PoWER Simulation Update

A. Steklain, L. Hirsch, M. Adames

Universidade Tecnológica Federal do Paraná

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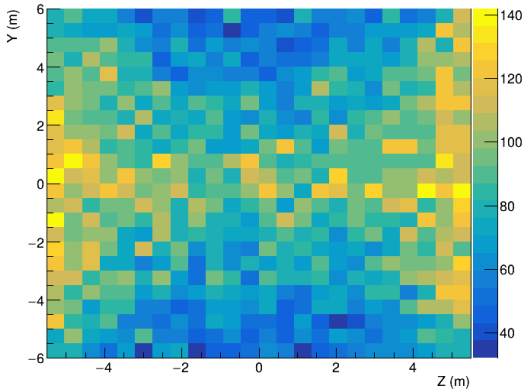
Introduction

- The main simulation has all required elements implemented.
- The default design provides <LY>=90 PE/MeV and LYmin=35 PE/MeV. Sufficient for DUNE physics goals, but inferior to APEX.
- The veto system is demonstrated to work in the simulation.
- The focus now is optimizing the LY performance, **without jeopardizing the veto**.
- We use the simulation to test some modifications to the original design:
  - Number of LDUs
  - LDU arrangement
  - Field Cage modification

Current Status - LightMap



$<LY> = 90$ PE/MeV, LYmin $= 35$ PE/MeV.

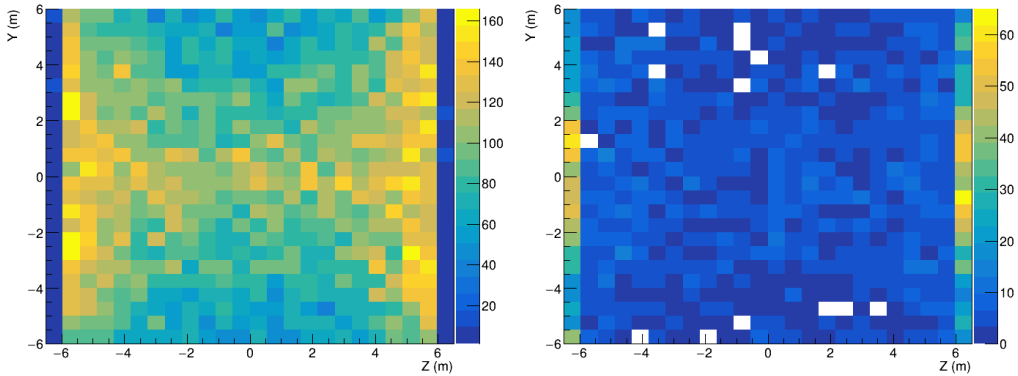
Current Status - Veto

- The idea is to identify events that take place in the buffer zone, outside the field cage.
- Events occurring inside the field cage generate photons that are converted to visible by the PEN. They are detected by both detectors.
- Events occurring in the buffer zone also contain not converted UV photons. they are unable to go inside the field cage as they are blocked by the acrylic foil, and are detected almost only by UV detectors.
- We use the proportion

$$R = \frac{n_{VUV}}{n_{VUV} + n_{VIS}}.$$

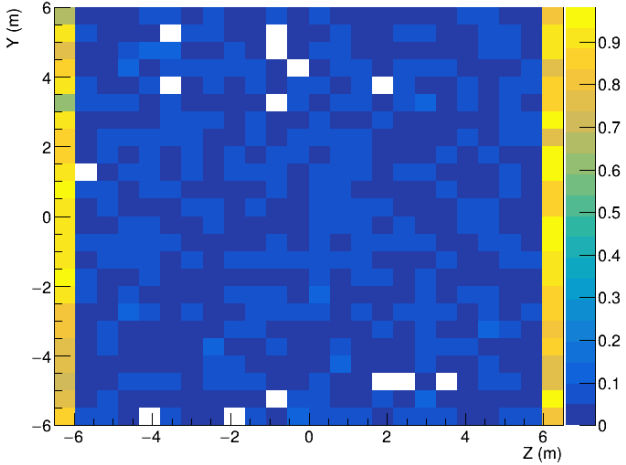
Events occurring inside should have $R \approx 0$, and outside should have $R \approx 1$.

Current Status - Veto

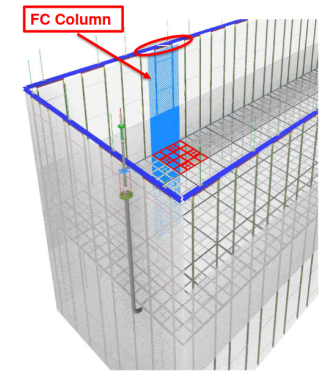


Left: Visible. Right: VUV.

