Preliminary considerations on light collection & detection

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(analytic model implemented by Sarthak Choudhary)

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European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 962480
Dark Wave

Outline

- Basic parameters for Ar and Kr
  - SiPM photon detection efficiencies (PDE)
  - Dark Count Rate (DCR) for Vis and VUV SiPMs in Ar and Kr
- LY for several configurations
- DCR and Ar-39 background
- Rough cost estimates

Ar and Kr

	Liquid Argon	Liquid Krypton
Z, A	18, 39.9	36, 83.8
Density	1.4 gm/cc	2.4 gm/cc
Radiation Length	14 cm	4.7 cm
Moliere Radius	9 cm	5.8 cm (NA48 says 4.7)
critical energy e (mu)	32 MeV (485 GeV)	17 MeV (277 GeV)
Minimum ionization	2.105 MeV/cm	3.28 MeV/cm
Ionization (eV) (atom)	15.8 eV	14.0 eV
Boiling point	87.3 K	119.9 K
index of refraction	1.23	1.3
scintillation wavelength	125 nm	147 nm
Yield	40000/MeV	25000/MeV
Triplet lifetime	1. 6 micros	0.09 micros
Drift velocity at 500 V/cm	1.6 mm/micro-sec	2.1 mm/micro-sec
Radioactiviity	Ar39, Ar42	Kr81, Kr85
Air abundance (ppm)	9300	1.14

https://pdg.lbl.gov/2012/AtomicNuclearProperties/HTML_PAGES/289.html
https://periodictable.com/Isotopes/018.42/index2.dm.html

$R_M \approx 0.0265 X_0 (Z + 1.2)$

Comparable Rayleigh scattering lengths:

TABLE III. Rayleigh scattering length for liquefied rare gases.

liquid	scintillation wavelength nm	dielectric constant	scattering length calculated cm	scattering length measured cm
He at 4.2 K	78	1.077[a]	600	
He at 0.1 K	78	1.089[a]	2×10^4	
Neon	80	1.52[b]	60	
Argon	128	1.90[b]	90	66[d]
Krypton	147	2.27[b]	60	82[d], 100[g]
Xenon	174	2.72[c]	40	29[d], 40[e], 50[f]

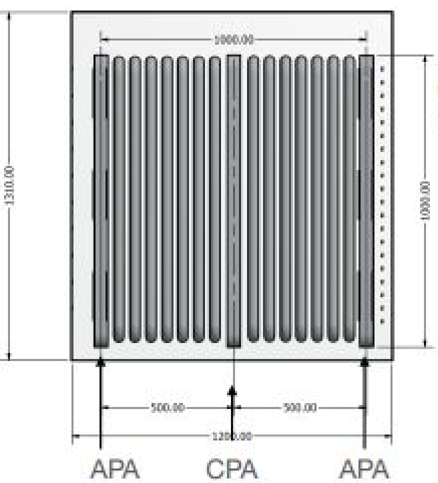
Sediel et al. 2001

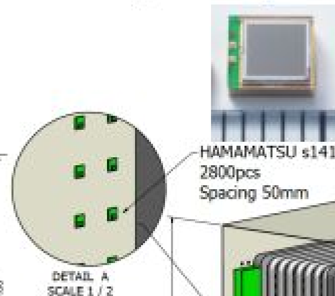
FLArE Detector Preliminary Drawings

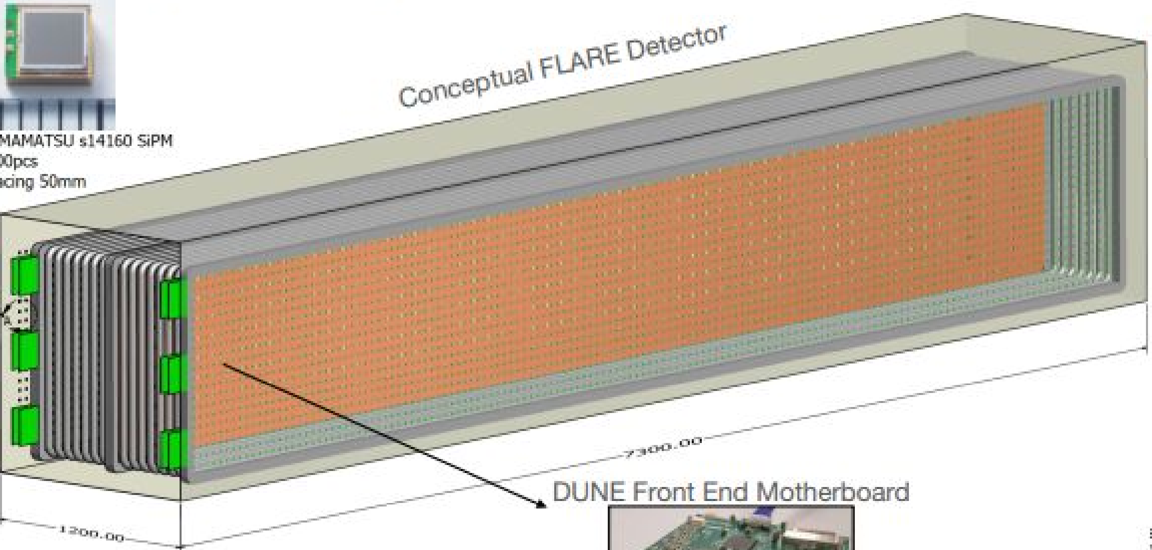
- **All dimensions are in milimeter (this is not a design, just a sketch)**
- **In particular, the GTT cryostat has corrugations which need to be considered (Bo Yu)**
- **The gap needed for safety is inspired by NeXO design with similar HV needs**

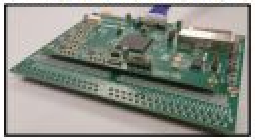
Volume	**11.5 m^3**
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W

