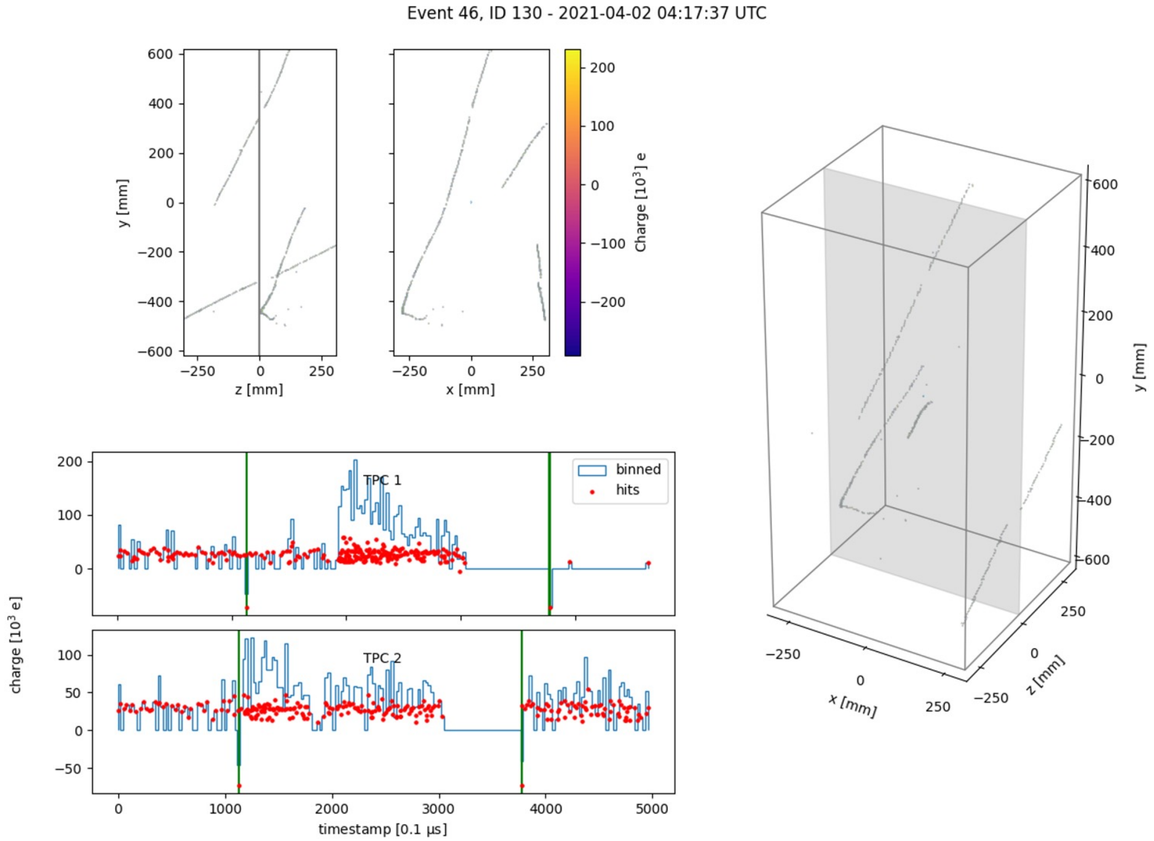
VGA control unit

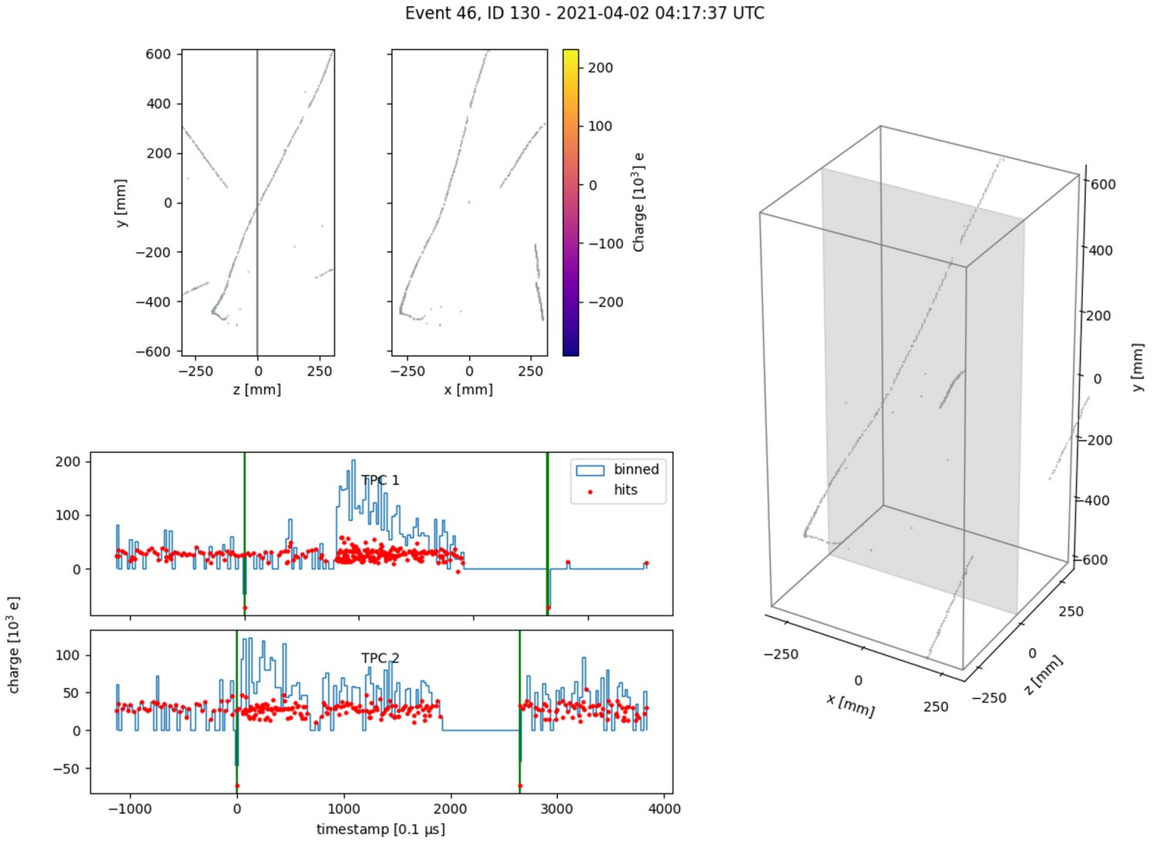
2

Module test at Bern



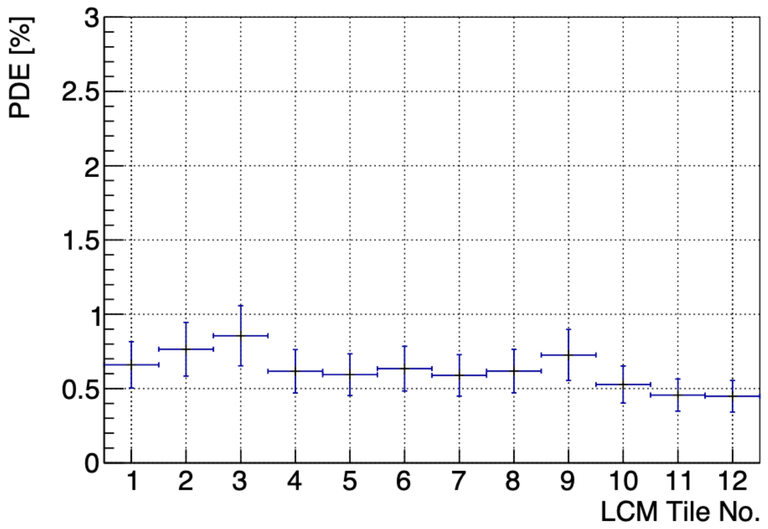
t0 correction using light detection system