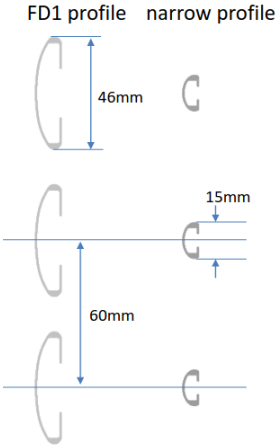
Current Status - Veto



Field Cage

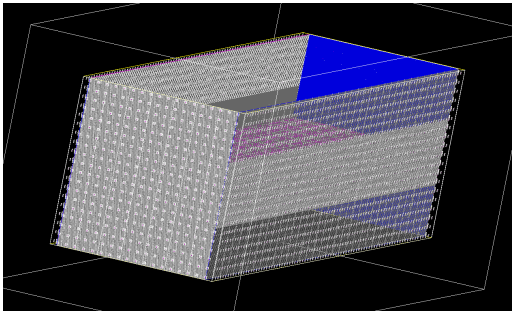


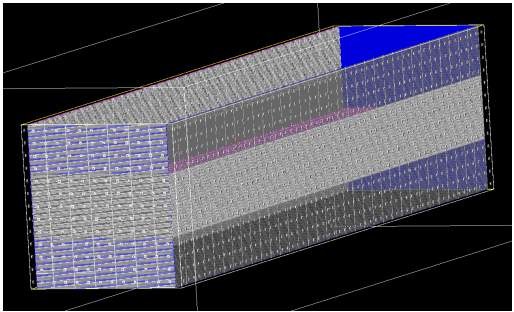
Average Transparency: $\sim 45\%$.



- FD 1 profile Transparency: $\sim 23\%$.
- Narrow profile Transparency: $\sim 75\%$.
- Narrow profiles cover the long walls 2.5m from the cathode.
- Vertical bars: $13\text{m} \times 45\text{mm} \times 8\text{mm}$;
- Distance between two vertical bars: 1.8m.

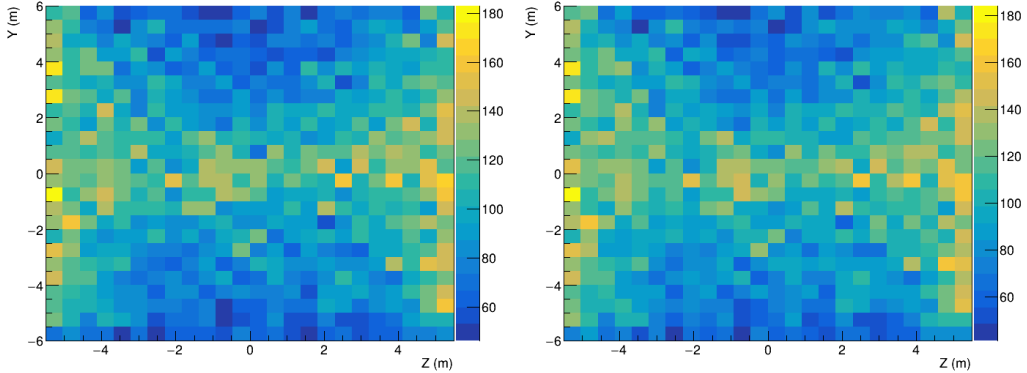
New Field Cage Proposal





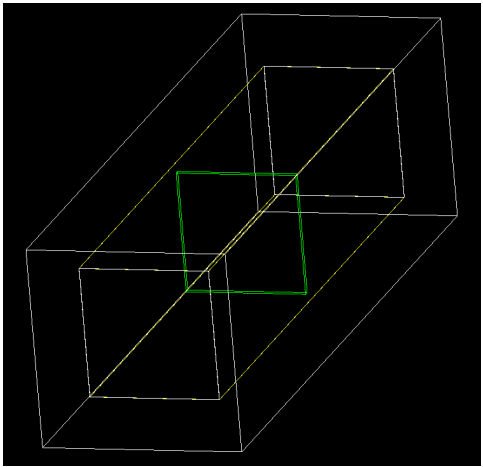
New Field Cage Proposal - Lightmaps

Left: Original FC design. Right: Proposed design.



There were no significant differences in <LY> and LYmin.

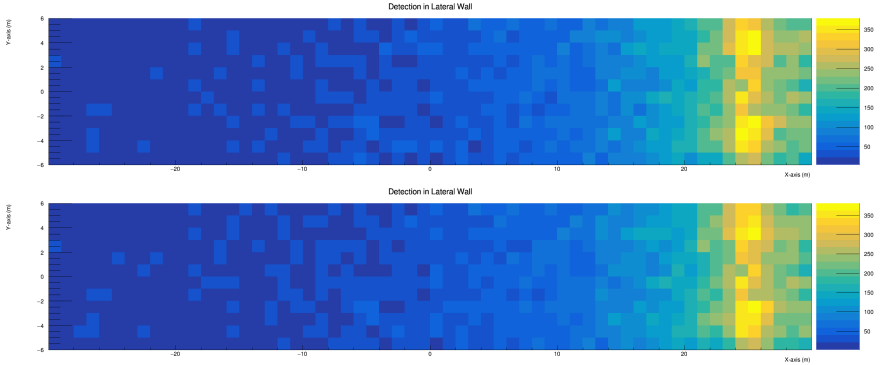
Photons



- Photons produced randomly over different positions inside a parallelepiped of dimensions $6\text{m} \times 6\text{m} \times 0.5\text{m}$. The directions and polarizations are random.
- Total of 14.4 million photons, resulting in approximately 25,000 photons/MeV per voxel of dimensions $0.5\text{m} \times 0.5\text{m} \times 0.5\text{m}$.

