

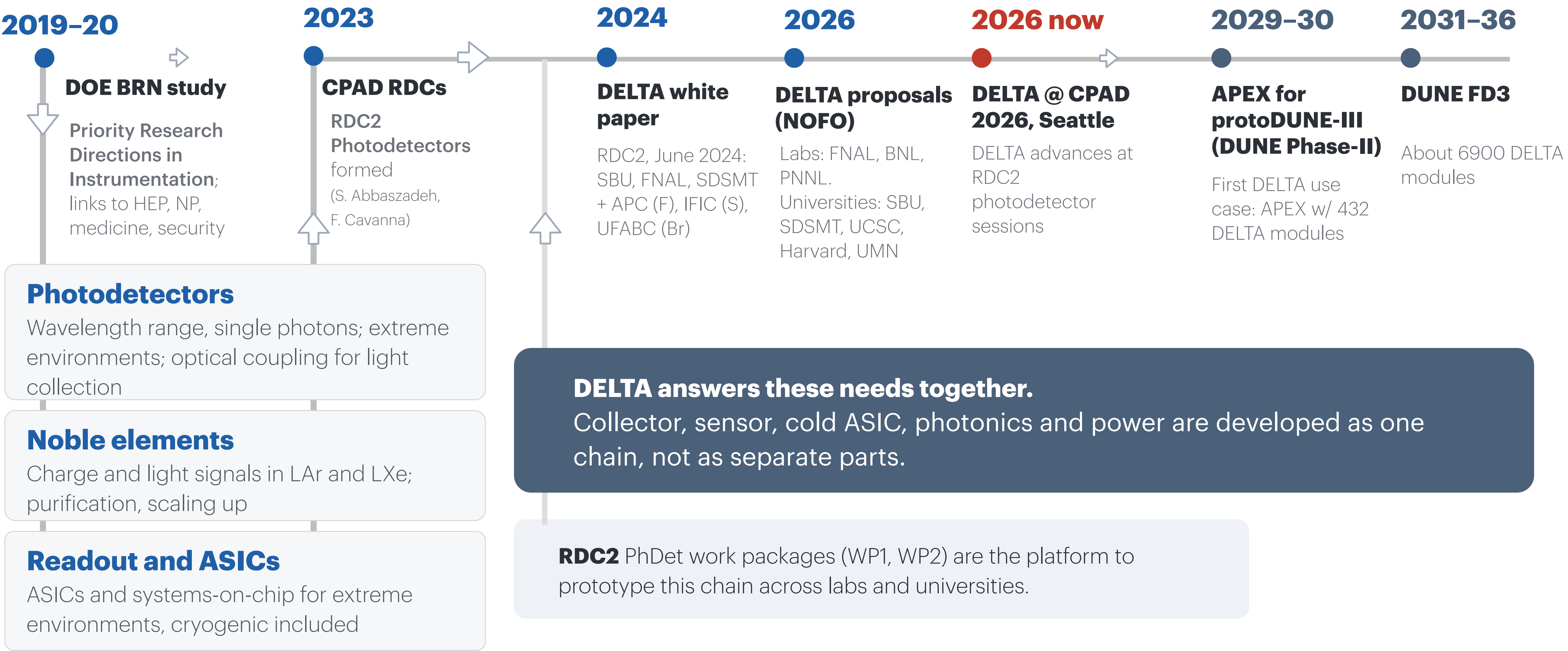
DELTA

Digital End-to-end Light Trap Assembly

A photodetector concept and an R&D platform: from incident photons to digital signals

F. Cavanna (Fermilab), W. Shi (BNL) on behalf of the DELTA R&D collaboration/WG [CPAD-RDC2]

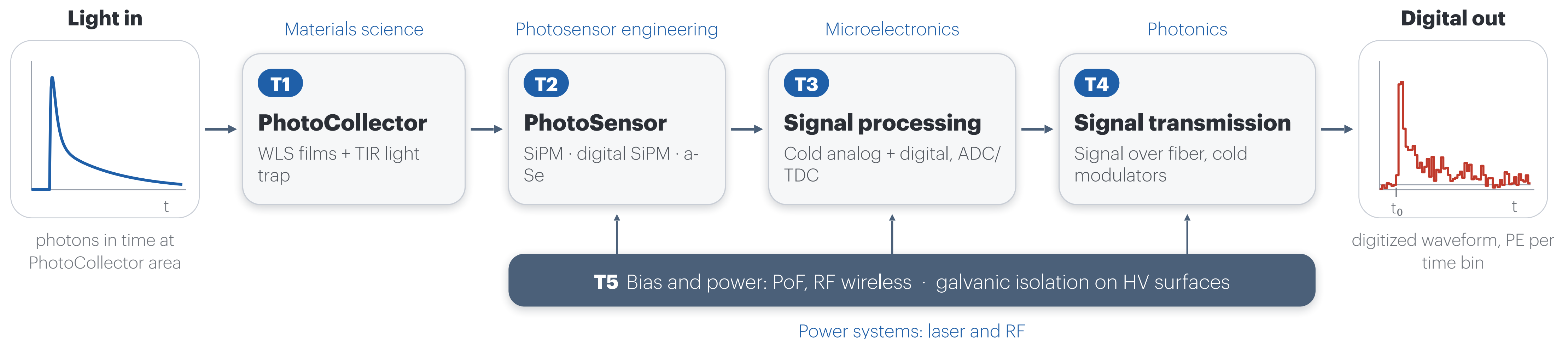
Detector R&D priorities from the BRN study to DELTA



THE CONCEPT · MANY APPLICATIONS

DELTA: new-gen light trap, from incident light to digital output

A new generation after PMTs, LAPPDs and X-ARAPUCA light traps: PhotoCollector, PhotoSensor, signal processing, power and signal transmission integrated as one digital system.



Light in. A large-area collector of photo-sensing material collects and traps light from scintillation or Cherenkov media.

Sensors. Small-area photosensors, optically integrated onto the collector, detect the trapped photons.

Digital out. On-board fast electronics give time-resolved photon counting as a digital output.

Power and Signal. Laser photonics provide noiseless power-in (PoF) and signal-out (SoF).

DELTA TWO ROLES

One design for a class of PhDetectors and an R&D platform

DELTA as PhDetector

A class of digital photodetectors, each tailored to its application

- One unified system, not separate units
- Each realization meets application-specific requirements within a common design
- Applications: HEP noble-liquid neutrino and dark matter, nuclear physics, medical imaging, space, security

DELTA as R&D platform

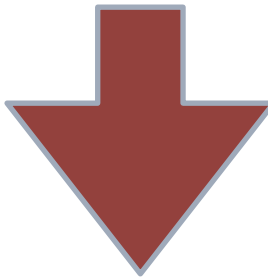
Simultaneous R&D on all components, distributed across labs and universities

- Labs bridge materials-science innovation and full detector technology, paired with university partners
- Blue-sky sensor research plus photonics, micro-device engineering, low-power cryogenic electronics, fiber power and communication
- Full-chain prototype tests at FNAL-NLTF and BNL 260-L

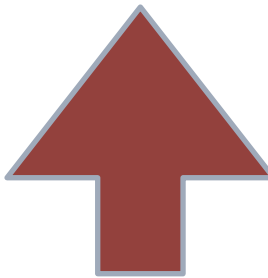
Next:

one example DELTA application: light detection in liquid argon, then its first **use case**, APEX for DUNE Phase-II.

Options in a common design

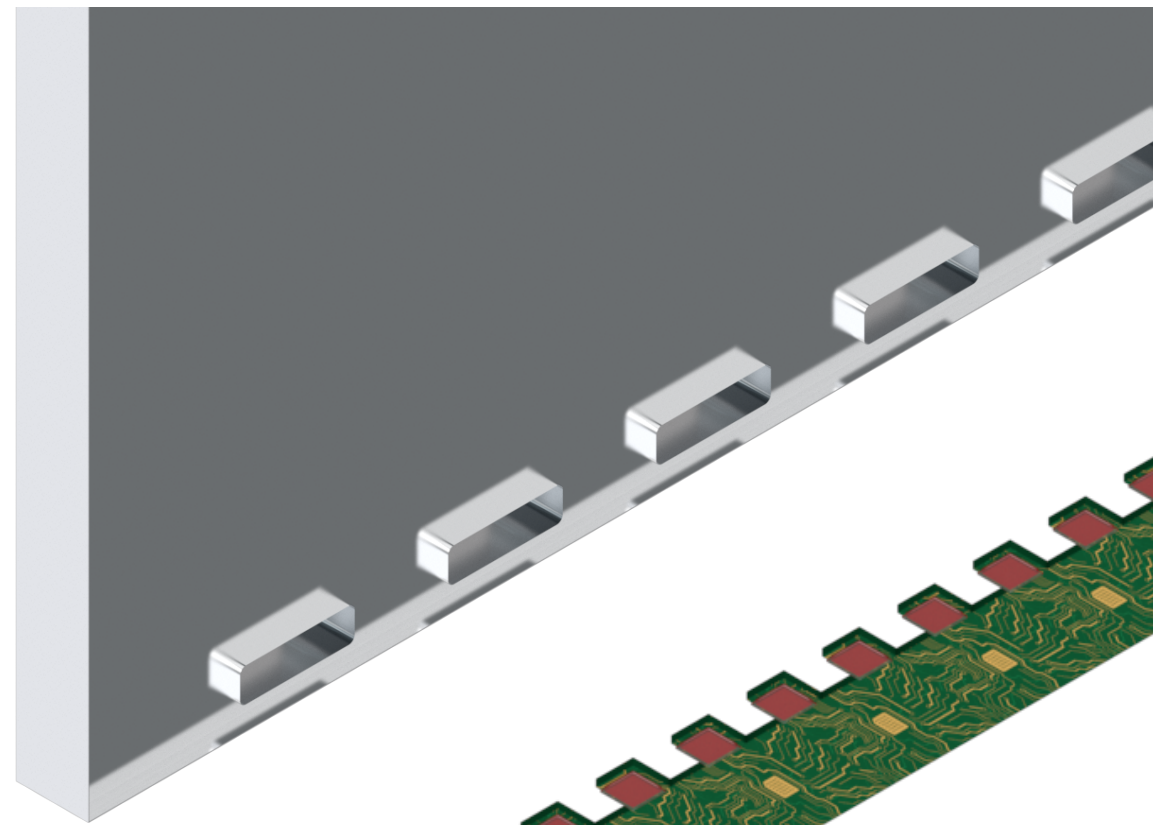


Block	Baseline	Options under study <i>*Critical*</i> ==> ==>	Talk @ RDC2 - this Session	What it gains
PhotoCollector	2-layers, 2-stage WLS: (1) pTP film on FusSi layer (2) BBT in Acrylic layer 1-TIR trap (Reference DELTA)	<ul style="list-style-type: none">• automated chemical spray deposition (SD)• industrial vacuum deposition (PVD)• pTP and alternative WLS• High PCE light-trap: 2-TIR trap (Advanced DELTA)	<ul style="list-style-type: none">• R.F. Razakamiandra (Stony Brook)• M. Vicenzi (BNL)	<ul style="list-style-type: none">• scaling up optical coverage to X-large area (fast & lower cost per area)
PhotoSensor	high PDE (commercial) SiPM SiPMs edge-coupled to the acrylic layer	<ul style="list-style-type: none">• SiPM-to-Acrylic Optical Contact in cold: thin silicone-based optical coupling pads (compliant coupling layer)• Customized SiPM (PDE, VUV to NIR range)• digital SiPM• a-Se on a digital substrate	<ul style="list-style-type: none">• V.A. Chirayath (UT Arlington)	<ul style="list-style-type: none">• frameless design (lower cost/unit)• easier assembly and mass production• Higher PCE
Processing	Cold analog front-end and Warm digitization	<ul style="list-style-type: none">• Cold ADC• cryo-ASIC suite with fast shaping time and extended dynamic range		<ul style="list-style-type: none">• lower power, higher density• LAr-qualified reliability
Transmission	SoF - Signal over Fiber, laser diode	<ul style="list-style-type: none">• Cold integrated modulators (micro-ring, TFLN) for high bandwidth		Bandwidth with minimal heat load
Power	PoF - Power over Fiber (808 nm)	<ul style="list-style-type: none">• 1470 nm laser, high-power/high-V OPC, optical fibers• RF wireless power through liquid noble gas	<ul style="list-style-type: none">• J. Rodríguez Rondon (SDSMT)	<ul style="list-style-type: none">• improved power delivery• reduced heat dissipation• negligible IR light leakage

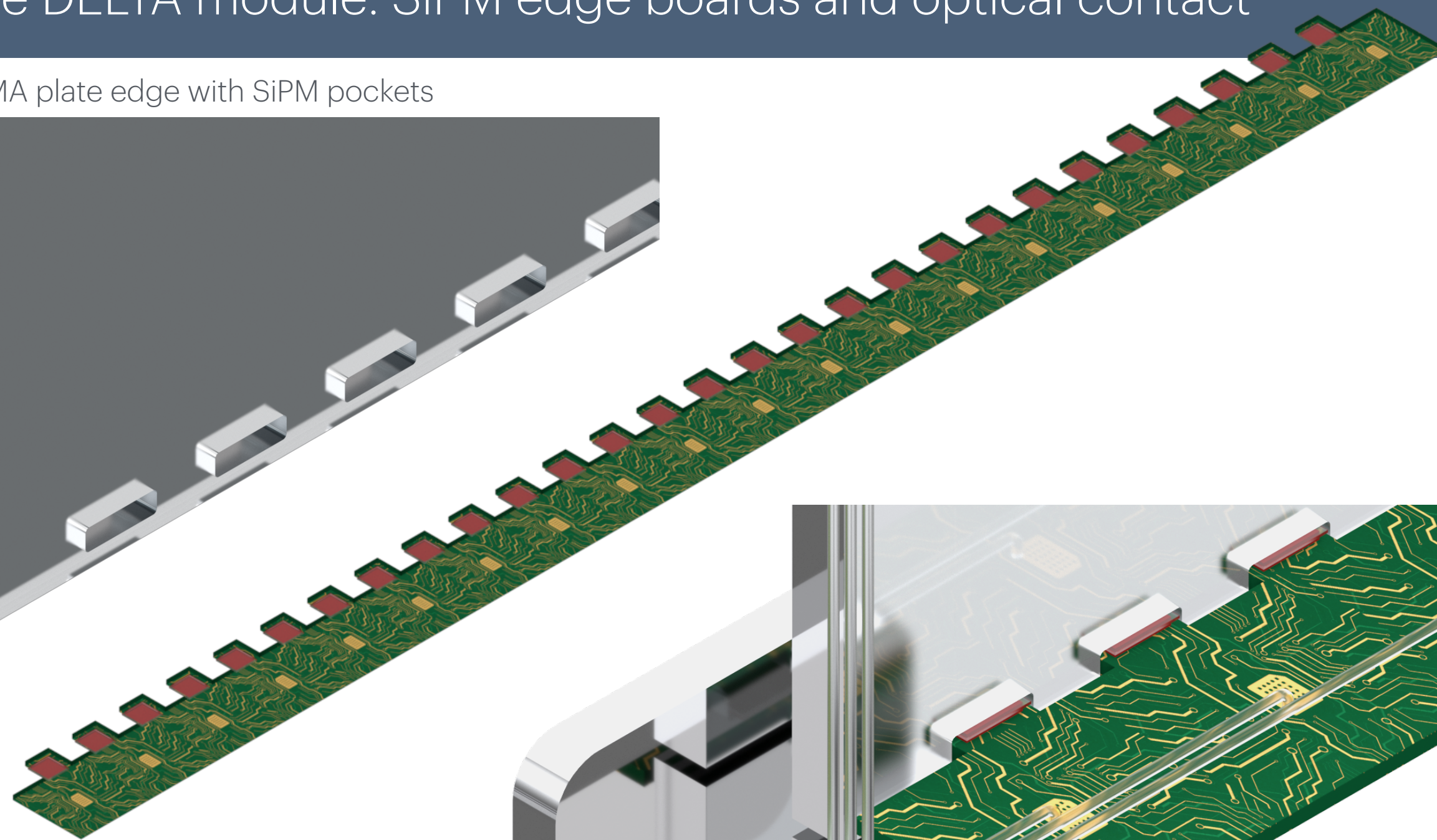


Each combination must fit one application, so the blocks are developed together.

