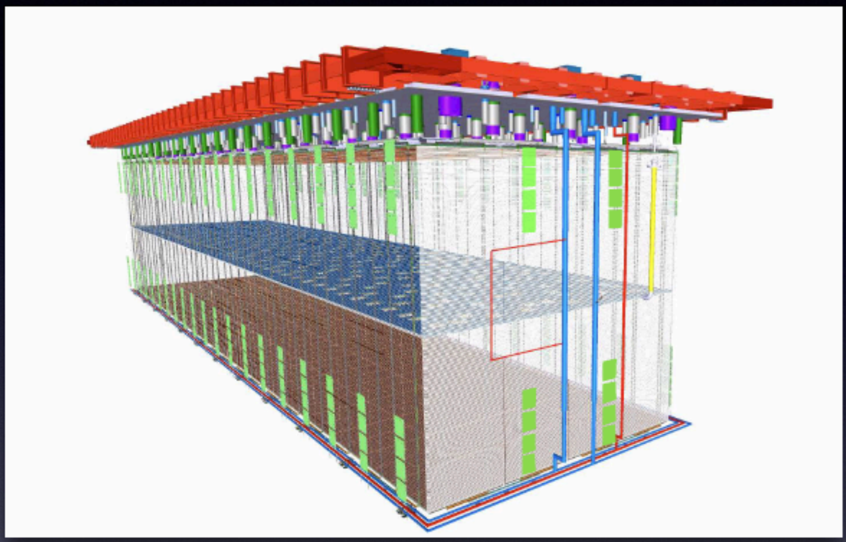
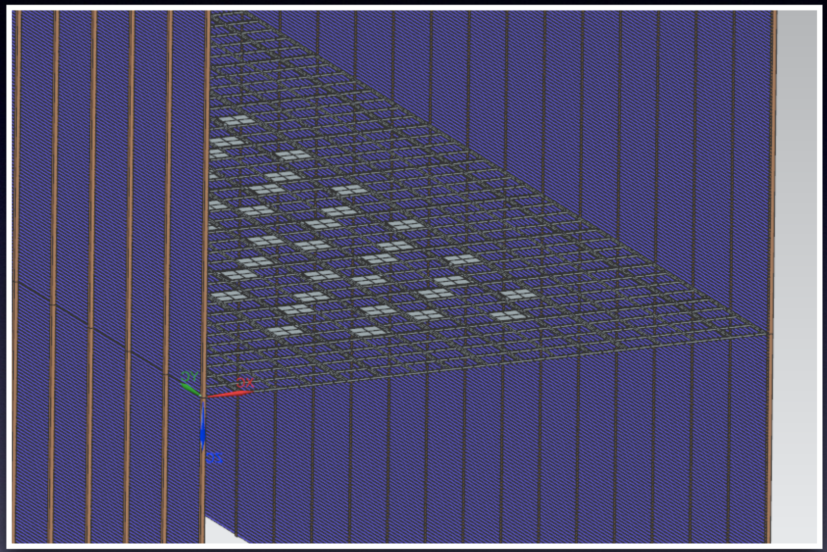
From this (FD2 - VD)



To this (FD3 - VD Optimized)



“VD Optimized” w/ enhanced PDS -

current thinking on how the FD3/4 PDS might look like

Apr 3→24, 2023

F. Cavanna

Fermilab

Optimized VD FD3/4

➡ ***Optimized VD*** Detector solution:

➡ Charge R/O (main): LArTPC single phase, vertical drift, CRP based (Top, Bottom planes - 6.5 m drift)

➡ Minimal Optimization: *active volume size* and *PCB perforated strip geometry*

➡ Light R/O (enhanced): *x-ARAPUCA modules framed in FieldCage electrodes* for an extended optical coverage (power and signal transmission via optical fiber - PoF and SoF - as for FD2 modules on HV Cathode)

➡ Mature technologies, cost-effective, well defined optimization development path

➡ ***optimized VD*** solution for **FD3-4** modules:

➡ meet > 40kT fiducial LAr Volume necessary for DUNE to meet P5 goals

➡ retain DUNE unique strengths: excellent PId and energy reconstruction over the entire *beam energy range* **(500 MeV to ~5 GeV)**

➡ extend the physics reach to lower energies for SN neutrinos, Solar neutrinos Physics (and improve energy resolution at the Beam energies)

➡ Expect moderate overall cost increase and reduced R&D risks

<u>Optimized Vertical Drift FD3-4</u>: Charge R/O technology optimization

LArTPC optimisation options:

- **CRP technology is "close to ideal" (after 4 major generations of developments)**
  - *(1) Wire Planes + Warm Electronics (ICARUS),*
    - *Wire Planes + Cold / Warm Electronics (MicroBooNE)*
  - *(2) APA-Wire Plane + CE - (protoDUNE-SP, SBND, ⇒ DUNE **FD1**) [technologically perfect ! but complicated, labor-intense and expansive]*
  - *(3) CRP-Perforated PCB + CE (⇒DUNE **FD2**) [technologically simpler, based on commercially available components ⇒ fast construction and cost effective]*
  - ***Any possible further CRP optimization step?***
    - Ind, Coll pitch design for LowEn event reco (maybe)
    - expand Active Vol ?
    - Further improve S/N (??)

OR

- **Change core feature of TPC design**
  - **Pixel read-out** to improve charge reconstruction performance

OR

- **Change technology of Charge signal read-out**
  - **Dual Phase Optical read-out** [ARIADNE] to reduce cost and great potential

Optimized Vertical Drift FD3-4: Light R/O technology optimization

Most (if not all) large mass, UG detectors for LowEn (solar) neutrino are Light r/o (scintillator or Cherenkov) based detectors
[featuring 4π coverage for a high & uniform LY - the base for a high detection efficiency and good energy resolution for LowEn events]

LAr-PDS optimization options

- **ARAPUCA(w/ SiPM) technology is still young, with large margins of improvement thanks to well proven flexibility**
    - *ARAPUCA bar w/ few (12)SiPM/channel + Warm Elec [Anode plane coverage] - protoDUNE-SP-2018*
    - *X-ARAPUCA bar w/ more (48)SiPM/channel + Cold & Warm Elec [Anode plane] ⇒ DUNE **FD1- 2022***
    - *X-ARAPUCA large tile w/ many (80)SiPM/channel + **PoF-CE-SoF** & Warm ADC [HV Cathode plane & Membrane Walls] ⇒ DUNE **FD2 - 2023***
- **Next "natural" optimization step:**
    - X-ARAPUCA + **PoF & CE(FE+ADC) & SoF** + design flexibility for massive increase of coverage on FieldCage

⇒ **convert TPC Field Cage structure into a fully active PDS**

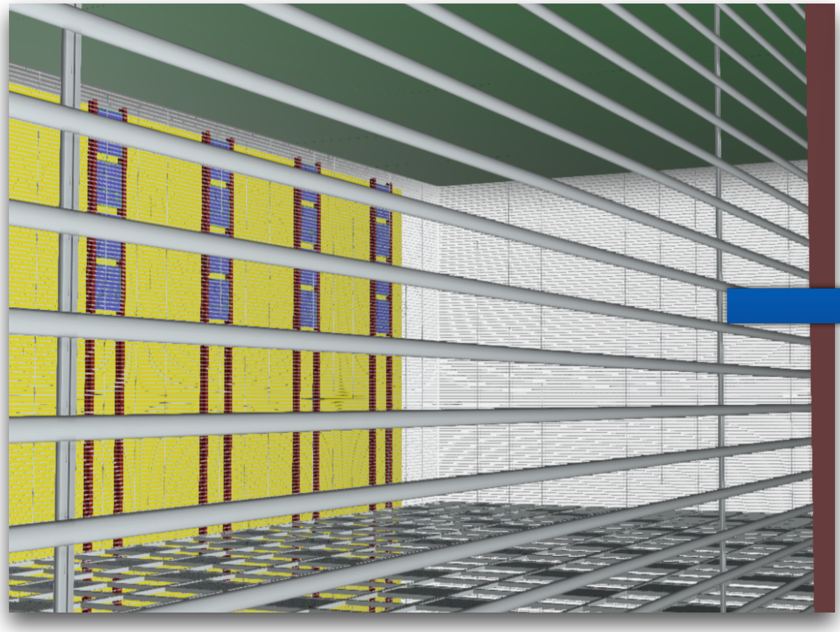
- extended optical coverage for High and Uniform (Scintillation) LY

OR

- **Change technology of Light signal read-out**
    - **Integrated light pixels in Anode plane (Solar/Q-pix)**
    - **Combine light pixels in Anode plane with X-ARAPUCA tiles on the Cathode plane**

LArPDS from FD2 to FD3-4 (conceptual design)

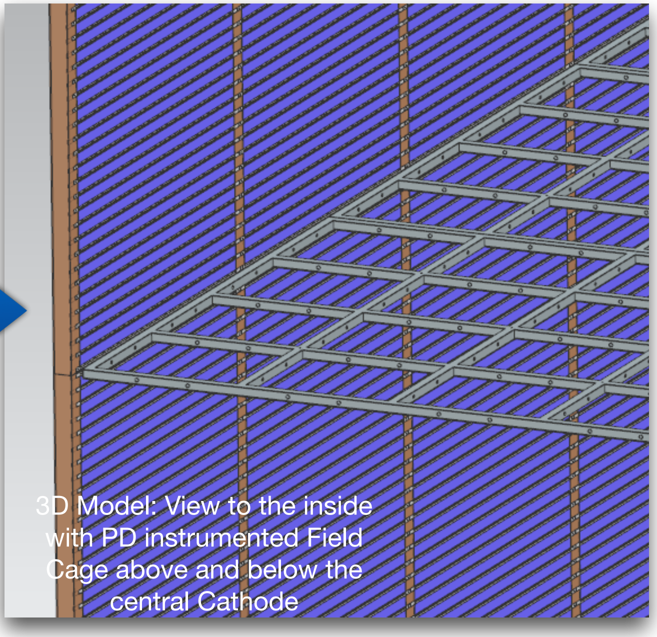
FD2



FC - 70% T

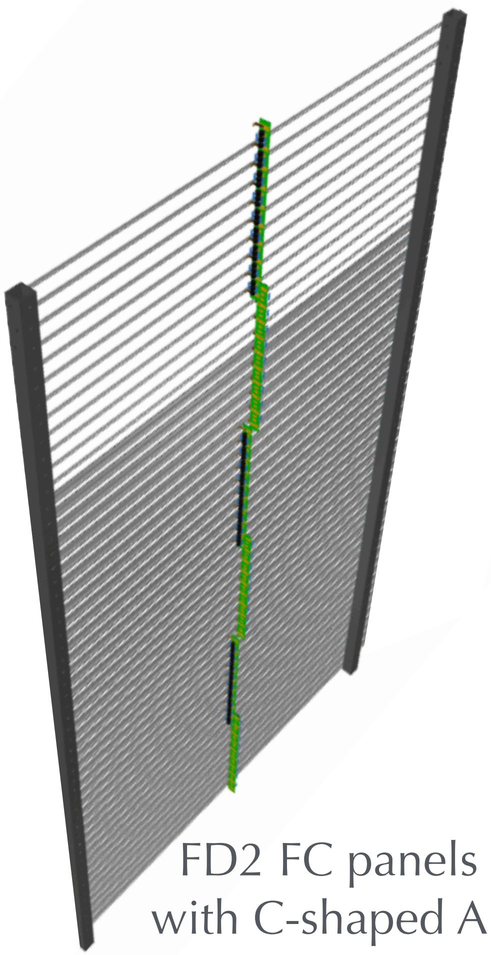
View of the FD2 Lower Volume from behind the FC, as seen by the Membrane PD modules

FD3-4



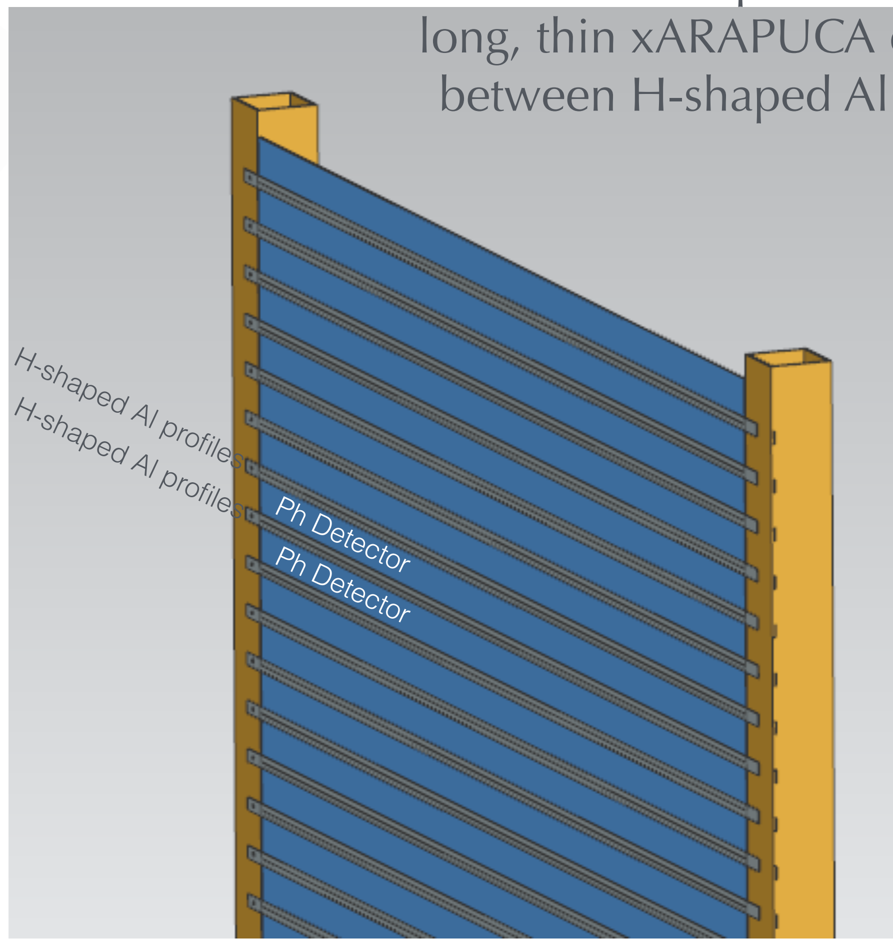
- Naturally expand x10 optical coverage (wrt FD2 PDS)
- Provide optimal mechanical frame structure for xARAPUCA bars in between (reduce fabrication & installation complexity (and costs))
- Retain FC electrical functionality for TPC

convert TPC Field Cage structure into a fully active PDS



FD2 FC panels formed
with C-shaped Al profiles

FD3-4 FC panels with
long, thin xARAPUCA detectors
between H-shaped Al profiles



Simulation setup

- Same optical properties as for ProtoDUNE-VD simulations
  - LAr refractive index, Rayleigh scattering, absorption
  - Reflectivity of membrane, anode, cage field, etc
  - PTP emitted photons are now also tracked
- Assumption Detector efficiency: 2%
- 25000 photons/MeV deposited