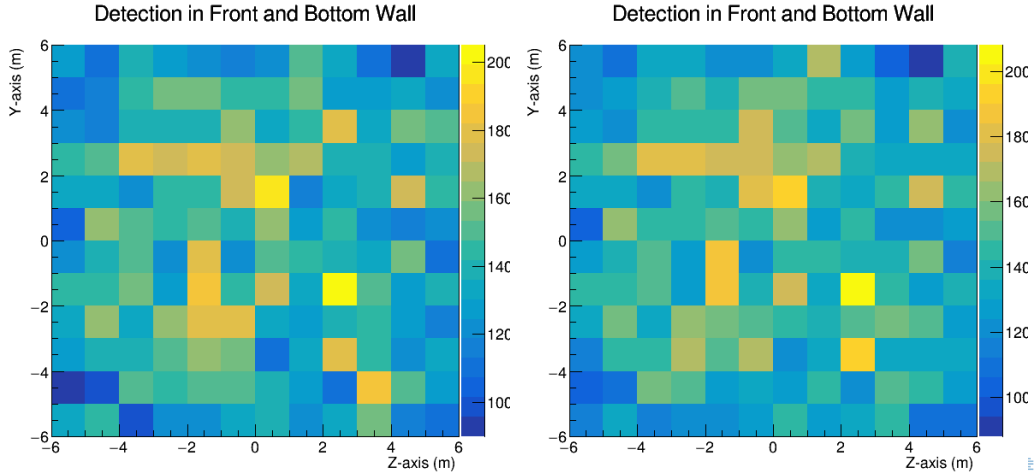
New Field Cage Proposal - Signal

Left: Original FC design. Right: Proposed design.



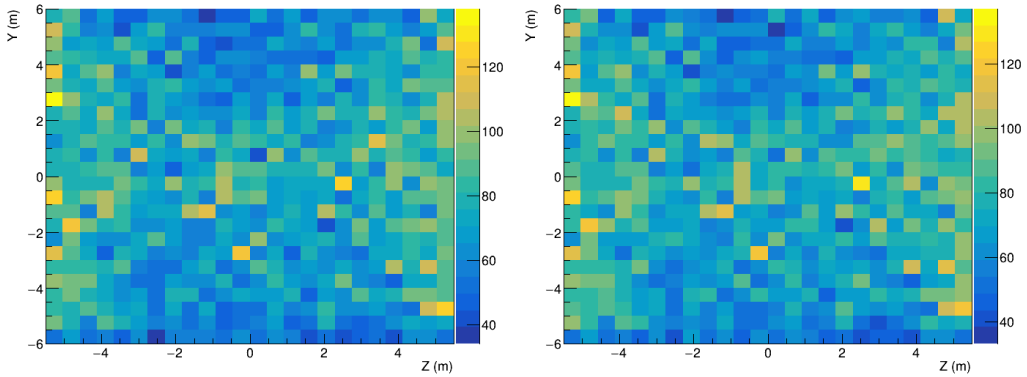
New Field Cage Proposal - Signal

Left: Original FC design. Right: Proposed design.



New Field Cage Proposal - Lightmaps

Left: Original FC design. Right: Proposed design.



There is no significant difference when the source is close to the front/bottom walls.

Number of LDUs

Variation of the space between LDUs (and the number of them). LY given in PE/MeV. APEX: <LY>=180, LYmin=109.

Distance (m)	LDUs	Area (m^2)	<LY>	LYmin
1	1872	75	90	35
0.9	2400	96	122	54
0.8	3060	122	150	71
0.7	3876	155	190	87

New LDU Arrays

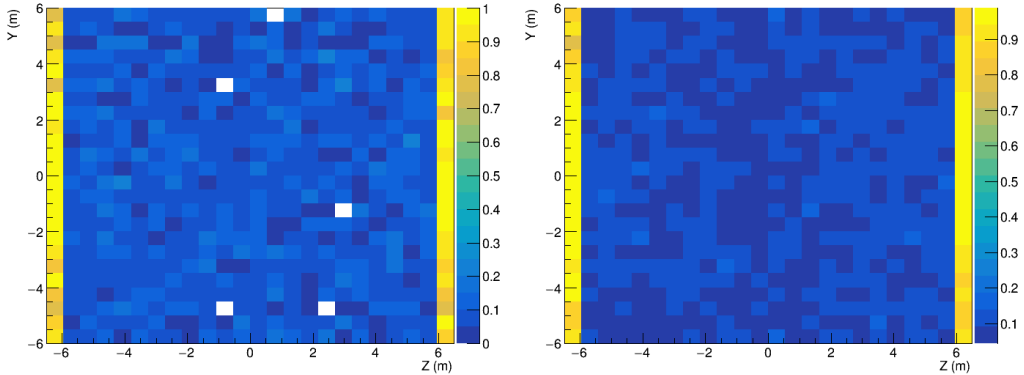
- In addition to increasing the number of LDUs we tested a new arrangement.
- In this design, the LDUs are arranged only in the 70% region.
- In the other regions, we use only VUV SiPMs.