TPC-side view 2

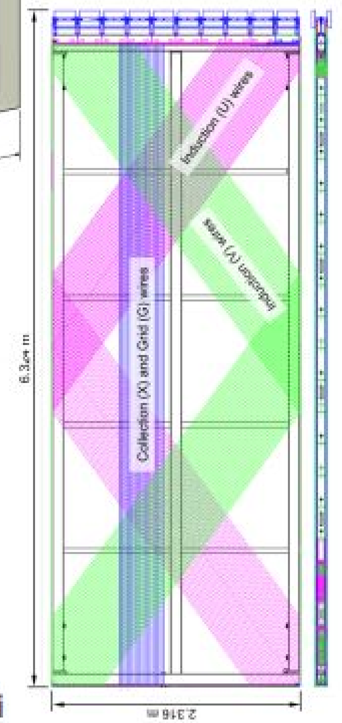


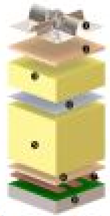




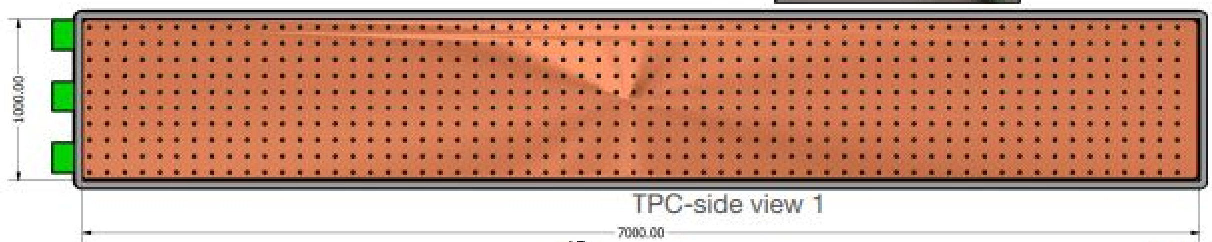


DUNE APA for scale only





Membrane Cryostat Insulation



TPC-side view 1

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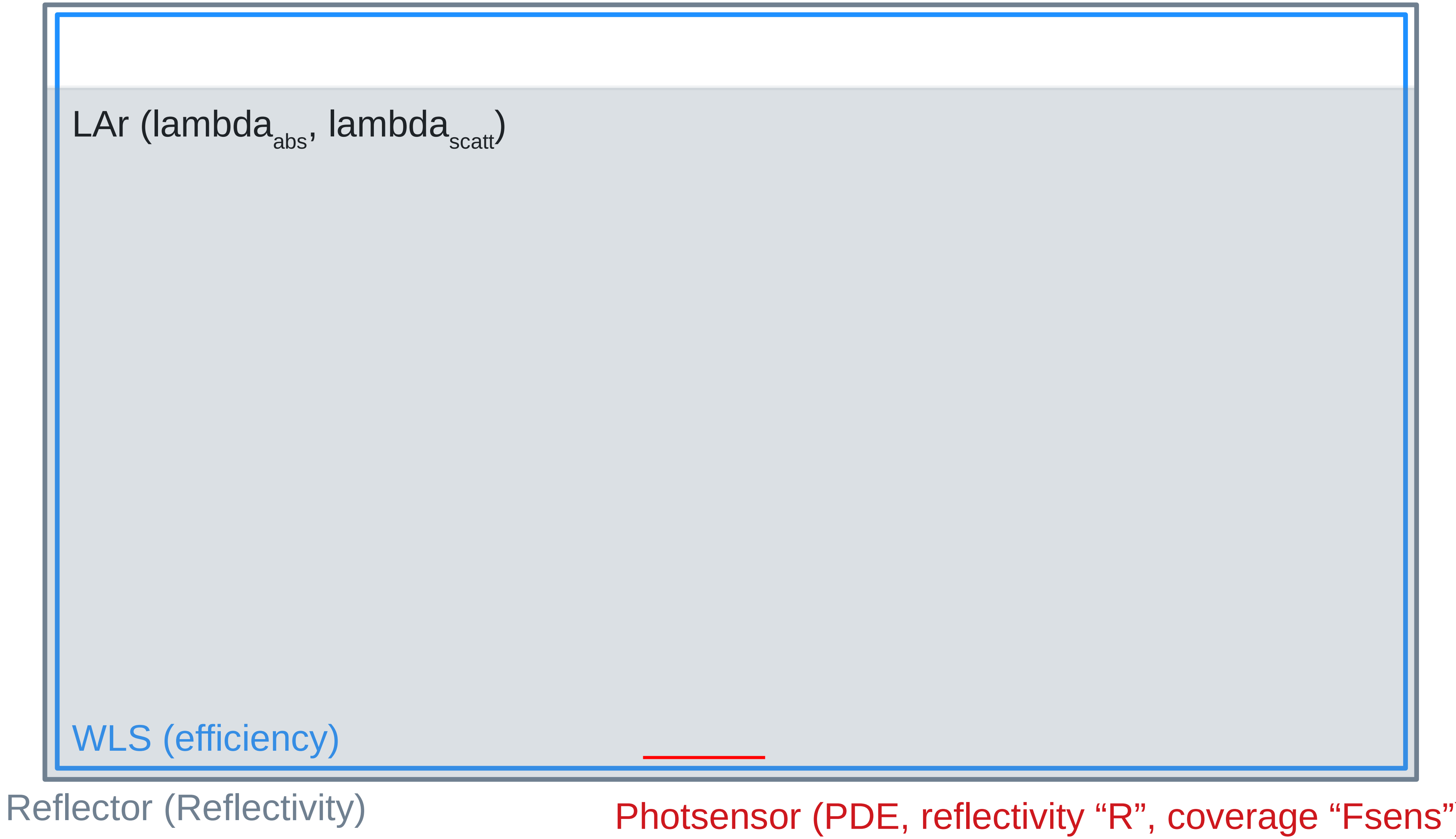
Yichen Li

Basic scheme



$$LY = 40\ [\mathrm{ph/keV}] \cdot PDE\ [\mathrm{pe/ph}] \cdot WLSE \cdot \frac{F_{sens} \cdot FF \cdot (1 - R_{sens})}{1 - (F_{sens} \cdot R_{sens} + (1 - F_{sens}) \cdot R_{wall})}$$

To first order light yield can be modelled analytically with high accuracy. For large detectors, Fsens tends to be small -> this makes the system very sensitive to average wall reflectivity.