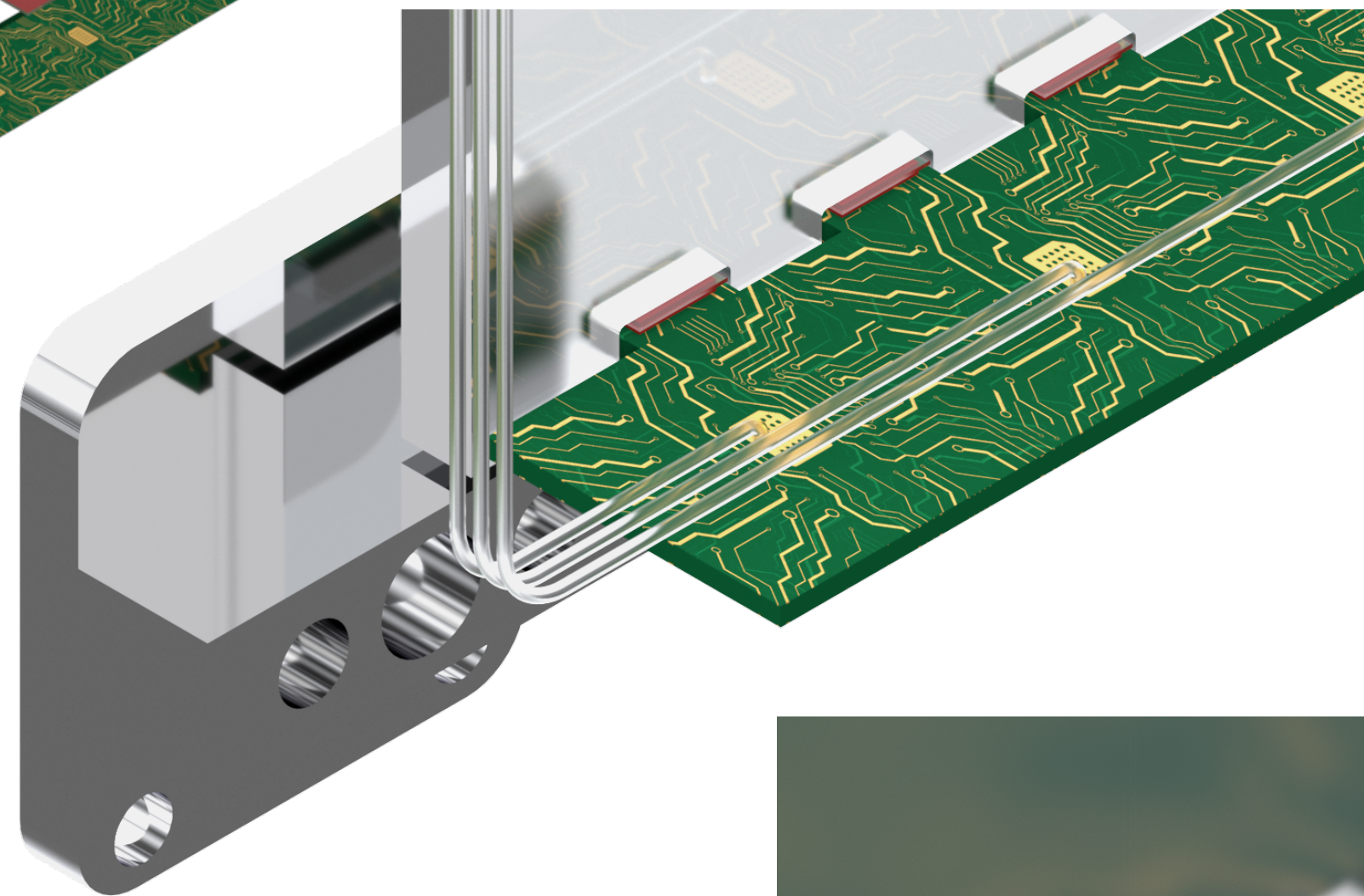
PMMA plate edge with SiPM pockets



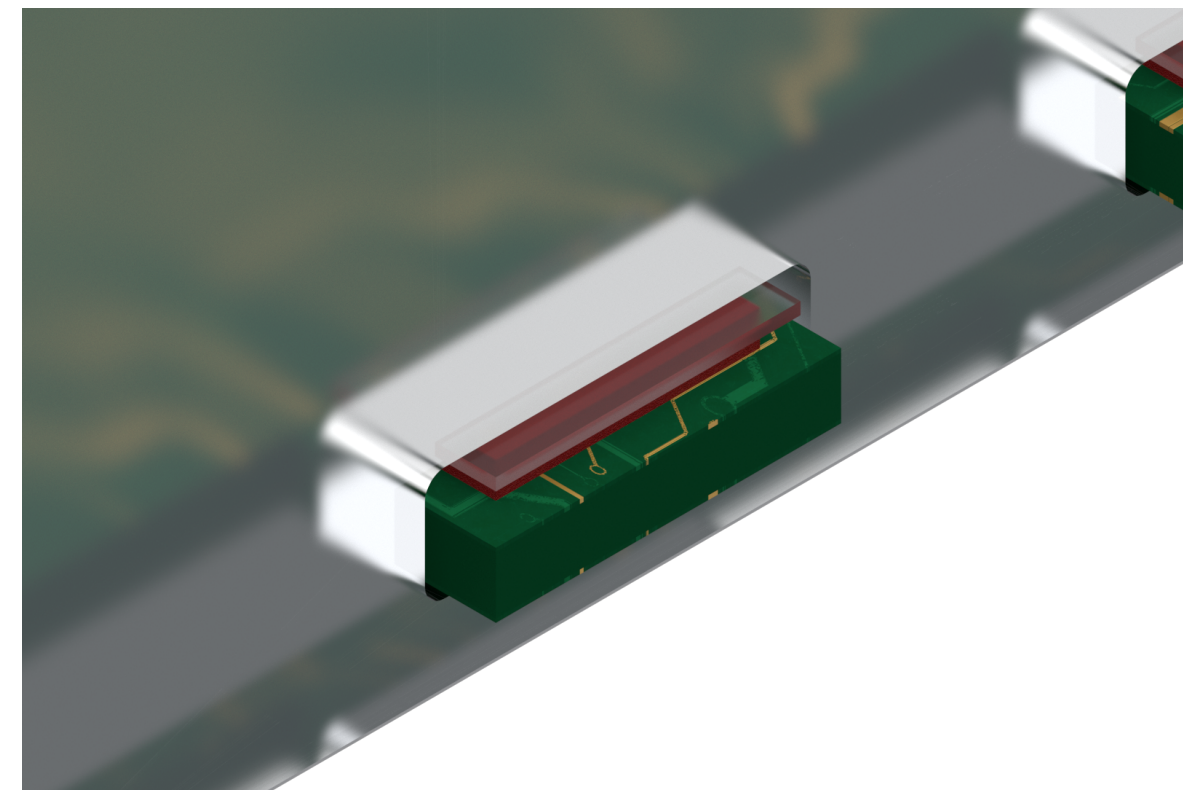
SiPM edge board: 25 SiPMs along one plate edge



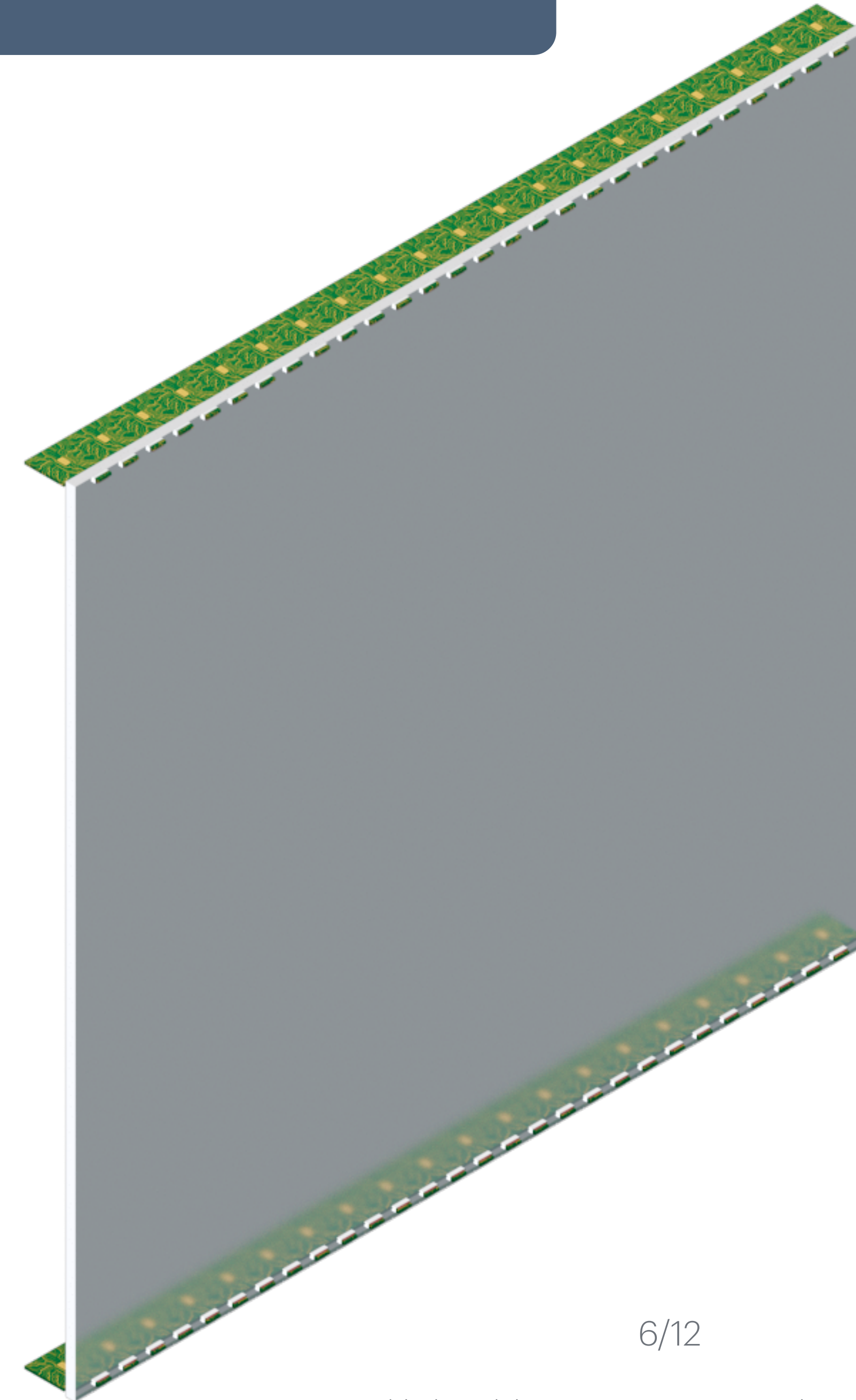
Corner detail: edge board seated in the plate, corner bracket, PoF/SoF fibers



- SiPM-to-PMMA contact at 87 K: rigid PCB insert in a through-bore with a compliant coupling layer