New LDU Arrays

Variation of the space between LDUs (and the number of them). LY given in PE/MeV. APEX: <LY>=180, LYmin=109.

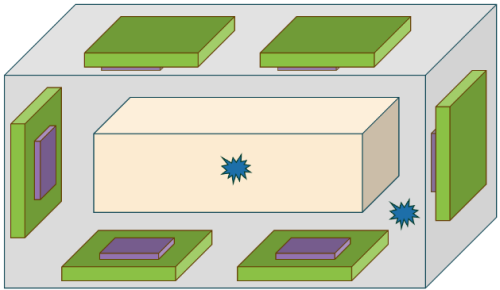
Distance	LDUs	VUV SiPMs	Area (m^2)	<LY>	LYmin
1 m	1152	720	47.88	54.4	20
0.9 m	1600	800	66	74.1	34
0.8 m	1800	1260	75	82.5	38
0.7 m	2448	1428	101	113.2	57
0.6 m	2880	2160	121	133.6	58
0.5 m	4672	3212	195	193.4	97

New LDU Arrays - Veto



Left: 1m distance between LDUs. Right: 50 cm distance between LDUs.

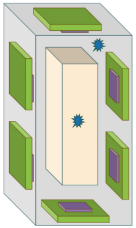
Prototype



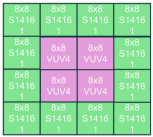
- **External Chamber**: Covered with reflector SiPM matrix on the sides.
- **SiPM**: Hamamatsu type:
  S14160-6050HS - VIS
  S13370-6050CN - VUV
- **Internal Chamber**: PEN or PEN+ACRYLIC
- **Source**: Gamma, Beta, Alpha:
  241Am - 133Ba - 57Co -137Ce - 22Na - 90Sr - 235U

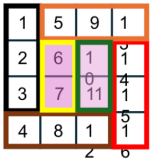
Prototype

LIGHT-YELD



- 6 SiPM arrays
- Photosensor surface: (2,4cm X 2,4cm) = 5,76 cm^2
- Total active area: 6 X 5,76 = 34,56 cm^2
- Reflector surface = 810 cm^2
- Coverage = 34,56/810 = 4,3%

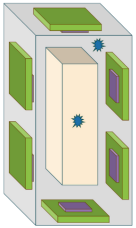




Prototype

LIGHT-YELD

LY = PhotonYeld X PEN Eff X Collection Eff X PDE SiPM



Collection Eff = Coverage / (1-R(1-Coverage))

R --> reflectivity of (Reflector + PEN) @ 420nm

Collection Eff = 0,043 / (1-0,9(1-0,043)) = 0,31

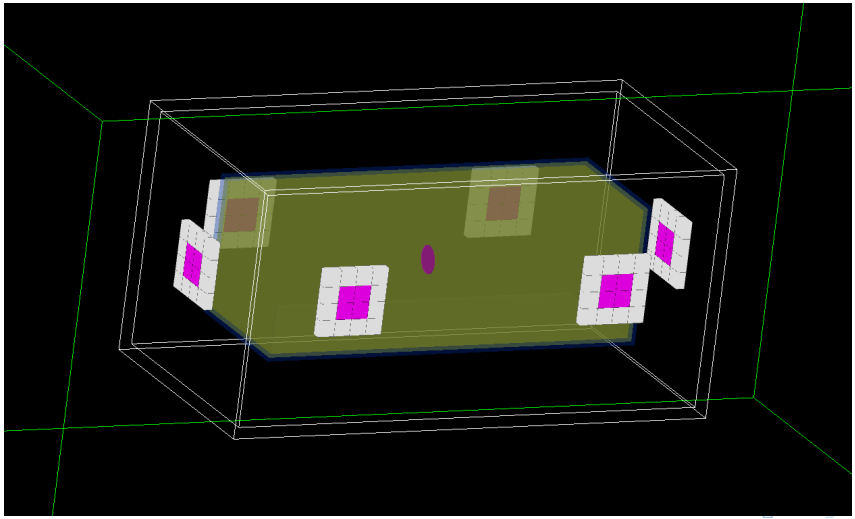
LY = 40 X 0,5 X 0,31 X 0,5 ≈ **3,0 phel/KeV**