https://arxiv.org/abs/1110.6370

Blue sensitive SiPMs: DCR and PDE

8 x 8 array of Hamamatsu S14160

Nuclear Inst. and Methods in Physics Research, A 980 (2020) 164488

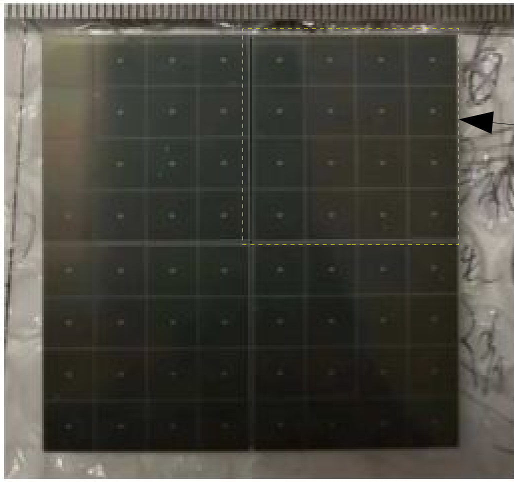
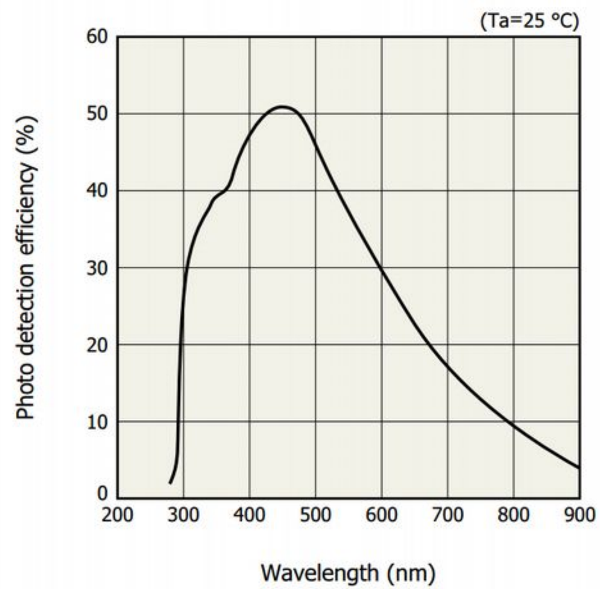


Fig. 6. The picture of the SiPM array used in the test.

- Suited for cryogenic operation
- 1kEUR per 4 x 4 piece (I have one)
- Blue sensitive



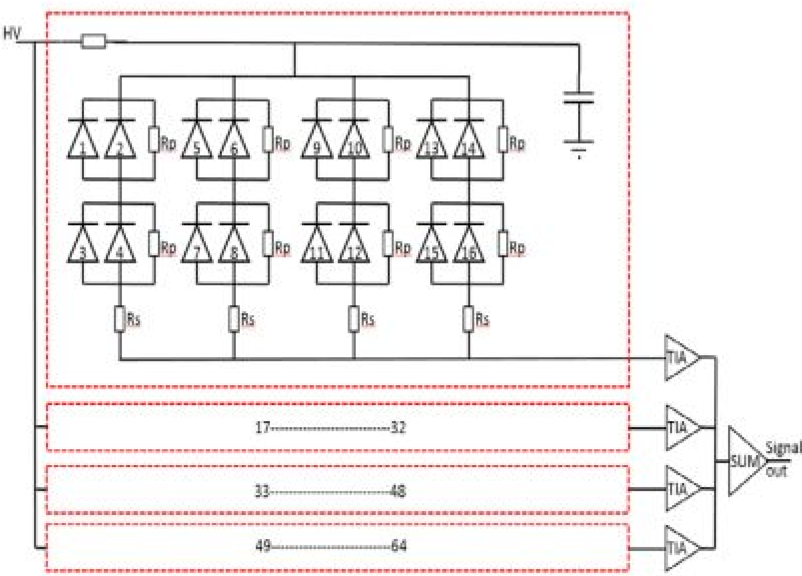


Fig. 7. The schematic diagram of the readout board.

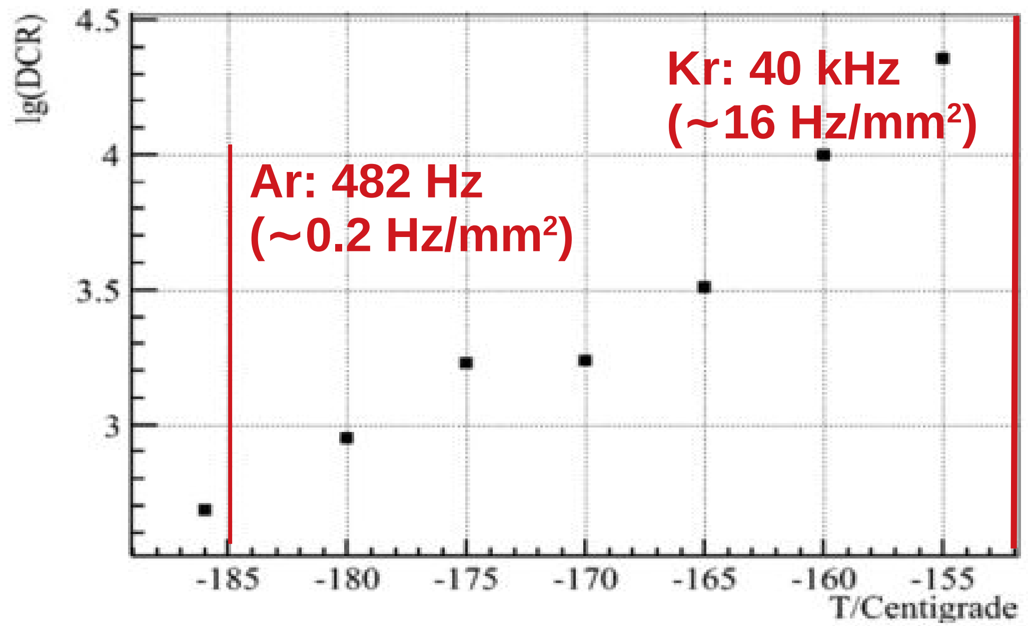


Fig. 13. The measured DCR for the SiPM at different temperature. The threshold is set to ~0.5 p.e. and the over voltage is ~5 V.