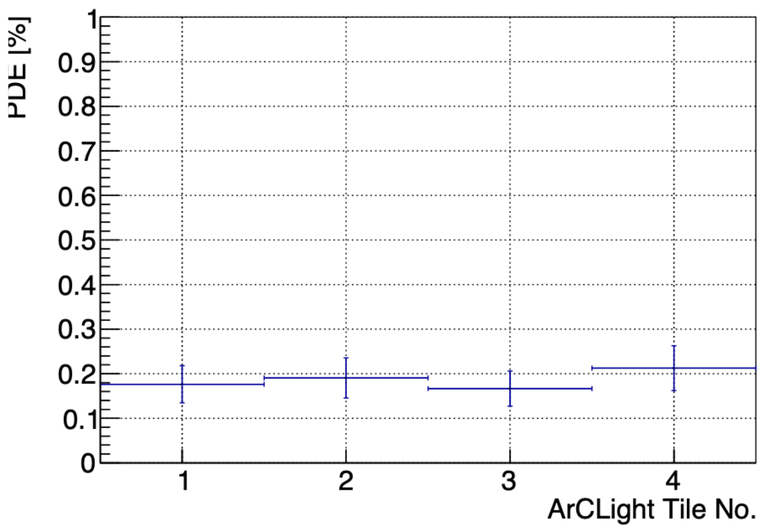


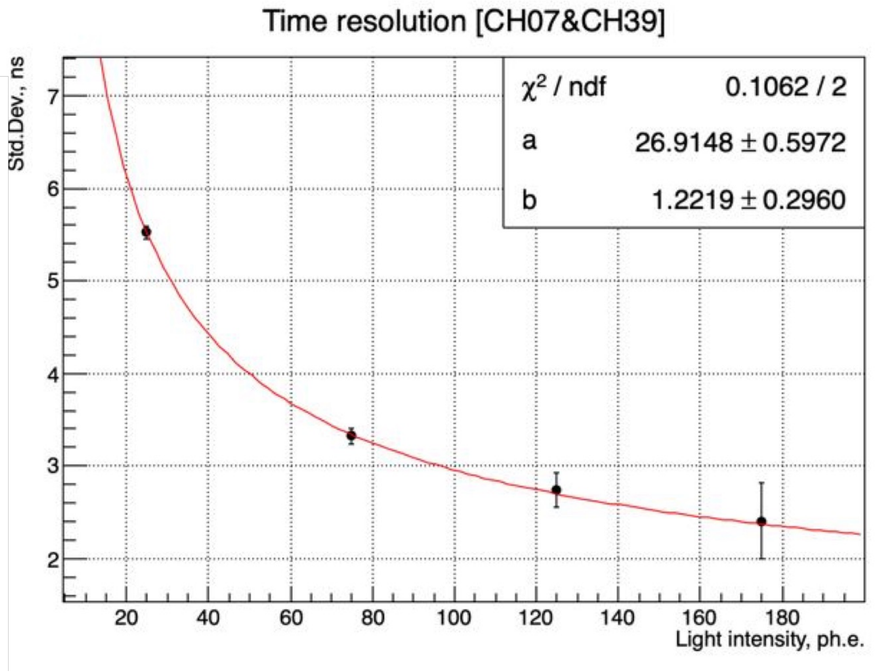
Light system performance

LCM PDE~ 0.67 %



ACL PDE~0.2%

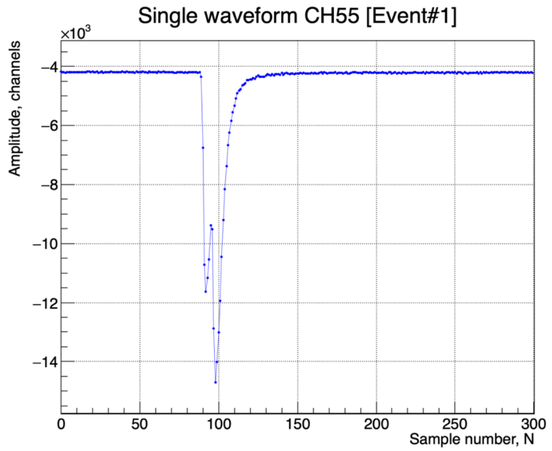




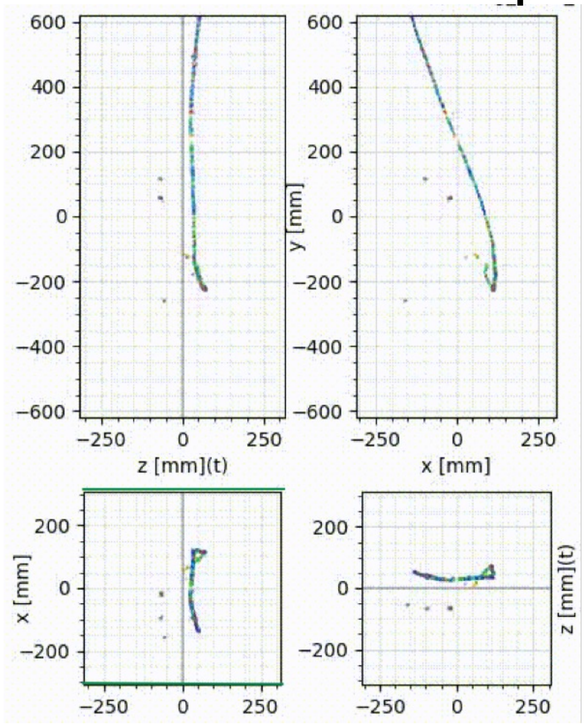
Light system performance

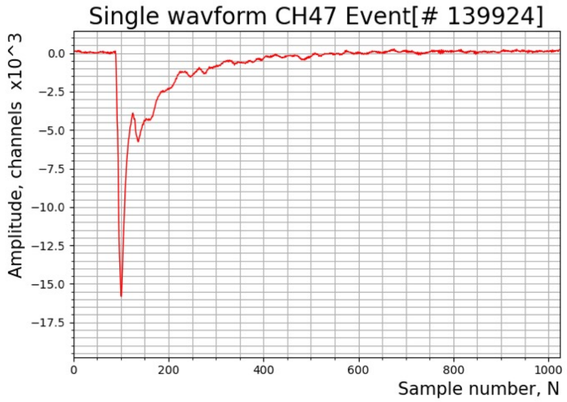
pile-up ~ 3-5 events/10us

100 ns, LED double pulse

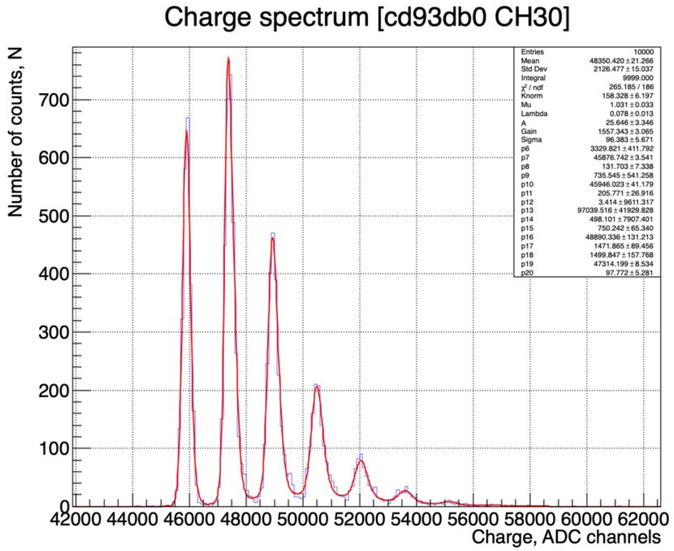


~250 ns pile-up, Michel event





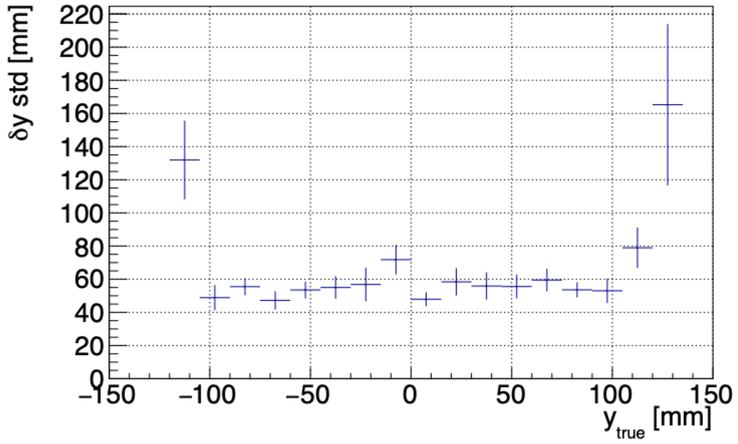