Prototype

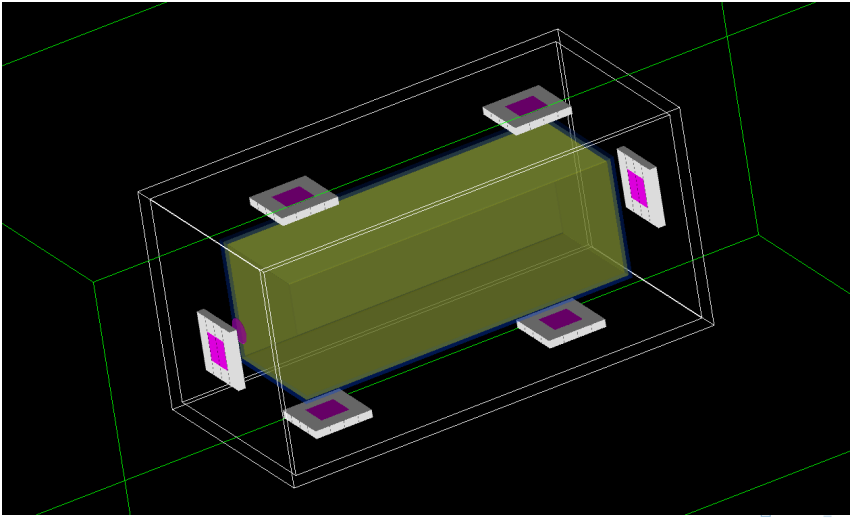
$$CollectionEff = \frac{Coverage}{1 - R(1 - Coverage)} = \frac{0,043}{1 - 0,98(1 - 0,043)} = 0,69$$

$$LY = 40 \times 0,5 \times 0,69 \times 0,5 \approx 7 \text{ phel/KeV}$$

Prototype



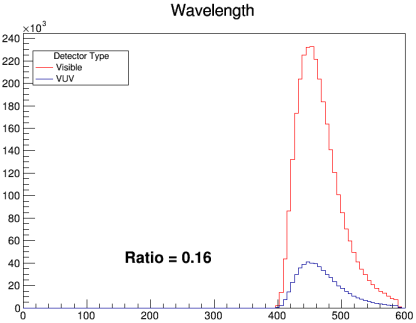
Prototype

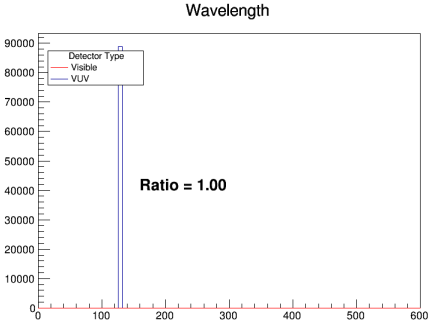


Light Simulation

- We use a photon box of dimensions 8 cm $\times$ 8 cm $\times$ 16 cm
- We generate photons inside and outside the PEN+Acrylic box
- We generate approximately 40000 photons at each voxel of dimensions 1 cm $\times$ 1 cm $\times$ 1 cm.
- LY $\approx$ 11 kphel/KeV for photons generated inside the PEN+Acrylic box.

Light Simulation

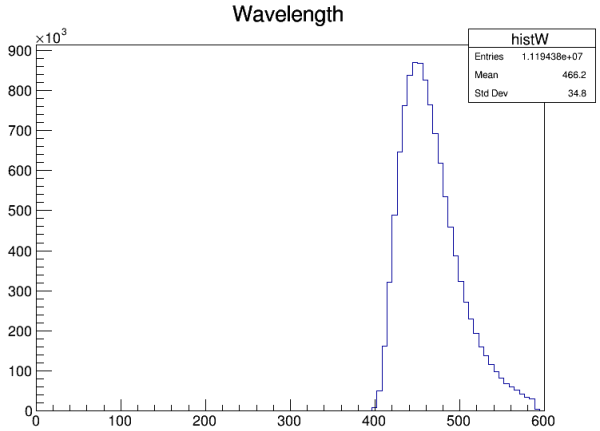




Alpha Source

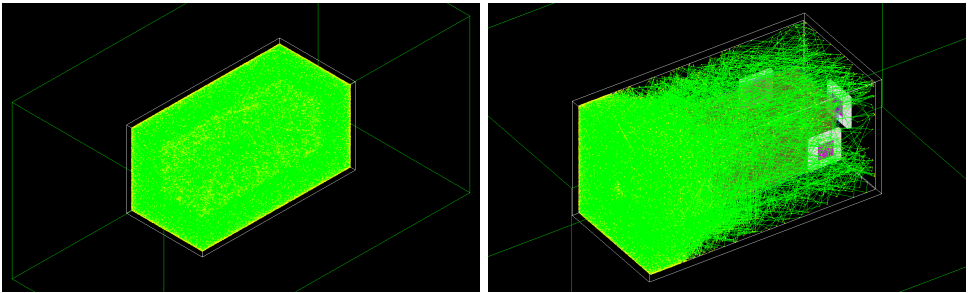
- Alpha source to be used: Uranium-Aluminium alloy
- Three isotopes presented: U234, U235 and U238
- The source is modeled by generating only the respective alpha particles with respective abundances.