https://arxiv.org/abs/1911.01378

VUV sensitive SiPMs

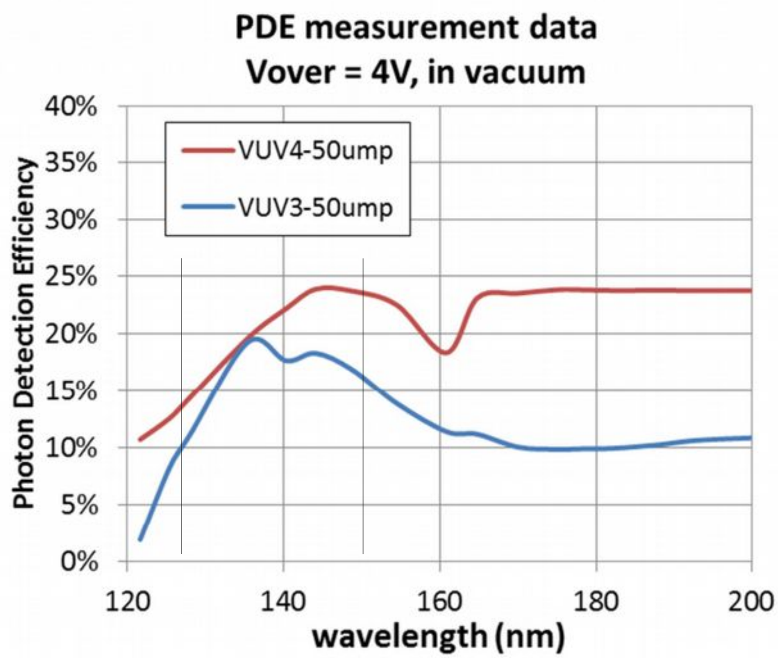
Hamamatsu S13370-6050CN (aka VUV4)

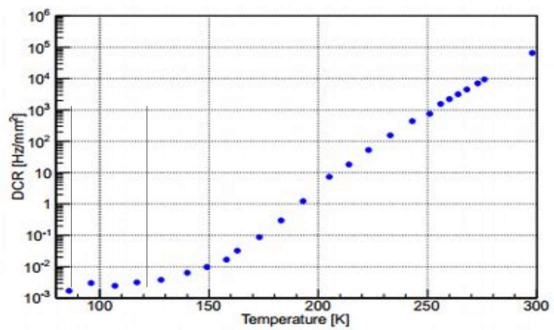
DCR:

- Ar and Kr: ~0.003 Hz/mm^2

PDE:

- Ar: 12%
- Kr: 24%





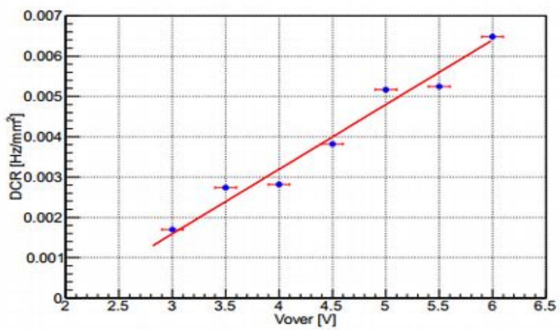


Figure 12: Left: Change of DCR with temperatures, V_{over} is set to 4 V during the test, errors of the X-axis are the temperature accuracy of ± 1 K, errors of the Y-axis are statistical only. Right: Change of DCR with V_{over} at 87 K, the errors shown in the X-axis are caused by the temperature variation and errors in the Y-axis are statistical only.

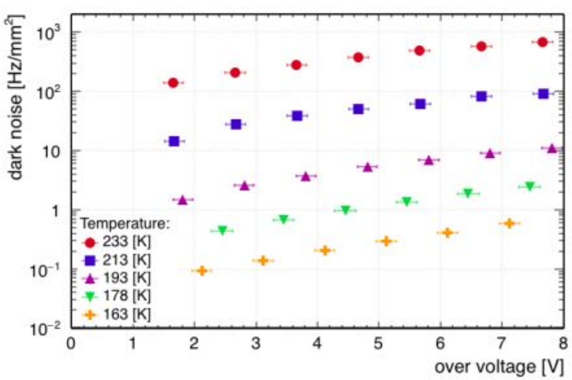


Figure 12: Dark Noise (DN) rate normalized by the SiPM photon sensitive area as a function of the applied over voltage for different SiPM temperatures.

https://arxiv.org/abs/2101.04295

https://arxiv.org/abs/1903.03663

Reflectivity

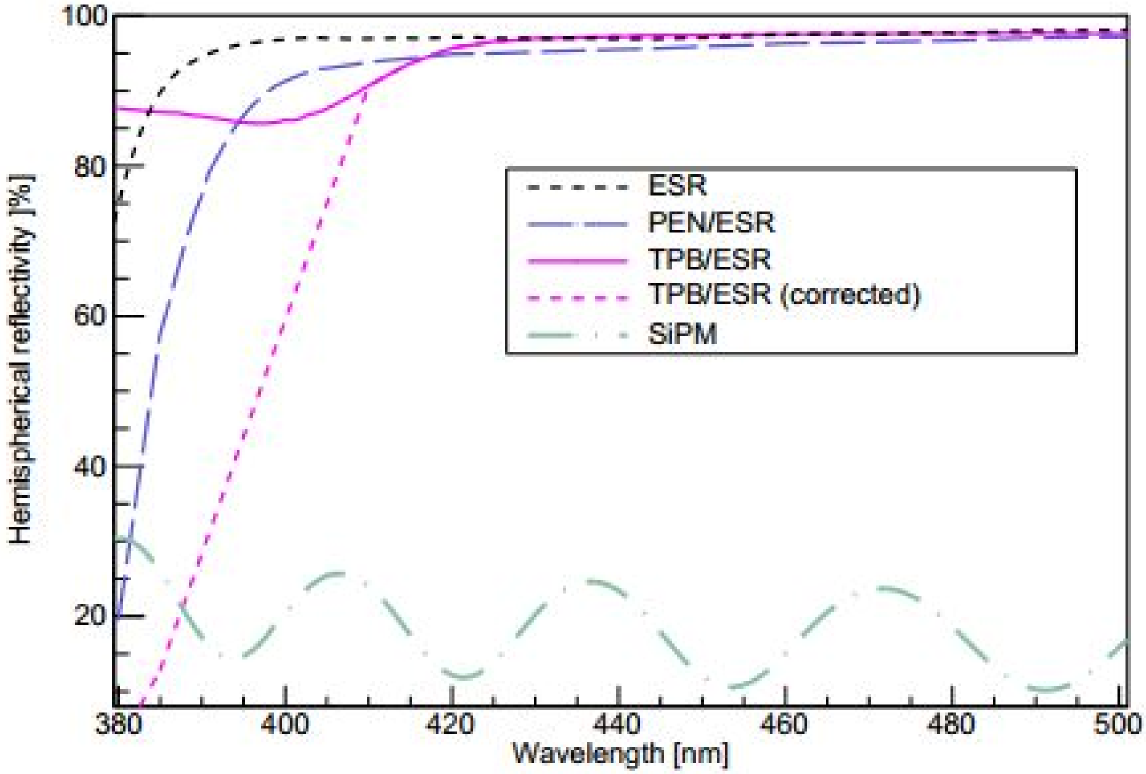
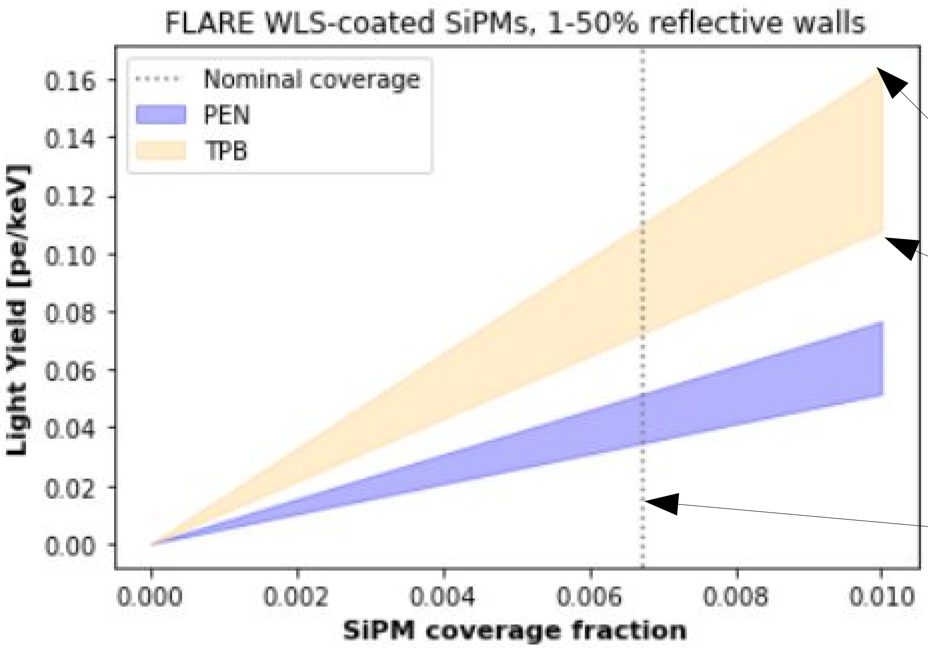