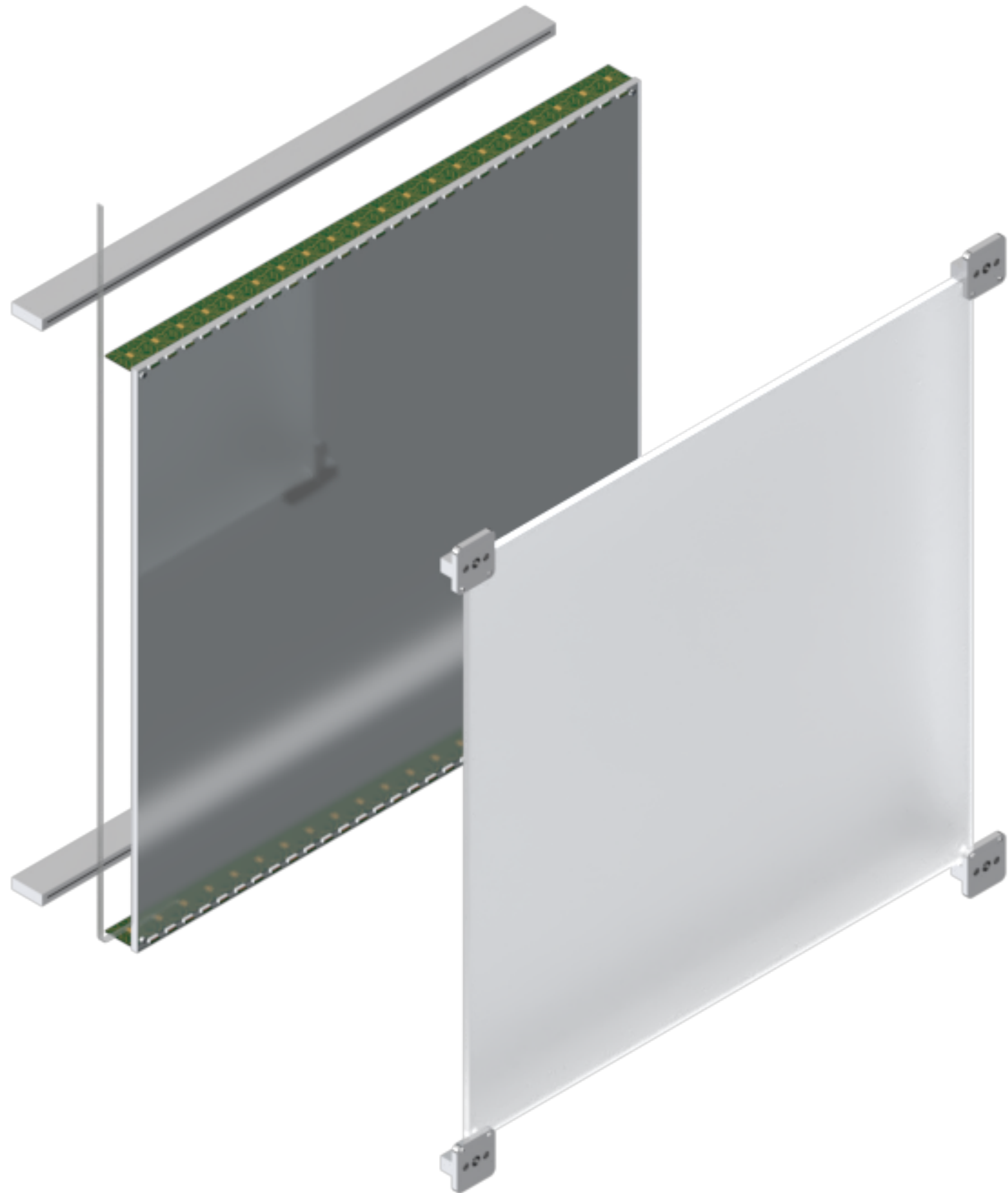


Renders: ICArch

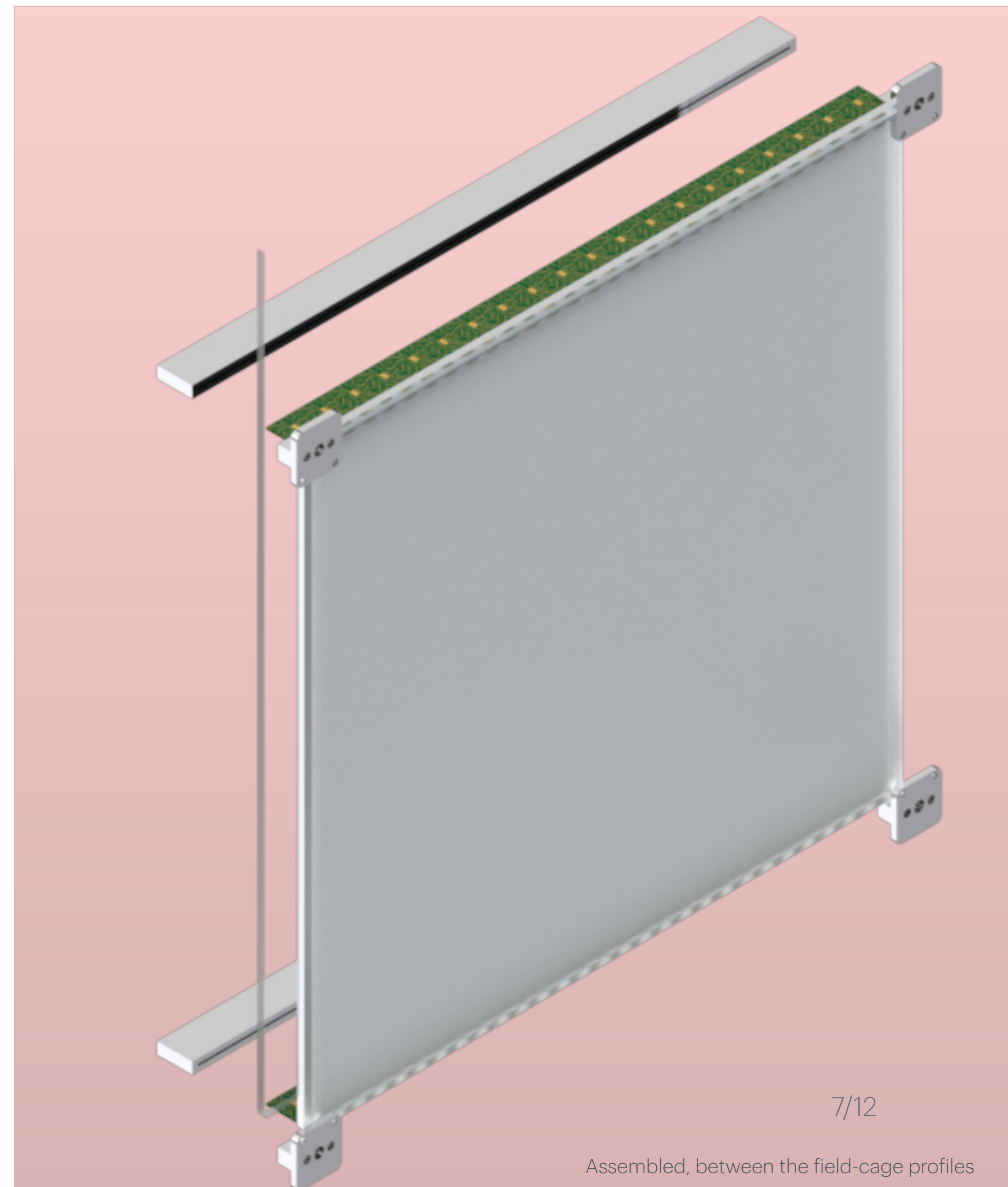


6/12

Assembled module, ~50 × 50 cm² PMMA plate



Exploded: PMMA light guide with SiPM boards, front plate on corner spacers, field-cage profiles

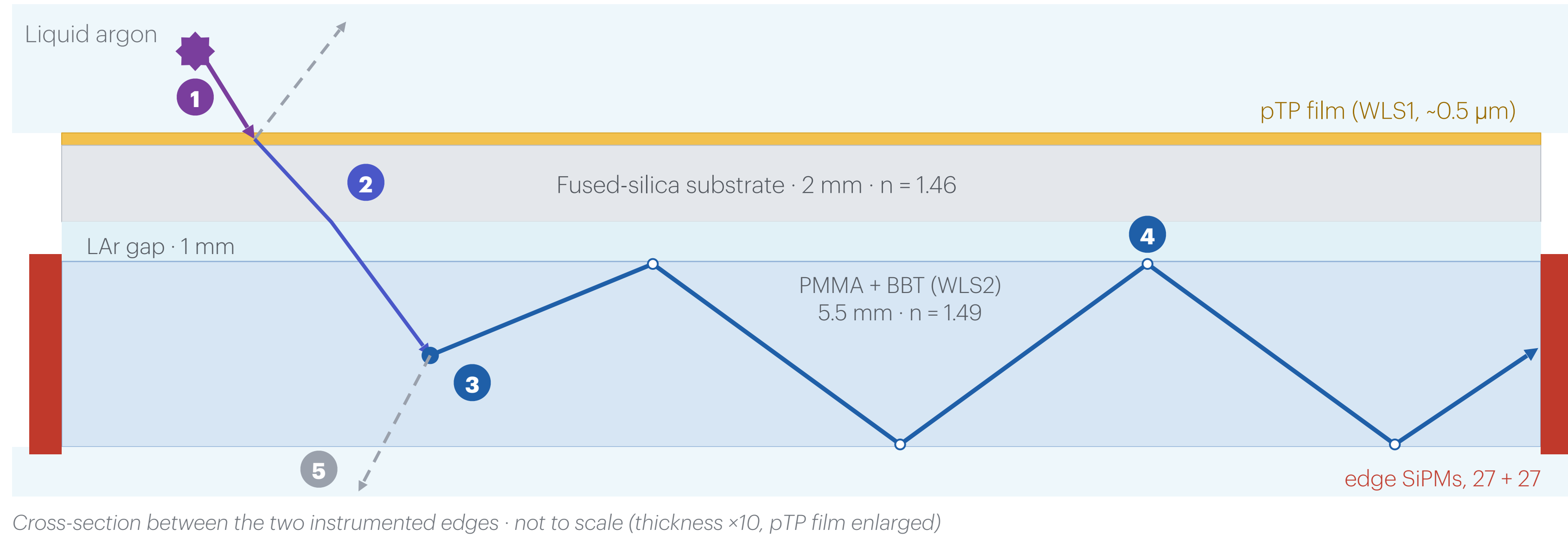


Assembled, between the field-cage profiles

EXAMPLE: LIGHT DETECTION IN LIQUID ARGON

VUV light in LAr: trap it, use fewer sensors

Reference DELTA
2-layers, 2-stage WLS:
(1) pTP film on FusSi layer
(2) BBT in Acrylic layer
1-TIR trap



- 1** **128 nm VUV from LAr**
absorbed in the pTP film
- 2** **350 nm, isotropic**
part goes back to LAr (lost)
- 3** **BBT in PMMA**
converts 350 $\rightarrow$ 430 nm
- 4** **430 nm above $\theta_c = 56.3^\circ$**
TIR-trapped to edge SiPMs
- 5** **430 nm below θ_c**
escapes through the faces

θ_c : pTP/LAr 48.7° , silica/LAr 58.1° ,
PMMA/LAr 56.3°

Down-conversion. Two WLS stages in sequence: pTP shifts the 128 nm VUV to about 350 nm, PMMA with BBT to 430 nm.

Trapping. The index step between LAr (1.24) and acrylic (1.49) traps light by TIR above a 56° critical angle.

Fewer sensors. Higher trapping efficiency cuts the number of costly small-area sensors: SiPMs on the edges.

Reference DELTA: simulated performance

Configuration

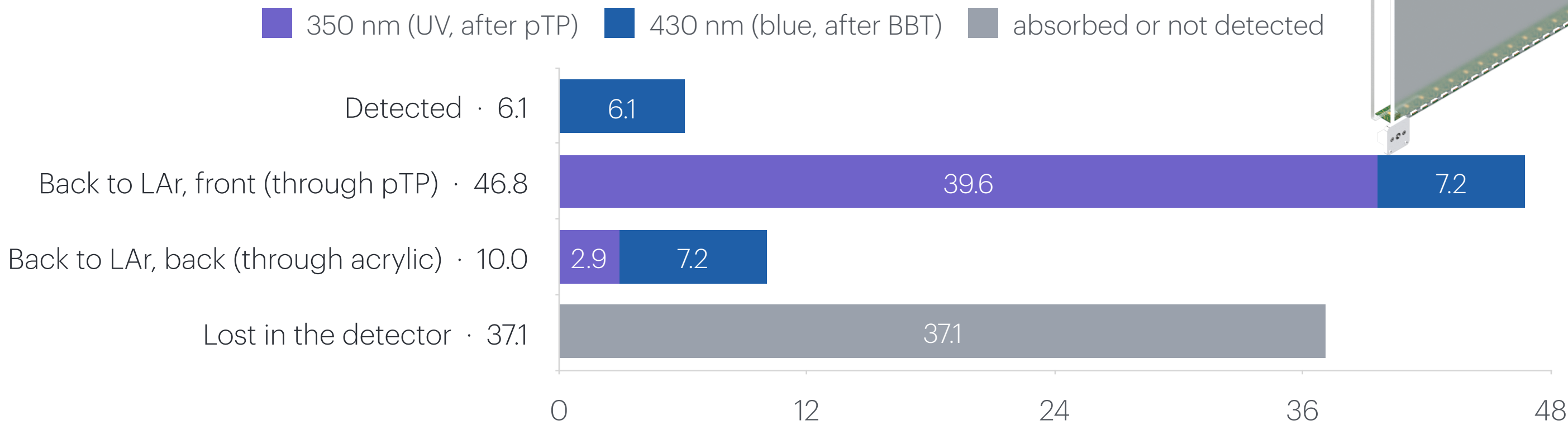
2 WLS stages (pTP, BBT), 1 TIR layer (Acrylic-PMMA)
495 × 450 mm² · 27 + 27 edge SiPMs · f_{si} = 1.34%

6.07% **PCE**
photons detected per VUV
photon on the face; ±0.05% (stat.)

16× **Figure of merit**
vs. bare pTP-coated SiPMs with
the same silicon area (PDE 28%)

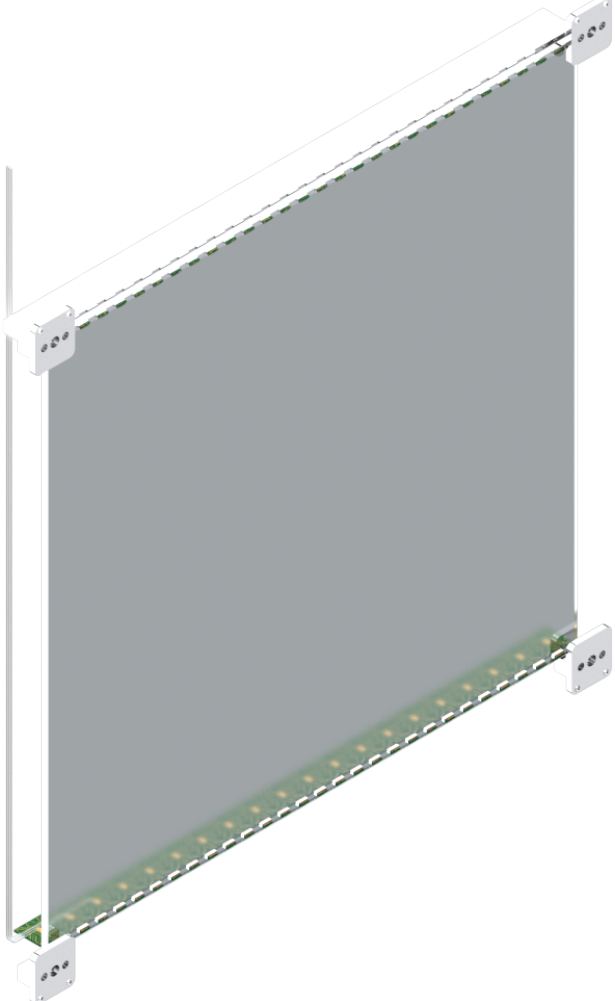
9.6% **Reach an SiPM**
trapping and transport before the
PDE (63%); 41 TIR bounces per
detected photon

Fate of 200,000 VUV photons hitting the face (%)



Lost in the detector, by cause (%)