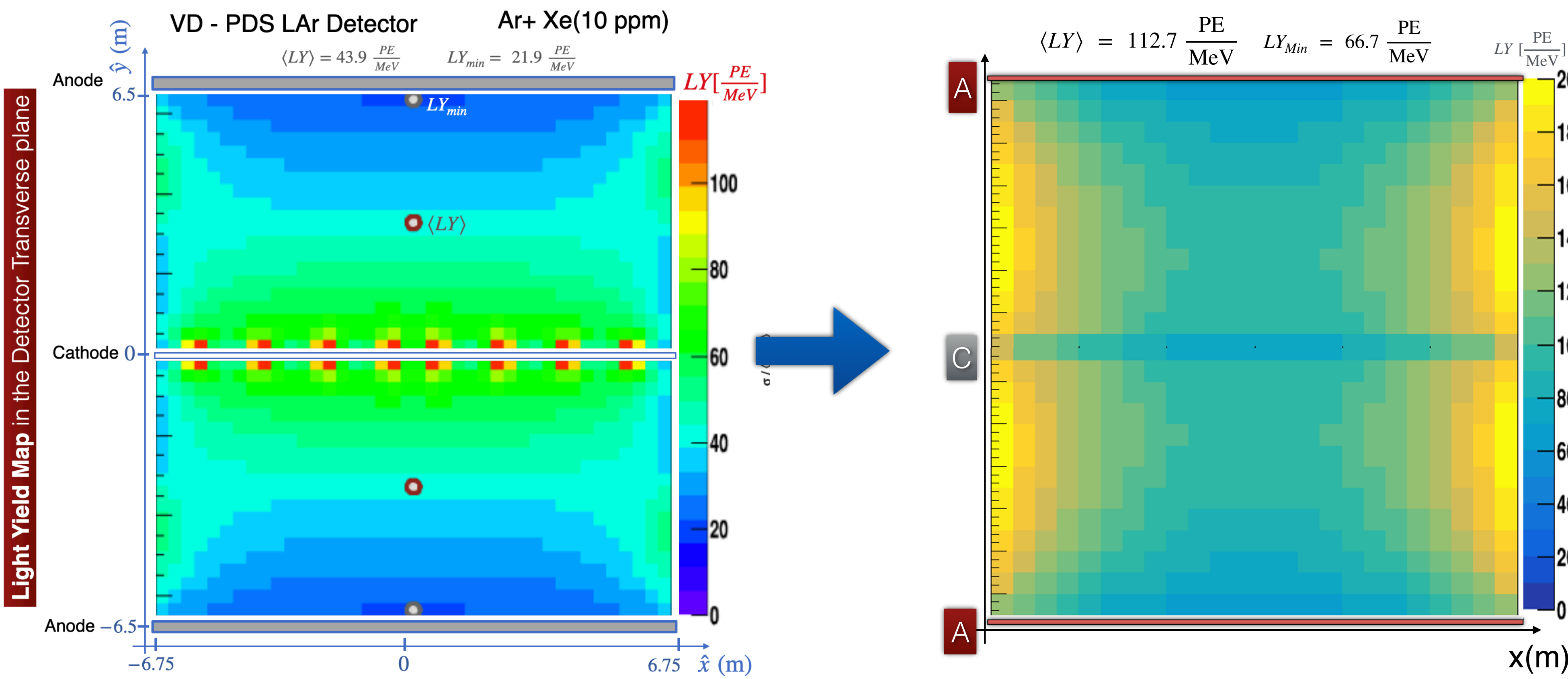
- Total light yield increase due to backward ptp emissions: +60%

LY map
(x,y) plane a z=0

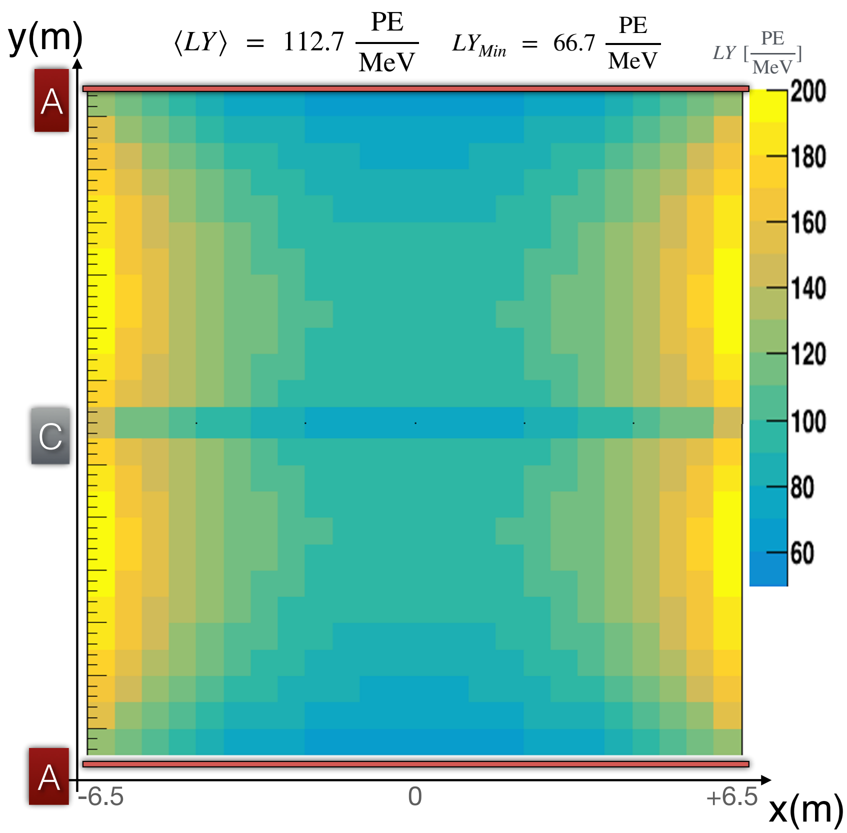
From FD2 - VD

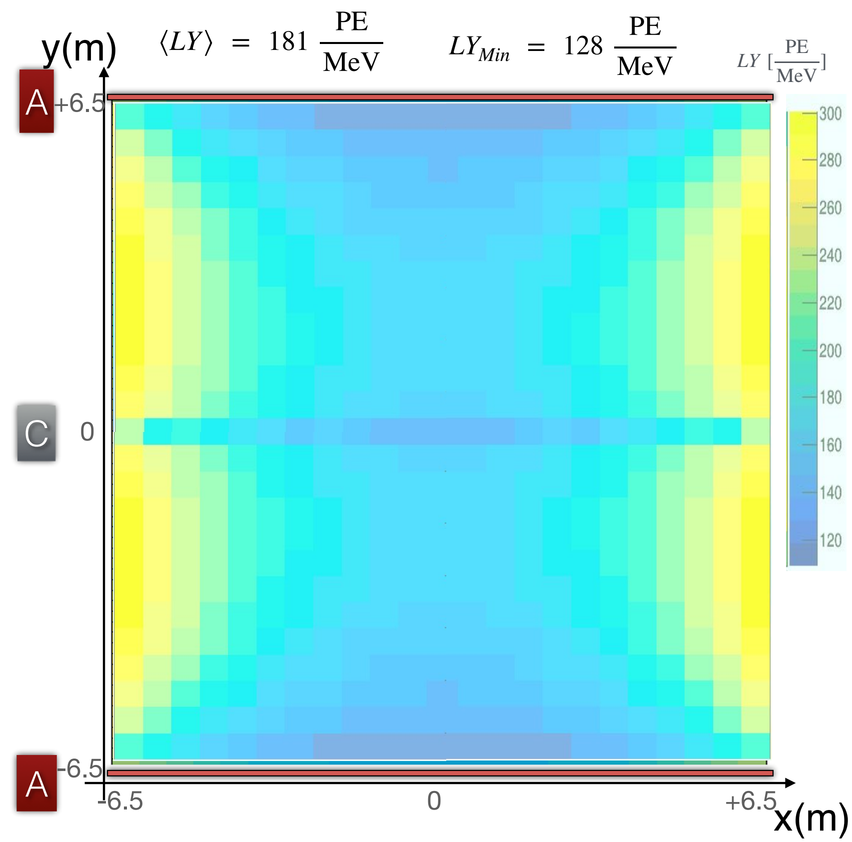
To FD3 - VD Optimized)

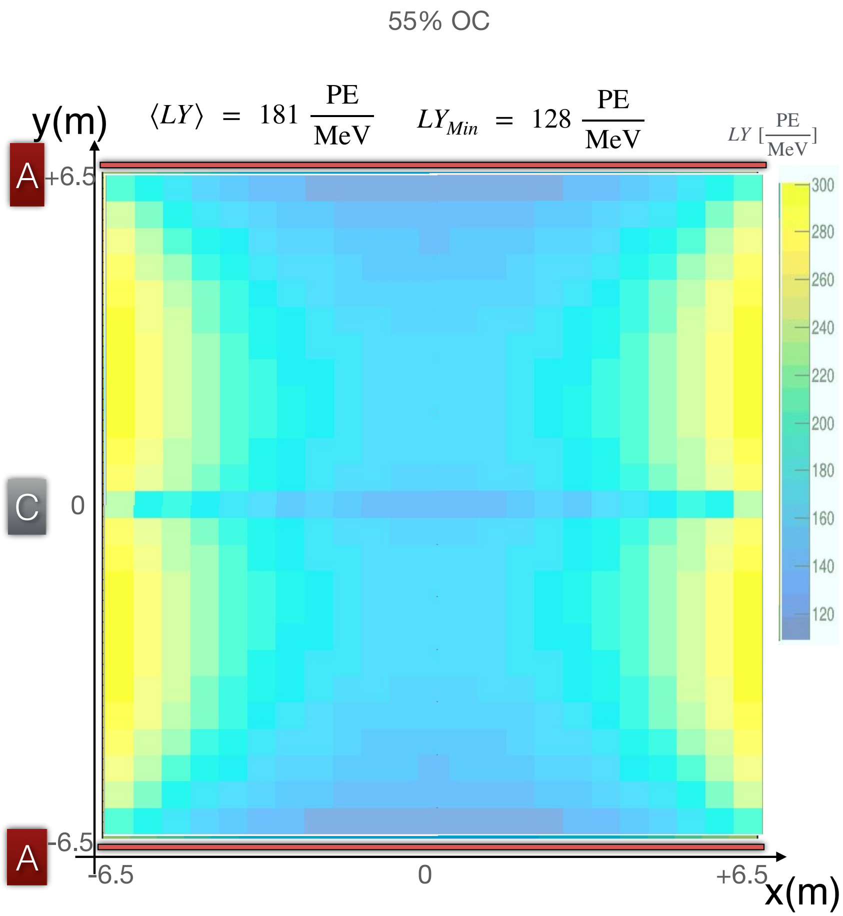
NB: ONLY DIRECT LIGHT (Ar&Xe) in G4 Simulation
collection of Vis light - wl-shifted and back-emitted into LAr volume -
NOT ACCOUNTED YET