Fig. 7 Hemispherical reflectivity measured at 7° angle of incidence with a spectrophotometer equipped with an integrating sphere for: ESR, PEN air-coupled to ESR, TPB evaporated on ESR, TPB evaporated on ESR corrected for the spurious fluorescence component based on [2], and SiPMs (see legend).

Light yield predictions: Ar

Assuming WLS efficiency of 1 for TPB and 0.47 for PEN, **using blue sensitive SiPMs**

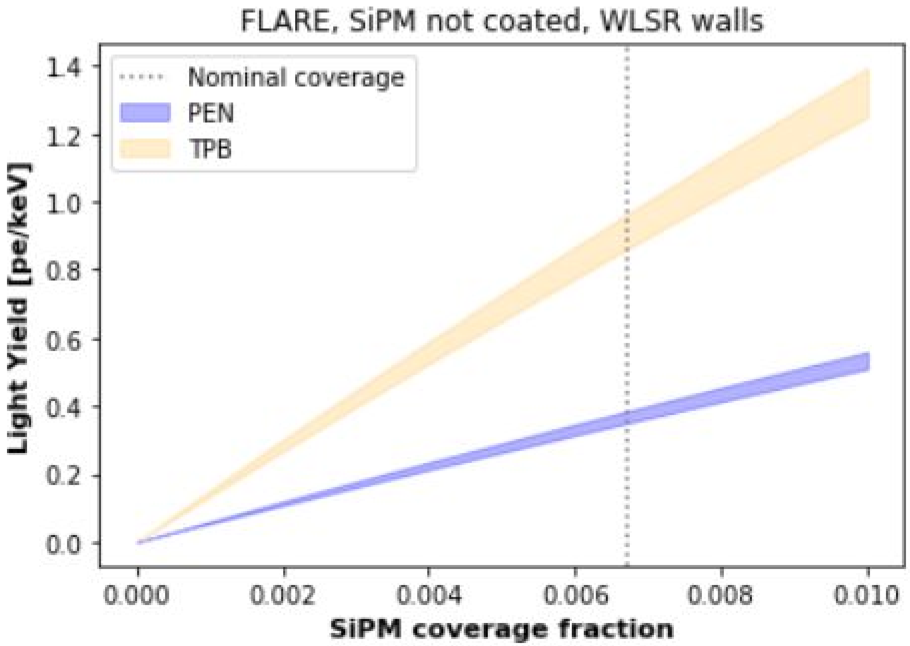


Walls can be:

- 50% reflective (e.g. ESR reflector on APAs only)
- Nearly black
- (not a huge difference in this case)

This is 2800 6mm x 6mm SiPMs on each APA

Low reflectivity configuration:
0.03 – 0.1 pe/keV



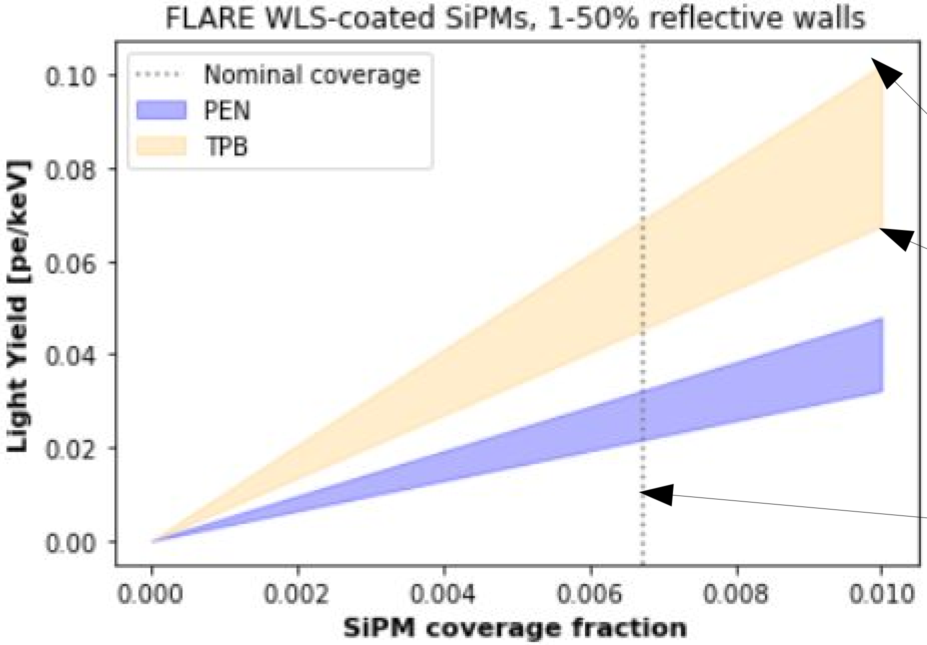
Here all surfaces (both APAs and the inside of the field cage are lined with WLS and ESR reflectors).