Calibration spectrum



Light system performance

Spatial resolution (preliminary, Bern simulation)

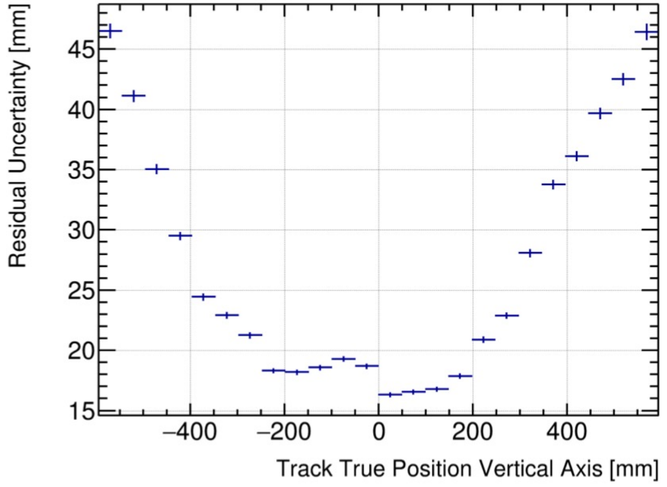
ArCLight spatial resolution ~ 5-6cm



ArCLight spatial resolution reconstructed

from SingleCube data (Vertical direction)

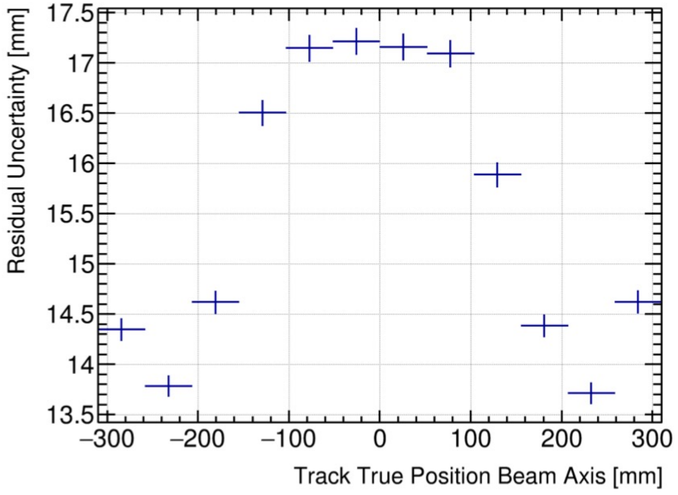
Common vertical spatial resolution ~ 2-4 cm



Light Readout spatial resolution simulation

for ArgonCube TPC (Vertical direction)