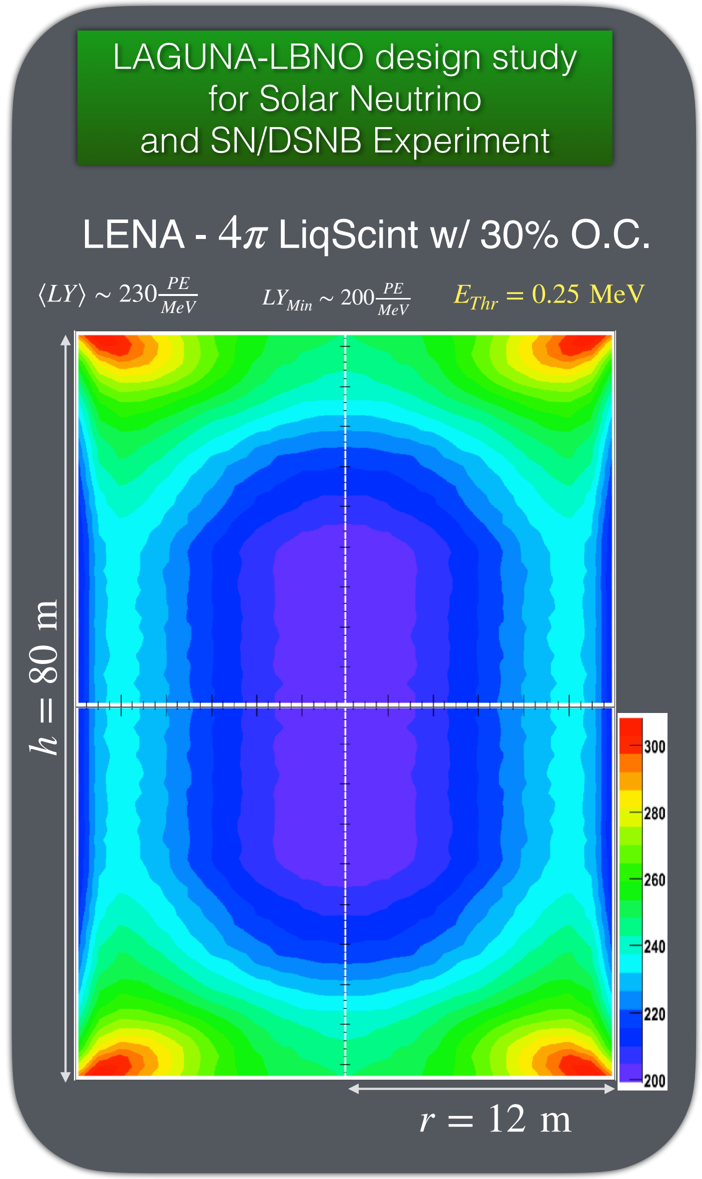
When
collection of Vis light (wl-shifted and back-emitted into LAr volume) is included,
> 60% increase of LY is obtained
thanks to the very large optical coverage of the LArPDS







55% OC
y(m)
$\langle LY \rangle = 181 \frac{\text{PE}}{\text{MeV}}$
$LY_{Min} = 128 \frac{\text{PE}}{\text{MeV}}$
$LY\ [\frac{\text{PE}}{\text{MeV}}]$
A
+6.5
C
0
A
-6.5
-6.5
0
+6.5
x(m)
300
280
260
240
220
200
180
160
140
120



LAGUNA-LBNO design study
for Solar Neutrino
and SN/DSNB Experiment
LENA - 4π LiqScint w/ 30% O.C.
$\langle LY \rangle \sim 230 \frac{PE}{MeV}$
$LY_{Min} \sim 200 \frac{PE}{MeV}$
$E_{Thr} = 0.25$ MeV
$h = 80$ m
$r = 12$ m
300
280
260
240
220
200

R&D path
twd enhanced LArPDS
for
Optimized VD FD3/4

➡ New design PD module framed in FC electrodes
➡ high efficiency, high power PoF system
➡ CE (F/E & ADC) + large transmission bandwidth SoF

and a staged Prototyping program

Three elements of novelty in the *FC-PD System* are identified:

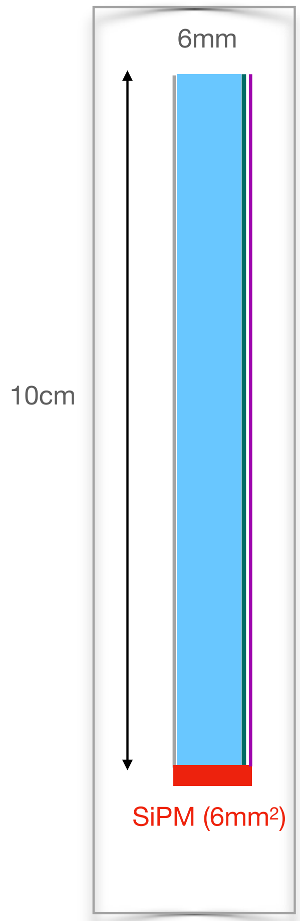
➡ **the PD module framed in the FC electrodes.** The PD module, based on the X-ARAPUCA technology concept, and the FC electrodes, based on standard Al profile, to be developed into a new design. Simplified solutions (SiPM-WLS, ALD dichroic, ..) to be developed (with specialized industry partnership) and demonstrated at prototype level at Lab’s

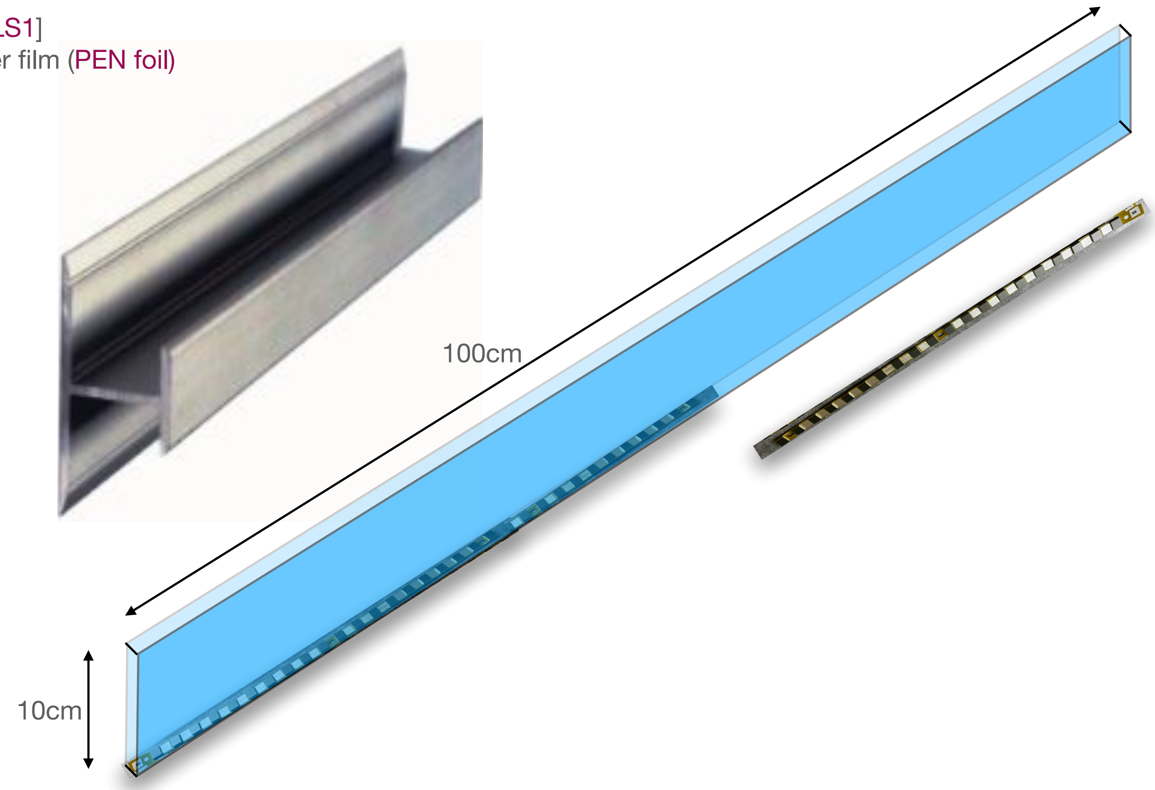
➡ **The high efficiency PoF system.** The PoF solution developed for DUNE FD2 cathode-mount PDS will require a new technological advancement to cope with the higher power demand of the PD system. High efficiency, high power OPCs (Optical Power Converter - core element of the PoF) must be designed in sync with the PD, developed in collaboration with specialized Industry and validated by lab tests.

➡ **The large bandwidth SoF.** Signal digitization in cold and transmission through fiber is a novelty item. Some development has been recently carried out at FERMILAB, with encouraging results.

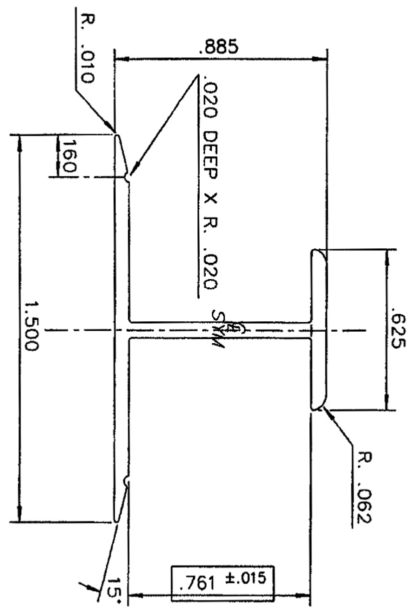
Simplified **ARAPUCA** concept

[Reflector - WLS2 - Dichroic - WLS1]
VIKUITI foil - PMMA - ALD - pTer film (PEN foil)



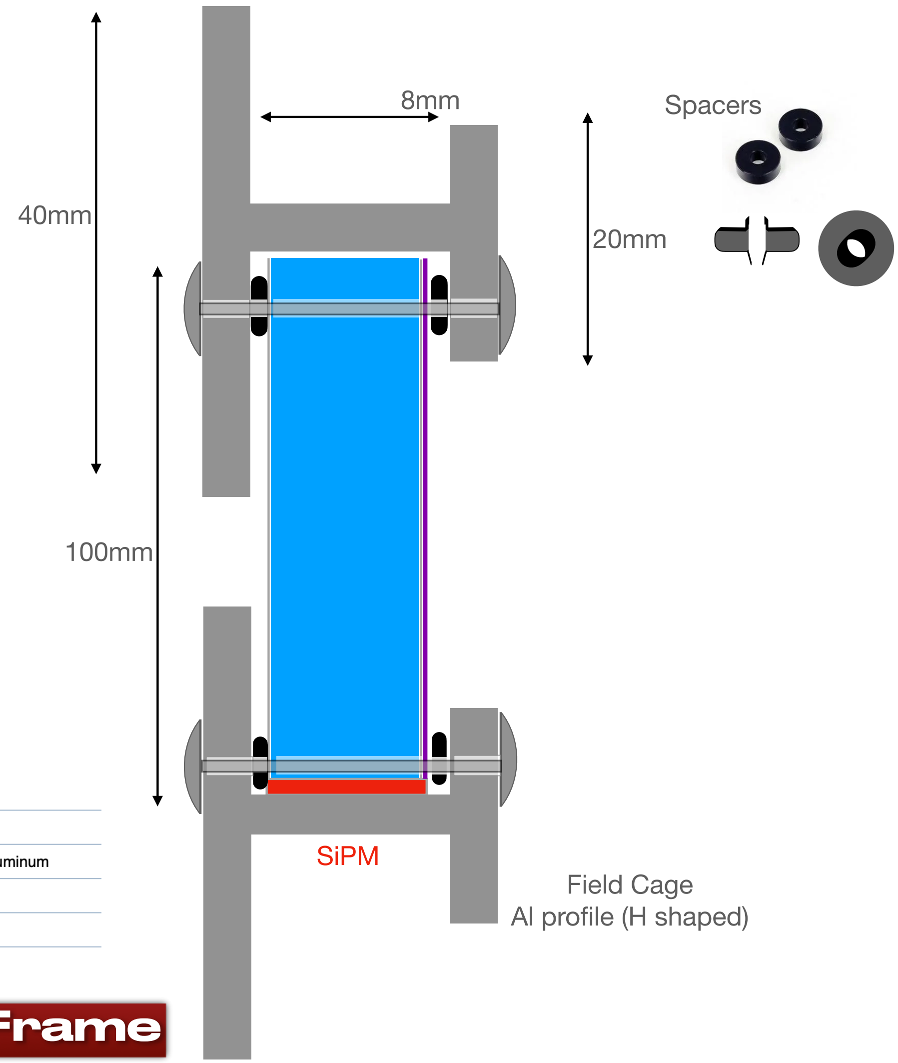


HI-TECH GLAZING SUPPLIES



TECHNICAL SPECIFICATIONS

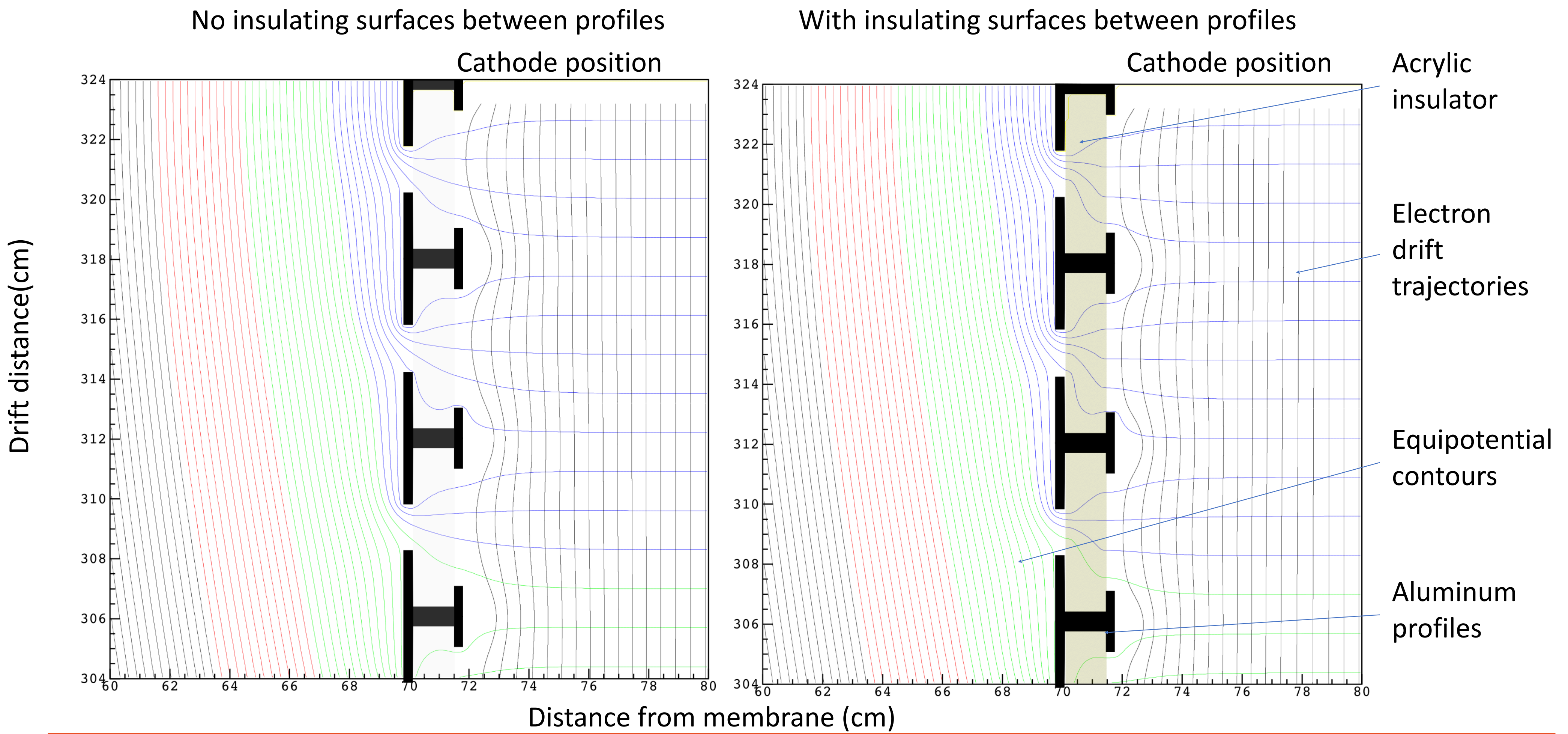
Product №	31311210	Height	57/64 in
Width	1 1/2 in	Color	Aluminum
Length	144 in	Material	Anodized Aluminum
Interior Measurements	49/64 in	Front Facing Height	5/8 in
Finish	Satin	Shape	H



