FD2 Photon Detection System

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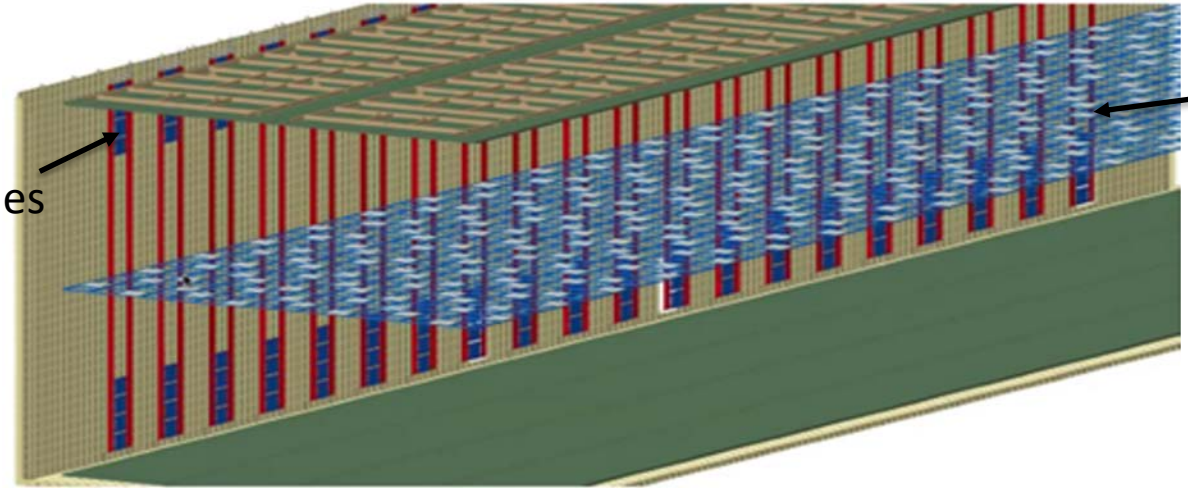
LBNC meeting, Nov 15, 2021

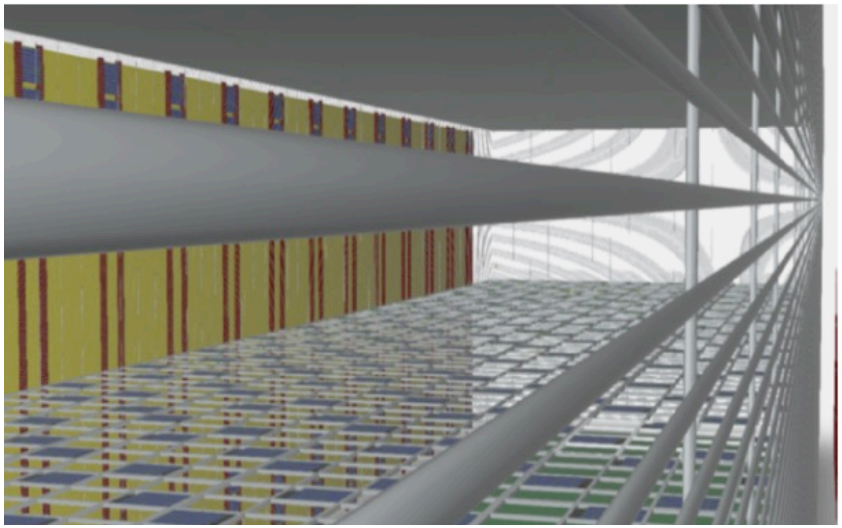
The path toward establishing the baseline



- 320 cathode tiles
- 320 membrane tiles
- Cold analog readout
- Warm digitizers
- 70% field cage transparency for 40% membrane coverage

A substantial reduction of channels and sensors…

Item	Quantity	Detector Surface
X-ARAPUCA modules	320 double-side	Cathode plane
	320 single-side	Membrane long walls
Dichroic Filters	34,560	
WLS plates	640	
PhotoSensors (SiPMs)	51,200	Cathode plane
	51,200	Membrane long walls
Signal Channels	640	Cathode plane
	640	Membrane long walls
SiPMs per channel	80	
Optical Area	115 $m^2 \times 2$	Cathode plane
	115 m^2	Membrane long walls
Active coverage	14.8%	Cathode plane
	7.4%	Membrane long walls



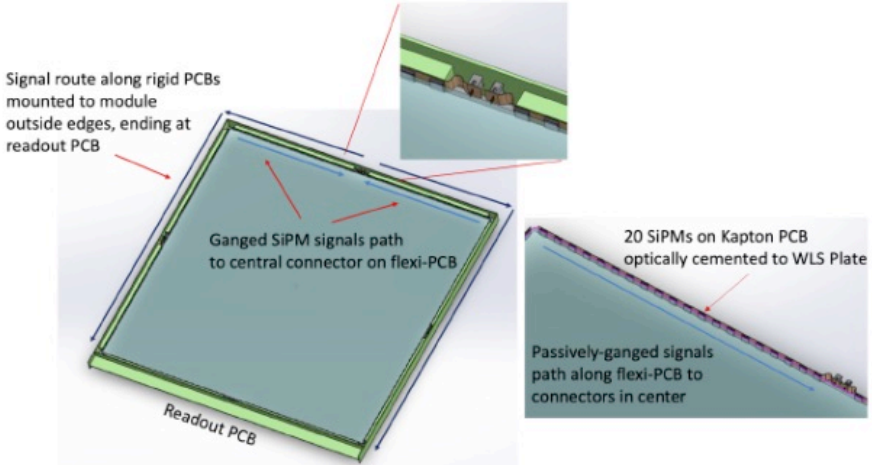


Table 6.5: PD basic unit: X-ARAPUCA module.