Alpha Source

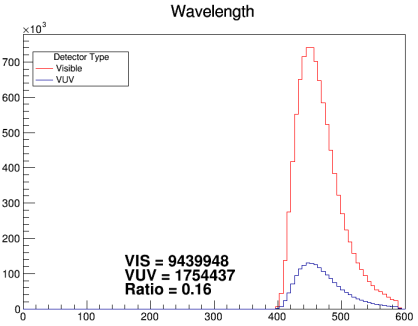


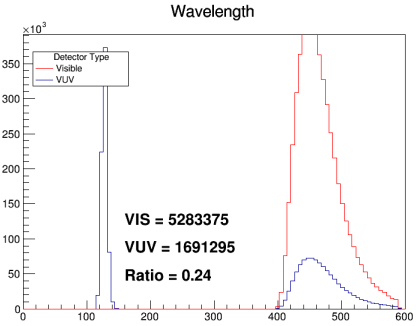
LY ≈ 11000 phel/ alpha

Alpha Source



Alpha Source





Conclusions

- New FC design and different LDU arrangements showed no improvement in the LY.
- It is possible to achieve APEX performance by doubling the number of LDUs.
- The prototype is implemented using photons, alpha particles. The implementation of the full alloy is being tested.
- The veto works well with photons, but using alpha sources might result in a signal generated inside the active volume, biasing the veto.

[1] Manzanillas L. et al. *Optical properties of low background PEN structural components for the Legend-200 experiment*, **JINST**, 17 P09007 (2022).

[2] Abraham Y. et al., *Wavelength-Shifting Performance of Polyethylene Naphthalate Films in a Liquid Argon Environment*, 2103.03232.

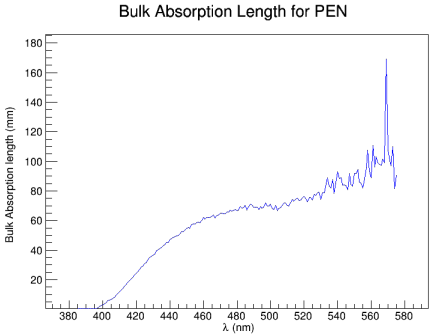
[3] Araujo G. R. et al., *R&D of Wavelength-Shifting Reflectors and Characterization of the Quantum Efficiency of Tetraphenyl Butadiene and Polyethylene Naphthalate in Liquid Argon*, **Eur. Phys. J. C** 82, 442 (2022).

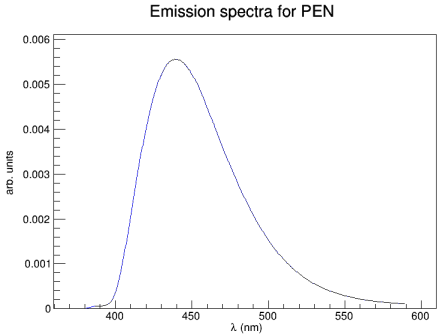
[4] Boulay, M.G. et al. *Direct comparison of PEN and TPB wavelength shifters in a liquid argon detector*. **Eur. Phys. J. C** 81, 1099 (2021).

Thanks!

Backup slides

PolyEtylene Naphtalate - PEN

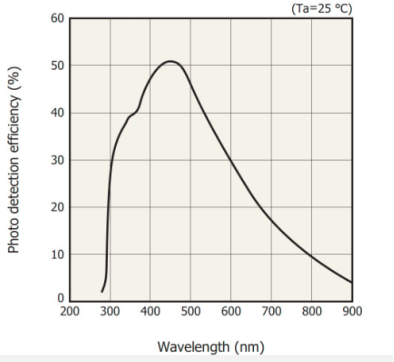


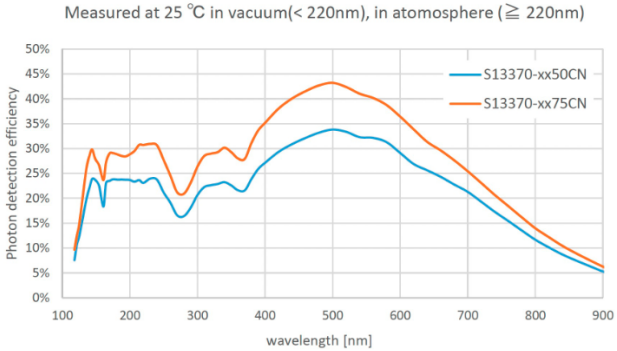


Refractive Index: 1.65
Data from Luis Manzanillas.