Common spatial resolution along beam ~ 2 cm



Light Readout spatial resolution simulation

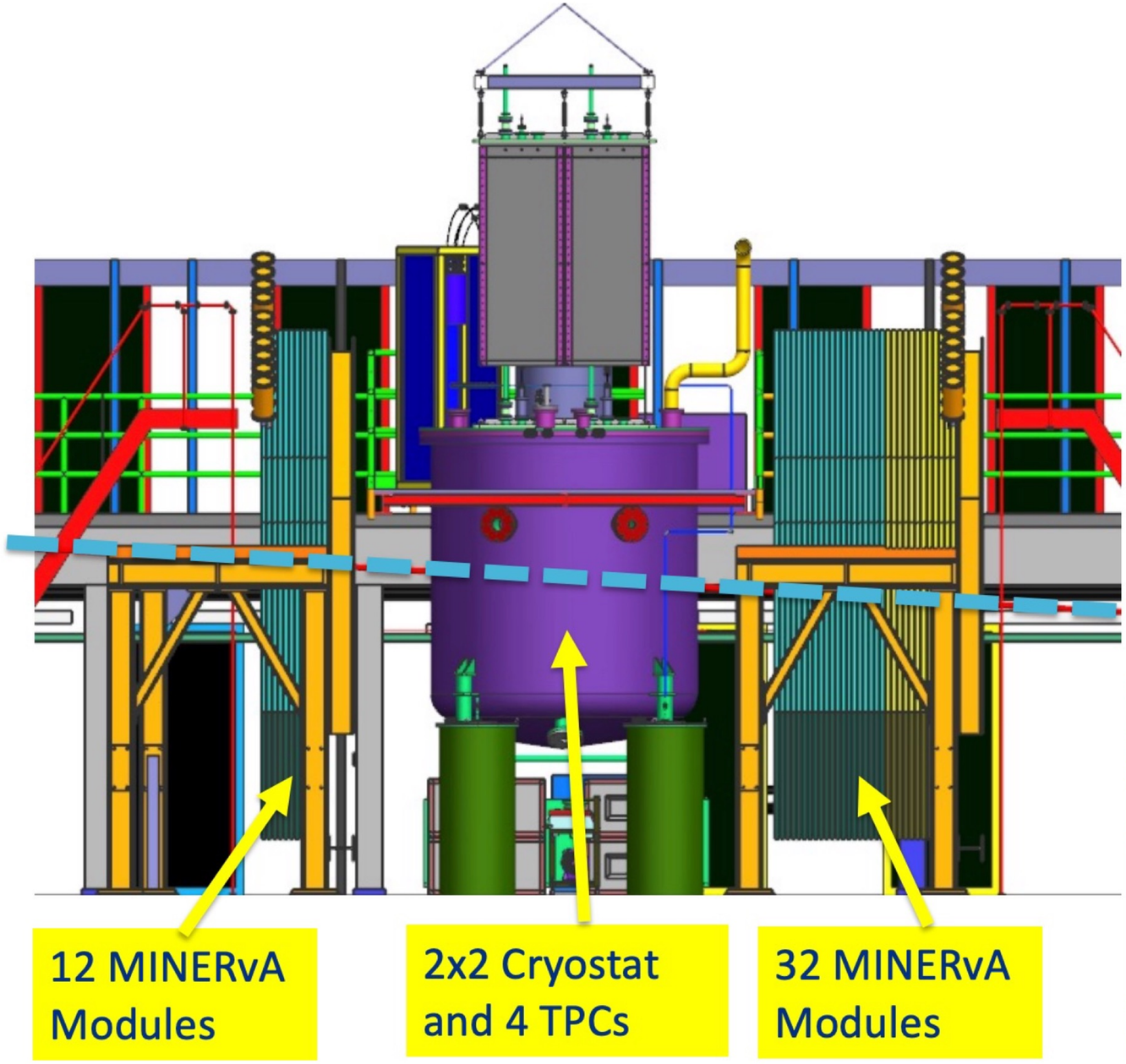
for ArgonCube TPC (along beam direction)

Module Performance Summary

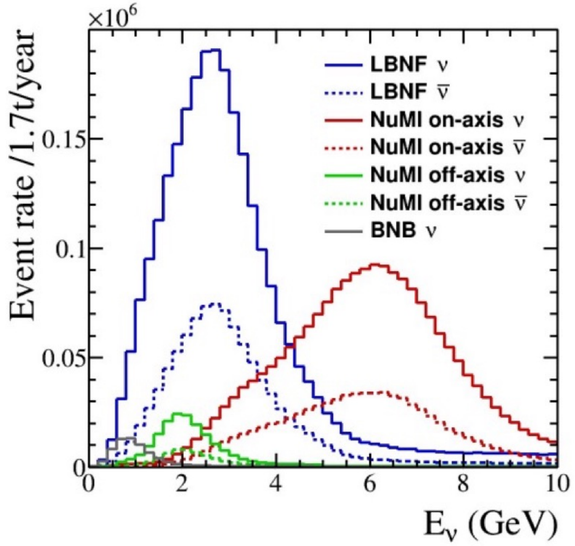
	Module-0	Module-1	Module-2
LRS PDE: LCM	0.6%	0.7%	0.7%
LRS PDE: ArCLight	0.06%	0.2%	0.2%
LRS threshold	~ 5 MeV	~ 1.6 MeV	< 1.6 MeV
LRS timing	< 2 ns	1.2 ns	1.2 ns
LRS inactive channels[1]	8.3%	1.0%	0%
CRS threshold	5.8 ke- (~1/4 MIP)	4.5 ke- (~1/5 MIP)	7.5 ke- (~2/5 MIP)
CRS noise	920 e-	920 e-	830 e-
CRS inactive channels[2]	7.8%	2.4%	9.0%[3]
Electron lifetime	> 2 ms	> 2 ms	> 2 ms
Maximum electric field tested	1 kV/cm	0.5 kV/cm	0.8 kV/cm

By B. Russel, I. Kreslo

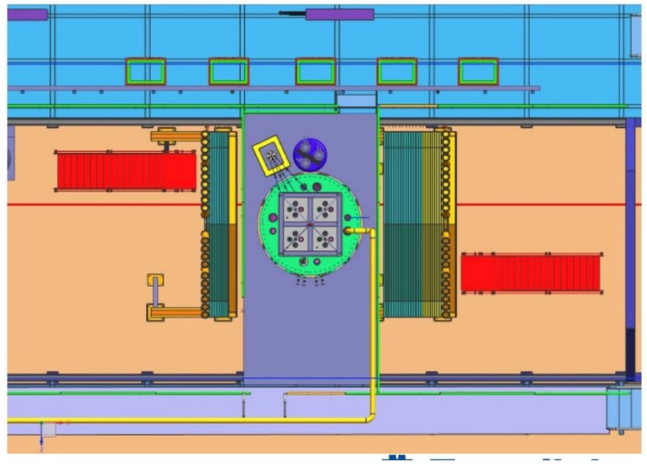
2x2 Demonstrator



Expected event rates for 2x2



NuMI Beamline



By J. Raaf

Electronic review at Fermilab 2022

DUNE-doc-#	Title	Author(s)	Topic(s)	Last Updated
25617-v5	Light Readout System DC distribution diagram for ArgonCube 2x2	Alexander Selyunin	ArgonCube2x2	12 Jul 2022
25657-v2	Light Readout System VGA control module ORC	Alexander Selyunin	ArgonCube2x2	09 Jun 2022
25655-v1	Light Readout System SiPM PS PCB ORC	Alexander Selyunin	ArgonCube2x2	08 Jun 2022
25653-v2	Light Readout System Adapter card ORC	Alexander Selyunin	ArgonCube2x2	08 Jun 2022
25650-v1	Light Readout System SiPM PS control board ORC	Alexander Selyunin	ArgonCube2x2	08 Jun 2022
24754-v3	Light System ADC64ve_v3.2	Alexander Selyunin	ArgonCube2x2	02 Jun 2022
24868-v3	Light System VGA board	Alexander Selyunin	ArgonCube2x2	01 Jun 2022