Item/Parameter	Quantity	Dimensions
Area	1	644 mm × 675 mm = 0.4 m^2
Thickness	1	22.4 mm
Weight	1	∼ 5.5 kg
Optical Area	2 (two-sided)	600 mm × 600 mm = 0.36 m^2
Dichroic Filters	36 × 2 sides	97 × 97 mm^2
WLS plates	1	600 mm × 600 mm = 0.36 m^2
SiPMs	160	6 × 6 mm^2
Read-out Channels	2	
SiPMs per channel	80	

… comes with technical challenges

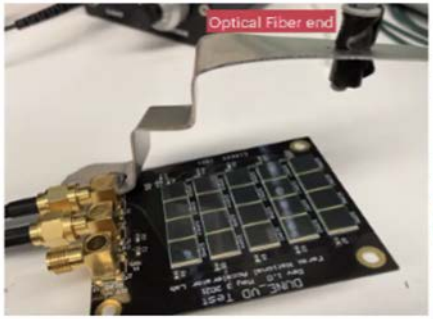
- Can we gang up to 80 SiPMs per tile at the same S/N of FD1-HD?
- Can we reach a >3% efficiency per tile as in FD1-HD?
- Can we power the cathode tile with the Power over Fiber?
- Is the performance of cathode tiles comparable with membrane tiles
- Are the FD2 tiles reliable for the expected duration of the DUNE data taking?
- Is the implementation safe for the PDS and the rest of the TPC?
- Does optical signal transmission fulfil the noise and uniformity requirements?

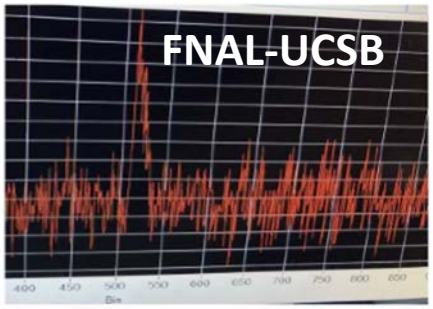
Impact on physics, cost and schedule:

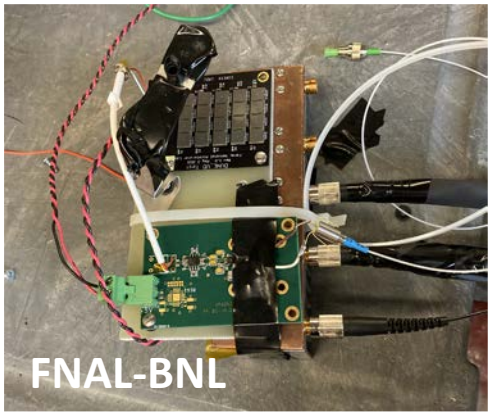
Worth dedicated investigation | Important | Critical

General strategy to validate the VD concept (I)

- Lab tests of systems in **standalone mode**:
  - Ganging (Fermilab, UCSB, Milano-Bicocca)
  - Power over fiber at 77 K (Fermilab, BNL)
  - WLS bars (CSU, Milano-Bicocca)
  - SiPM-WLS and flexible PCB (CSU, Milano-Bicocca, Naples, UCSB)
  - Digitizers and DAQ (UK, Fermilab)







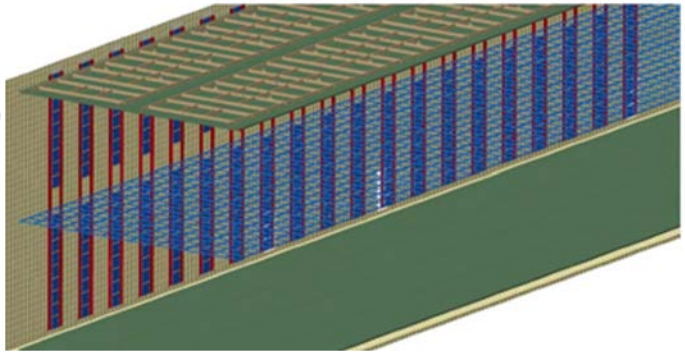
- **Cold box tests** (CERN, PDS Consortium). See below
- **Module-0** @ CERN

General strategy to validate the VD concept (II)

Staying focused on the validation of the baseline option does not mean overlooking:

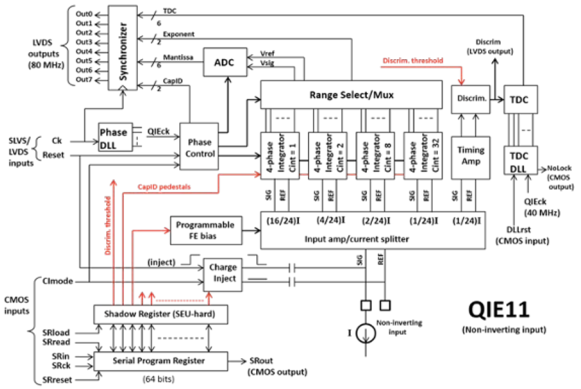
The **fallback option** in case the installation of the cathode tiles is not viable (see FD2-VD CDR)

- 720 Membrane-only tiles
- Cold analog readout, warm digitizers, copper power supplies
- Requires “full” 70% field-cage transparency