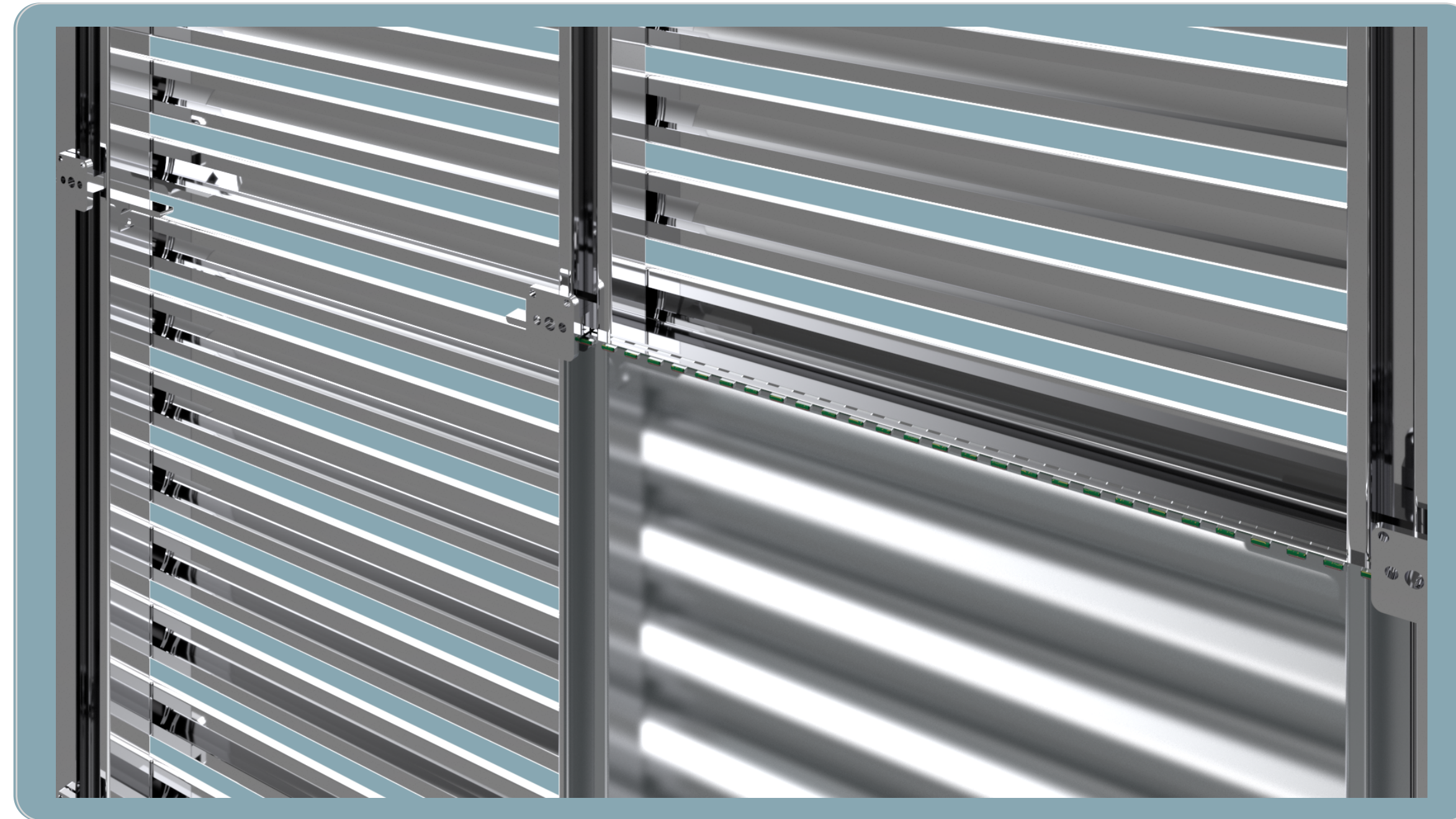
pTP conversion failure (PLQY 0.82)	17.2	BBT conversion failure (PLQY 0.90)	3.6
PMMA bulk absorption (430 nm)	7.5	Reached an SiPM, not detected (1 – PDE)	3.5
VUV not absorbed in 0.5 μm pTP	4.5	Absorbed on Vikuiti reflector	0.7



Checks: detected / reaching SiPM = 63.2% (PDE 63%); pTP PLQY loss 17.2% vs 18% expected. **Open inputs:** pTP PLQY at 128 nm, pTP thickness and VUV absorption, $\lambda_{att}(430\text{ nm}) = 2\text{ m}$ (flagged), smooth interfaces.

FIRST USE CASE

APEX: DELTA on a high-voltage surface



DELTA module between field-cage profiles (renders: ICArch)

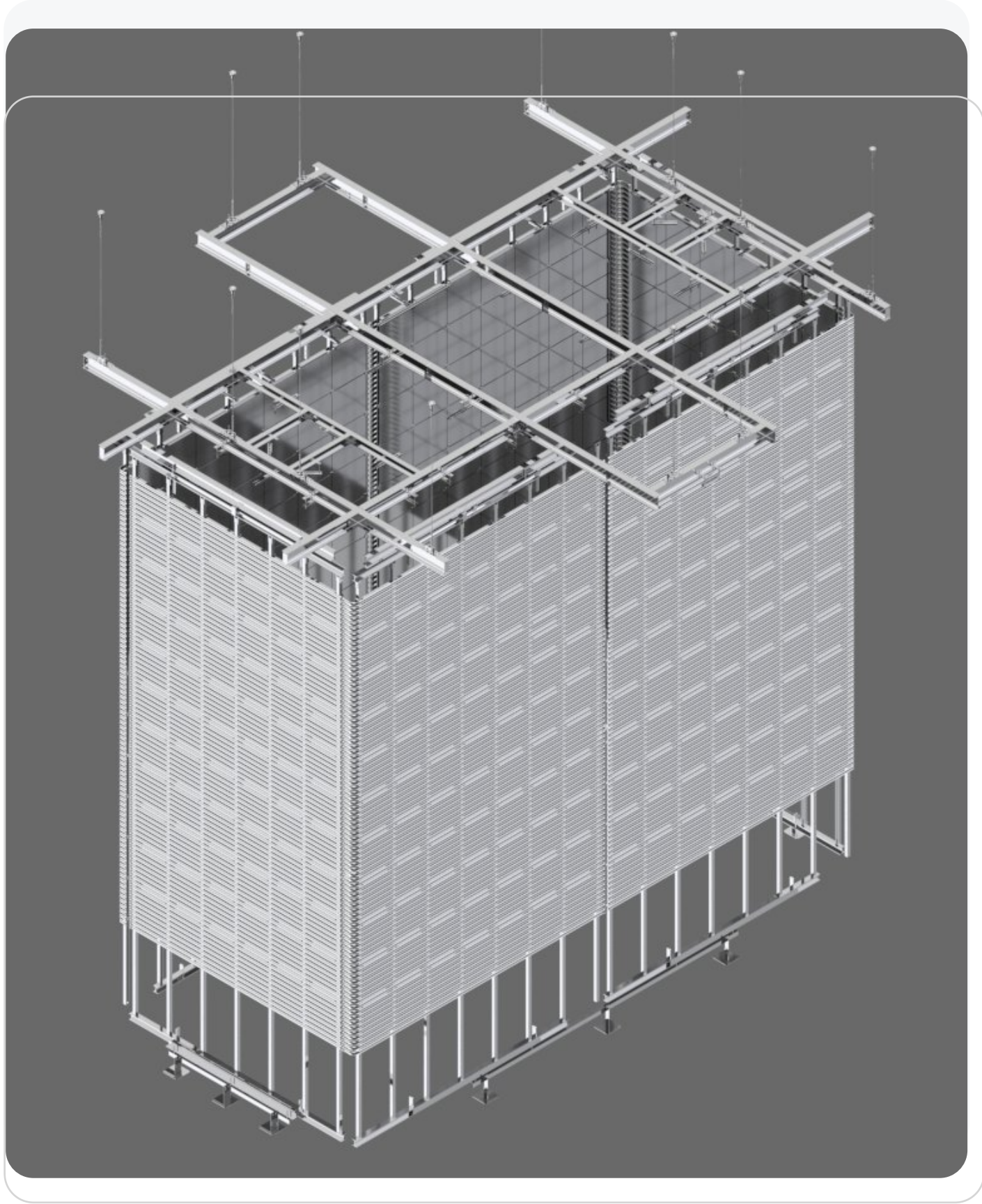
Heritage. PoF and SoF in DUNE FD2 (TRL 2 to 7, 2020–24).

- APEX turns the field cage of the LAr TPC into a photon detector
- The field cage sits at high voltage, so the detector must be galvanically isolated
- **Power over Fiber** brings bias and power in; **Signal over Fiber** takes the data out
- No copper cables: less mass, less noise, no discharge path



SAME USE CASE, AT SCALE

APEX in DUNE Phase-II: a very large, low-background detector



protoDUNE-III field cage

R. Maramara-SBU
G. Stavrakis - Liverpool U.
ICArch - renders

F. Cavanna · DELTA · CPAD Instrumentation

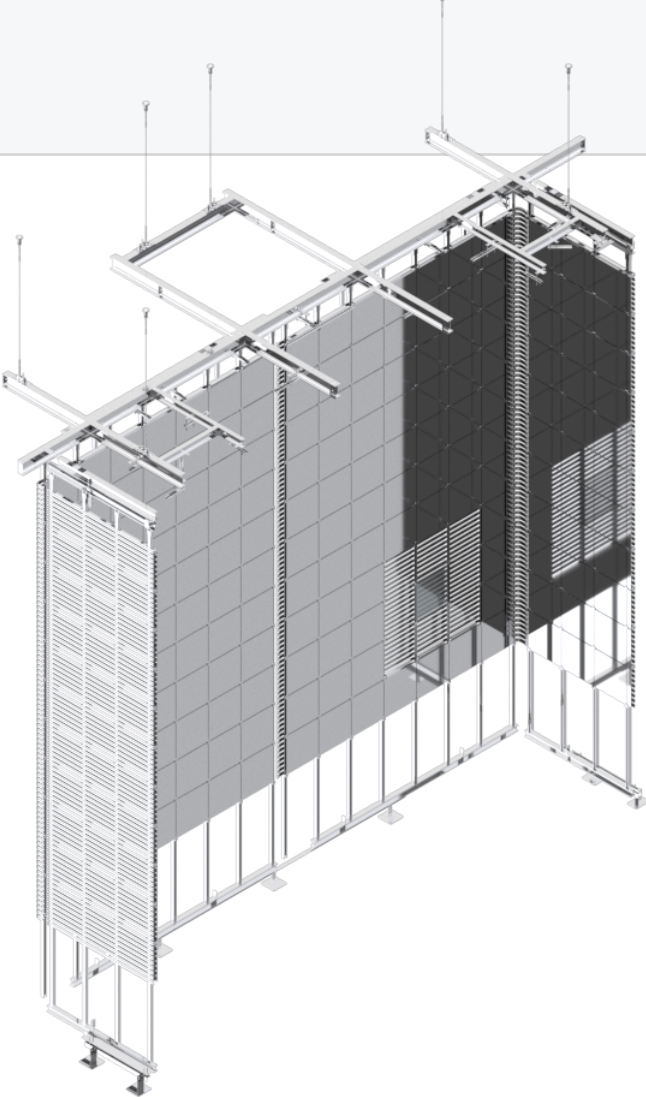
Underground need	DELTA answer
Low-energy physics, low background	Radiopure materials, assayed by ICP-MS
Very large optical coverage	About 60% coverage, 1700 m ² , at least 180 PE/MeV
Scale to extended surfaces	Modular, low-cost, frameless, built for mass production
Single-PE sensitivity	Low-noise cold readout, digital at the source

protoDUNE-III, 2029–30

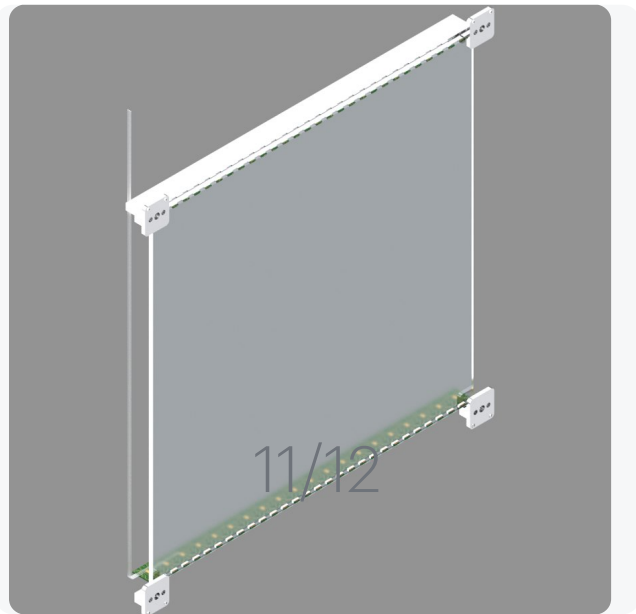
432 modules, about 22k SiPMs, 864 channels

DUNE FD3, 2031–36

about 6900 modules, 350k SiPMs, 14k channels



Module: frameless PMMA plate of about 50 × 50 cm², ~50 SiPMs of 6 × 6 mm², 2 readout channels, about 1.8 kg.



SUMMARY

DELTA: a detector and a platform

Concept

- Digital photodetector from photons to disk
- One common design, many application variants
- Distributed R&D platform

Progress

- Automated pTP spray films and their model
- Industrial pTP vacuum deposition (PVD)
- SiPM candidates: cold tests at BNL
- Second-generation PoF at 1470 nm: no SiPM light leak in LN2
- Cross-lab cryo-ASIC initiative for DELTA/APEX launched

Next

- LN2 tests of the SiPM-to-PMMA contact pad
- Full-chain tests at NLTF and 260-L
- Baseline for the protoDUNE-III TDR

BACKUP

Backup slides

Simulated PCE, building blocks (sensors, optical contact, coatings, cold readout, power, photonics), prototyping, thrusts, applications