(Here SiPMs are not WLS-coated, adding WLS brings modest (<10%) enhancement.)

High reflectivity configuration:
0.3 – 1 pe/keV

Light yield predictions: Kr (i.e. Ar rescaled by 25/40)

Assuming WLS efficiency of 1 for TPB and 0.47 for PEN, **using blue sensitive SiPMs**

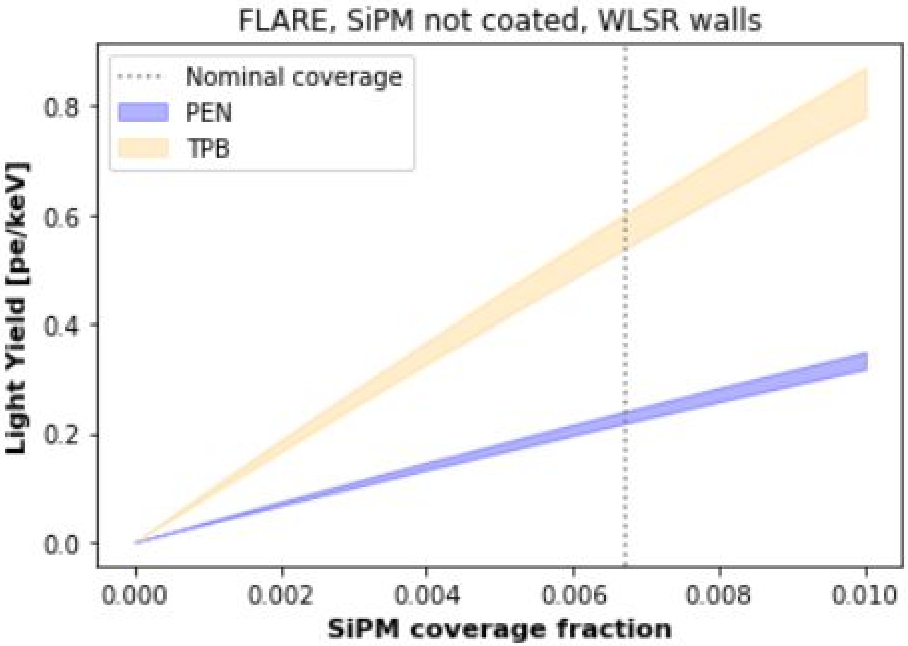


Walls can be:

- 50% reflective (e.g. ESR reflector on APAs only)
- Nearly black
- (not a huge difference in this case)

This is 2800 6mm x 6mm SiPMs on each APA

Low reflectivity configuration:
0.02 – 0.07 pe/keV

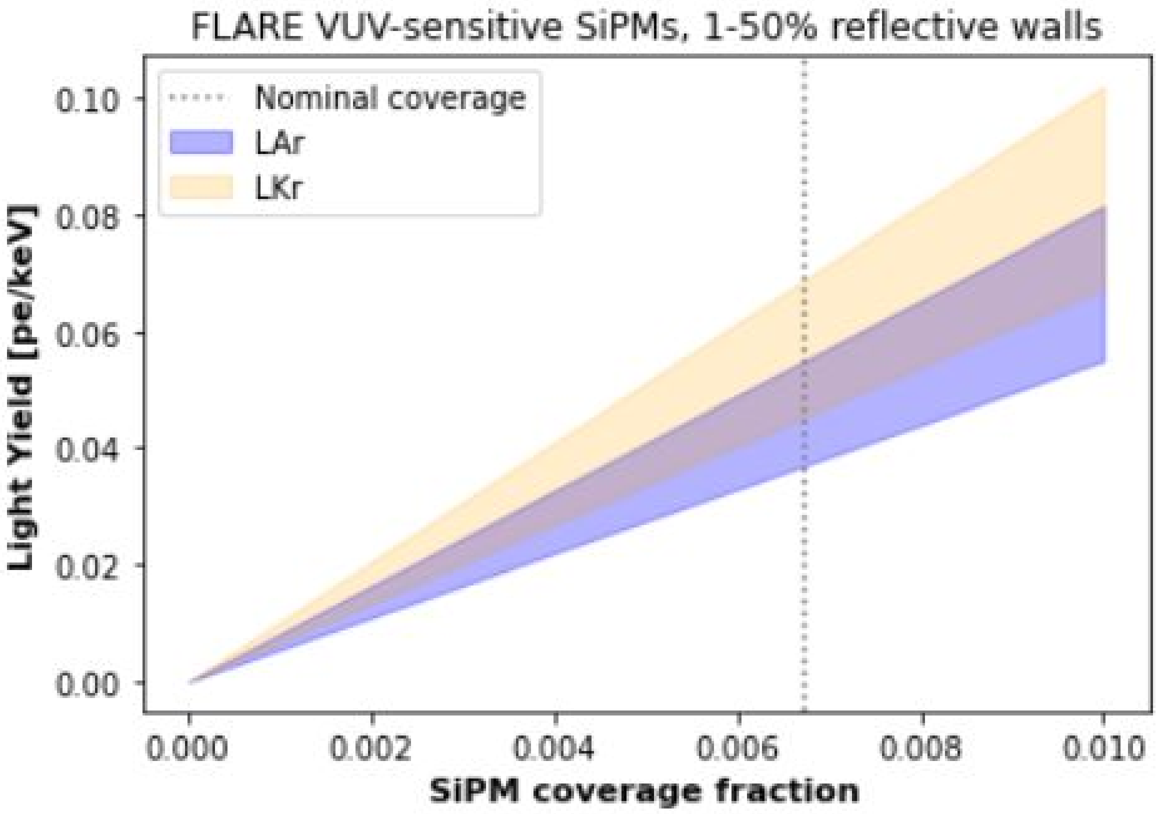


Here all surfaces (both APAs and the inside of the field cage are lined with WLS and ESR reflectors).

(Here SiPMs are not WLS-coated, adding WLS brings modest (<10%) enhancement.)

High reflectivity configuration:
0.2 – 0.6 pe/keV

VUV sensitive SiPMs



Lower scinitillation yield of LKr partly is compensated by higher PDE.