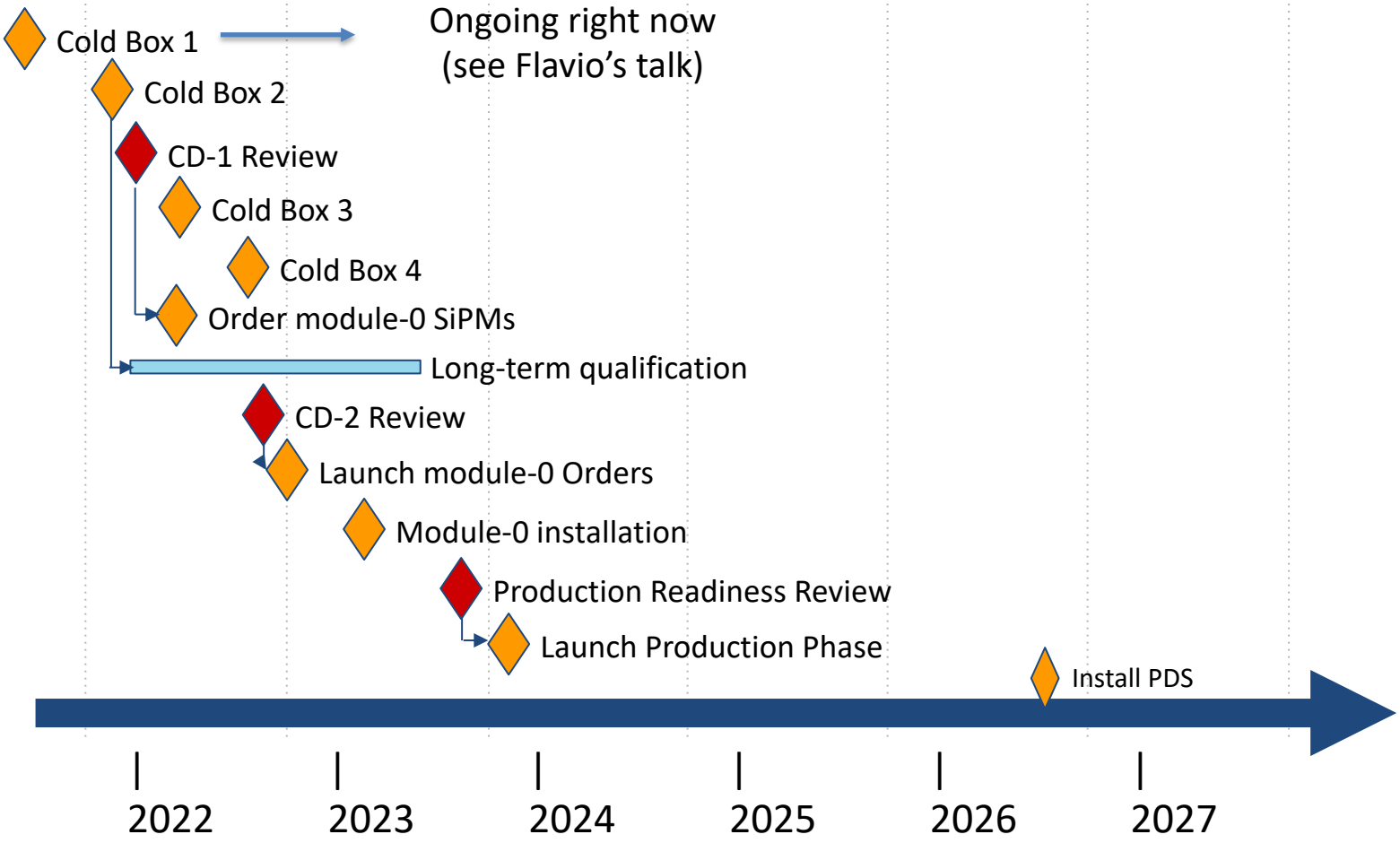
The **opportunities** to further increase the performance:

- Digital cold electronics
- From “membrane” to “field cage” tiles



We inserted branches to address these items in the baseline validation master plan.

Timeline


Cold Box 1
Ongoing right now
(see Flavio's talk)
Cold Box 2
CD-1 Review
Cold Box 3
Cold Box 4
Order module-0 SiPMs
Long-term qualification
CD-2 Review
Launch module-0 Orders
Module-0 installation
Production Readiness Review
Launch Production Phase
Install PDS
2022
2023
2024
2025
2026
2027

The cold box validation programme

Cold Box 1 (in progress)

- Detector module, **power-over-fiber,** analog readout.

Cold Box 2 (February 2022)

- Improved cathode-mounted detector module, power-over-fiber, analog readout.
- **Membrane-**mounted detector module, power, readout.
- DAQ integration.

Cold Box 3 (July 2022)

- Further test cathode-mounted detector module, power-over-fiber, analog readout.
- Further test membrane-mounted detector module, power, readout.
- Improved DAQ integration.

Cold Box 4 (November 2022)

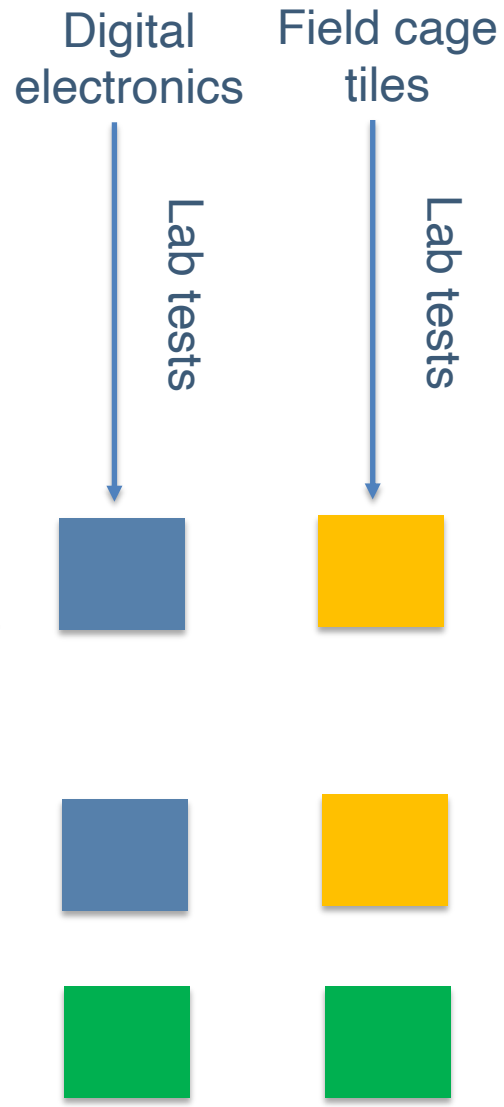
- Improved cathode-mounted detector module, power-over-fiber, analog readout.
- Improved membrane-mounted detector module, power, readout.
- Improved DAQ integration.