BACKUP · DELTA-sim CONFIGURATIONS

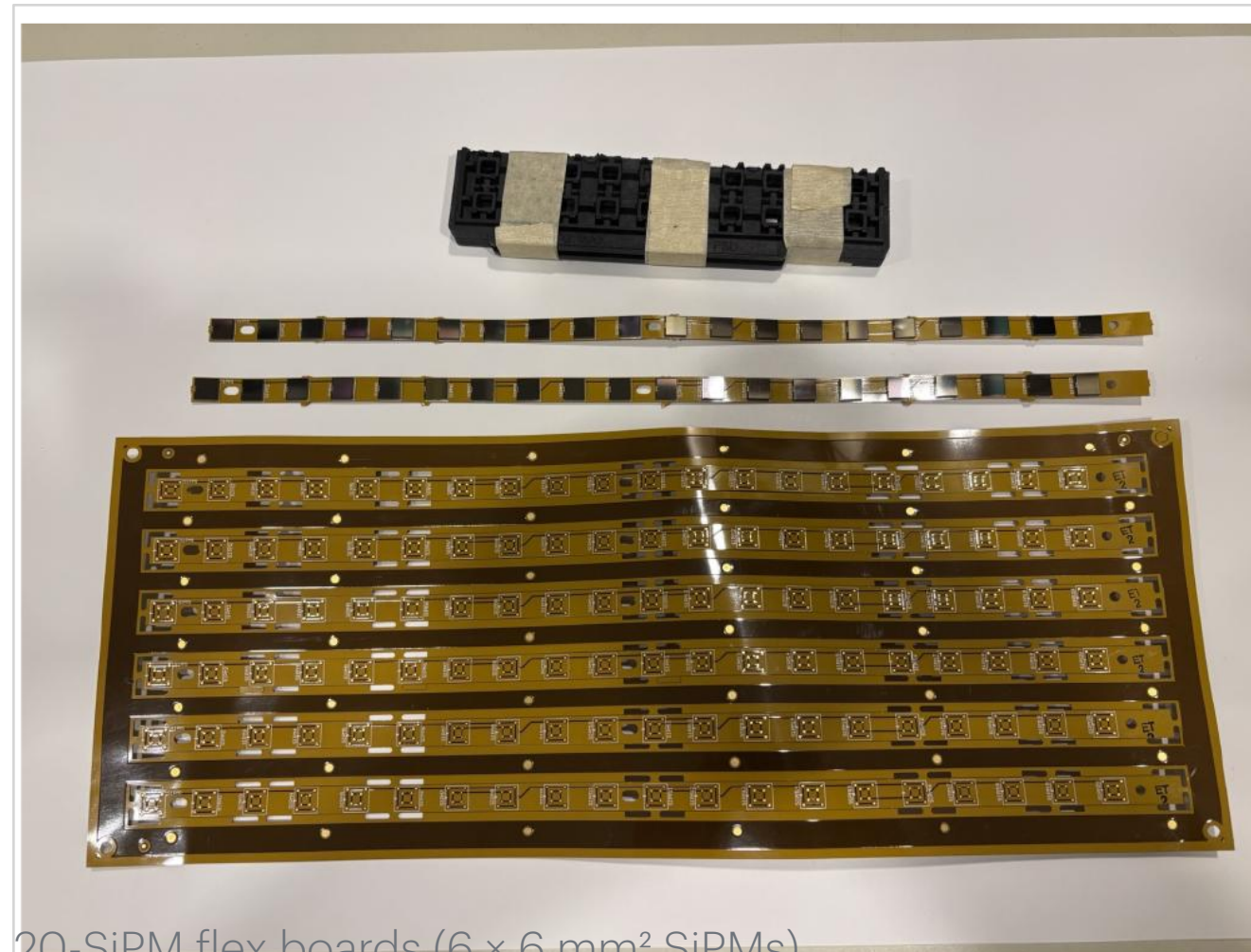
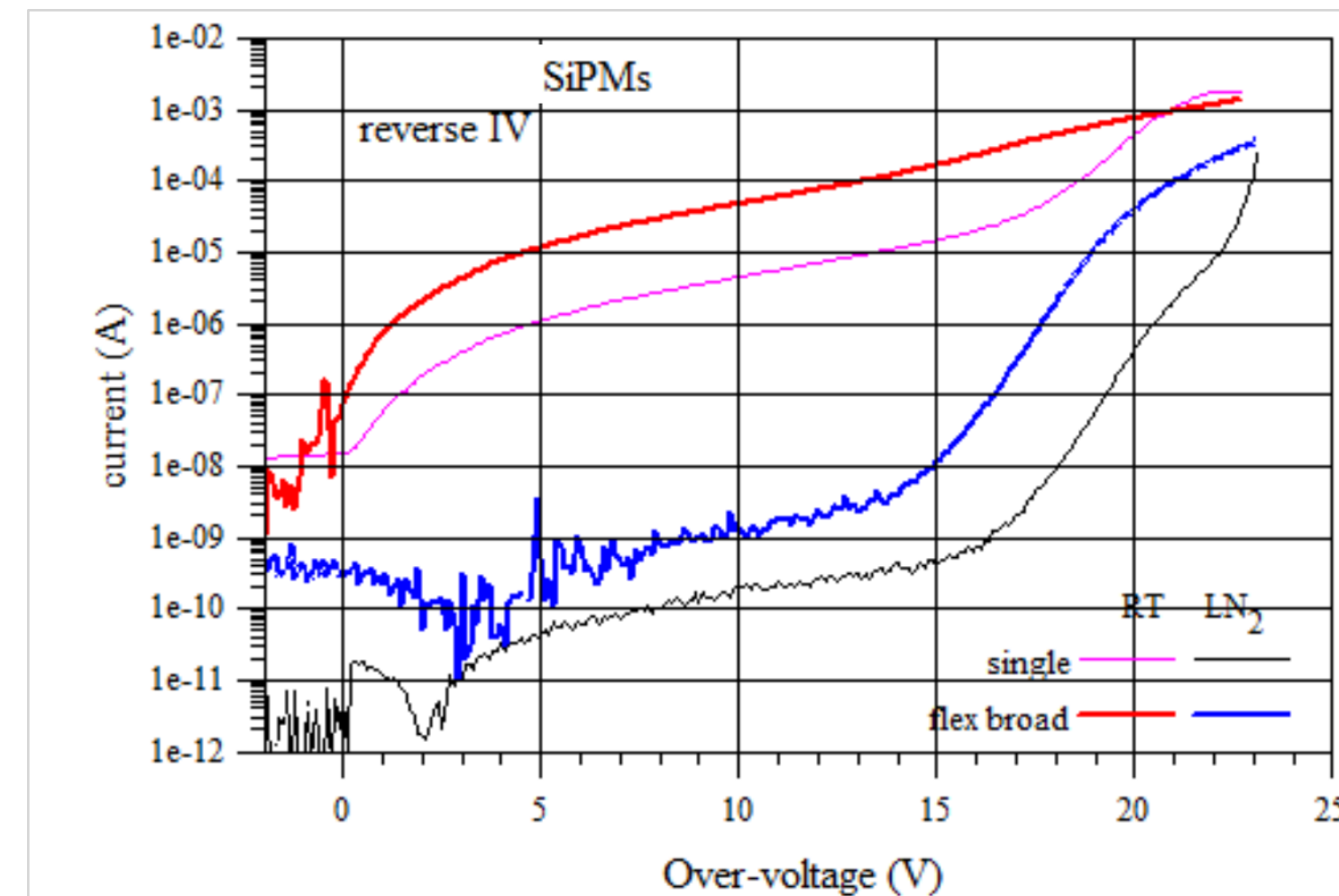
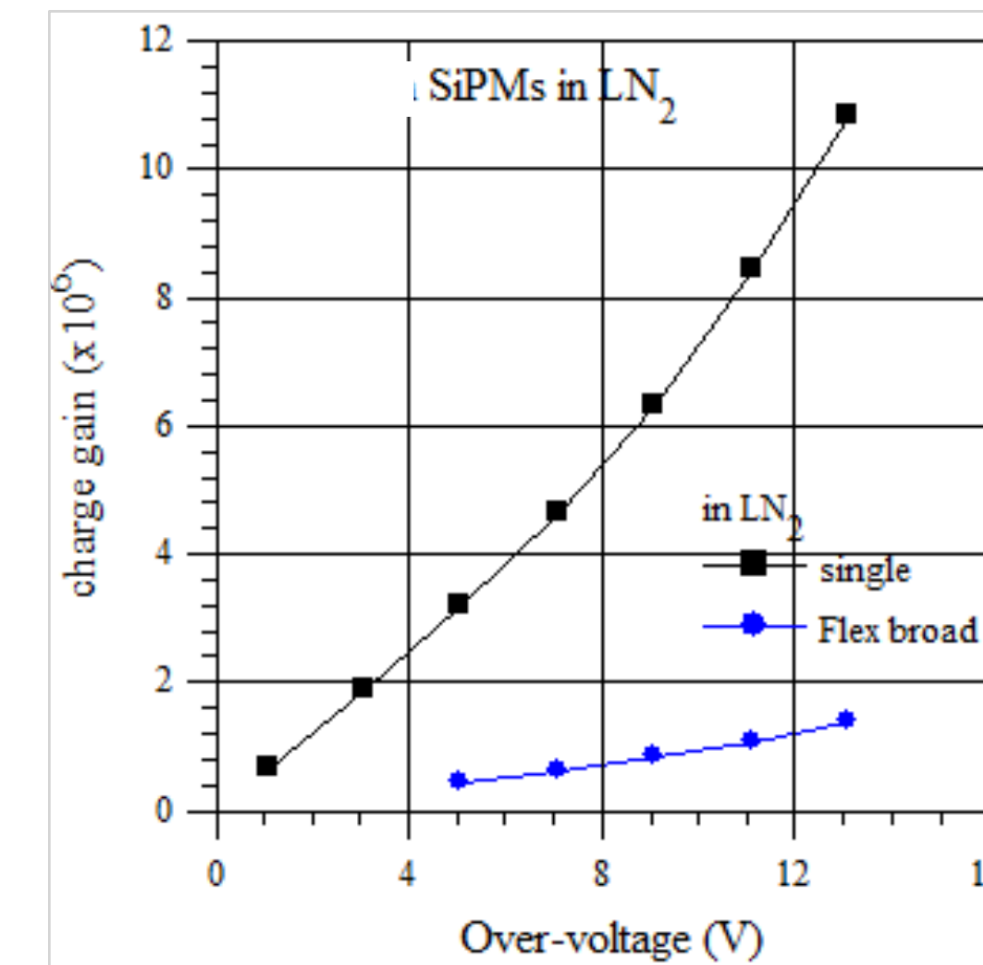
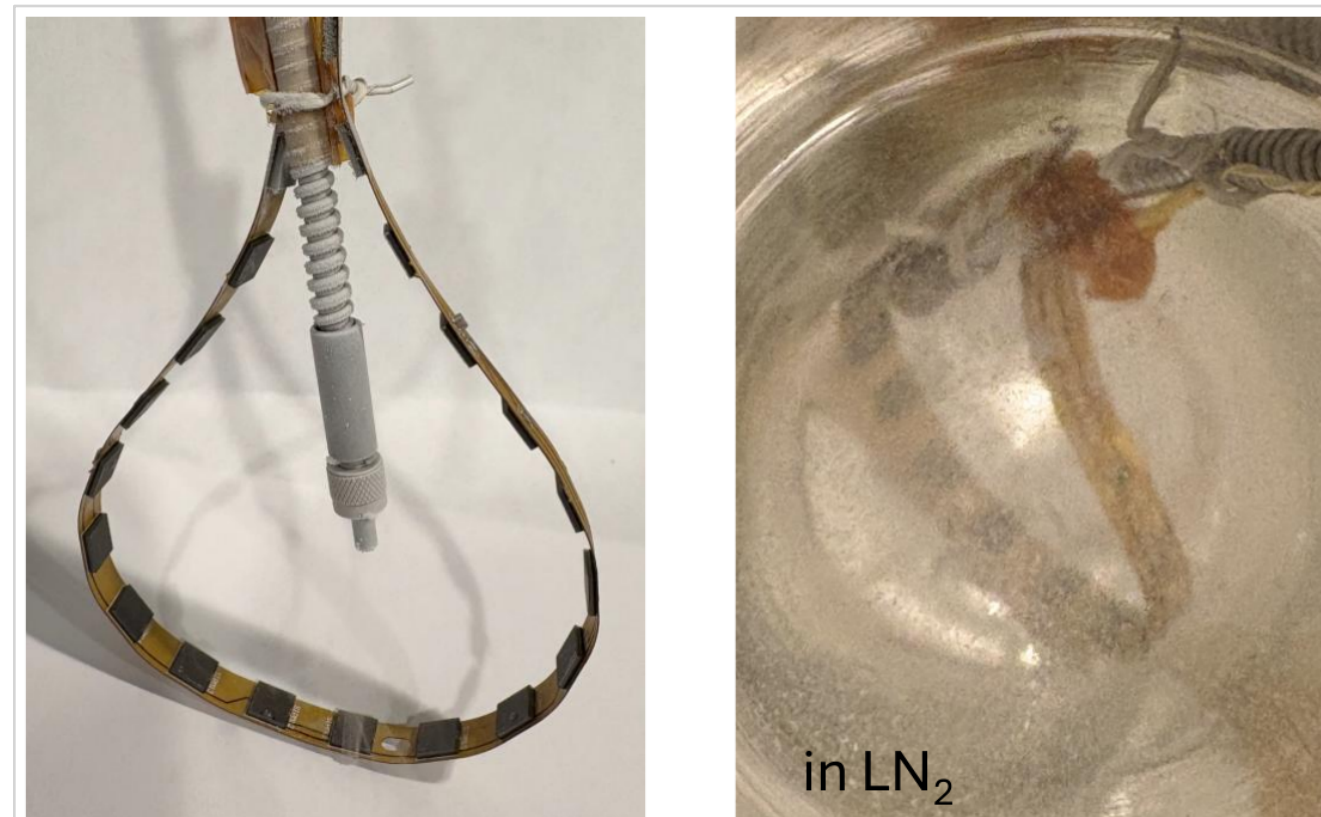
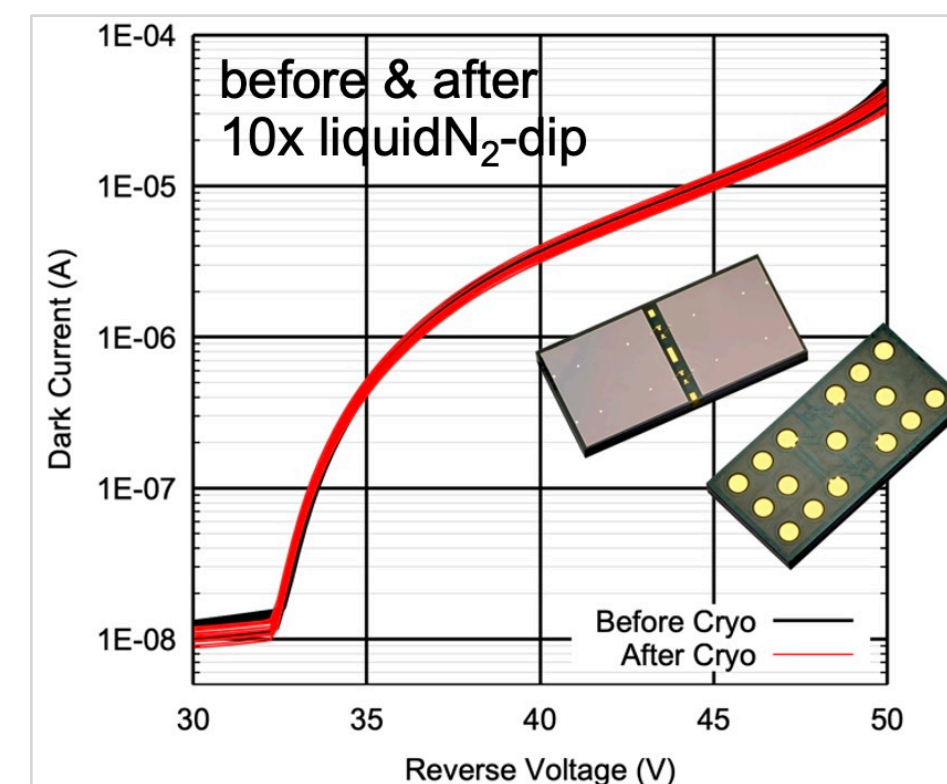
From Reference to Advanced DELTA: simulated PCE

Configuration	WLS stages · TIR layers read out	SiPMs (z-edges)	fsi	PCE (%)	FoM
Reference DELTA	2 WLS · 1 (PMMA)	27 + 27	1.34%	6.07 ± 0.05	16.2
Double Coverage	2 WLS · 1 (PMMA), edges filled	54 + 54	2.68%	8.25 ± 0.06	11.0
Advanced DELTA, 2-TIR	2 WLS · 2 (PMMA + fused silica)	54 + 54	2.68%	8.74 ± 0.06	11.6
Advanced DELTA, 3-TIR (Model 2)	3 WLS · 3 (+ EJ-280), 2-element SiPM	68 + 68	4.40%	8.16 ± 0.09	6.6
Advanced DELTA, 3-TIR (Model 3, 6 mm)	3 WLS · 3, one SiPM row per layer	3 × (69 + 69)	6.69%	10.53 ± 0.13	5.6
Advanced DELTA, 3-TIR (Model 3, 4 mm)	3 WLS · 3, one SiPM row per layer	3 × (106 + 106)	3.85%	9.14 ± 0.12	8.5

PCE = detected / VUV photons on the 495 × 450 mm² face; ± statistical. **FoM** = PCE × A(face) / (0.28 × A(SiPM)): more silicon raises PCE and lowers FoM.
3-TIR rows include the green (EJ-280) channel, about 1% of PCE. Model 3 uses a PMMA candidate as WLS1 substrate with a placeholder attenuation length. Same open inputs as the Reference.