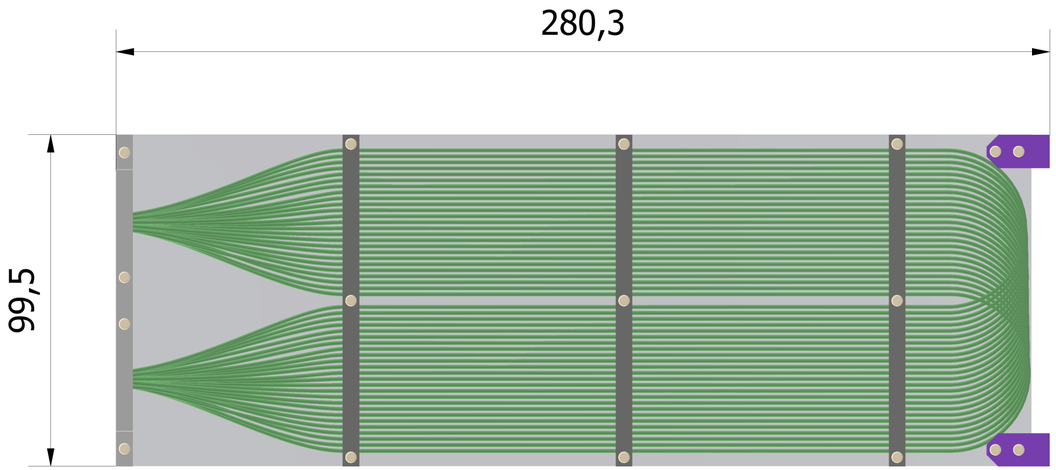
Modules preparation for 2x2 at Fermilab

- 3 Modules delivered to FNAL
- QA/QC testing after shipment
- 2x2 cryostat installed

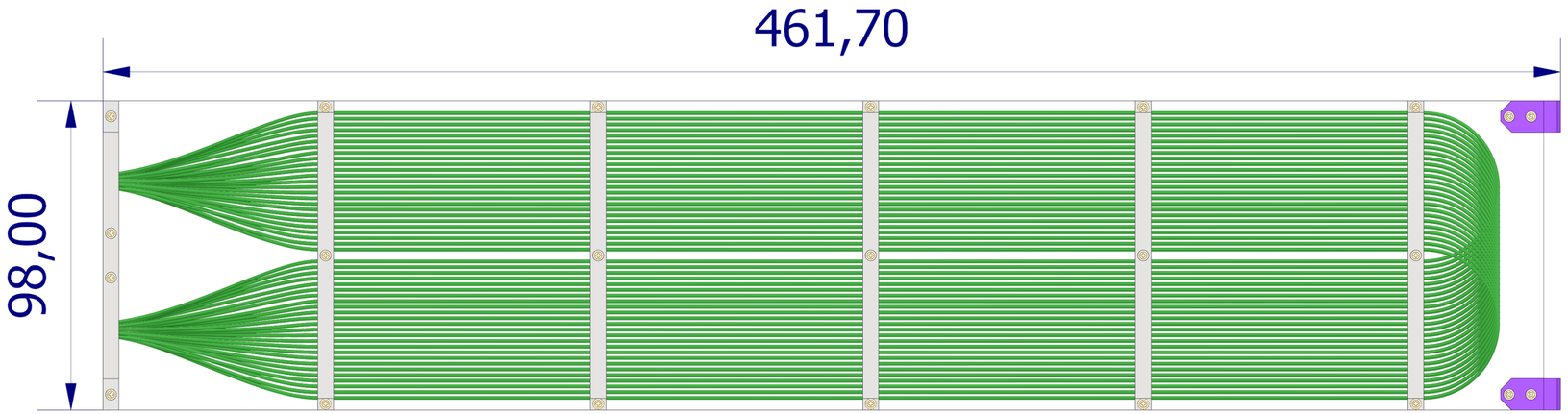
Key Documents for Preliminary Design Review

Light Readout Documentation	Description	EDMS Link
Light Readout Folder	Top level folder for Light Readout documentation	https://edms.cern.ch/project/CERN-0000217529
Requirements	Spreadsheet with all ND-LAr requirements, see sheet "Light Readout (06)"	https://edms.cern.ch/document/2589287
Internal ICDs	Interface control documents (ICDs) internal to the ND-LAr Consortium	https://edms.cern.ch/project/CERN-0000223195
Analyses	Collection of analyses write-up: FEAs, bench testing, 2x2 prototype evaluations	https://edms.cern.ch/project/CERN-0000231222
QAQC Plan	Subsystem QAQC plan with focus on high-level QAQC test plans	https://edms.cern.ch/document/2587876
Manufacturing Plan	Subsystem Manufacturing plan with focus on manufacturing methods of key items	https://edms.cern.ch/document/2605604
Procurement Plan	Subsystem Procurement plan with focus on procurement management of key items	https://edms.cern.ch/document/2605605
Previous Review Tracking	Spreadsheet with previous review recommendations, see "Light Readout"	https://edms.cern.ch/document/2741842
Cost	High-level cost estimate for ND-LAr and subsystems	https://edms.cern.ch/document/2742778
Schedule	High-level "one-pager" schedule for ND-LAr Consortium activities	https://edms.cern.ch/document/2603073
CAD Model (Row Assembly, TPC Assembly)	Solidworks "Pack & Go" and Parasolid exports of CAD models	https://edms.cern.ch/project/CERN-0000230732
Mechanical Component Drawings	Subsystem mechanical component drawings	https://edms.cern.ch/project/CERN-0000218197
Mechanical Assembly Drawings	Subsystem assembly drawing	https://edms.cern.ch/project/CERN-0000218198
Parts List	Subsystem parts list	https://edms.cern.ch/project/CERN-0000220723
Electrical Schematics and Board Layouts	Subsystem electrical schematics and board layouts	https://edms.cern.ch/project/CERN-0000218199
Electrical Cabling and Wiring Specification	Specification of electrical cables/wiring	https://edms.cern.ch/project/CERN-0000217668

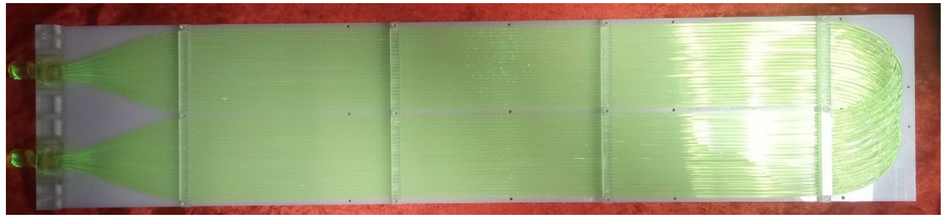
LCM for Full Scale Demonstrator (FSD)