Highly approximate!

Reflectivity of SiPMs can play a significant role – did not treat that rigorously for this plot.

VUV sensitive configuration:
0.03 – 0.07 pe/keV

(General caveats for the analytic model estimates:
- This is all highly preliminary
- For blue sensitive SiPMs used FBK PDE curve which is similar to Hamamatsu, for VUV rescaled by a factor of 0.5 for Kr and 0.25 for Ar
- I'm ignoring the scintillation yield reduction with E-field, which is a ~20% effect for LAr)

DCR and Ar-39

- From earlier slides LY: 0.02-1 pe/keV
- DCR seems managable in all cases:
  - 0.003-0.2 Hz/mm^2 for 0.2 m^2 of total SiPM surface area
  - (~16 Hz/mm^2 for blue SiPMs in Kr – but for Kr the acquisition window can be 100 times shorter)
  - Translates to 0.6-40 kHz (single pe) over the entire detector
  - For comparison:
    - In DEAP-3600 we achieved an ~40pe threshold with 127 kHz DCR (255 PMTs, 0.5 kHz each); not limited by DCR
    - This translates to 40 keV - 2 MeV for nominal coverage in FLARE, LY-dependent
- Ar-39 beta decay (endpoint 565 keV) rate:
  - 1 Bq/kg => 10 kHz of events for 10 tonnes of LAr
  - Each event results in 6 – 282 pe on average, LY-dependent
  - More significant than DCR
- Similar reasoning for Kr-85 in Lkr (not sure about the specific activity)

Cost estimates

- SiPMs:
  - 300 kEUR (25 mm x 25 mm array) - 600 kEUR (single chips)
- Front end boards: .... **wild guess for now** 50-100 kEur ?
- Cables and feedthroughs: ~300 Eur per channel
  - ~~4160 ch (2080*2) : 1.2 MEur~~
  - 260 ch (2080*2/16) : 80 kEur
  - 65 ch (2080*2/64) : 20 kEur
- Digitizers
  - VX2740B, 64 channel, 125 MS/s: ~18 kEur per card
    - ~~4160 ch (2080*2) : 1.2 MEur~~
    - 260 ch (2080*2/16) : 90 kEur
    - 65 ch (2080*2/64) : 36 kEur
- Power supplies
  - Mainframe CAEN SY4527LC: 6 kEur
  - CAEN A1539B, 32-ch, 100V, 20 mA, 6 kEur per card
    - ~~4160 ch (2080*2) : 400 kEur~~
    - 260 ch (2080*2/16) : 66 kEur
    - 65 ch (2080*2/64) : 22 kEur
- Reflectors + WLS
  - 10 kEur (if with PEN)

Total: ~650 kEur

Alternative readout electronics

- Main question - how important is the granularity:
  - Can we live with 25mm x 25 mm arrays and 20 cm spacing?

- If not better options suited for large number of channels:

https://www.caen.it/subfamilies/fers-5200/

/ Products / Modular Pulse Processing Electronics / Read Out Systems / FERS-5200

FERS-5200

Front-End Readout System

Request info | Brochure

- Platform for the readout of **large arrays of detectors** (SiPM, MA-PMTs, Gas Tubes, Si detectors, ...)
- Based on a complete family of Front-End cards (FERS units) + Concentrator Board
- **Scalability**: from a single **standalone** FERS unit for prototyping to many thousands of channels, with simple tree network structure.
- **Flexibility**: FERS units can be tailored to specific detectors and applications
- A5202 Front-End unit for SiPM readout with Weeroc CITIROC chip
- **Modularity**: multiple FERS units can be managed via a single Concentrator board DT5215 (max. 8192 channels for A5202)
- **Concentrator Board**: multiple Concentrator Boards can be synchronized to build extremely large readout systems
- **Compact size**: high-channel density FERS units are very efficient in terms of

Summary

- Analytic model predicts LY between:
  - 0.02-0.06 pe/keV (low reflectivity configuration or VUV SiPMs)
  - or order of magnitude higher with WLS and full reflector coverage
- DCR managable for all cases, but Ar-39 rate will affect how we trigger
- First very rough cost estimate: 650 kEur

Backup

3M reflectors

- The usual candidate: Vikuiti Enhanced Specular Reflector (ESR) – from the line of VM2000 and VM3000 reflectors

Nominal film properties

Film properties	Vikuiti™ ESR Film
Reflectance	>98%
Physical Characteristics	
• Thickness (microns)	65µm (2.6 mils)
• Shrinkage (15 minutes @ 150°C)	<1%
• Specific Gravity	1.29

The technical data for the products are typical, based on information accumulated during their life, and are not to be used in the generation of purchase specifications which define property limits rather than typical performance.

Product Size Offering

- Custom Sizes—Converted to Customer Sizes
- Product Kits—30 Sheets 11″ x 11″

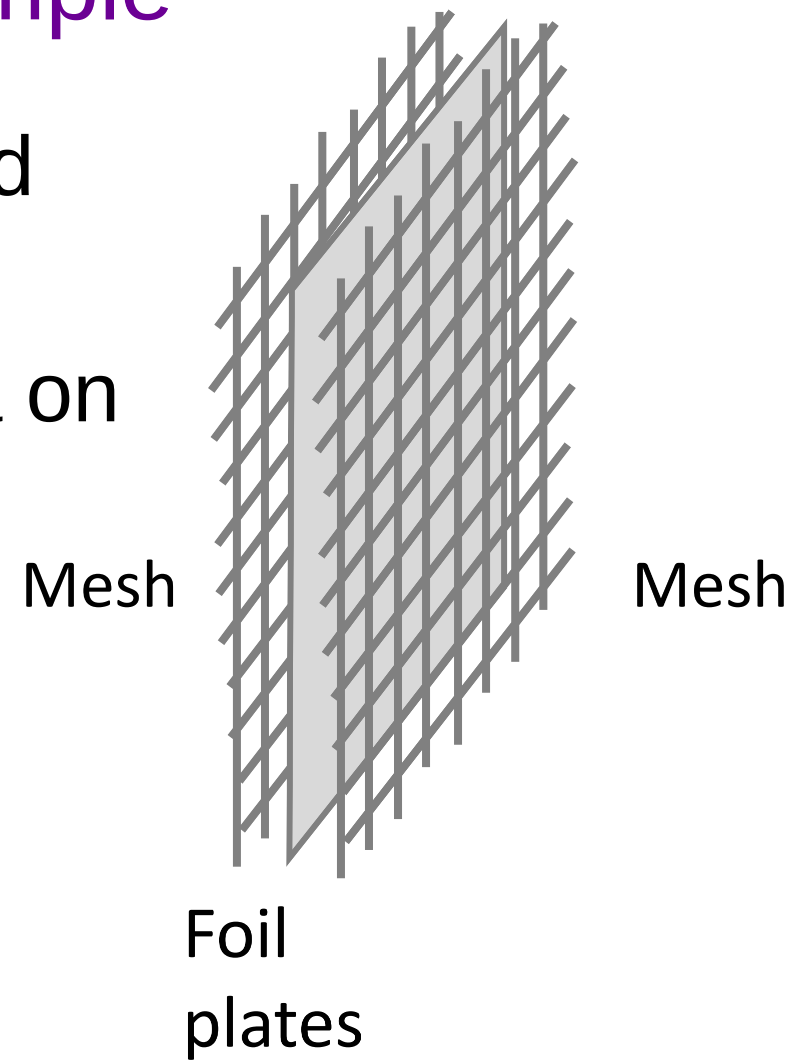
Pricing:

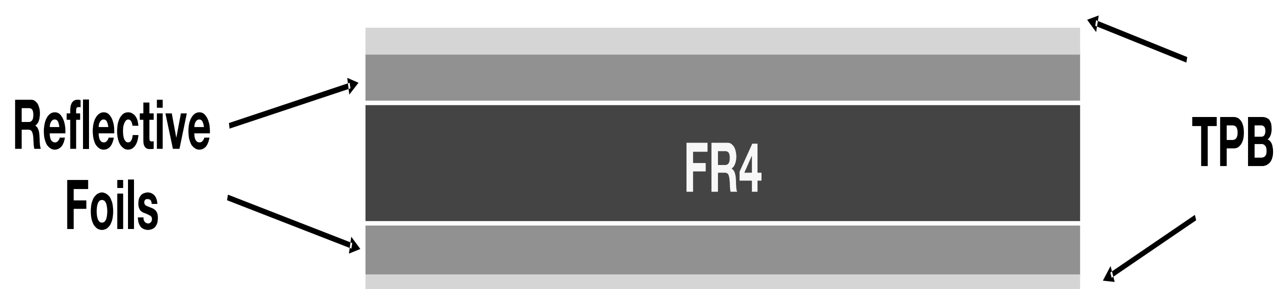
- hundred 17x17” sheets (0.19 m^2) = 5.2 kEUR
- **~281 EUR per m^2**
- Will buy a large amount for us in DarkSide
- Cheaper products exist

https://www.digikey.ca/product-detail/en/3m/98-0440-2750-0/3M162763-ND/4021339

SBND Example

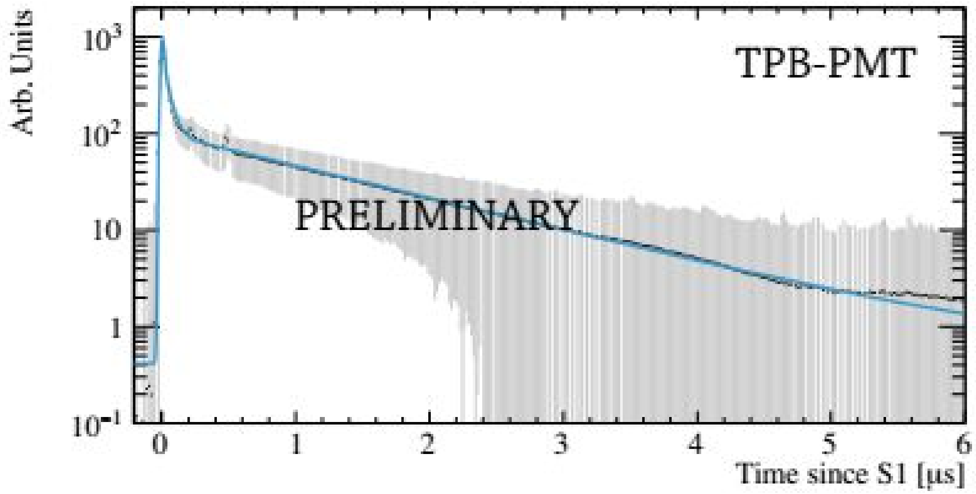
- SBND will run with TPB-coated reflector foils on the cathode.
- Required coating 38m^2 of area on double sided plates.
- Will be sandwiched inside of metal mesh in the detector to avoid any effects on drift field.

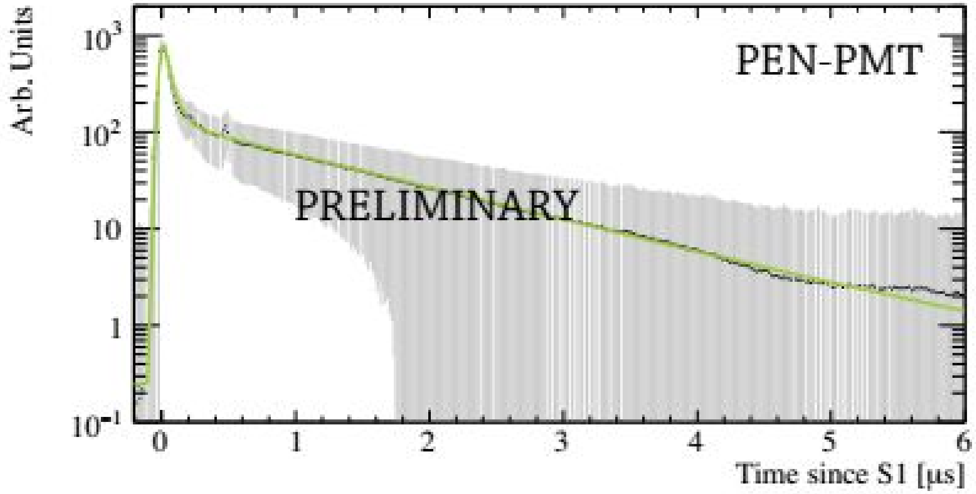




Preliminary averaged waveforms

No drift field applied





- First average waveform in LAr from PMT self trigger events - LAr purification system not yet activated
- Fitted with a gaussian convoluted with 3 exponentials [fast, intermediate and slow components]
- Preliminary fit results suggest:
  - τ_{int} ~ 50-60 ns
  - τ_{slow} ~ 1280 ns

  for both WLS technology

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L. Zambelli - LIDINE 2019 - LDS in protoDUNE-DP