BACKUP • PHOTSENSORS

Commercial SiPM candidates: cold tests under way at BNL (T. Tsang)

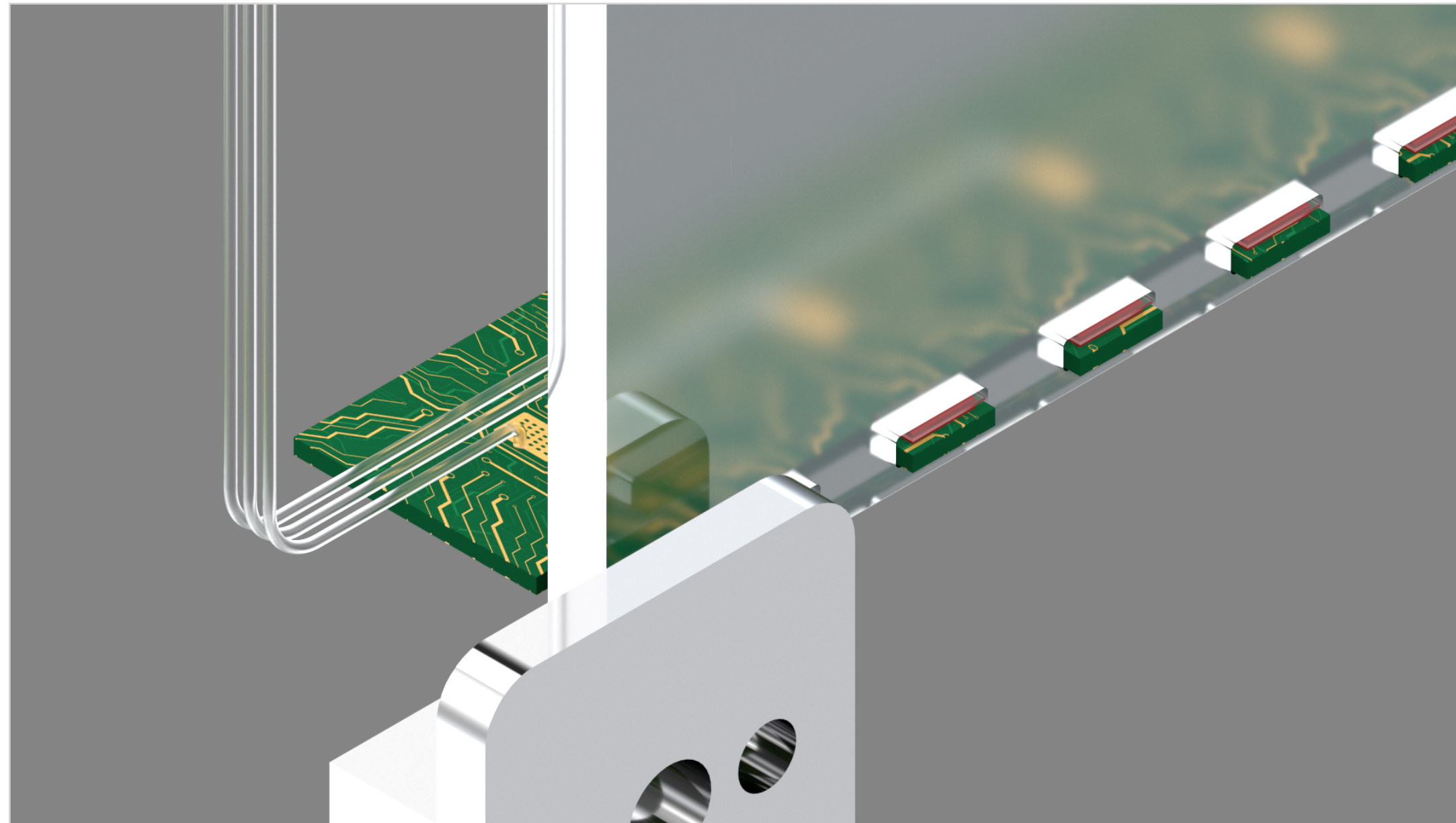


- Commercial NUV SiPMs, 6 × 6 mm², packaging adaptable to DELTA edge boards
- Single photoelectrons resolved in LN2: S/N 24 (single SiPM), 9.5 (20 on one flex)
- Dark current drops by orders of magnitude from RT to LN2
- Package unchanged after repeated LN2 thermal cycles

BACKUP • OPTICAL CONTACT

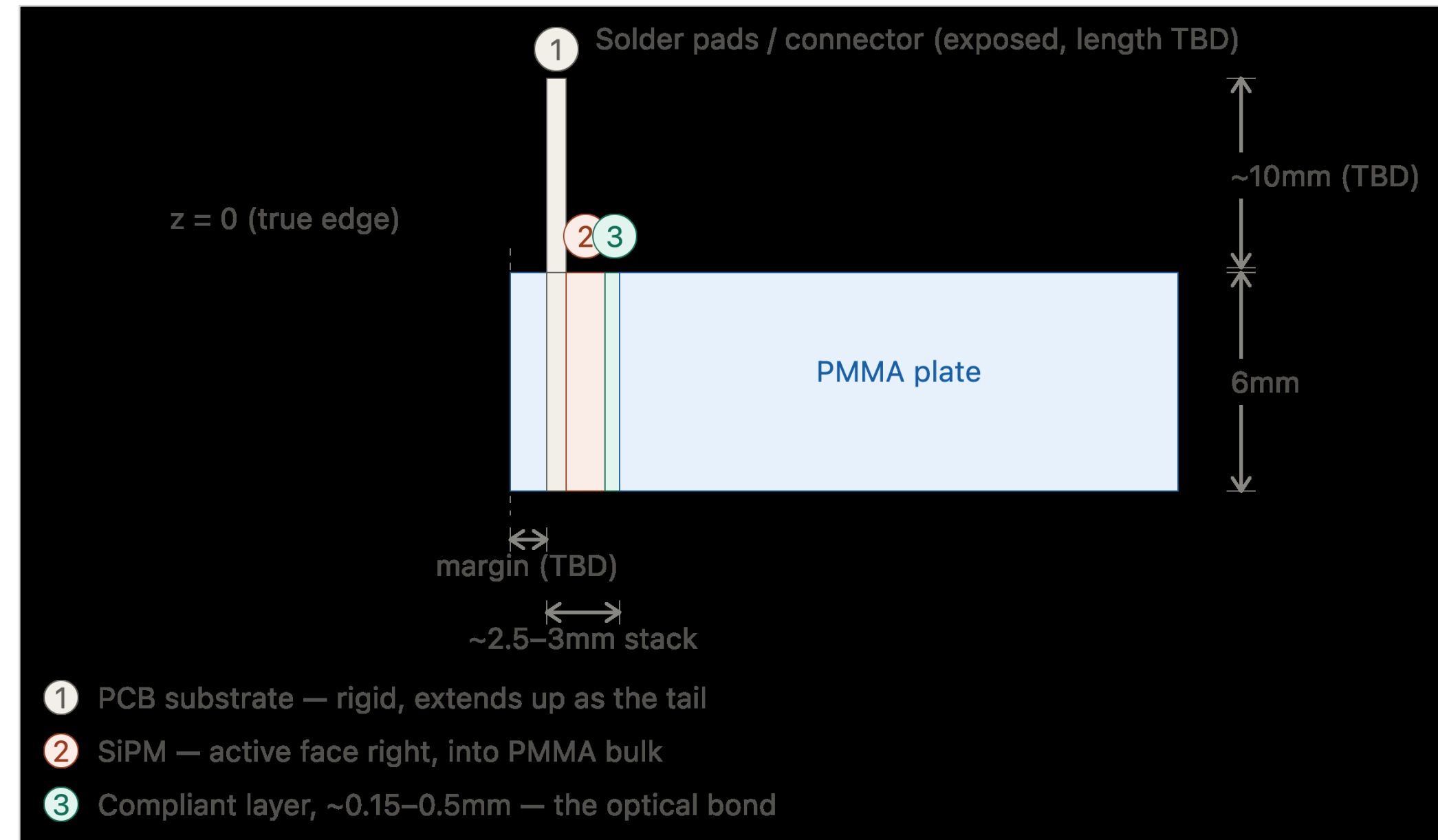
EXPLORATORY

SiPM-to-PMMA optical contact at 87 K: first explorations



SiPM edge board seated in the PMMA plate (render)

- Frame-free plate: no spring-loaded contact as in X-ARAPUCA
- Ruled out: casting SiPMs into PMMA or rigid glue (PMMA shrinks about 50× more than silicon)
- Approach: SiPM on a rigid PCB insert in a through-bore, coupled by a thin compliant layer



Insert in a through-bore: PCB (1), SiPM facing the plate (2), compliant layer (3)

- Silicones turn glassy above 87 K: the layer must survive the transition, not stay soft
- Candidate: MAPSIL QS1123, a space-qualified silicone molded as a thin pad on SiPMs (POLAR-2); $n \approx 1.53$, > 98% transmission from 350 nm
- Next R&D test: QS1123 pad molded on a SiPM, pressed into a PMMA bore, cycled in LN2 (transmission, haze, delamination)

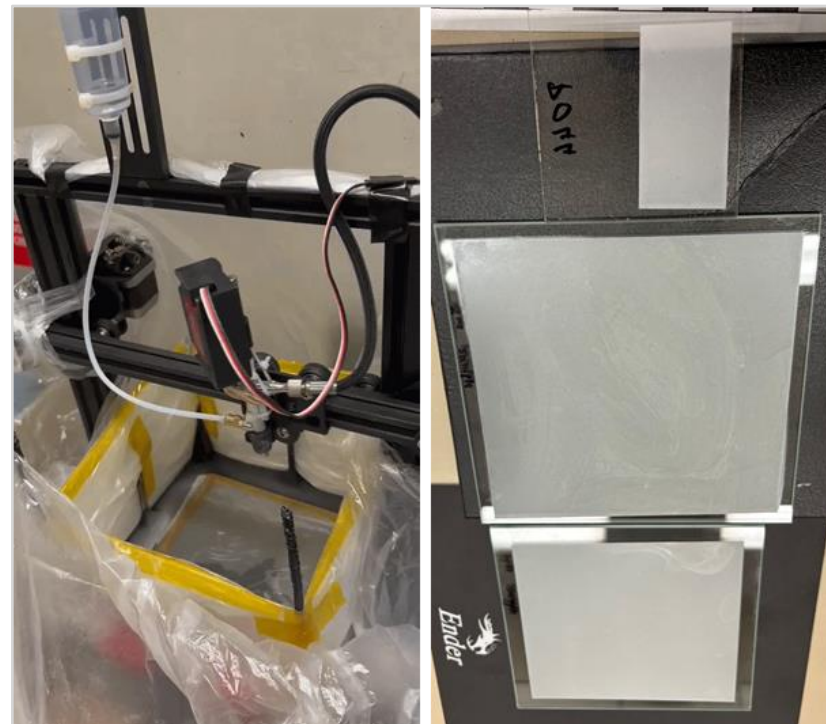
BACKUP · PHOTOCOLLECTOR

pTP coating for large areas: spray and industrial PVD

Goal: coat about 2,000 m² for APEX in DUNE FD3 faster and cheaper. The Phase-I vacuum approach would need more than 6 years.

Spray deposition · SBU

Talk: R.F. Razakamiandra



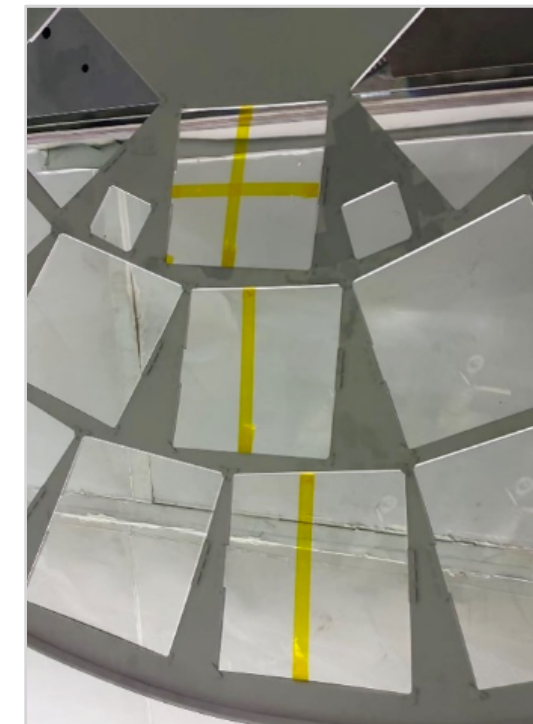
Automated spraying on a repurposed 3D printer

- pTP in solvent, sprayed on UV-transparent acrylic: low cost, light, radiopure substrate
- Automated up to 15 × 15 cm²; scaling to 30 × 30 cm² with an industrial spray gun
- Film stable after LN₂ cycling; VUV conversion measured at IFIC (130 nm)

Suits DELTA: 2 layers · 2 WLS · 1 TIR read out

Industrial vacuum deposition (PVD) · BNL

Talk: M. Vicenzi



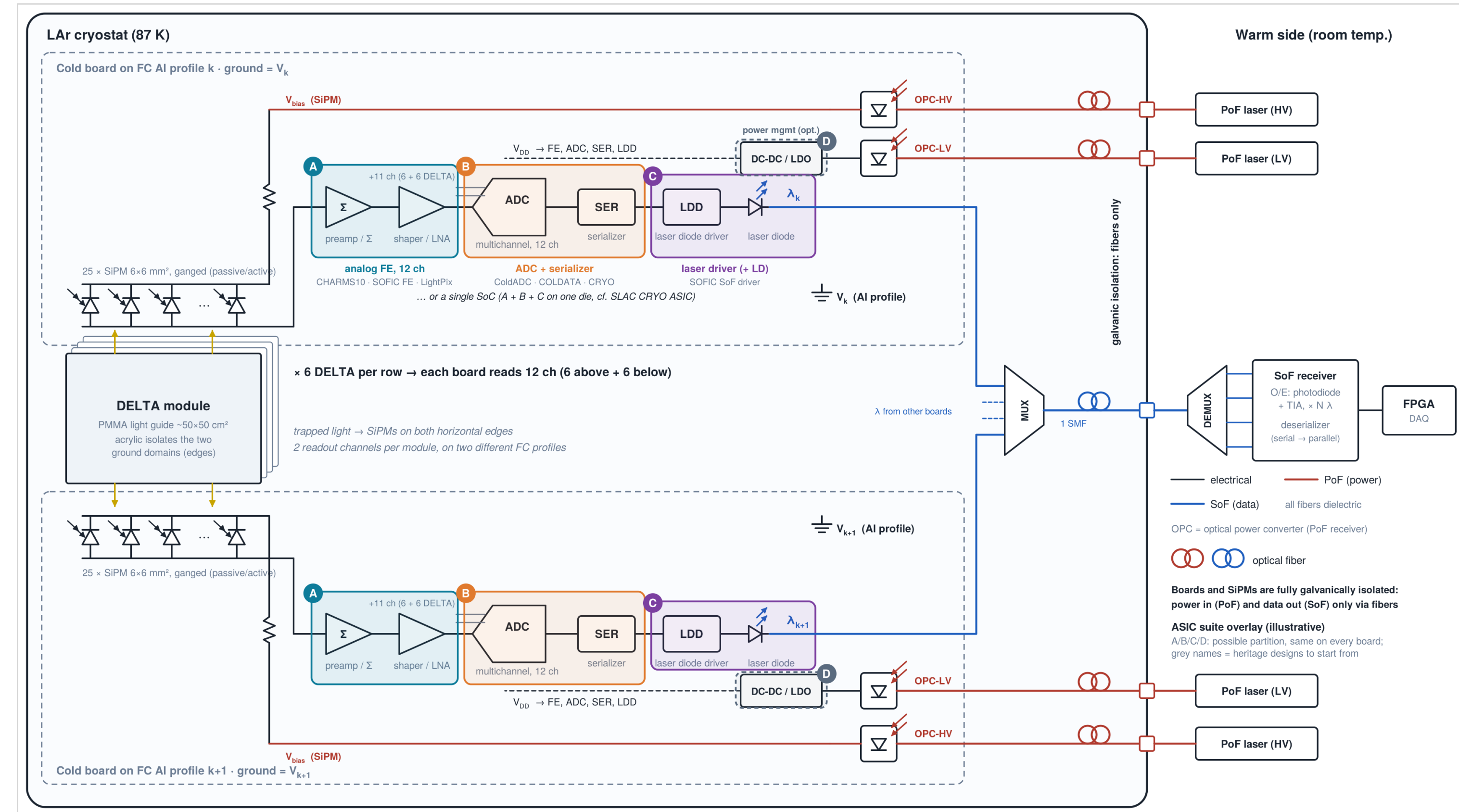
Rotating dome loaded with substrates (industrial vendor)