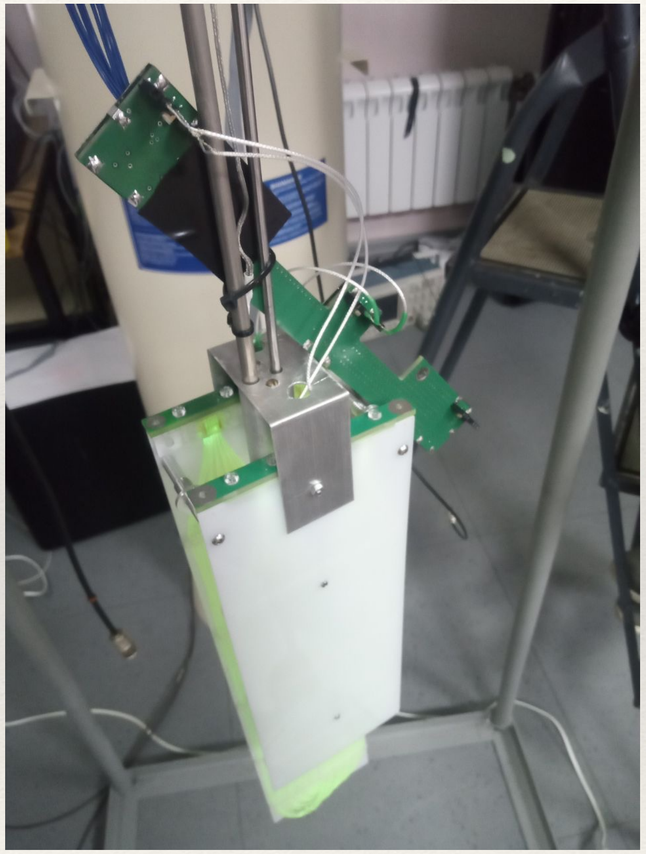
2x2 Version ~ 20 m of WLS fiber



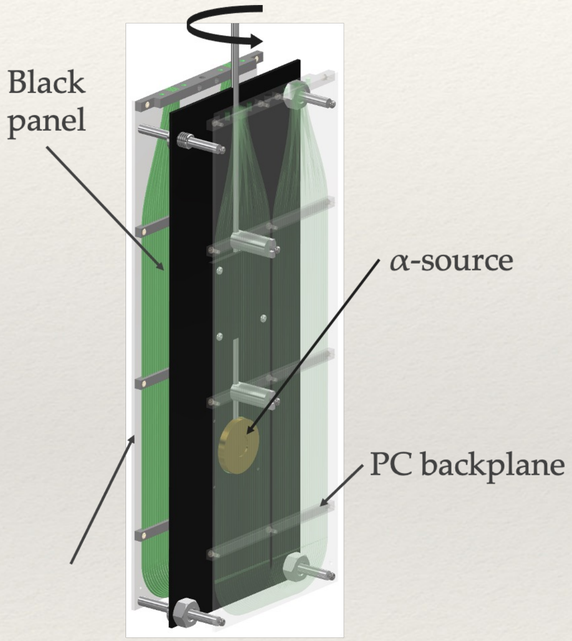
FSD Version ~ 30 m of WLS fiber



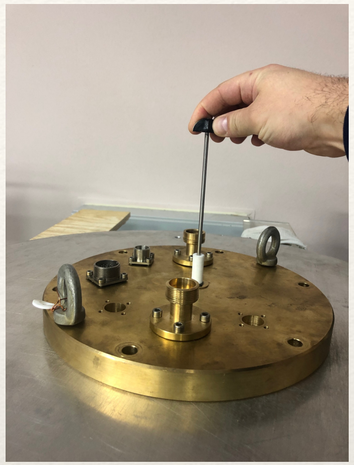
Cryogenic stand at JINR



Studies with real LAr signal -> pre-test of the readout chain in LAr



3D model prototype



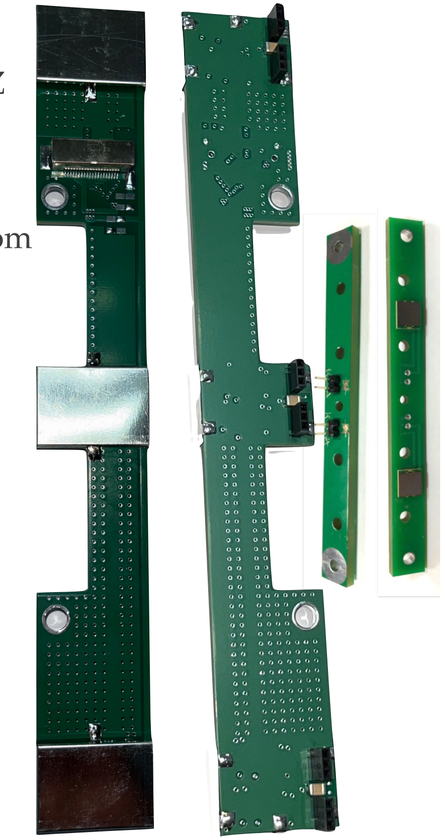
We use
^{241}Am α-source

Purchase LAr from Kurchatov's Institute
Purity of LAr at level 10^{-5} - 10^{-6}

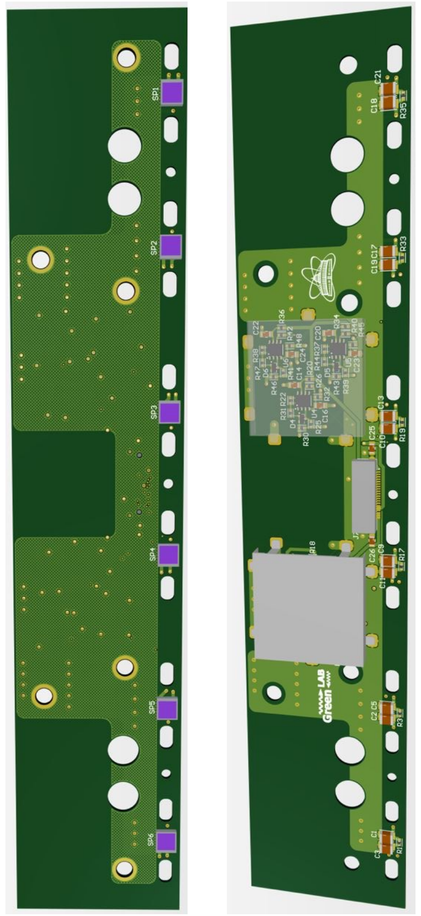
Cold PCB for FSD

2x2 Version

- E-PCB carrying 6 preamps
- Cold preamps (LMH6624) Gain ~ 5
- Power ~ 30-40~mW each @ BW of ~ 30MHZ (~10 ns rise time).
- Interface to 3 SiPM boards (3 LCMs or 1 ArCLight)
- Metal screens use to cancel clock pick up from Charge readout.
- Samtec connectors
- Left and right boards



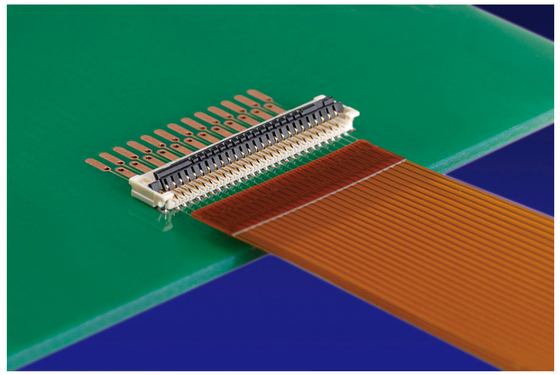
FSD Version



- FSD PCB carrying 6 preamps + 6 SiPM
- 6 SiPM are integrated onto the board
- Cold preamps (LMH6624) Gain ~ 5
- Power ~ 30-40~mW each @ BW of ~ 30MHZ (~10 ns rise time).
- Metal Screens
- **Interface to 3 LCMs or 1 ArCLight**
- SiPM number can be doubled (?)
- **Samtec** or flex cable (?) connector