LDUs Configuration

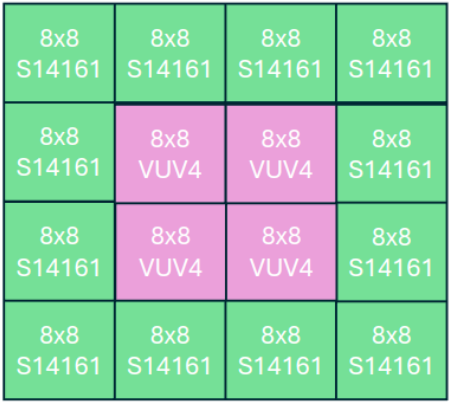
From Ana and Francesco's presentation in PoWER kick-off Meeting

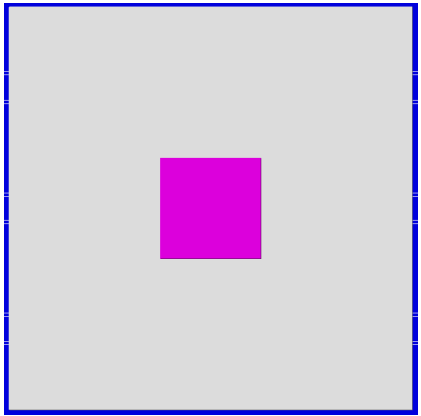




In PEN emission peak (450 nm) the efficiency for visible sensitive SiPMs is about 50%, but for UV sensitive SiPM is about 30 % - 45%.

LDUs Geometry





Length UV / Length LDU $= 1/4$

Reflectors

- 98% reflectance on the cathode, field cage, and membrane.
- 30% reflectance on anodes.
- Average reflectivity: 74%.

FD2 VD

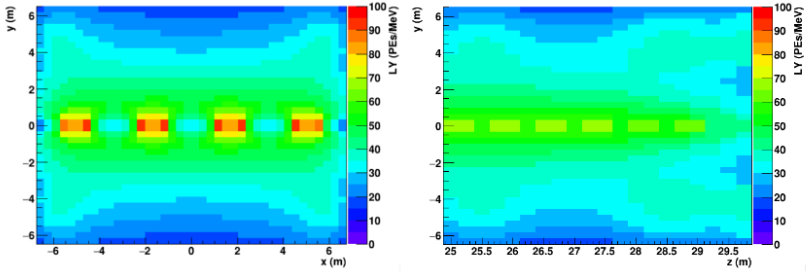


Figure 6.4: (Left) Map of the light yield (LY) in the central (x, y) transverse plane at $z = 0$ for the reference configuration. (Right) Map of LY in the central (z, y) longitudinal plane at $x = 0$, close to the detector boundary at $z = 30$ m in front of one of the membrane short walls, for the same PDS configuration.

FD2 VD

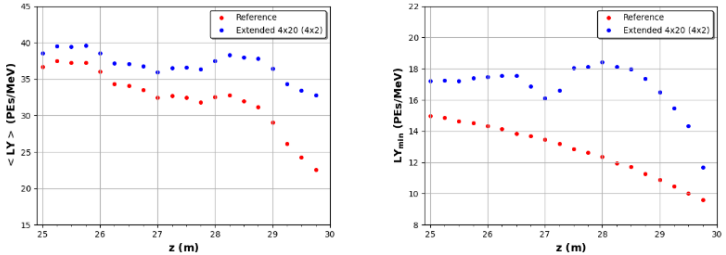


Figure 6.5: Values for average (left) and minimum (right) LY in (x, y) planes as a function of the z direction, obtained close to the detector boundary at $z = 30$ m. Light yield values for two detector configurations are shown: reference configuration including X-ARAPUCAs on the membrane short walls in blue, without short wall X-ARAPUCAs in red.

APEX

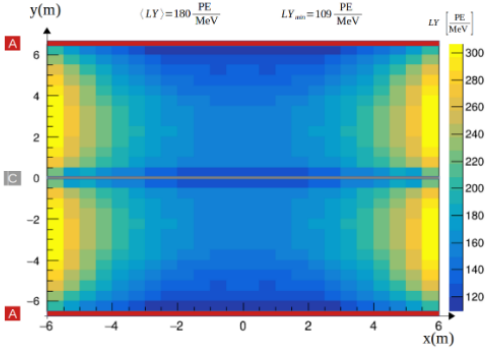
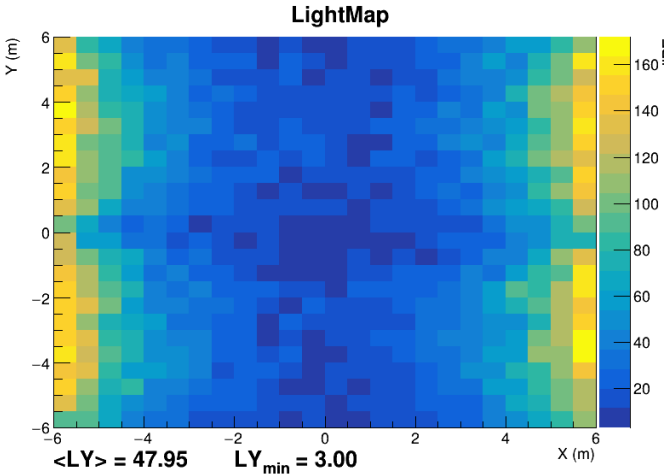
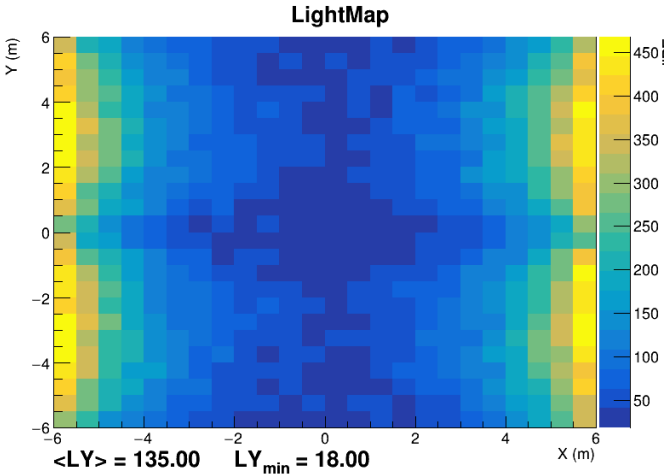