ProtoDUNE2 1/20th scale module-0 (2023)

- Baseline implementation

Branches: opportunities

- Cold Box 1 (in progress)
  - Detector module, **power-over-fiber,** analog readout.
- Cold Box 2 (February 2022)
  - Improved cathode-mounted detector module, power-over-fiber, analog readout.
  - **Membrane-**mounted detector module, power, readout.
  - DAQ integration.
- Cold Box 3 (July 2022)
  - Further test cathode-mounted detector module, power-over-fiber, analog and readout.
  - Further test membrane-mounted detector module, power, readout.
  - Further test DAQ integration.
- Cold Box 4 (November 2022)
  - Improved cathode-mounted detector module, power-over-fiber, analog readout.
  - Improved membrane-mounted detector module, power, readout.
  - Improved DAQ integration.
- ProtoDUNE2 1/20th scale module-0 (2023)
  - Baseline implementation

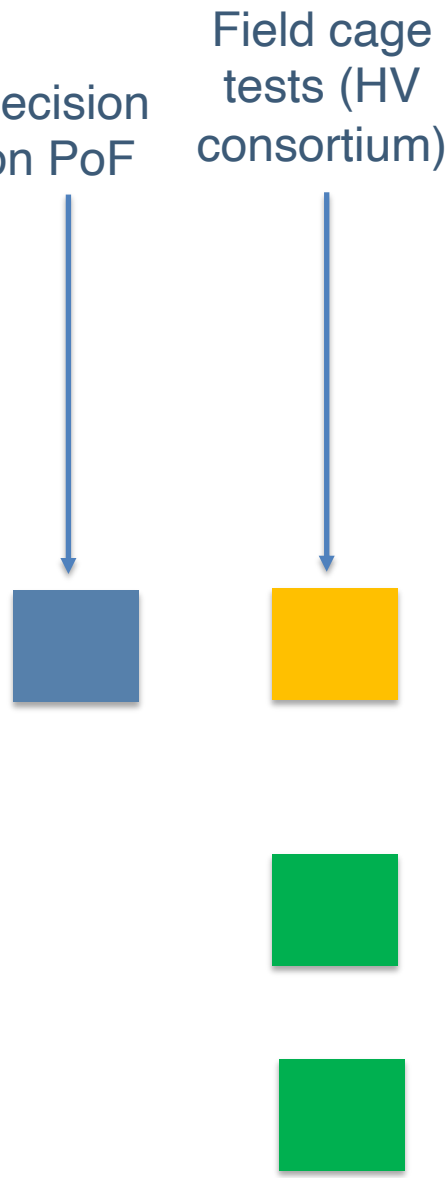


Test on cathode at appropriate voltage

Test of both options (decision bef. module-0)

Branches: fallback

- Cold Box 1 (in progress)
  - Detector module, **power-over-fiber,** analog readout.
- Cold Box 2 (February 2022)
  - Improved Cathode mounted detector module, **power-over-fiber,** analog readout.
  - **Membrane** mounted detector module, power, readout.
  - DAQ integration.
- Cold Box 3 (July 2022)
  - Further test cathode-mounted detector module, **power-over-fiber**, analog and readout.
  - Further test membrane-mounted detector module, power, readout.
  - Improved DAQ integration.
- Cold Box 4 (November 2022)
  - ~~Improved cathode-mounted detector module, power-over-fiber, analog readout.~~
  - Improved Membrane-mounted detector module, power, readout.
  - Improved DAQ integration.
- ProtoDUNE2 1/20th scale module-0 (2023)
  - Baseline implementation



Standalone

Critical decision

Resources until module-0

Do we have resources to carry on the baseline validation and the two branches described above? Yes, since we now benefit from **US and EU (CERN, Czech Rep., France, INFN, Spain) contributions**

- US:
  - Main driver of the FD-2 VD design to date. **Coordination of the cold box validation program** [in collaboration with CERN]
  - **Mechanics** of the tiles [in collaboration with Brazil]
  - **Digital electronics**, Cryosub [in collaboration with UK]
  - **Cold electronics** [in collaboration with INFN]
  - **Power over fiber**
- EU:
  - **SiPMs** and **WLS**
  - **Dichroic filters** [in collaboration with Brazil]
  - **Optocoupler** [France in collaboration with FNAL]
  - Design and integration of the **membrane tiles**

Core costs (EU)

EU/Brazil Core M&S Line Item	USD	
All Production SiPMs w/9% spare	$	1,562,624
All Production Dichroic Filters w/9% spare	$	1,009,567
All Production WLS plates w/9% spare	$	279,040
All Production Warm Electronics w/9% spare	$	470,880
Membrane Production fibers/cables/flanges	$	175,000
Membrane Support Structure Mechanics	$	30,000
Membrane Production Calibration System w/9% spare	$	231,080
All module-0 SiPMs w/20% spare	$	129,024
All module-0 Dichroic Filters w/20% spare	$	83,359
All module-0 WLS w/20% spare	$	23,040
All module-0 Warm Electronics	$	60,000
Membrane module-0 Calibration System	$	30,000
EU/Brazil Core Total USD:	$	4,083,613
USD to EURO conversion		0.85
EU/Brazil Core Total Euro:	€	3,471,071