Samtec microcoax cable

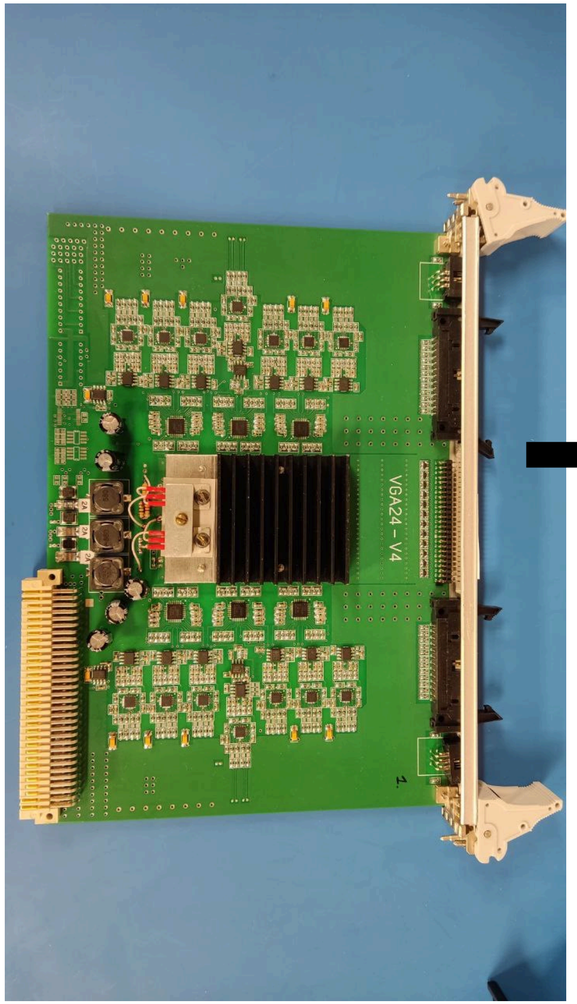
Flexible PCB



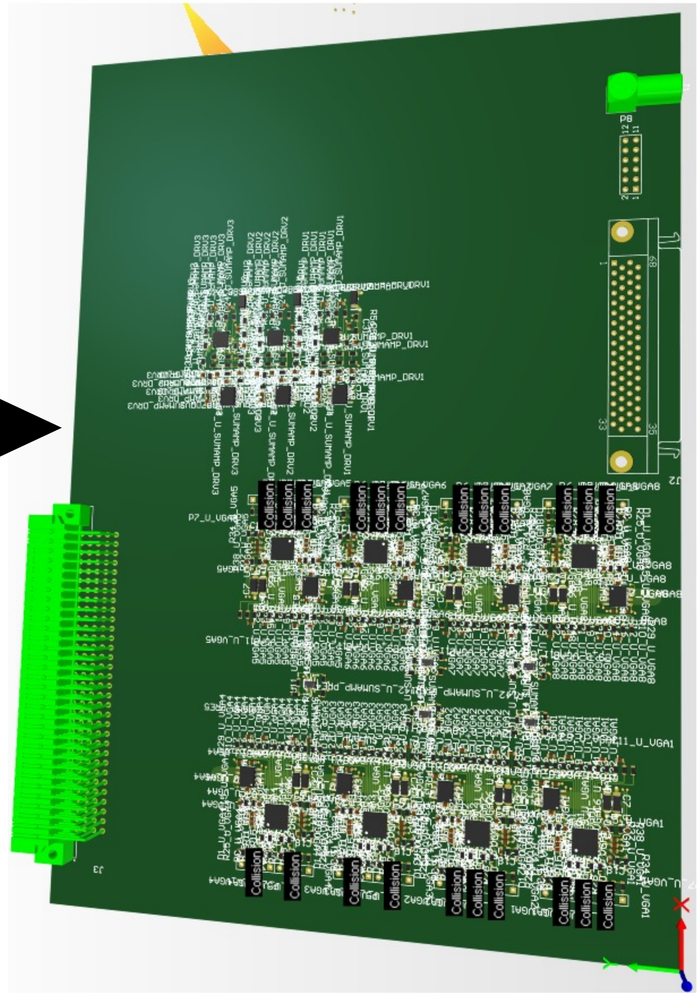
VGA for FSD

2x2 Version

- VME module
- 24 channels
- Needs adapter board for Power and Signal decoupling
- External E-PCB power
- External gain controller



FSD Version



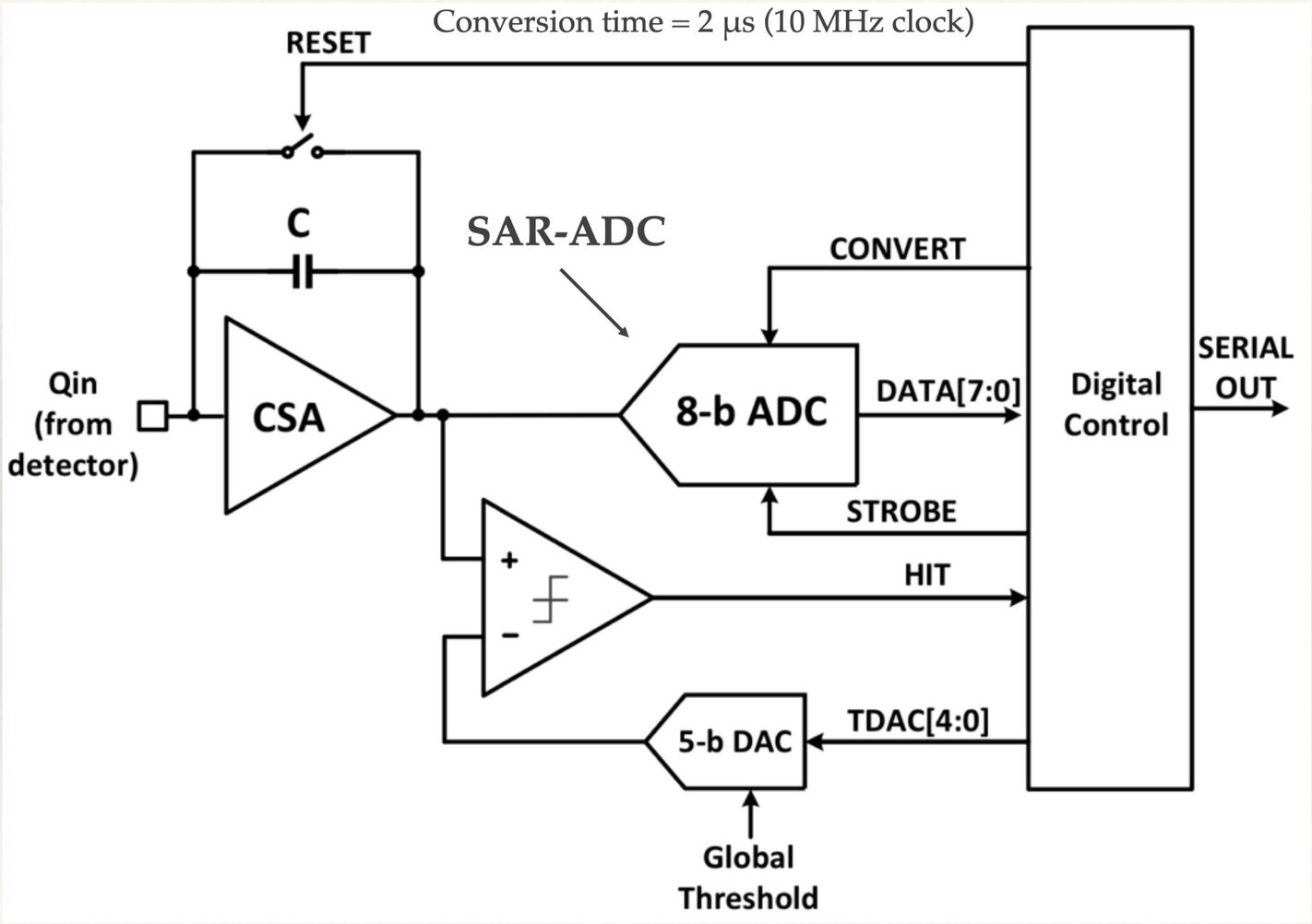
- VME module
- 30 channels
- Onboard Power and Signal decoupling
- Onboard Cold-PCB power
- Onboard gain controller CAN-open