- Process from OLED display production: about 5.4 m²/day, 2,000 m² per year, about \$3M in total (vendor estimate)
- Films 1–2 μm with < 10% thickness variation; QY 59%; no change after LN₂/LAr cycling
- Optically smooth film: TIR already in the pTP-coated layer

Suits DELTA: 1 layer · 1 WLS · 1 TIR, or 2 layers · 2 WLS · 2 TIR read out

BACKUP · COLD READOUT

Cryo-ASIC suite for DELTA/APEX: a cross-lab initiative



- Launched Oct 2026: cryo-ASIC developers from FNAL, BNL, SLAC, LBNL and APC Paris
- Goal: a cryogenic ASIC, or a suite, for the DELTA/APEX readout at 87 K
- Blocks: A front end, B ADC + serializer, C laser driver for signal over fiber
- Starting from heritage designs (LArASIC/CHARMS, ColdADC, LArPix/LightPix, CRYO, SOFIC)
- Next: requirements, partition options, a standing collaboration

BACKUP • POWER OVER FIBER

Second-generation power over fiber for APEX/DELTA

Laser • 1470 nm

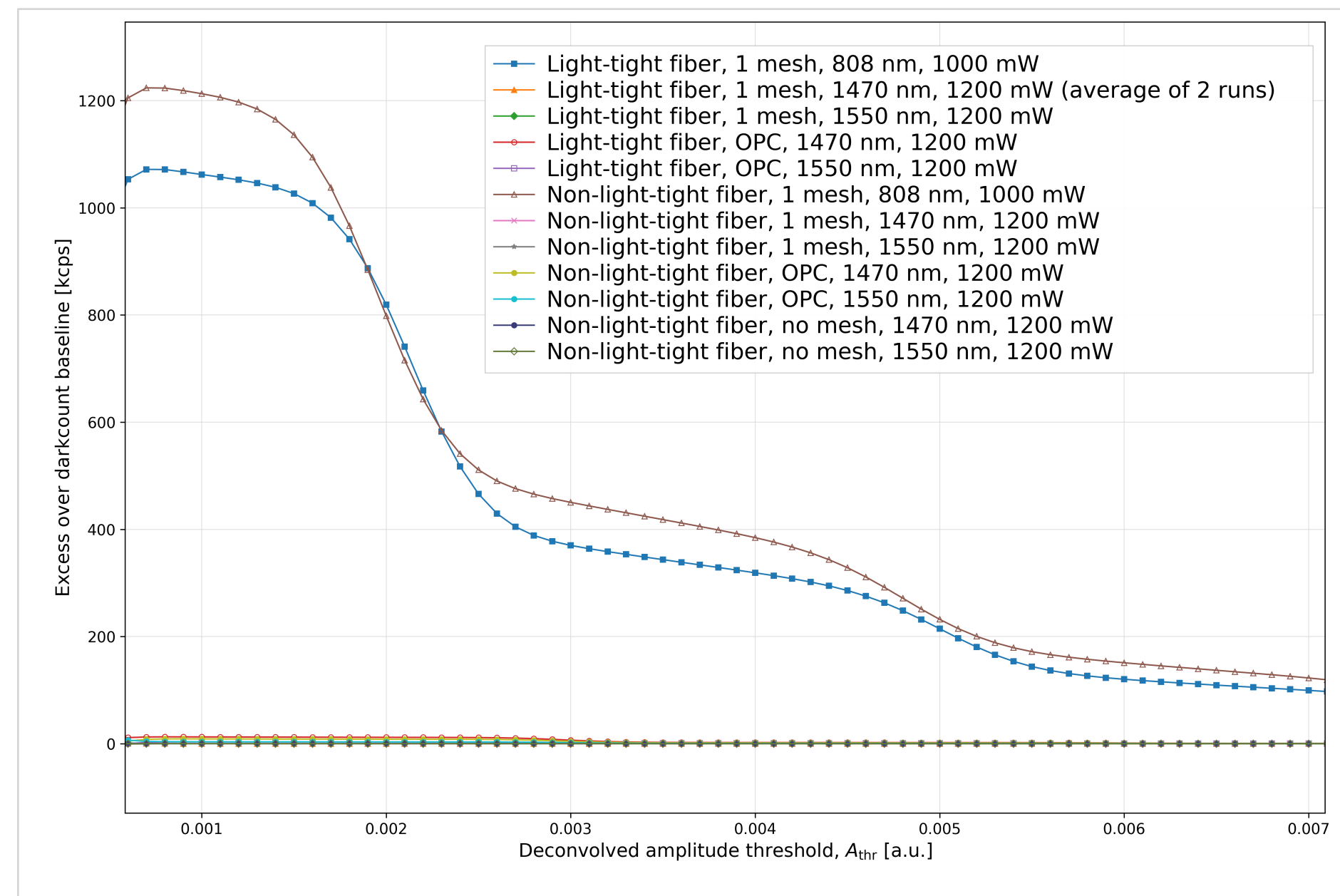
Fiber-coupled, up to 2.5 W; custom driver prototype, output stable to about 1% over 1 h

Optical fiber

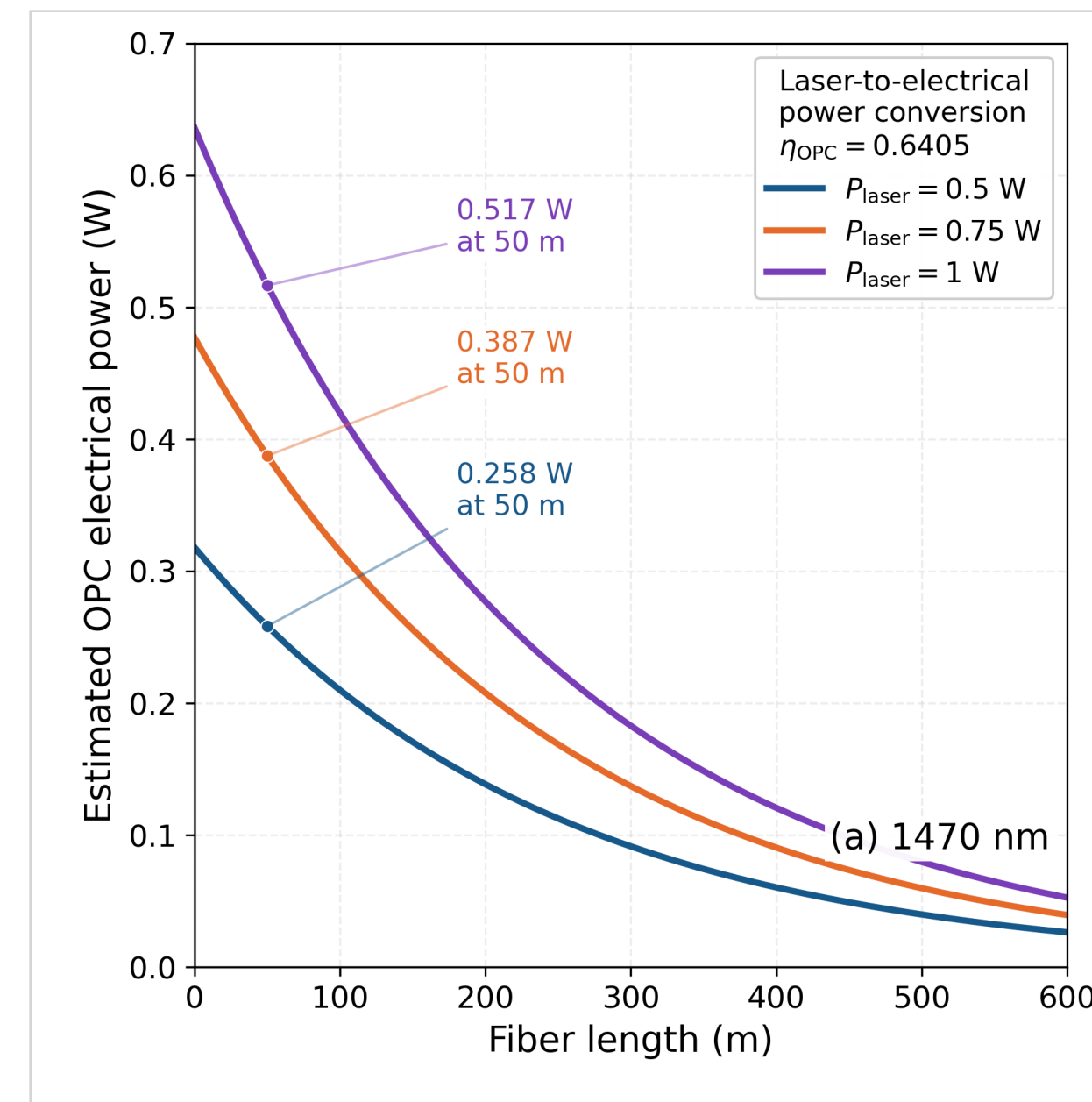
Multimode fiber characterized in LN2: about 20% power loss over 50 m

Optical power converter

InGaAs converter: 64% optical-to-electrical in LN2 (808 nm GaAs: 50–55%)



SiPM light-leak rate in LN2: 808 nm (top) vs 1470/1550 nm (near zero)

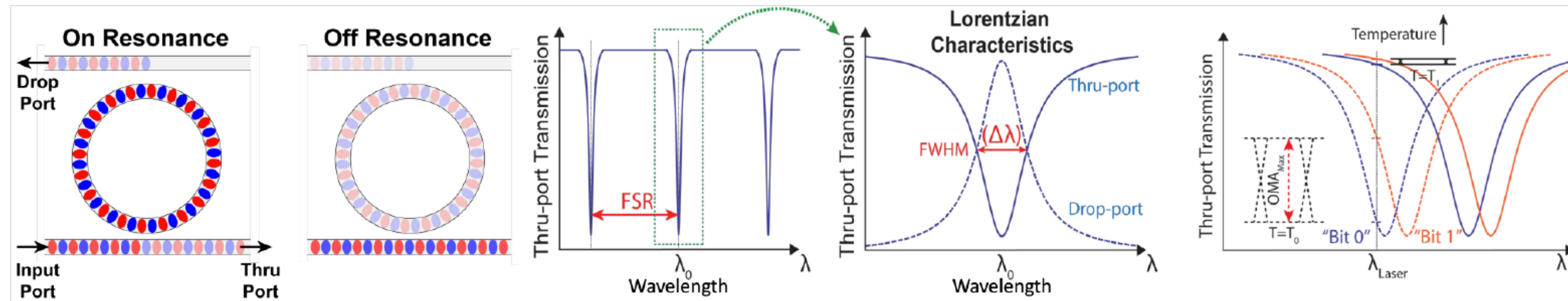


Electrical power after the fiber, 1470 nm

- Light leaking from fibers and converters: at least 100× lower than at 808 nm, at the dark-count level
- Higher conversion efficiency: 1 W of laser light gives about 0.5 W at the cold electronics, 50 m away
- Next: power budget of the full cold readout, then protoDUNE-III

BACKUP · PHOTONICS

Signal over fiber with cold modulators: BNL–Harvard R&D



Micro-ring modulator: the data shift the ring resonance across a fixed laser line, switching the transmitted light on and off

Micro-ring modulators (silicon)

- Compact and low power; one ring per wavelength, so many channels share one fiber (WDM)
- The resonance must be held on the laser line: temperature tuning and locking at 87 K
- Silicon ring tests in parallel with CERN

Thin-film lithium niobate (TFLN) modulator

- Packaged 65 GHz intensity modulator, rated cryo-compatible, from HyperLight (Lončar's Harvard spin-off)
- Mach-Zehnder type: broadband, no resonance to lock
- Procurement and cold tests at BNL from Oct 2026



TFLN-G2-IM-1550-65 (cryo)

Same function, different mechanism: the cold electronics modulate a laser fed from the warm side; a ring shifts a resonance, the TFLN device interferes two arms.