Note: warm electronics

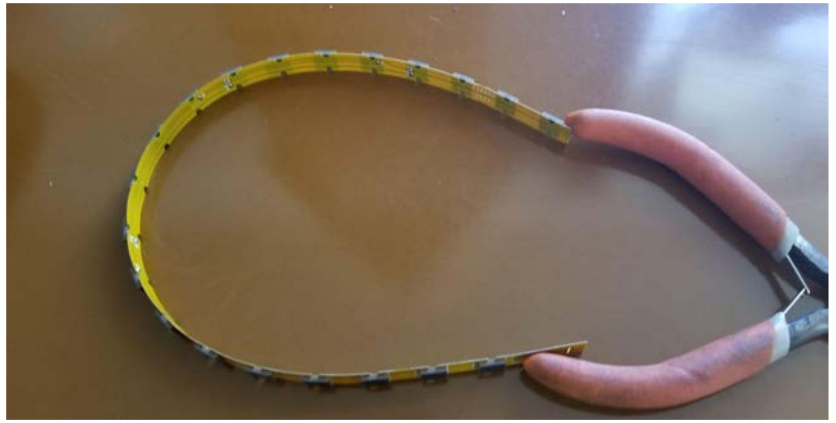
- Baseline [and fallback] option: inherited from DAPHNE (FD1-HD) during the cold box programme. Final design (minor optimizations) for module-0.
- FD2-VD production: EU

Core costs (US)

US Core M&S Line Item	USD	
All Production xARAPUCA mechanics w/9% spare	$	1,078,720
All Production Cold Electronics w/9% spare	$	837,120
All Production Power-over-Fiber w/9% spare	$	1,183,304
Cathode Production fibers/cables/flanges	$	180,000
Cathode Support Structure Mechanics	$	30,000
Cathode Production Calibration System w/9% spare	$	231,080
All module-0 xARAPUCA mechanics w/20% spare	$	48,845
All module-0 Cold Electronics w/20% spare	$	115,200
All module-0 Power-over-Fiber w/20% spare	$	116,544
All module-0 fibers/cables/flanges	$	16,641
Cathode module-0 Calibration System	$	50,000
US Core Total USD:	$	3,887,453
USD to EURO conversion		0.85
US Core Total Euro:	€	3,304,335

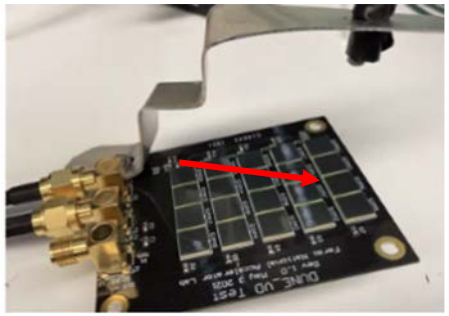
Can we gang up to 80 SiPMs per tile at the same signal/noise of FD1-HD?

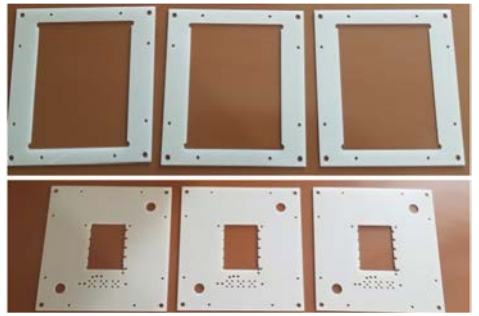
Sept 16, 2021: 160 SiPMs on first flex circuits ready at CSU for gluing in 60cm x 60cm X-ARAPUCA module



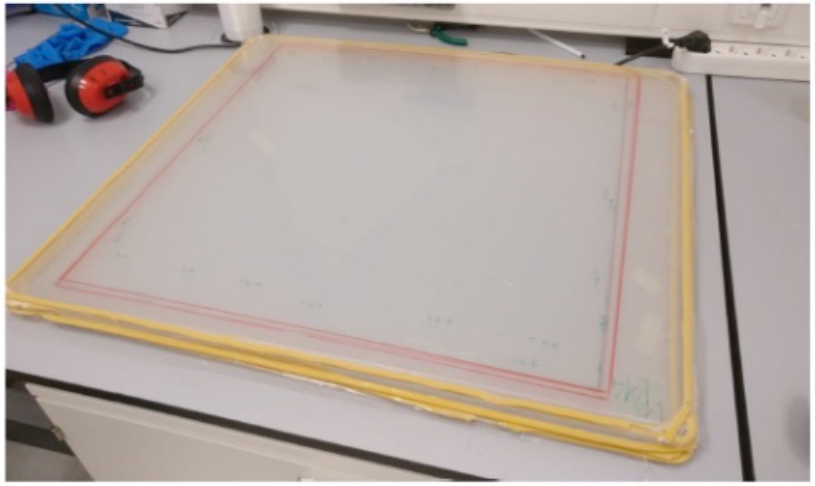
Target S/N achieved on bench-tests

- At FNAL using the MEG-2 topology and S14160 MPPC
- At Milano-Bicocca using the FD1-HD topology with a 2 transistor amplifier with DUNE SiPMs + parasitic capacitance [preliminary]





Can reach a >3% efficiency per tile?



	EJ-286 w/o Vikuiti	EJ-286 w/ Vikuiti	FB118
SPE Gain (ADC·ns)	1680 ± 80	1690 ± 80	1735 ± 90
En. res. (σ/μ)	6.3 ± 0.2 %	6.0 ± 0.2 %	3.6 ± 0.1 %
S/N	6.8 ± 0.3	7.3 ± 0.3	7.3 ± 0.3
ϵ_{raw}	2.1 ± 0.1 %	2.3 ± 0.1 %	3.5 ± 0.1 %
τ_T	1294 ± 35 ns		
LAr purity correction	+ (1.4 to 2.6) %		
Cross-talk correction	- (18 ± 1) %		
ϵ	1.8 ± 0.1%	1.9 ± 0.1%	2.9 ± 0.1%

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Enhancement of the X-Arapuca photon detection device for the DUNE experiment