FC Profile assembly ≡ PD Mechanical Frame

FC-PDS Electrical performance

Bonus: improved EF uniformity at FC boundaries



FD3 FC-PD Names and Numbers:

FC-PD Module (L 200 x H 10 cm2)

[1 H Al profile (L 200 cm x H 2 cm) + 2 Acrylic bar (WLS) (L 100 x H 10) + 2 Flex PCB (L100 cm) + 40 SiPMs + pTer film/PEN foil (L 200 x H 10 cm) + VIKUITI foil (L 200 x H 10

FC-PD Panel (L 2 x H 6 m2)

FD3 LongWall (L 60 x H 6 m2) x 2 x 2 - 2=R,L wall, 2=Top,Bot wrt Cathode Plane
FD3 ShortWall(2 x L12 x H 6 m2) x 2 x 2 - 2=Upstream/Downstream, 2=Top,Bot wrt Cathode Plane

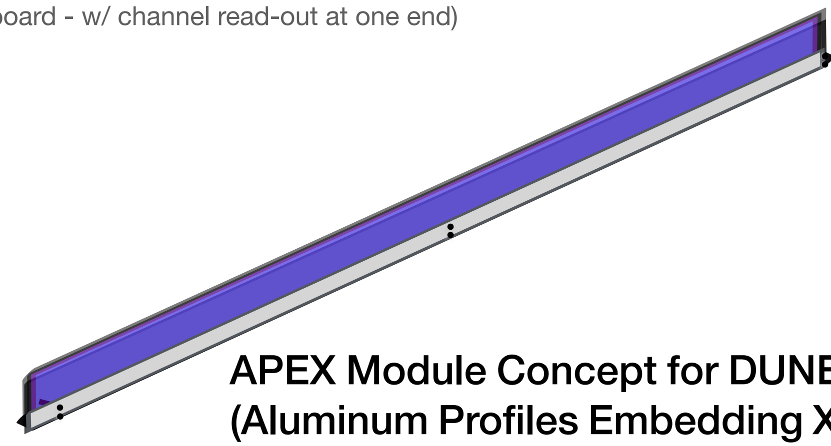
1 Opt Channel = 1 Flex Board (assume 1m long flex board - w/ channel read-out at one end)
N. Opt Channels/Module: 2
N. FlexBoards/Module: 2

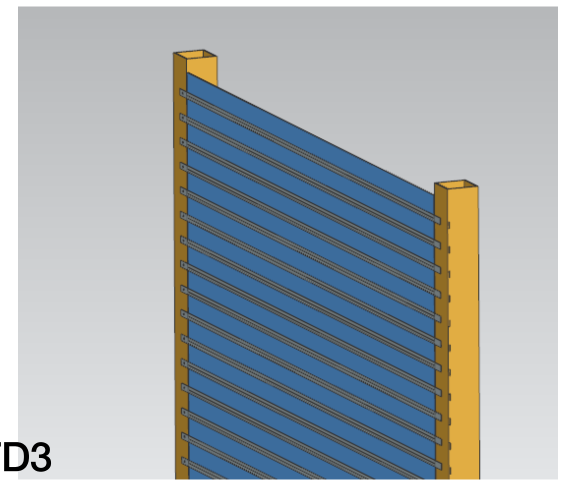
N. SiPMs/FlexBoard: 20
N. SiPMs/Channel: 20

N. Modules/Panel: 60
N. Opt Channels/Panel: 120
N. SiPMS/Panel: 2400
N. Opt Channels/Electronic Channel: 4

N.Panels/LongWall: 30 x 2 x 2 = 120
N.Panels/ShortWall: 6 x 2 x 2 = 24

N. Tot Panels: 144
N. Tot Modules: 60 x 144 = 8640
N. Tot Opt Channels: 2 x 8640 = 17280
N. Tot Elec Channels: 17280/4 = 4320
N. Tot SiPMs: 17280 x 20 = 345600





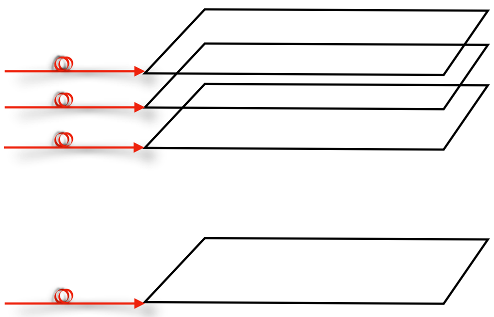
APEX Module Concept for DUNE FD3
(Aluminum Profiles Embedding X-Arapucas)

N. Tot Modules: 8640 ⇒

- **N. Tot H-Al Profile: 8640**
- **N. Tot Acrylic WLS Bars: 2 x 8640 = 17280**
- **N. Tot Flex Boards: 2 x 8640 = 17280**

N. WLS Bars/WLS Plate (100x100 cm2) = 10
N. Tot WLS Plates: 1728

Ring



PoF & PoF Fibres

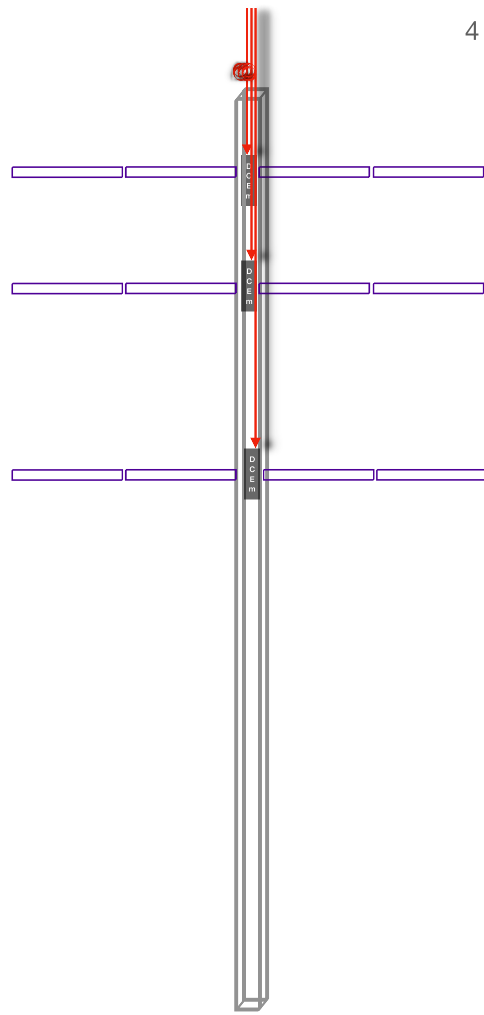
FC-PD ring (L =60 + 12 + 60 + 12 =144 m)
N. Tot Rings: 60 x 2 = 120

N. Modules/Ring: 144/2 = 72
N. FlexBoards/Ring: 72 x 2 = 144
N. SiPM/Ring: 144 x 20 = 2880

PoF for SiPM:
N. OPCs/Ring: 2 (Π) - (1 redundant) 400mW ElPwr
N. Fibre/Ring: 2 - (1 redundant)
N. DC-DCs/Ring: 1

N. Tot Fibre: 240
N. Tot OPCs: 240
N. DC-DC: 120

Post & Crosses (Xs)



4 Opt Channels—> 1Electronic Board (4-Ch ADC)
[Mini-DCEM (Digital)]

PoF & PoF Fibres

FC-PD Post
1 Post/**2** Panels
N. Posts/LongWall: 1/2 x 30 x 2 x 2 = 60
N. Posts/ShortWall: 1/2 x 6 x 2 x 2 = 12
N. Tot Posts: 72

FC-PD X
N. Xs/Post: 60
N. Tot Xs: 60 x 72 = 4320

N. Boards/X: 1
N. Boards/Post: 60
N. Tot. Boards: 4320

PoF for Elec Board:
N. OPCs/Board: 2 (Σ) - stacked- (1 redundant) 400mW ElPwr
N. Fiber/Board: 1
N. Fiber/Post: 60

N. Tot Fibre: 4320
N. Tot OPCs: 8640 (including x2 for redundancy)

Signal over Fiber

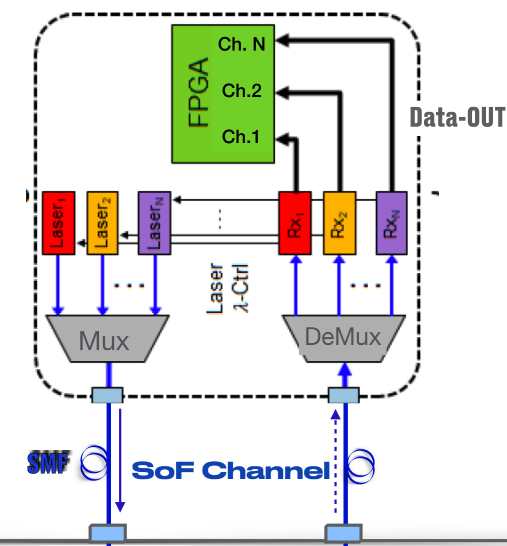
new state-of-art silicon photonics solution

MultiChannel Electro-Optical Interconnection

developed for advanced telecommunication
(Next-Generation 100G Interconnects)

to be
customized for cryogenic

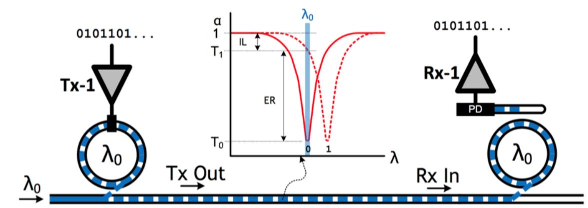
Resonator driver
Thermal wl management

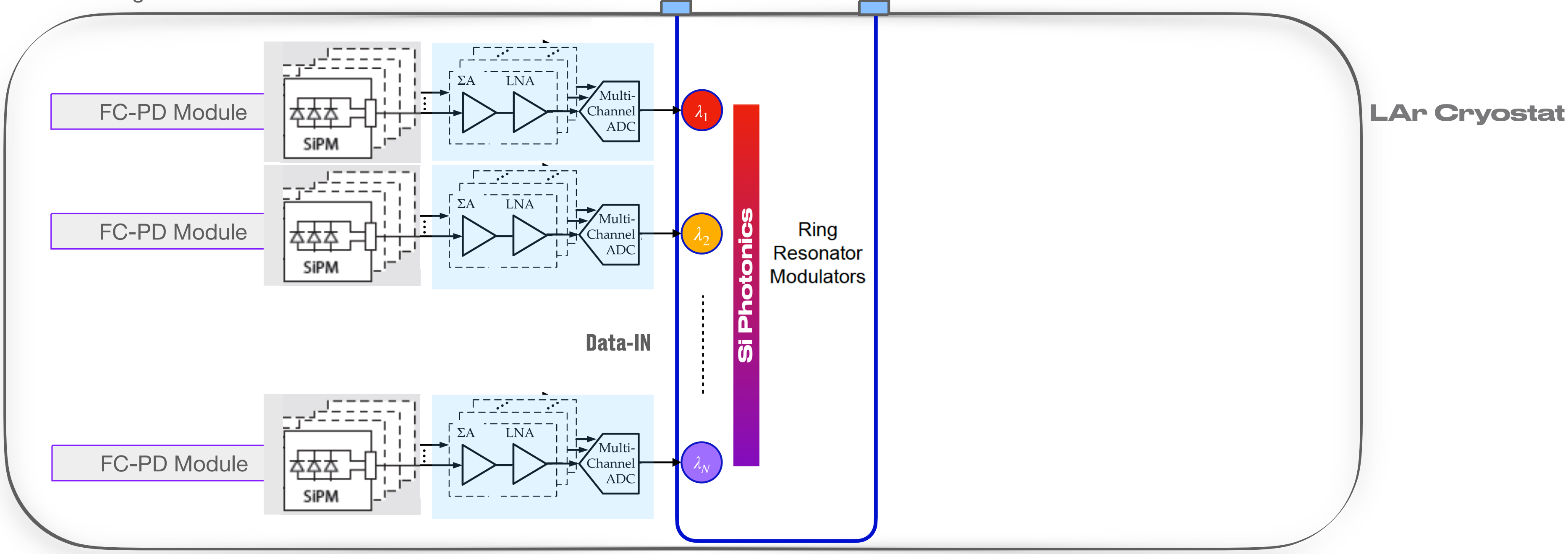


Ring Resonator Modulation

for Digital Data encoding
and
very large bandwidth transfer

[14(ADC-bits) x 67 Mbit/s] x 100 ch.s = 100 Gbit/sec





FD3-4 Vertical Drift optimized PDS

Cost estimate and organization

Parameters	
Parameter	**Value**
Estimate FY	23
Prototype FY	26
Module-0 FY	28
Production FY	31
Commissioning FY	34
Average Escalation/Inflation	4%
Average Procurement Overhead	10%