Figure 15: Map showing the expected in the central (x, y) transverse plane at $z = 0$ for the field cage-extended coverage APEX photon detection system. Dimmer regions are present near the anode planes (with no PDs on them) and at mid-height (near the non-instrumented cathode plane).

Pure Ar (50% PEN efficiency)



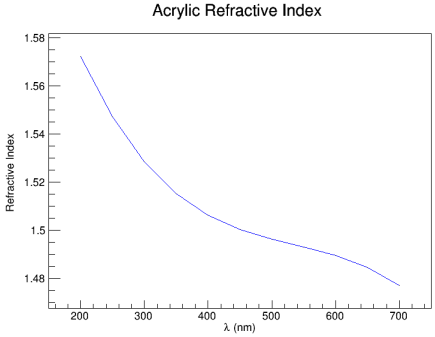
Pure Ar (100% PEN efficiency)

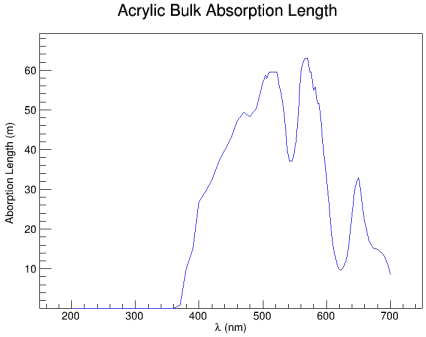


Acrylic Bulk Absorption Length

- We are using a 1mm thick acrylic foil.
- If the bulk absorption length is non-zero, we can expect some level of conversion by PEN in the case of events occurring in the buffer zone.

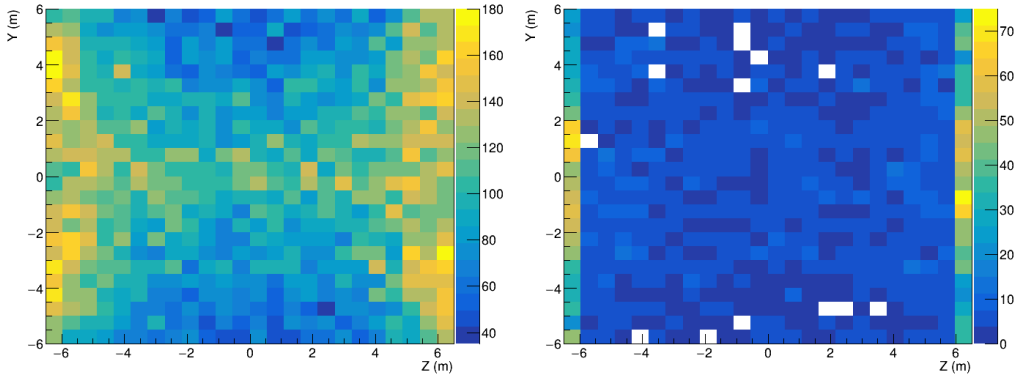
Poly(methyl methacrylate) - PMMA





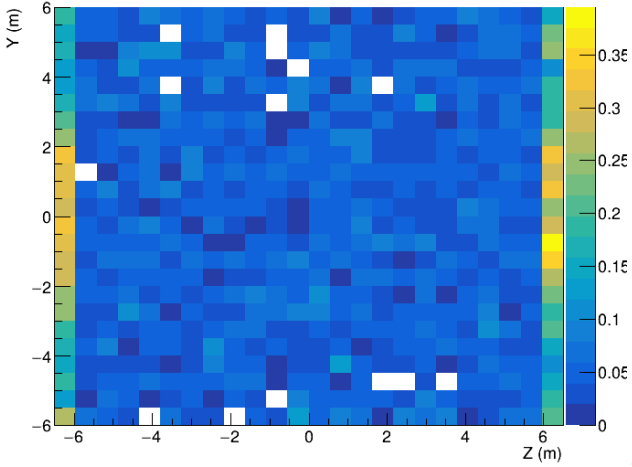
Common acrylic.
Data from Luis Manzanillas.

Lightmaps from nonideal acrylic (1cm Bulk Apsorption Length)



Left: Visible. Right: VUV.

Veto from nonideal acrylic (1cm Bulk Apsorption Length)



Field Cage - New Design