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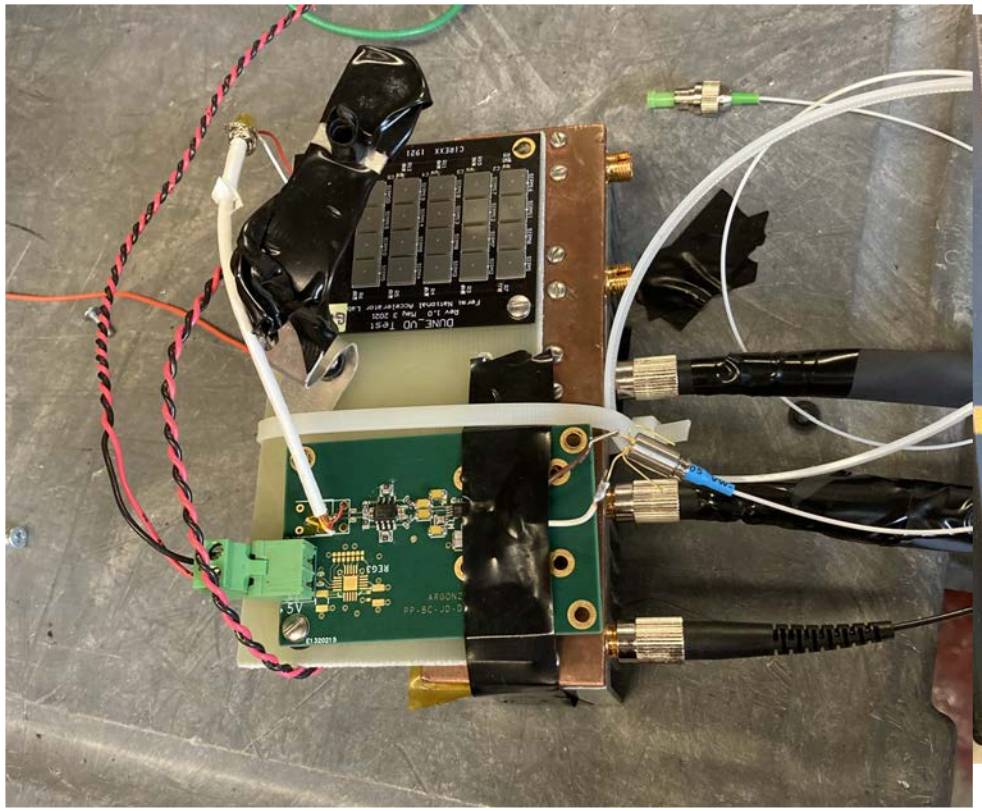
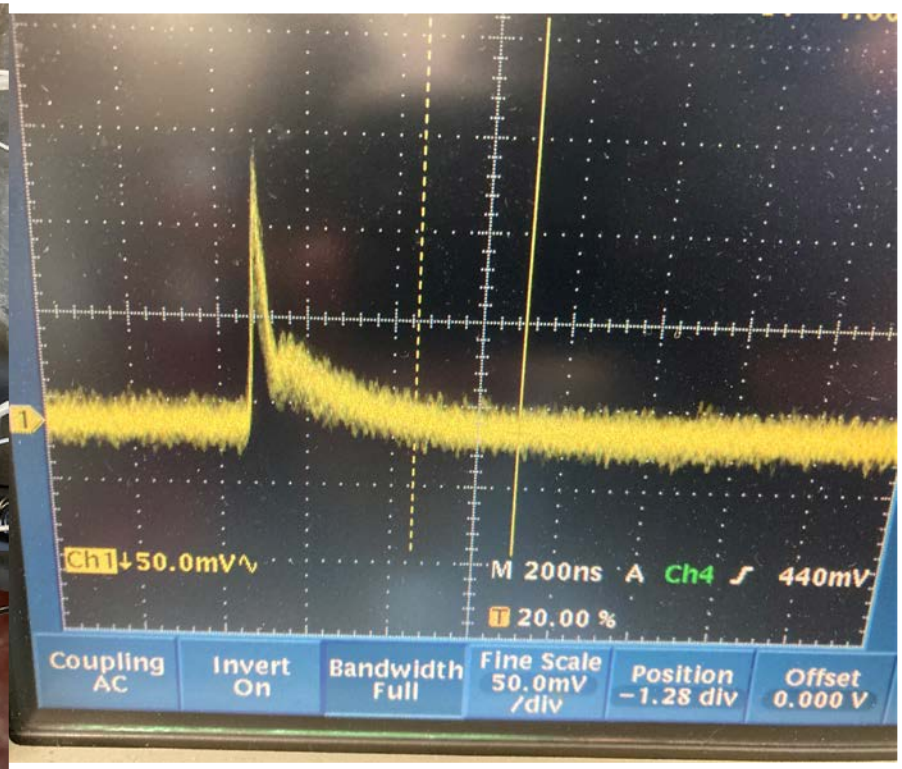
WLS bars from Glass to Power. OK!

In progress:

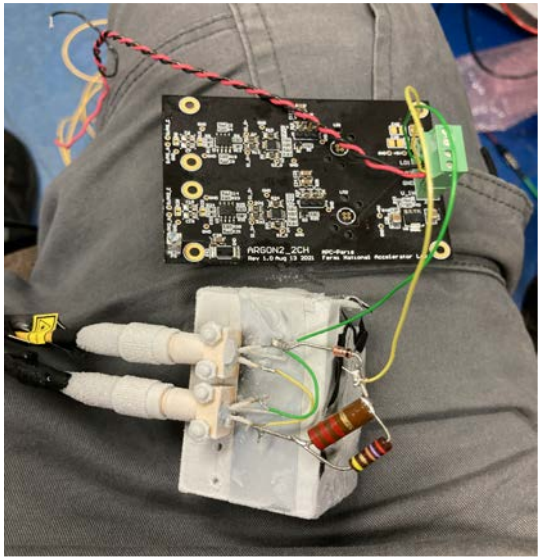
- SiPM-WLS connection with flexi boards
- Cold box test 2
- Final measurement before Cold Box test 3 in ARTIC@INFN Genoa [proposed]

Can we power the cathode tile with the Power over Fiber? Does optical signal transmission fulfil the noise and uniformity requirements?