Production
Production XA
Production SiPMs
Production PoF
Production Cold Electronics
Production Warm Electronics
Production RMS
Production Manager Hours
Production Sr Engineer Hours
Production Jr Engineer Hours
Production Technician Hours
Production Scientific Hours

Based on FD2 components current costs (M&S and Labor), and scaling up in quantity, a budget cap of < 3 x FD2 is obtained

Draft R&D topics:

Detector:

1. Dichroic Filter by Atomic layer deposition on WLS acrylic plates
2. pTer WLS deposition for large scale automatized “mass production”
3. Mechanical support in Field Cage
4. Channel count optimization
5. SiPM
6. Detector dimensions (drift field uniformity, channel count,…)
7. Detector simulation
8. Physics simulation

Electronics:

1. Front-end
   a. Faster LArASIC in 65nm
2. ADC (ColdADC, commercial,…)
3. Coldata?
4. PoF (separate SiPM and LV,…)
5. Power distribution (connect adjacent field cage pillars?)
6. SoF - Digital Data encoding with large bandwidth transfer

Prototyping FC-PDS

For

Optimized VD FD3

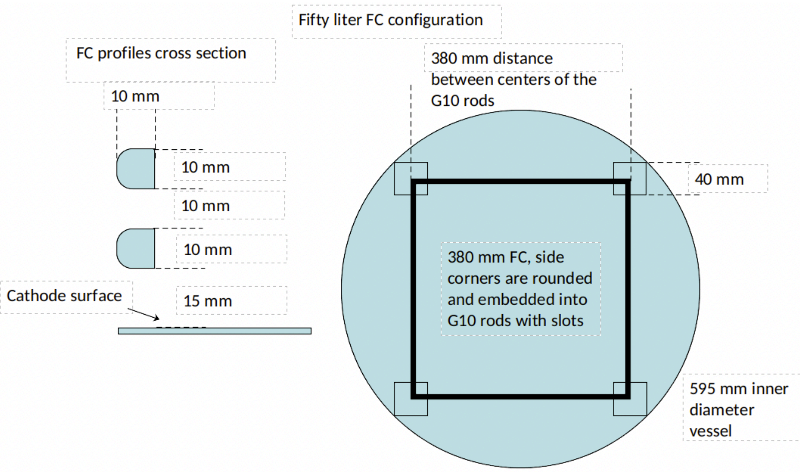
F. Cavanna Fermilab

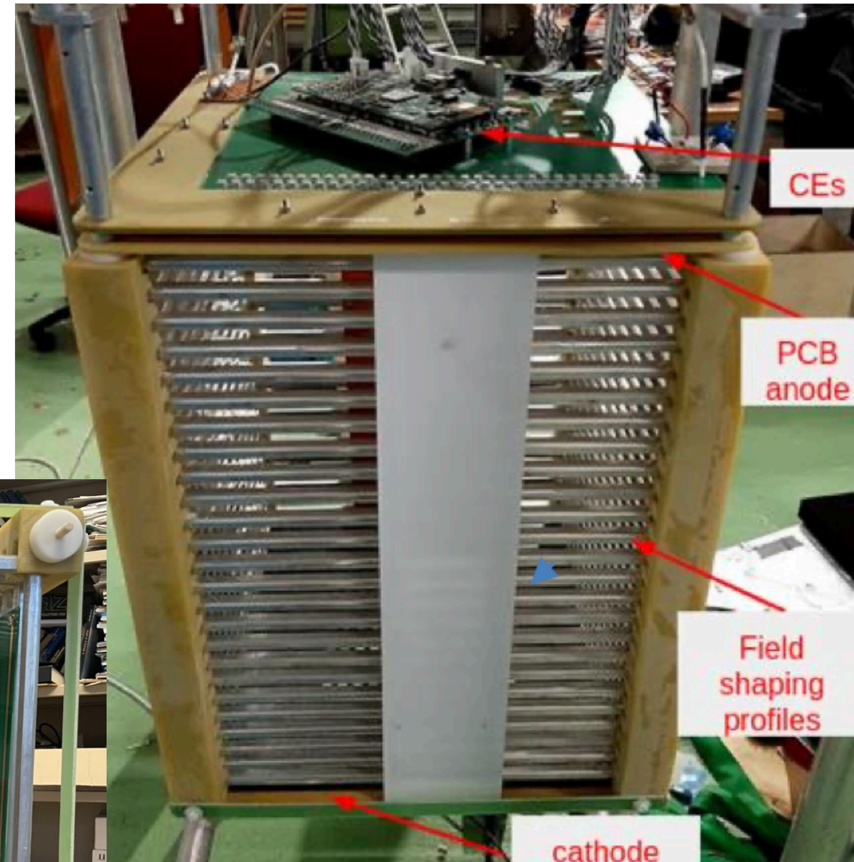
Demonstrator R&D: a staged prototyping path

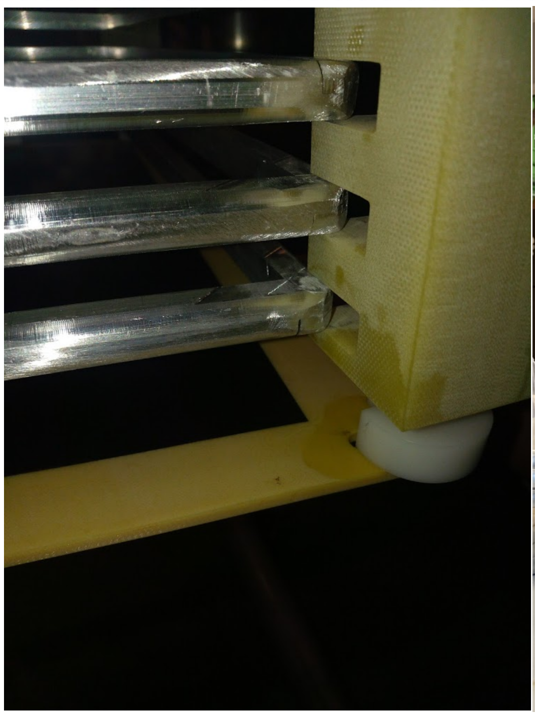
- **table-top size:** FC-PD module assemblies and electronic boards with PoF-OPC and digital SoF solution - 1yr (mid ’23-mid’24) - test @ *CERN 50lt facility*

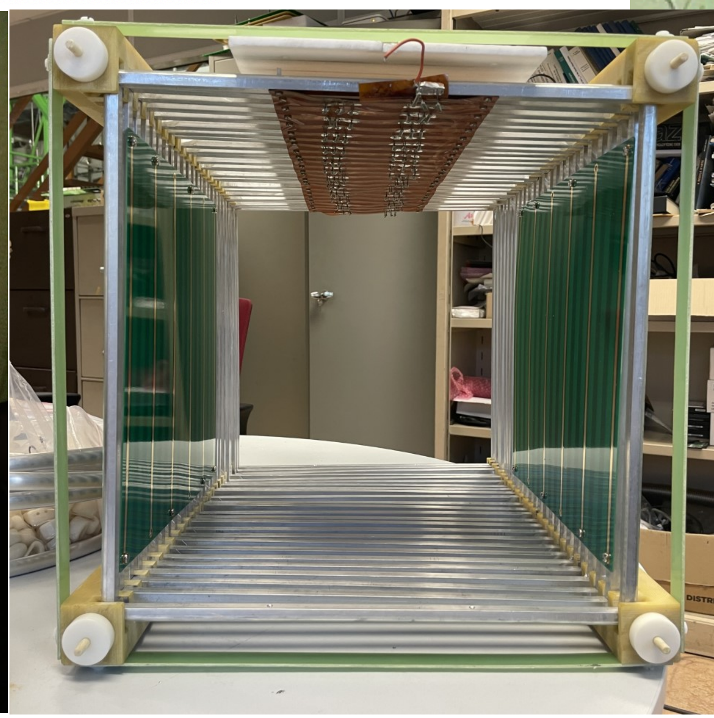
- **larger sized (m^3 of LAr)** - order of 100-channels SoF read-out and PoF (2024-25) - test @ LAr lab - IERC-EEdwards building - in the large 2mx2mx3m FNAL “*ColdBox*” facility

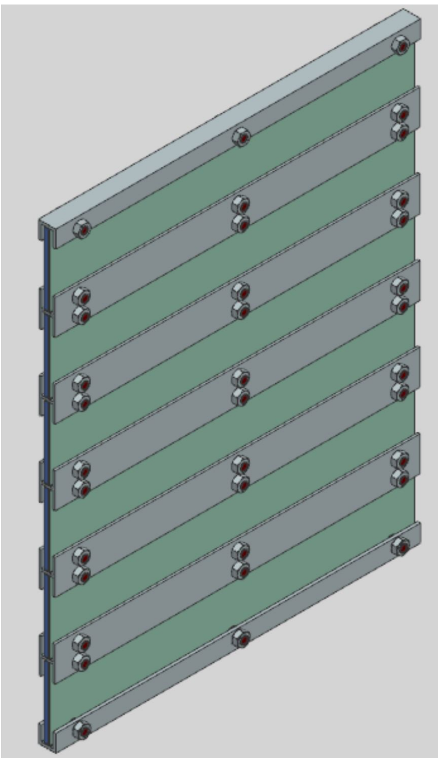
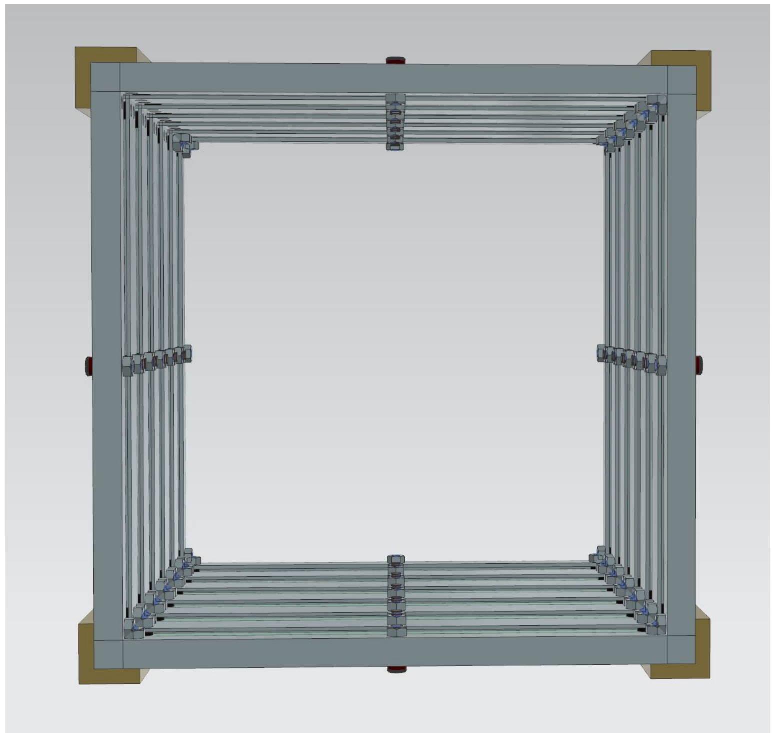
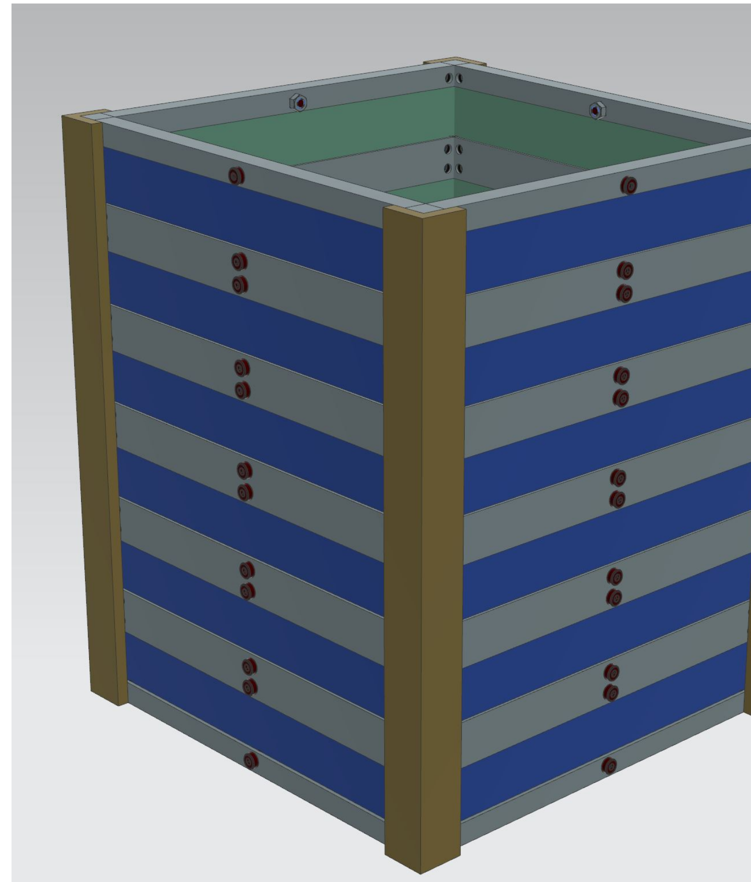
- deployment of a **full-sized**, **fully PD-instrumented FC** of a Vertical Drift LArTPC in the *protoDUNE* cryostat at CERN (2025), for a 1-kT scale validation in view of DUNE Phase-2 Far Detector (FD3) —> opportunity for combining into ARIADNE proposal to SPSC for a protoDUNE run