BACKUP · PROTOTYPING

Prototyping path and test facilities

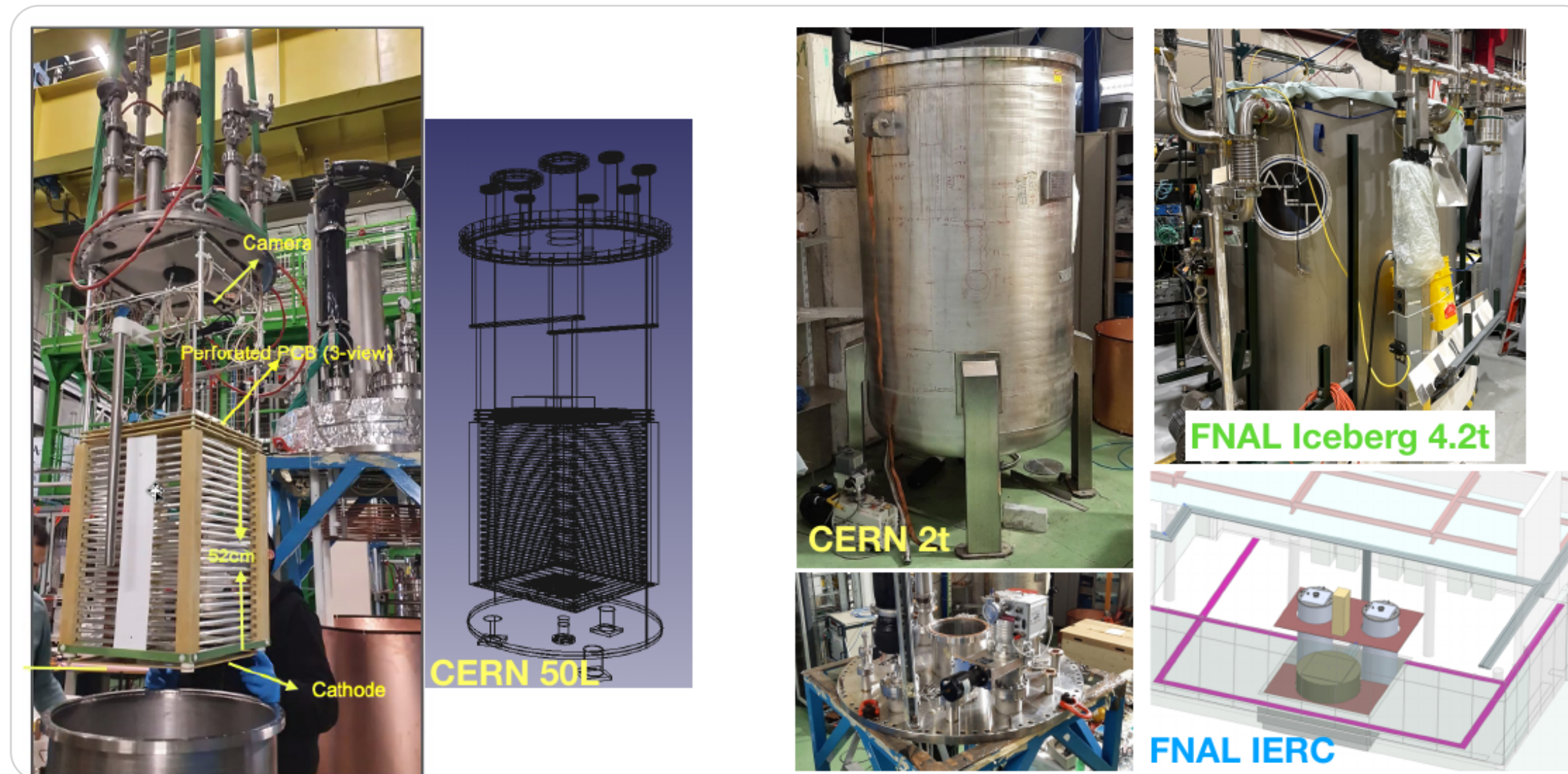


Table-top 50 L TPC, CERN 2 t, FNAL Iceberg 4.2 t, FNAL IERC

Table-top 50 L TPC, 2023

First tests at CERN, completed

Ton-scale ProtoAPEX

CERN 2 t and FNAL Iceberg 4.2 t

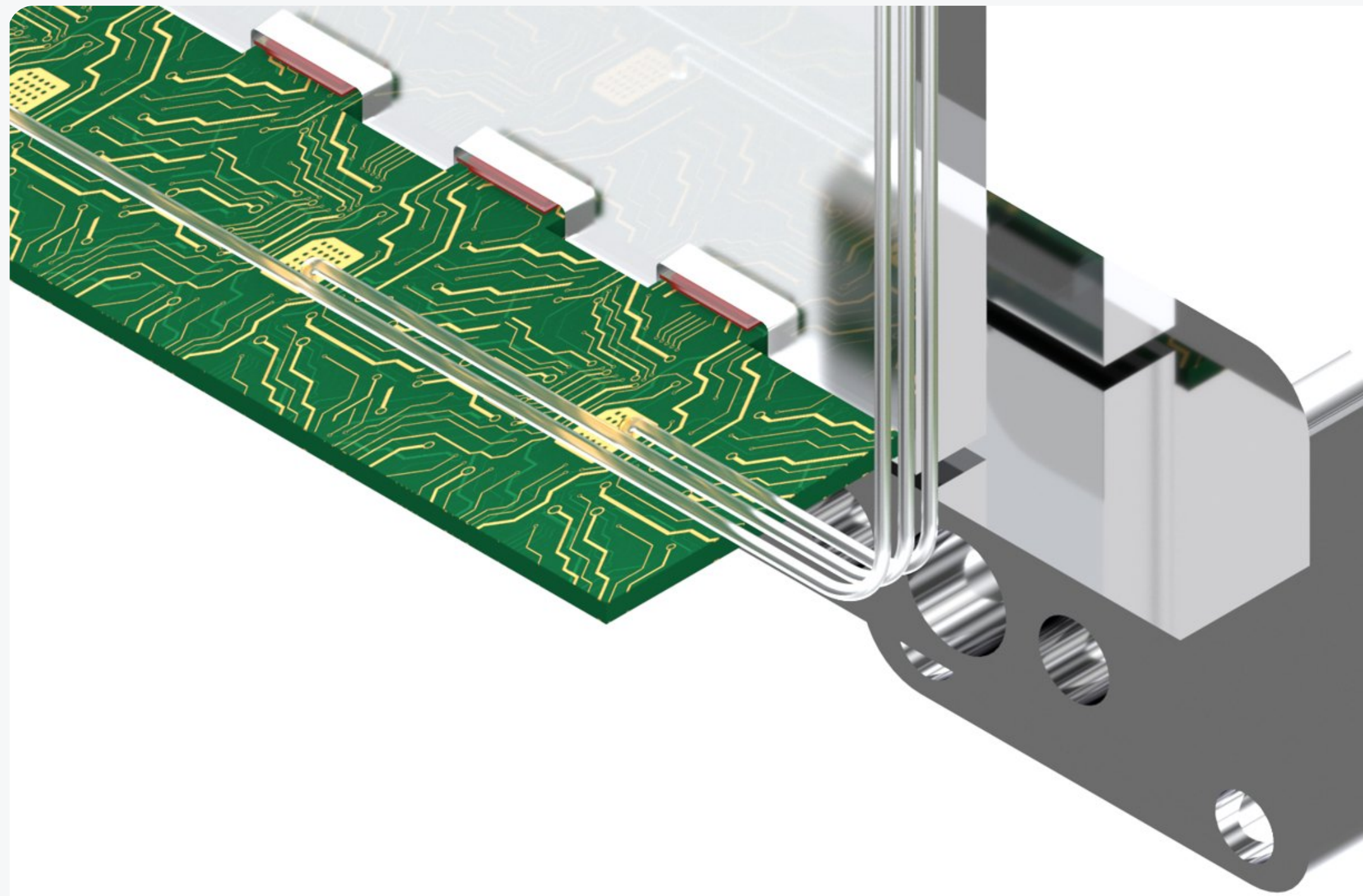
protoDUNE-III at NP02, 2029 to 2030

TDR requested by about end 2027

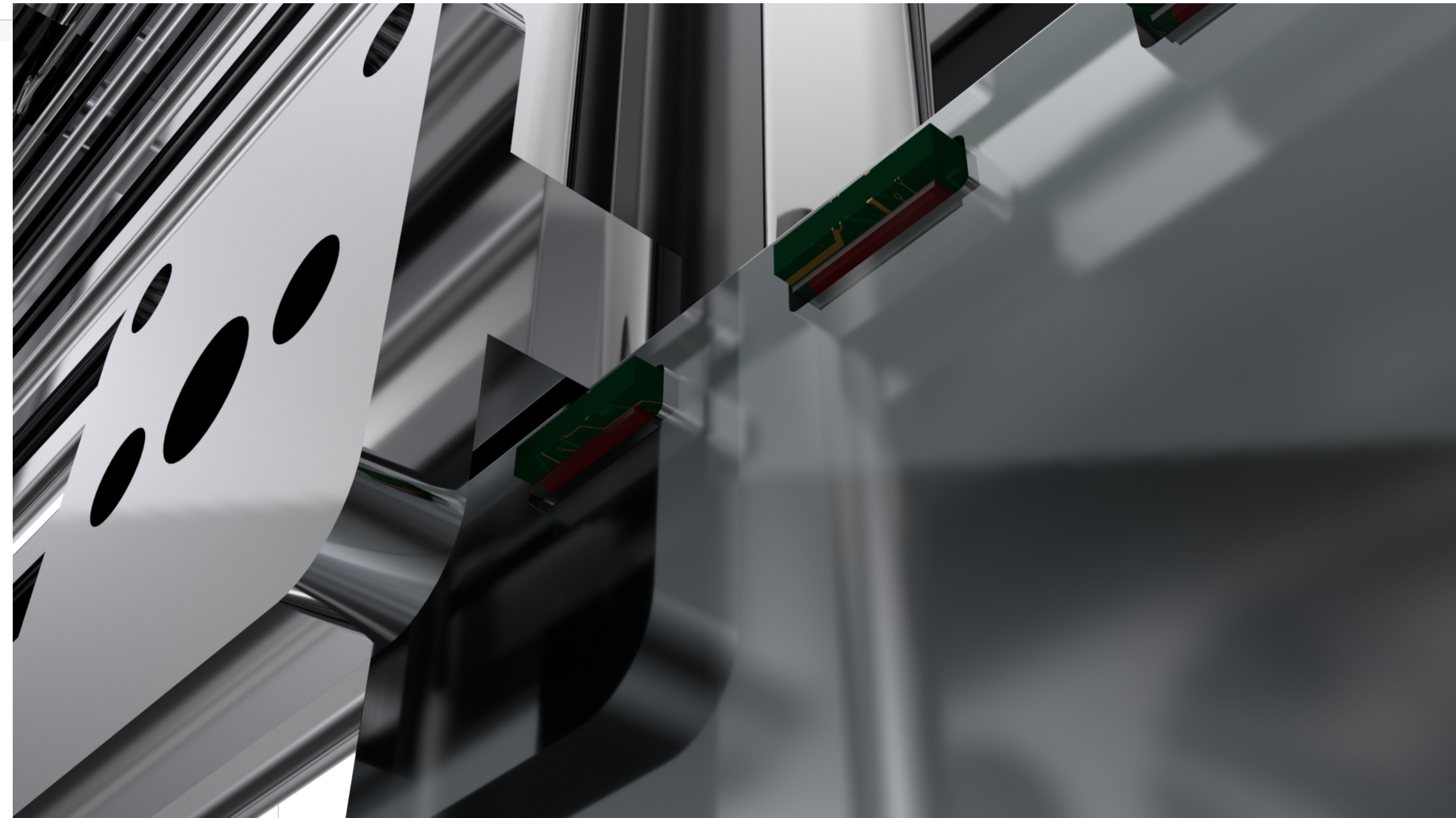
Full-chain DELTA tests use FNAL-NLTF and BNL 260-L; local test stands (SDSMT, BNL) serve the sub-components.

BACKUP • CAD RENDERS

The DELTA module in detail



Edge board: SiPMs on the light-guide edge, cold electronics, PoF and SoF fibers



Frameless module plate and anchoring to the field cage

BACKUP · R&D THRUSTS

Thrusts T1–T5 follow the chain of blocks

Thrust · block	Labs: FNAL, BNL, PNNL	Universities: SBU, SDSMT, UCSC, Harvard, UMN
T1 · PhotoCollector	BNL: WLS coatings (pTP, alternatives), light-trap geometry, cryo optics. PNNL: radio-purity assays, background models	SBU: chemical coating for fast, low-cost, large-area VUV down-conversion on radiopure acrylic
T2 · PhotoSensor	FNAL: SPICE digital SiPM backplane to test a-Se films and other materials; customized SiPMs with industry	UCSC: amorphous-selenium photosensors, at the edge or over the large back surface
T3 · Processing	BNL: dual-gain cryogenic ASIC, fast timing. FNAL: low-power cold ADC and TDC	UMN: digital cold readout, full-chain integration and prototype
T4 · Transmission	BNL: signal over fiber with cold micro-ring and TFLN modulators, with university and industry	Harvard: cryogenic micro-ring and TFLN modulators (with BNL). SDSMT: Signal over Fiber
T5 · Power	FNAL: RF wireless power through liquid noble gas to cathode planes at hundreds of kV	SDSMT: Power over Fiber, first PoF in ProtoDUNE-VD (808 nm); second generation at 1470 nm

Deliverable: a prototype end-to-end digital photodetector module that integrates all thrusts.

BACKUP • APPLICATIONS

DELTA-style detectors beyond HEP: candidate systems

Field	System	Light readout today	Collector size	Light level, sensitivity
Nuclear physics	LEGEND-1000 ($0\nu\beta\beta$, ^{76}Ge), LAr veto	TPB-coated WLS fiber curtains to SiPMs, underground LAr	Metre-scale fiber shrouds around Ge strings	Single PE: veto at ~ 0.3 PE (GERDA)
Nuclear physics	nEXO ($0\nu\beta\beta$, ^{136}Xe)	VUV SiPM tiles on the TPC barrel, 175 nm	$\approx 4 \text{ m}^2$, barrel 118 cm $\varnothing \times 124$ cm	Single PE; noise < 0.1 PE, DCR < 50 Hz/mm ^{2}
Nuclear physics	nEDM@SNS (LHe)	EUV 80 nm, dTPB coating, WLS to SiPMs	Cells $7.5 \times 10 \times 40$ cm (~ 3 L)	~ 20 PE per n- ^3He capture: few-PE regime
Medical	3Dπ total-body TOF-PET (LAr + Xe)	$\sim 10^6$ SiPMs, 10×10 mm ^{2}	2 m axial, 90 cm bore, 9 LAr layers	~ 41 photons/keV; TOF 151 ps: timing first
Space	GRAMS (MeV γ, antimatter), LArTPC	SiPMs for trigger and timing	$140 \times 140 \times 20$ cm (balloon), $1.5 \times 1.5 \times 0.3$ m (satellite)	MeV deposits; power and mass limits
Space	Fermi-LAT ACD (heritage)	Plastic tiles, WLS fibers, 194 PMTs	89 tiles, 15×32 to 32×32 cm; 8.3 m^2	~ 20 PE per MIP; threshold 0.3 MIP
Security	Radiation portal monitors	Large PVT panels, PMT readout	~ 14 L PVT panels (864 in ^{3})	Many PE; SiPM arrays tested, PMT still better
Security	PROSPECT (reactor $\bar{\nu}$ monitoring)	^6Li -loaded LS segments, PMT at each end	154 segments, $14.5 \times 14.5 \times 117.6$ cm	850 PE/MeV

What transfers: large-area light trap, few sensors per area, digital readout, galvanic isolation. Single-PE (low-noise) readout is essential for the rare-event cases; timing for PET; cost per area for security.

BACKUP · R&D STATUS

Advances and open items by block

Block	Advances	Open items
PhotoCollector	pTP coating for large areas: automated spray (SBU), industrial PVD (BNL); qualification at IFIC and INFN-PV	Large-area coating qualification in LAr (BNL 260-L)
PhotoSensor	SiPM candidates procured; ganging board (FNAL); cold tests at BNL	SiPM-to-PMMA contact (critical): FNAL study started, candidate pad, LN2 tests next
Processing	Cross-lab cryo-ASIC initiative launched (Oct 2026); new cold ASIC in design (APC); cold digitization (FNAL, SDSMT); new LArASIC (BNL)	Warm electronics (IFIC) to be confirmed
Transmission	Cold modulators: silicon micro-rings (tests with CERN), packaged TFLN modulator (BNL, Harvard)	Development phase
Power	Second-generation PoF at 1470 nm: 64% converter efficiency in LN2, negligible light leak (SDSMT)	INFN-MiB interested in contributing PoF solutions

Source: APEX session, DUNE collaboration meeting, September 2026; updated October 2026.