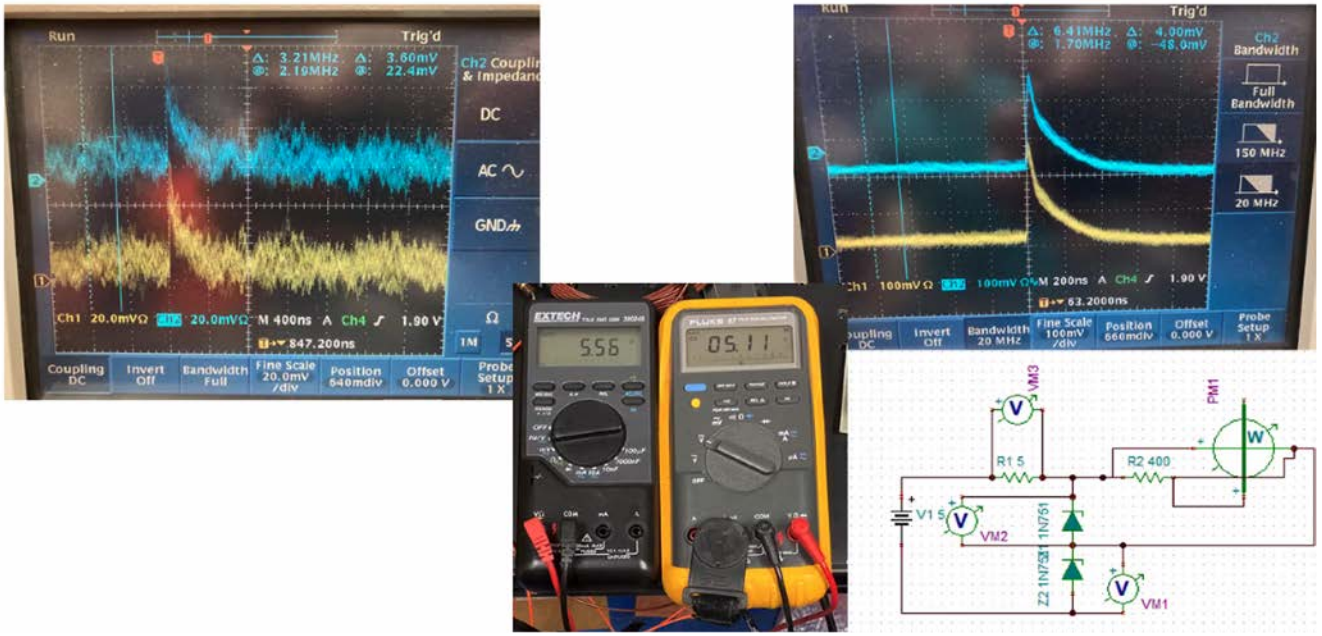


Aug 11, 2021: first demonstration of full chain in cold w/PoF!
Exposed bias PoF and insulated readout PoF



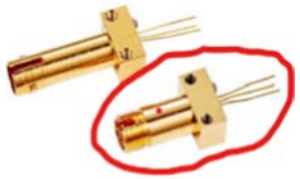
Aug 27, 2021: first demonstration of cold exposed readout PoF

Aug 31, 2021: first demonstration of stable dual-channel Exposed bias PoF and exposed readout PoF



Power-over-Fiber (PoF) path forward

- Cold Box 1 topology will be Si receivers (<10% efficiency cold)
  - Explored insulated versions (>20% efficiency), but could not validate insulation purity tests in time for Cold Box 1. Still pursuing.
  - Cost over efficiency for module bias.



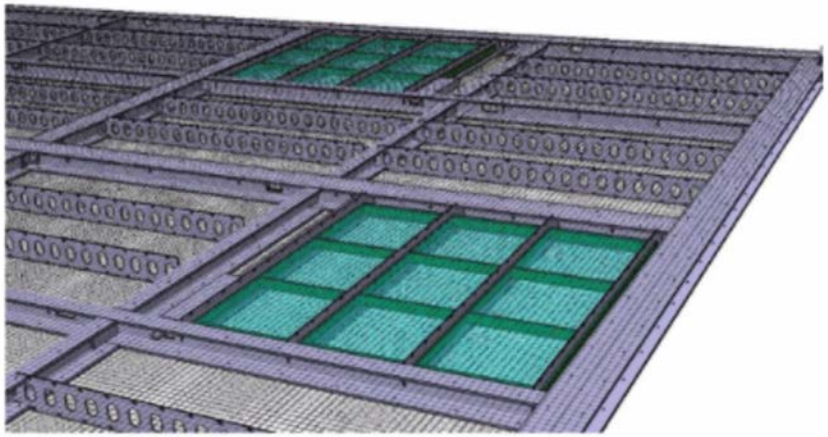
- Cold Box 2 will target GaAs receivers (>40% efficiency cold)
  - SOW with UIUC started to explore optimizations to GaAs photovoltaic cells in cold, targeting >60% efficiency with optimizations

Is the implementation safe for the PDS and the rest of the TPC?

Current guidance: If the cathode discharges at an arbitrary position, there may be 10Ks of voltage differential over meters for a few microseconds. Assume this happens a handful times over the lifetime of DUNE.