Fifty liter FC configuration
FC profiles cross section
10 mm
10 mm
10 mm
10 mm
Cathode surface
15 mm
380 mm distance between centers of the G10 rods
40 mm
380 mm FC, side corners are rounded and embedded into G10 rods with slots
595 mm inner diameter vessel


CEs
PCB anode
Field shaping profiles
cathode

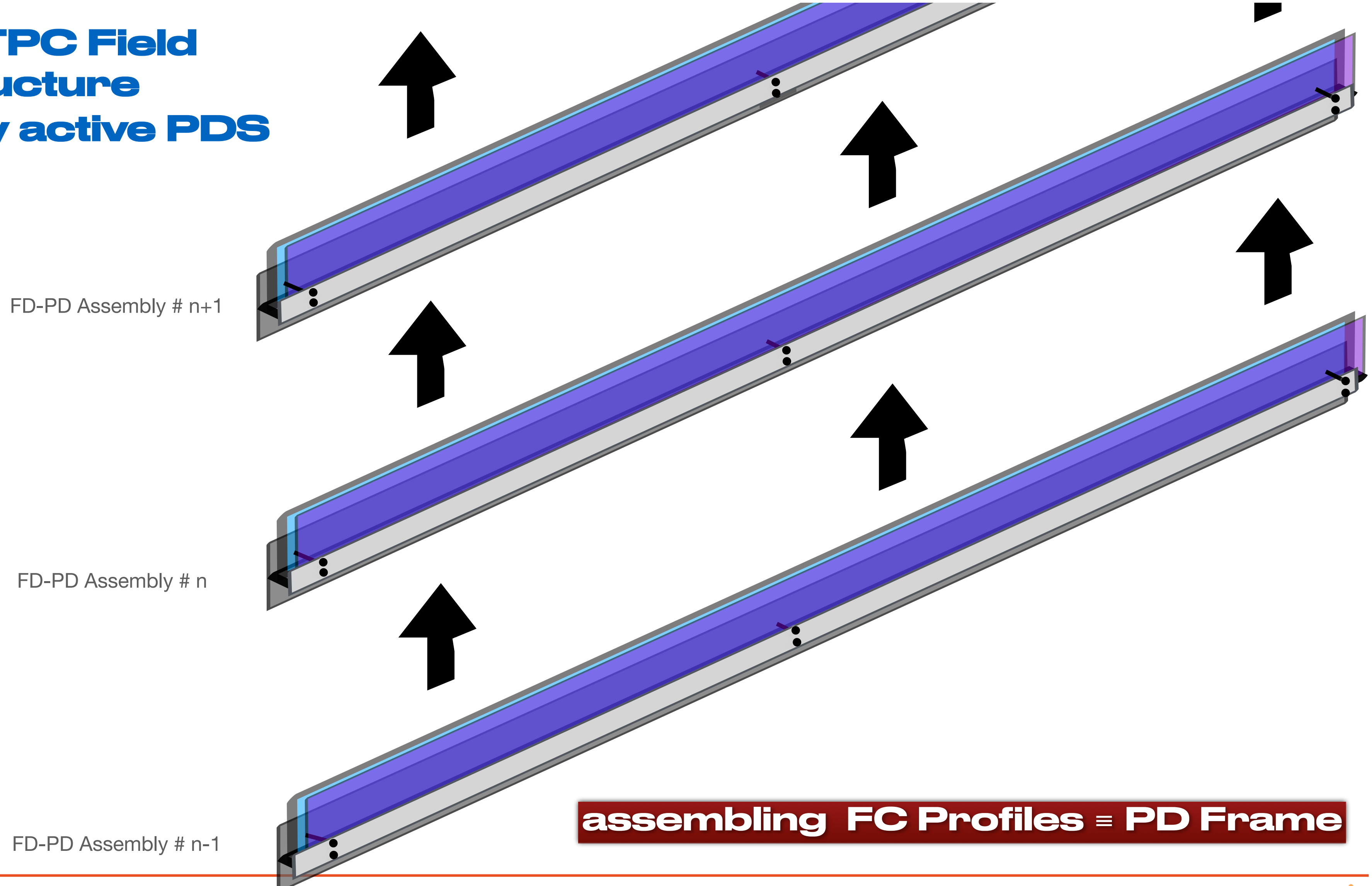




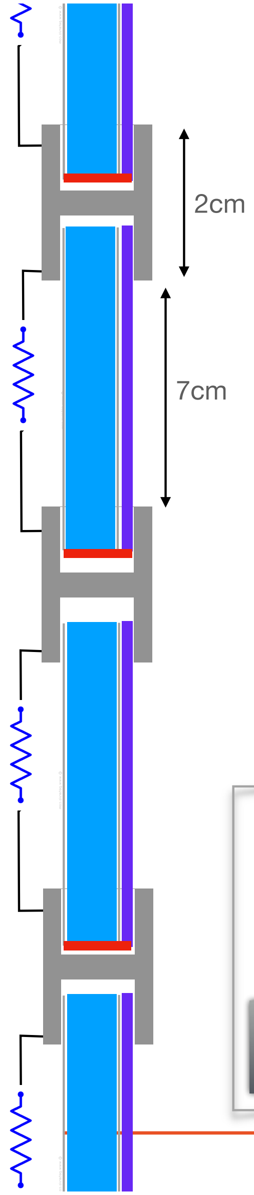




Back Up

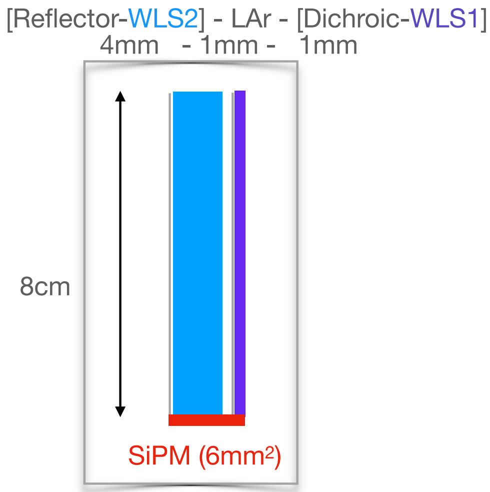
convert TPC Field Cage structure into a fully active PDS

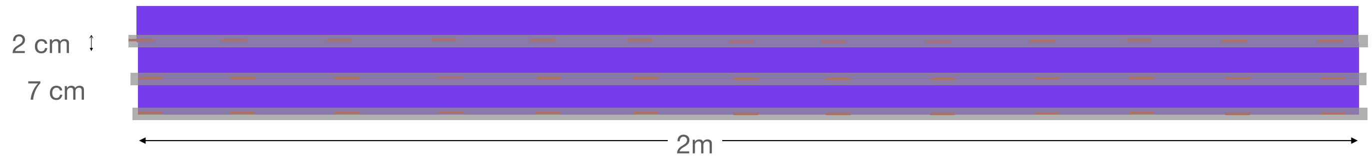


assembling FC Profiles ≡ PD Frame



Photon Detector
xARAPUCA
concept





xA-Bar Ph.Sensitive Area $A = 0.15\ m^2$

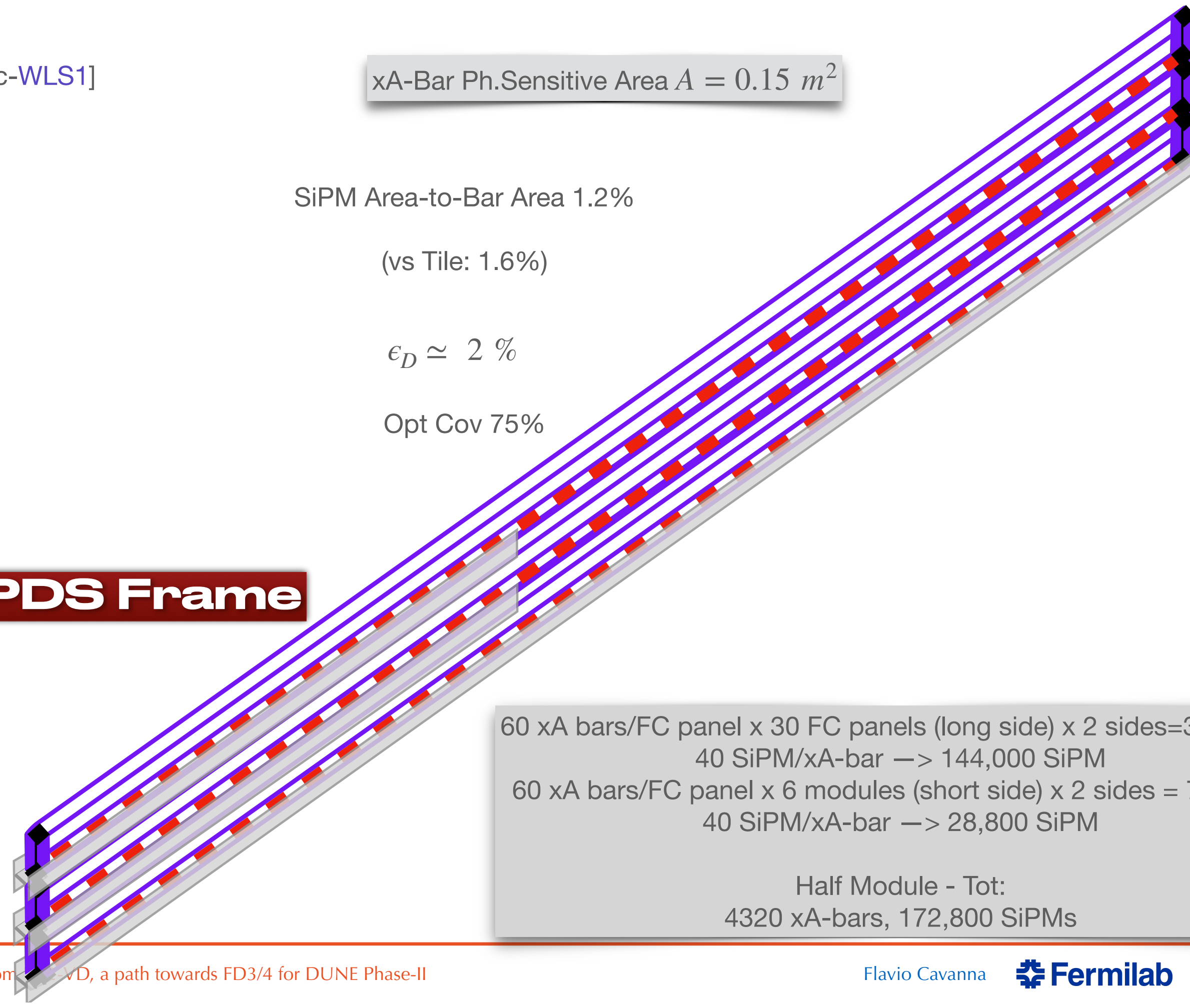
SiPM Area-to-Bar Area 1.2%

(vs Tile: 1.6%)