Планы на 2024-2026 гг.

- Производство компонент световой системы для прототипа 5-го модуля - модуль-X. Будут отрабатываться новые решения в криогенных тестах в Берне. 2024-2026 гг.
- Тесты матрицы модулей 2x2 на нейтринном пучке в Фермилабе - 2023-2024 гг.
- Производство компонент световой системы для полноразмерного модуля ближнего детектора: электроника, детекторы, система калибровки, кабели. Испытания компонент. 2024 г.
- Тесты полноразмерного модуля в Берне. 2024-2025 гг.
- Подготовка документации по итогам испытаний полноразмерного модуля ближнего детектора для прохождения FDR (final design review). 2025-2026 гг.
- НИОКР новых типов волокон с добавкой TPB и тесты. 2024-2025 гг.
- Подготовка к массовому производству компонент световой системы для Ближнего детектора DUNE. 2026 г.

Backup

Charge readout ASIC

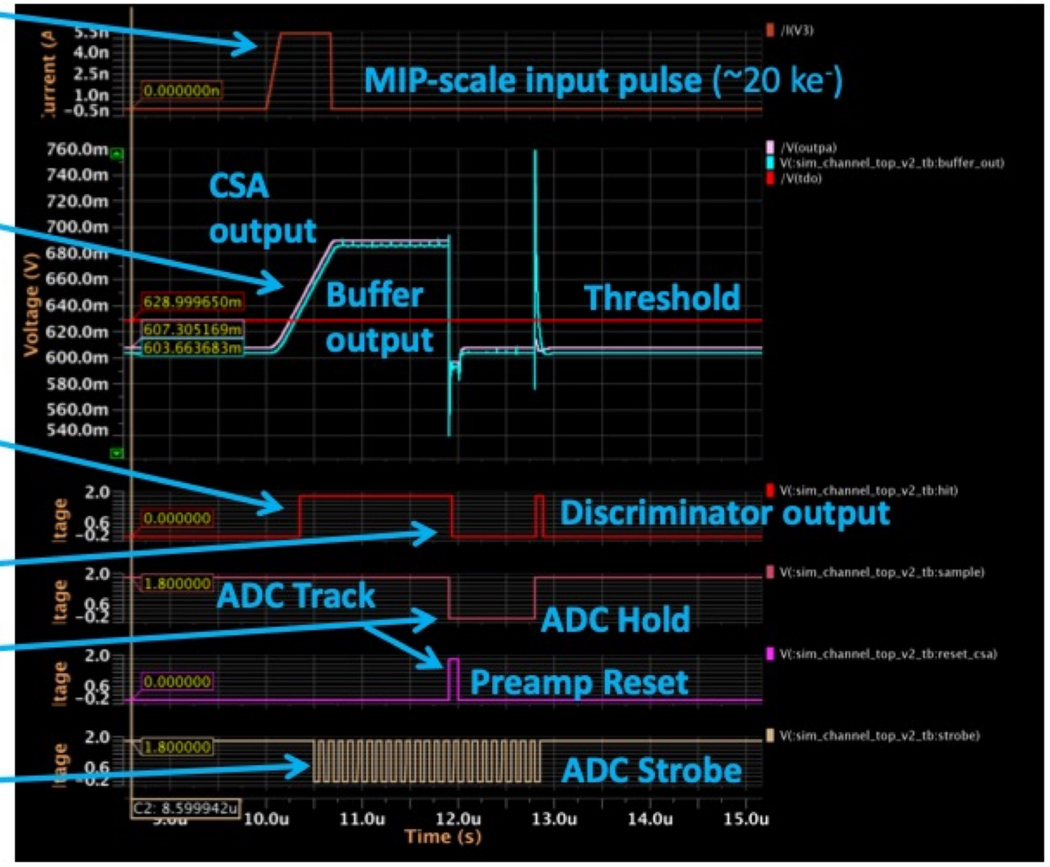


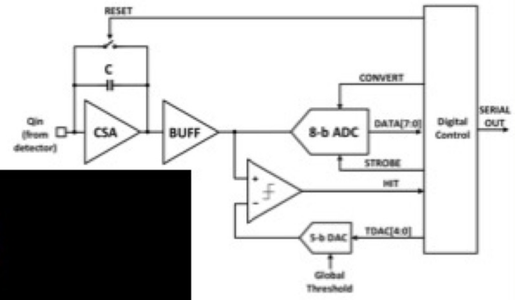
Analog and digital parts in the same chip!

Charge readout timing

LArPix Self-trigger Cycle

1. Drifting charge induces current on pixel.
2. CSA integrates current, buffer drives current to discriminator and ADC.
3. Signal exceeds discriminator threshold, hit cycle begins.
4. Channel 'waits' a tunable delay (typically 1.8 us) for full drift signal integration.
5. If discriminator still high after wait, ADC 'holds' signal and front-end is reset to discard charge on pixel. Channel ready for next signal.
6. ADC 'strobes', converting held signal to digital value. Sends ADC value, timestamp, and chip/channel ID to serial out.





Optional Burst Modes:

'Fixed' Burst:
Process 'n' hit cycles for each self trigger

'Dynamic' Burst:
Continue to process hit cycles until change in ADC value is below set value.

Note:
CSA does not reset until end of burst.

11 24 Nov. 2020 D. Dwyer | LArPix Overview

Total resampling time ~2.2 μsec, precision ~ 100 ns