1. Each tile with its own PoF line. Safest scenario but increase of costs.

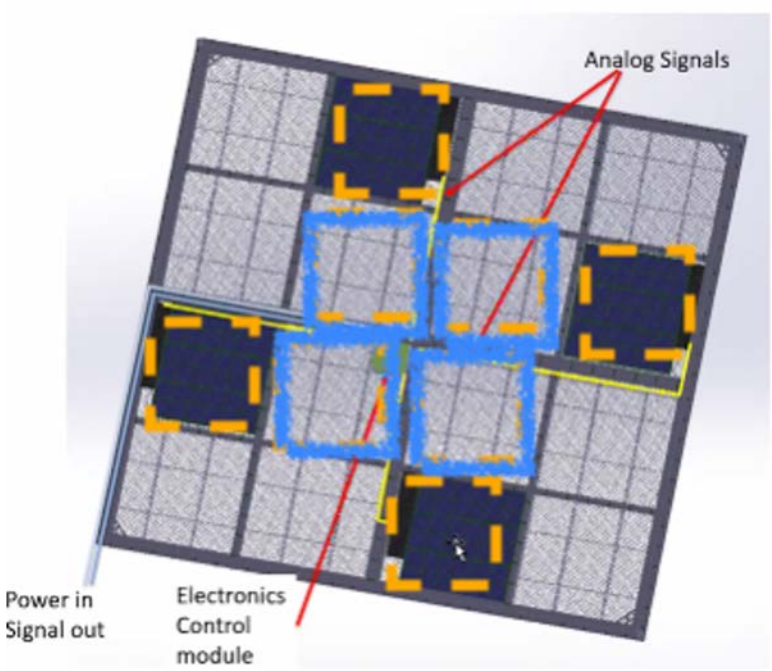
2. Power is ganged over several tiles
   - Simulation of current path [BNL, in progress]
   - Full test [planned]



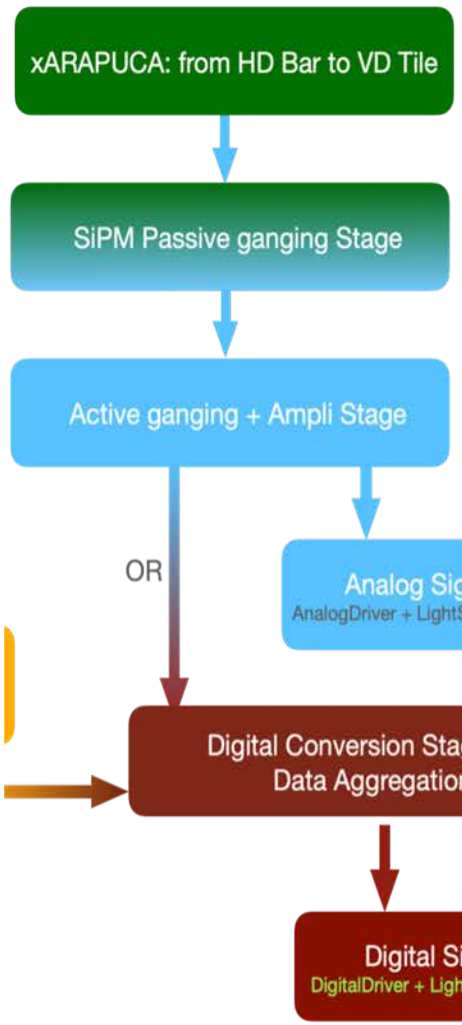
E.g., can these two xARAPUCA modules share a power bus?

Fallback topology

- Shift 4 X-ARAPUCA modules to neighboring cells (i.e. orange to blue squares) w/conductive mesh.
- Simulation (Nov 2021) indicates that deterioration in uniformity is marginal and the system meets physics requirements
- Need simulations and demonstration to confirm electronics can survive discharge



A summary of achievements in 2021



New generation xARAPUCA technology - Large Tile (60x60 cm^2) - 160 SiPM (40 SiPM/side - all 4 sides) in single Channel (MegaCell): design fully developed [CSU: mockup in production], validated by dedicated MC study (efficiency-Brz Grp.s), optimized with new HQE WLS plates (Mi-Bicocca) + improved SiPM-WLS Optical contact (Flex Kapton PCB mounted SiPM - Mi-Bicocca and CSU)

- Improvement: projected efficiency $\geq 3.5\,\%$

8 Groups of 20 SiPM in a (new) hybrid (4 Parallel x 5 Series) ganging [FNAL, UCSB], lower capacitance (compared w/ traditional passive ganging), signal fall time shorter, signal amplitude larger - at common Bias V for single SiPM, validated by SPICE simulation [Mi, FNAL], test board in production [FNAL-SCD, BNL], Flex PCB integrated on xARAPUCA frame.

- Improvement: projected S/N > 5, 20 SiPM passively ganged.

Analog F/E - Cold OpAmp validated in cold [different options available] - goal: 8 groups of 20SiPM summed into one channel (OpAmp), test board in preparation with selectable n. of groups (up to 8). Additional Cold OpAmp options can be considered before final selection.

- Improvement: projected $\sum$160 SiPM (8 x 20) → single channel

COTS Laser Diode validated in Cold, in-house made AnalogDriver tested ok in Cold, Opt.Coupling under development (DS-style connector) [APC-Paris + support from DS, + support from FNAL]

- Analog Transmission: full-chain Validation in Cold expected by May/June.

COTS ADC selection, tests and validation in Cold [different options available, 14 bits, 80 MSPS], test board OpAmp+ADC in preparation/in production, FPGAs selection and test in cold, compression algorithms, insulating techniques, transmission cold qualification (input from BNL, STFC UKRI, LBL, FNAL)

COTS Laser Diodes selection, tests and validation in Cold, modified COTS DigitalDriver 10 GBPS ADN2526 first test in Cold OK, Opt.Coupling & Fiber selection in progress [FNAL & SMU + support by Versatile Link Plus Collaboration @ CERN]

- Digital Transmission: full-chain in progress, Validation in Cold expected by June/July.

Conclusions

- We devised a strategy and timeline to validate the PDS FD2-VD concept
- It is based on 4 cold box tests + module-0 with input from lab tests at APC (Paris), CSU, Fermilab, INFN, NIU, UCSB, UK
- Thanks to the US and EU contributions, the schedule is resource loaded and it is sustainable with current funds.
- The schedule is oriented toward validating the baseline option but it does not overlook the fallback option (no cathode tiles) and the opportunities from digital cold electronics and field cage tiles.
- Tests at CERN (Cold Box 1) and at the Consortium labs are in progress and results achieved so far are very encouraging.