$\epsilon_D \simeq 2\ \%$

Opt Cov 75%

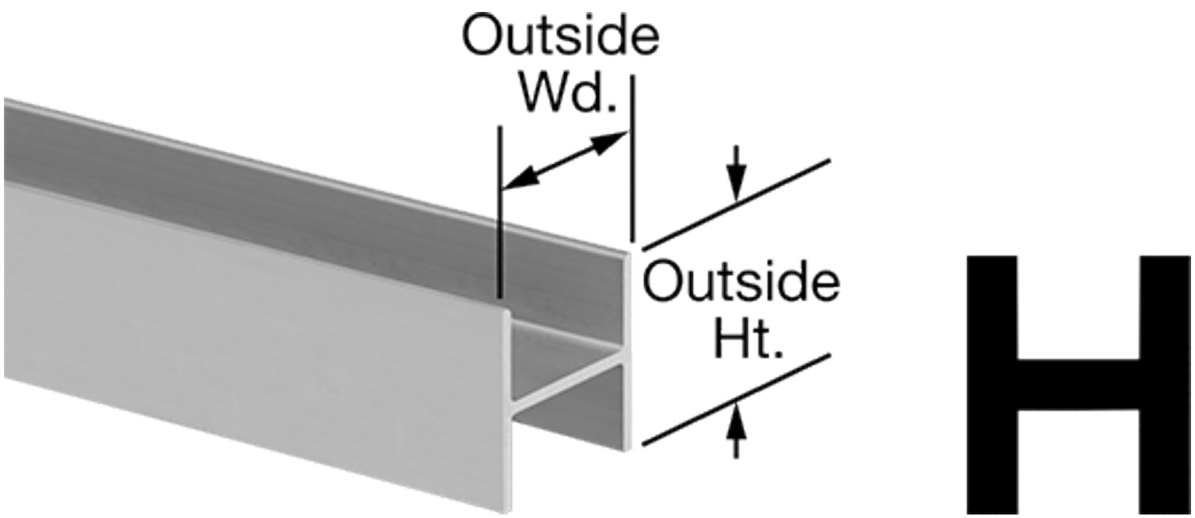
FC & PDS Frame

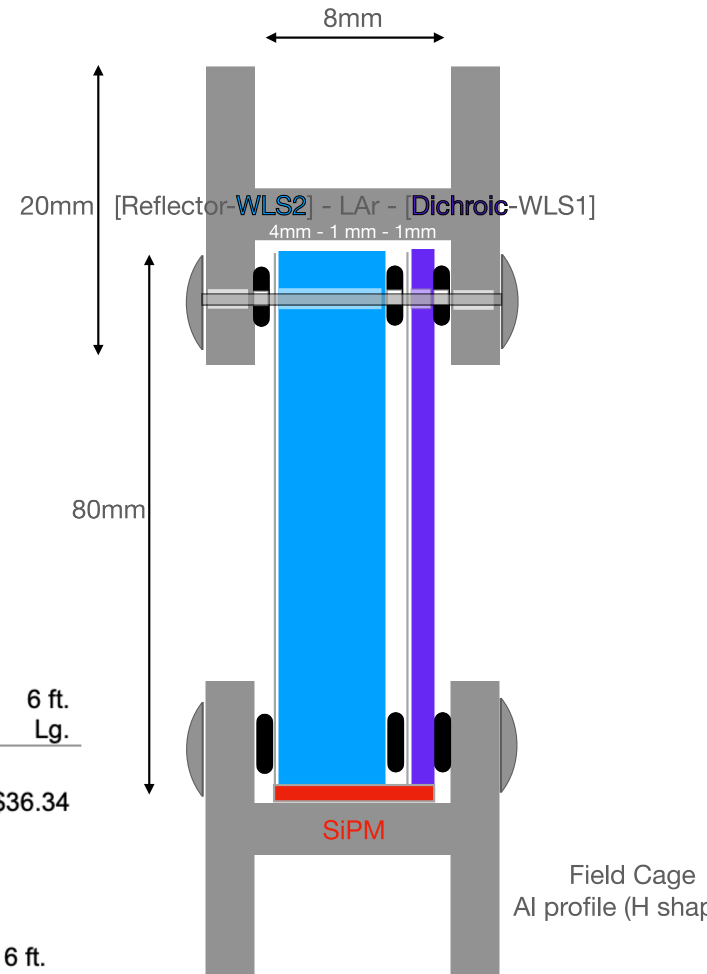


60 xA bars/FC panel x 30 FC panels (long side) x 2 sides=3600 bars
40 SiPM/xA-bar —> 144,000 SiPM
60 xA bars/FC panel x 6 modules (short side) x 2 sides = 720 bars
40 SiPM/xA-bar —> 28,800 SiPM

Half Module - Tot:
4320 xA-bars, 172,800 SiPMs

https://www.mcmaster.com/h-profiles/material~aluminum/shape~h-bar/

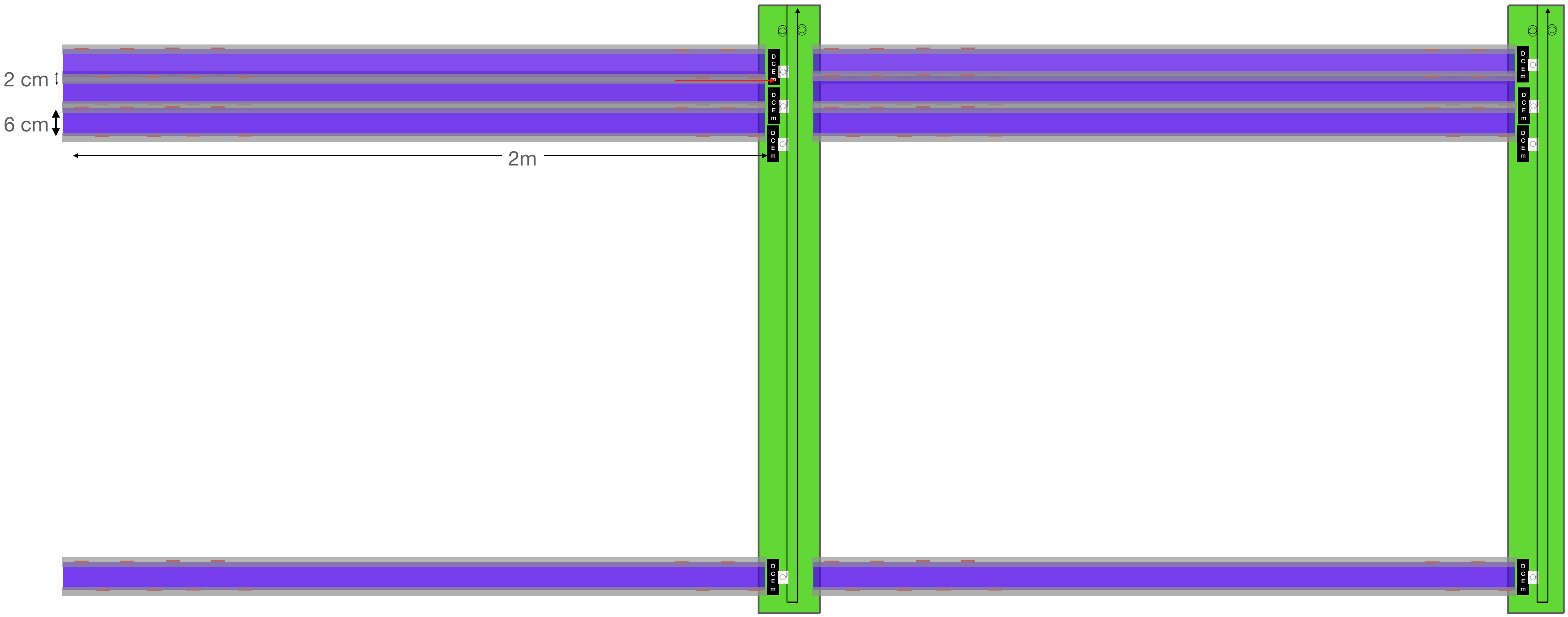




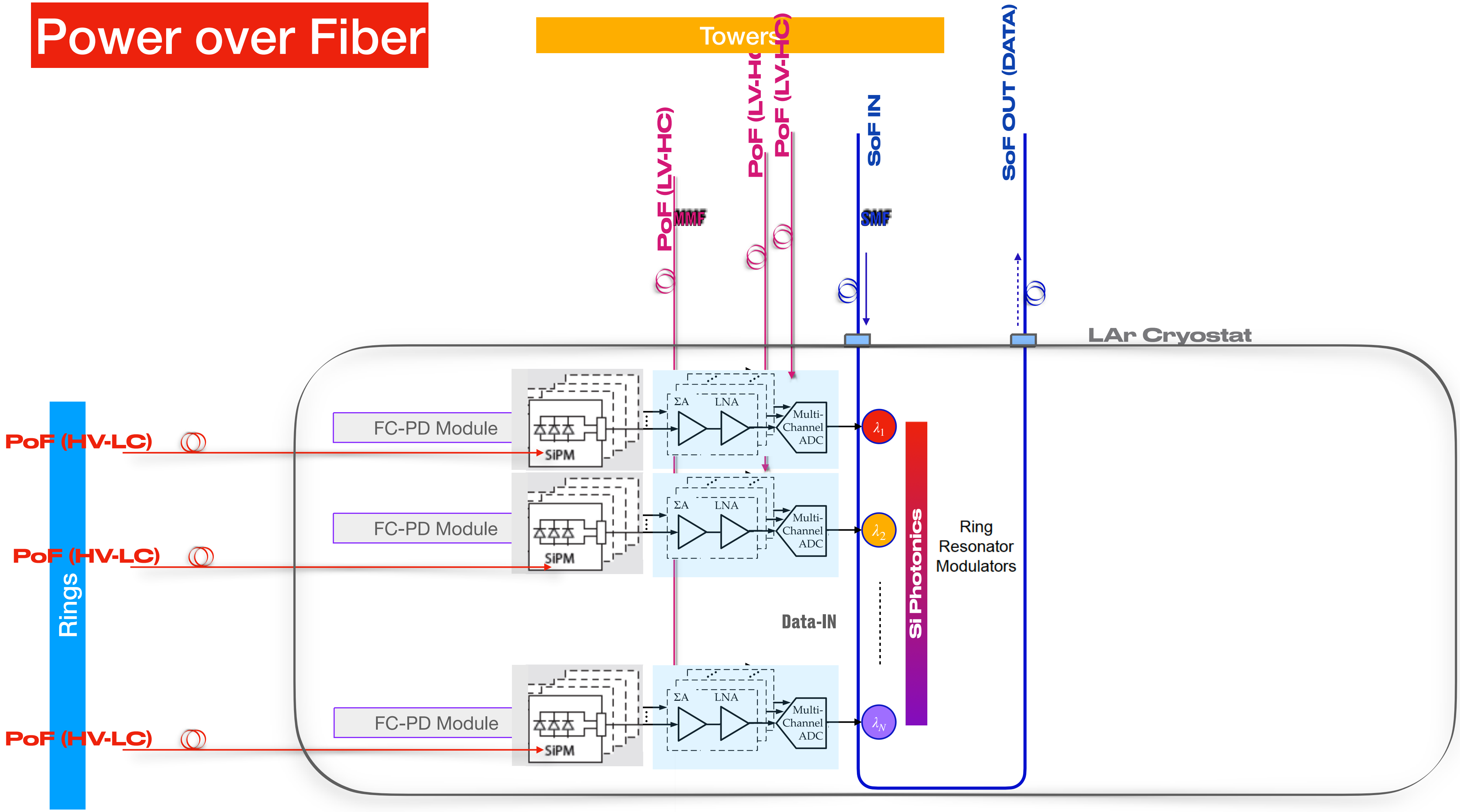
Outside Ht.	Outside Ht. Tolerance	Outside Wd.	Inside Wd.	Heat Treatment	Temperature Range, °F	Straightness Tolerance		1 ft. Lg.	3 ft. Lg.	6 ft. Lg.
0.094" Wall Thick. (-0.008" to 0.008" Tolerance)										
1.500"	-0.024" to 0.024"	0.688"	0.50"	Hardened	-320° to 212°	0.050" per ft.	**4558T55**	$9.45	$21.80	$36.34

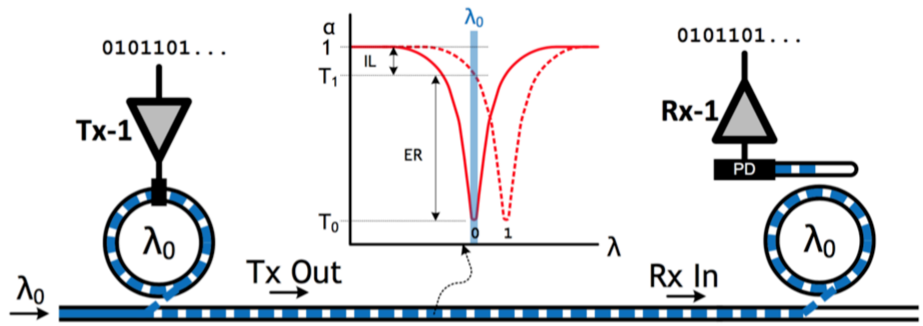
OR

Outside Ht.	Outside Ht. Tolerance	Outside Wd.	Inside Wd.	Heat Treatment	Temperature Range, °F	Straightness Tolerance		1 ft. Lg.	3 ft. Lg.	6 ft. Lg.
0.05" Wall Thick. (-0.008" to 0.008" Tolerance)										
1.060"	-0.024" to 0.024"	0.700"	0.60"	Hardened	-320° to 212°	0.050" per ft.	**4558T19**	$4.25	$9.80	$16.33


2 cm
6 cm
2m

Power over Fiber





Optical links can be realized by modulating a microring resonator's resonance wavelength.

This approach can be interpreted as the on-off keying (OOK) modulation of the input light in the frequency domain if the input laser wavelength is in the proximity of the resonance.

One way to modulate the resonance of these resonators is to use electro-optical properties of the ring material to change the refractive index. Silicon is a popular material used to fabricate these structures.

Changes in free carrier concentration causes linear change in the index of refraction. Hence, we can form active cavities by injecting or depleting carriers inside the cavity. PN junctions are the common means for this purpose as the depletion region width can be controlled by the bias voltage.

Ring resonators can be used on both transmitter and receiver sides. At the transmit side, modulator switches between two resonances imprinting data stream on the through-port optical intensity.

Main benefit of microring based optical links is the capability of communicating over multiple wavelengths simply by cascading them on transmitter and receiver side.

This scheme is called wavelength division multiplexing (WDM)

Thermal tuning of ring resonators can be done in a very power efficient way

Ring-modulators have been demonstrated in this process by placing interleaved lateral PN junctions along the looped around waveguide using existing doping levels for source/drain and well implants of transistors

Most serious objection on using microring modulators is the resonance wavelength sensitivity to the temperature. Transmit eye can be totally closed by the temperature variation of couple degrees. As a solution a closed loop thermal tuning scheme can be developed and implemented to continuously monitor the optical power level inside the ring and tune the ring temperature by using an embedded heater.

Summary

-The Field Cage, walls of thin electrodes surrounding 4 sides of the LAr-TPC volume, offers the largest available surfaces for an extended ($\rightarrow 4\pi$) optical coverage. If instrumented with photon detectors embedded in the FC electrodes geometry, this 4π coverage can be realized.

-Physics motivations should indicate what level of LY is necessary. For physics >5 MeV (Solar, SN, any yet unknown BSM signals..), w/ energy reconstruction (calorimetry) by the PD with high resolution, LY~200 PE/MeV look appropriate.

-More than the avg LY, uniformity of the LY across the volume is important, and the closer to 4pi coverage one can get the more uniform LY uniform.

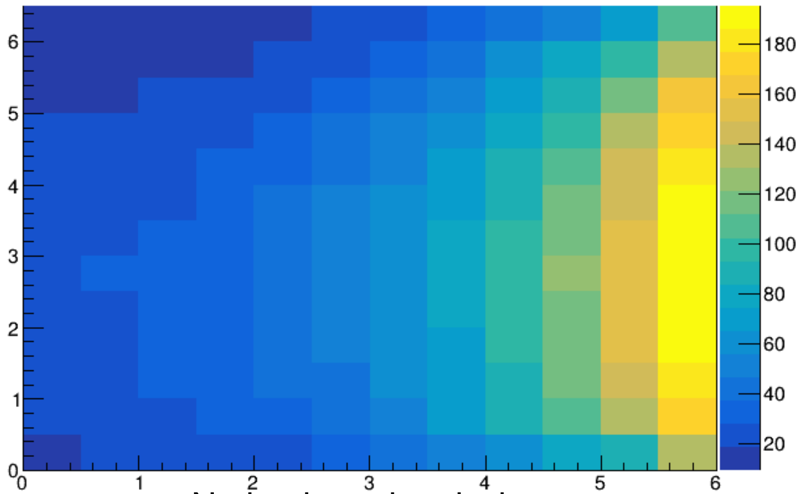
- Cost (and complexity, e.g. n.of channels) of detector should be taken into account. (Professional) cost estimate in preparation.
- The new xARAPUCA between FC profiles with relatively low n. of SiPM (compared to current xARAPUCA modules of equivalent area) – this reduces the overall efficiency, but
  - new generation High PDE are available and successfully tested in LAr (need complete qualification and possible customization) and
  - the very large optical coverage

  compensates (up to 90% of FC walls) - This should keep cost "low".

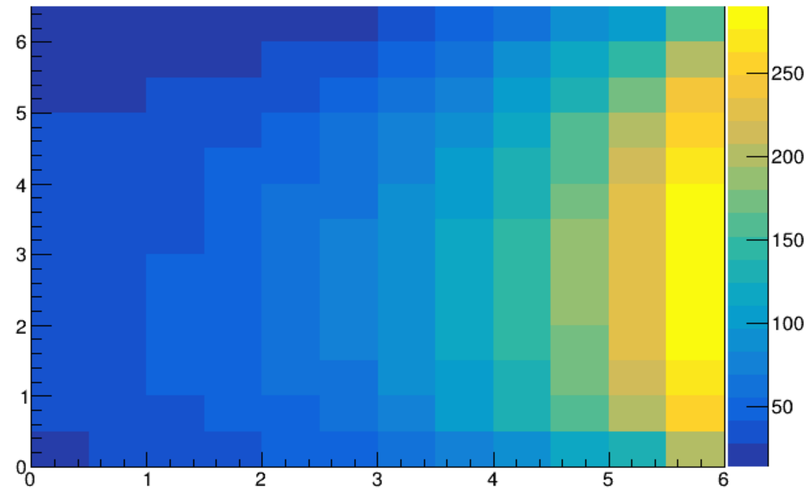
- the other main cost is for the dichroics. If the dichroics can be made on large surfaces on Acrylic substrate (rather than on glass or fused silica as currently done) cost will be reduced significantly, but here we need some R&D (underway). The frame and the assembly labor should also be largely reduced .. so in the end that might be moderated into reasonable boundaries even with a substantial increase of coverage.

-The granularity in Y (pitch of 8 to 10 cm) is surely too fine and not really needed, but it is determined by the FieldCage geometry. We cannot gang together different modules in Y in one channel, because they are at different potential and cannot be connected on copper. The granularity in Z can be ~1 m. Simulations are needed to say if that is giving an acceptable space resolution (old simulations indicate O(1 m) should be ok for a precision in the range of <50 cm in space).

LY_{LAr} [#pe/MeV]



No backward emission

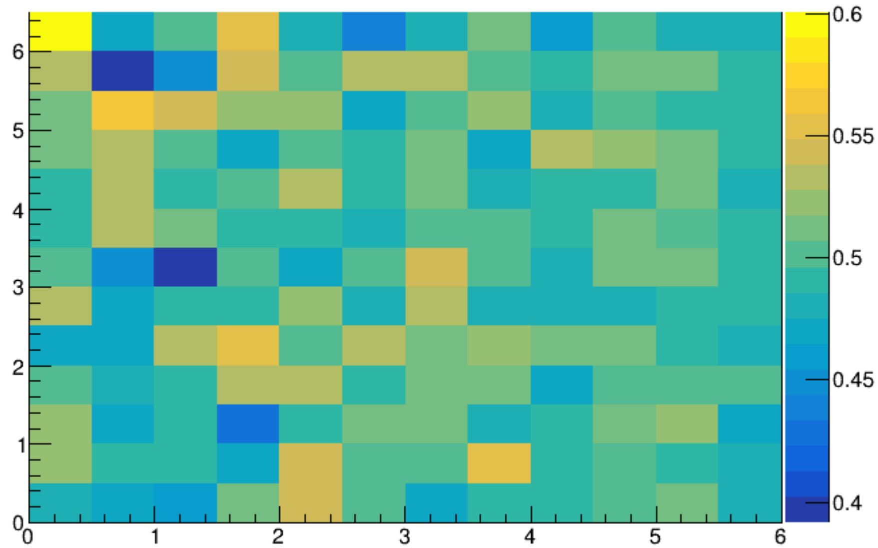


Including backward emission

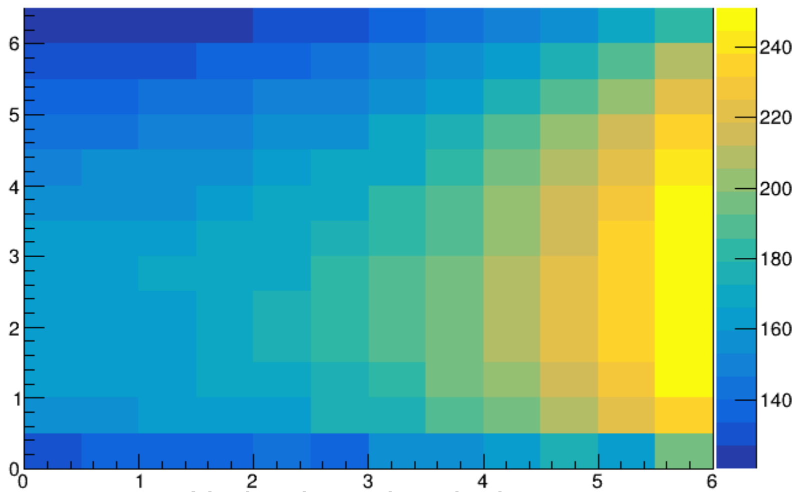
- Direct LAr light yield contribution increase due to backward ptp emissions

Increase: $(LY_{LAr}^{ptp} / LY_{LAr}^{no\ ptp}) - 1$

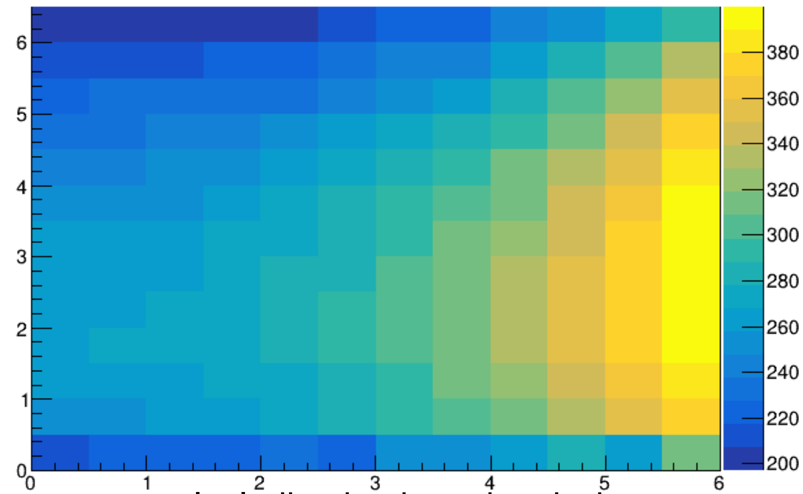
- Percentage ~50 %
  - uniform across volume



LY_{Xe} [#pe/MeV]



No backward emission

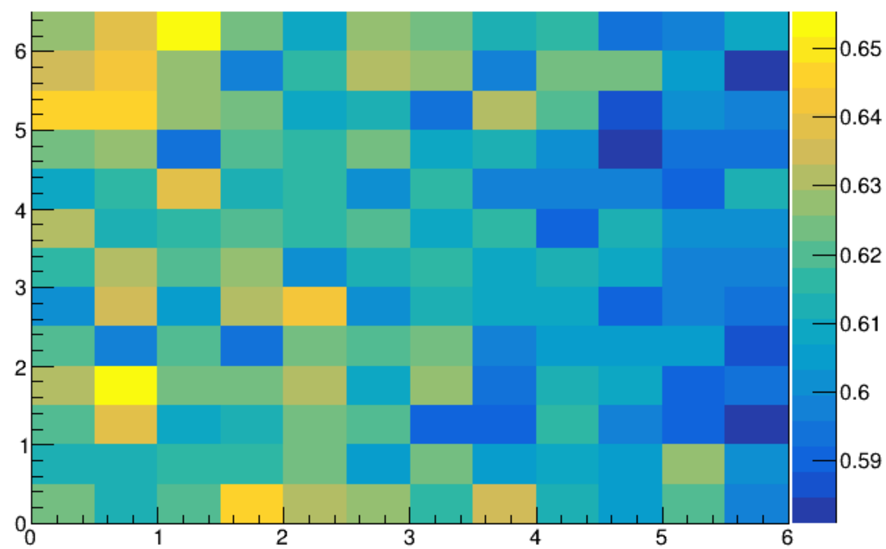


Including backward emission

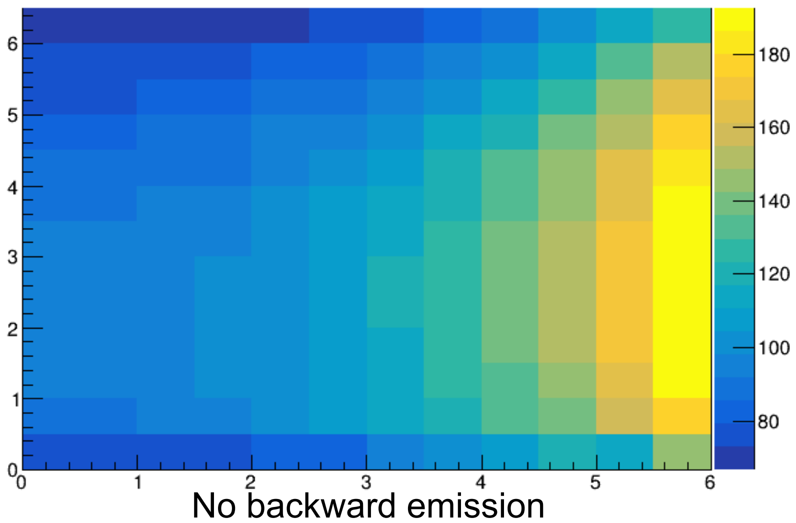
- Xe doping light yield contribution increase due to backward ptp emissions

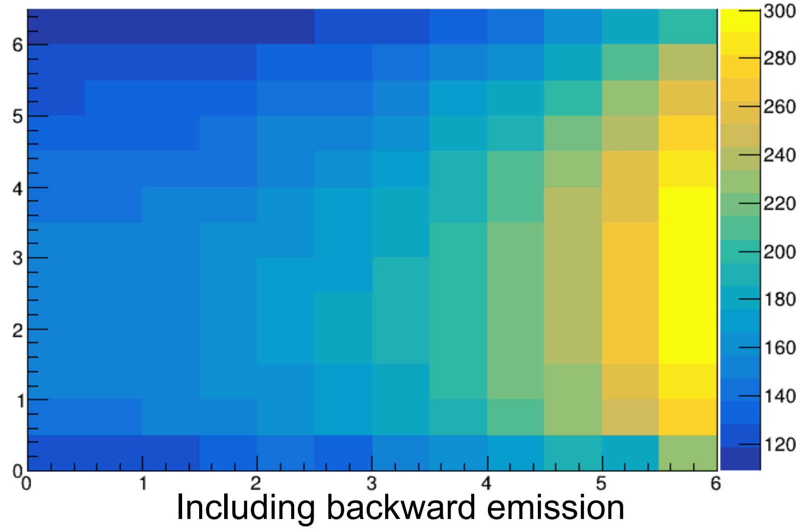
Increase: $(LY_{Xe}^{ptp} / LY_{Xe}^{no\ ptp}) - 1$

- Percentage >60 %
- Higher impact noticed closer to the lower LY region



LY_{total} [#pe/MeV]





- Total light yield increase due to backward ptp emissions

$LY_{total} = 0.31\ LY_{LAr} + 0.53\ LY_{Xe}$

Increase: $(LY_{total}^{ptp} / LY_{total}^{no\ ptp}) - 1$

- Percentage ~60 %