Light detection for Liquid Argon experiments

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Astroparticle Physics - XXIV cycle, DarkSide Project

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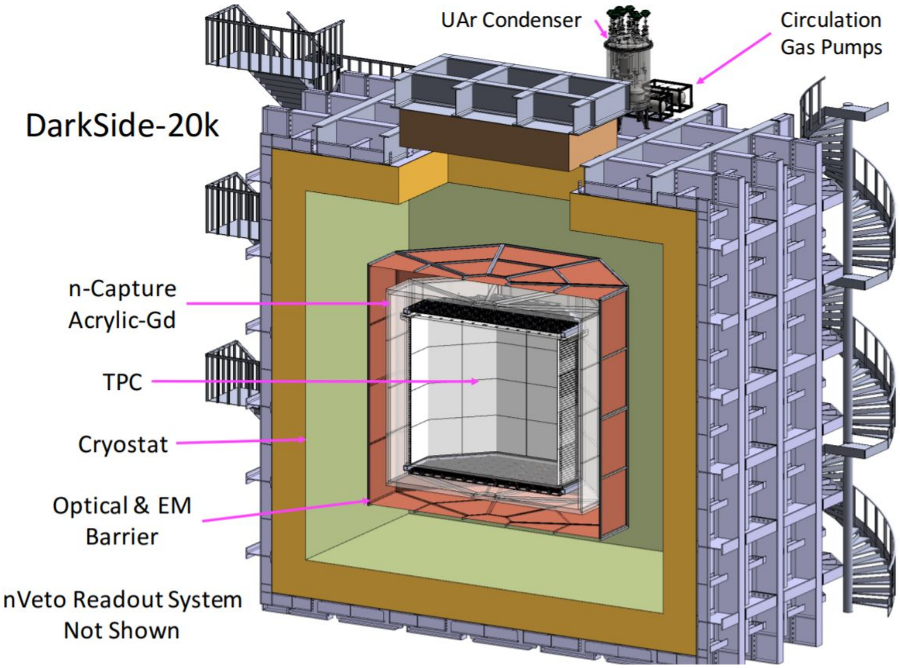
Outline

- Motivation: Maximization of Light Yield
- Investigation of detector geometries
  - Detector setup
  - STAR cryogenic setup
  - Characterization of energy response
  - Gross light yield & net light yield
- Investigation of wavelength shifters
  - 2PAC system
  - Analysis results
  - Estimation of relative WLSE of PEN
- Conclusions
- Work in progress & future plans

DarkSide-20k

- Dual phase TPC filled with 50 tons of liquid Argon (depleted in the short-lived ^{39}Ar component).
- Silicon Photomultipliers will be used as photodetectors with total instrumented surface of ~ 28 m^2.
- It will search for high-mass WIMP DM particles which will produce nuclear recoils in the energy range of (30 - 200) keV_{nr}.
- Scintillation photons emitted, following a particle interaction in the active volume, form the signal for the photodetectors.



Detector sensitivity & light yield

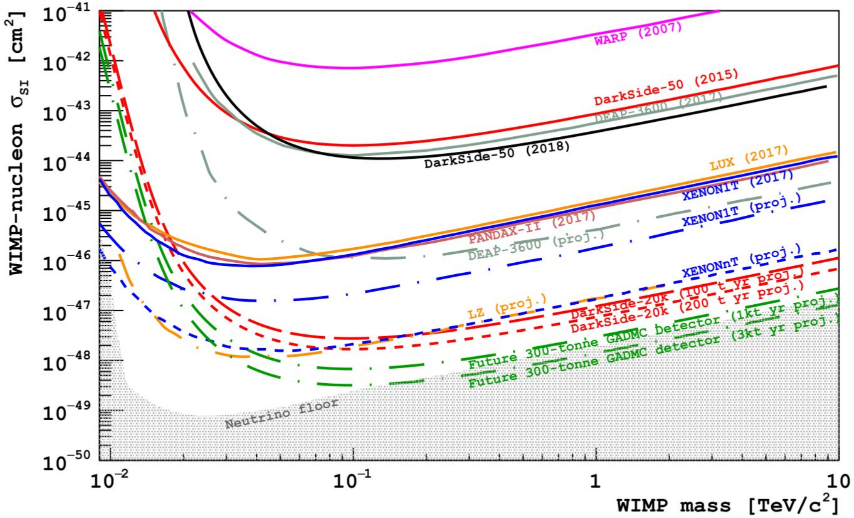
Projected sensitivity to spin-independent interactions is around 10^{-47} cm^2 for a WIMP mass of 1 TeV.

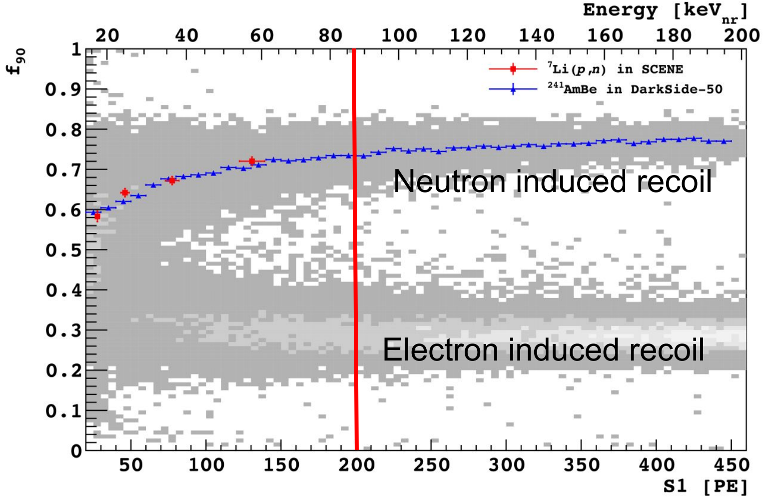
This projected sensitivity is based on the requirement of observing a light yield of at least 10 pe/keV.

System observable: Number of detected photoelectrons

By maximizing the number of detected photoelectrons (or equivalently, the detector light yield):

- Increased particle discrimination capabilities
- Achieve lower-energy threshold levels





Light Yield

LY ∝ Scintillation yield (SY) · Photon Detection Efficiency (PDE) · Light Collection Efficiency (LCE)

- SY of LAr ≈ 40 photons/keV (experimental observations)
- PDE of the SiPMs ≈ 50% @ room temperature for blue light

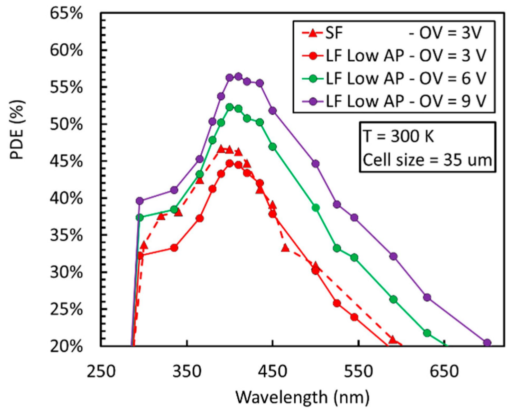
❖ Factors contributing to the LCE of the system:

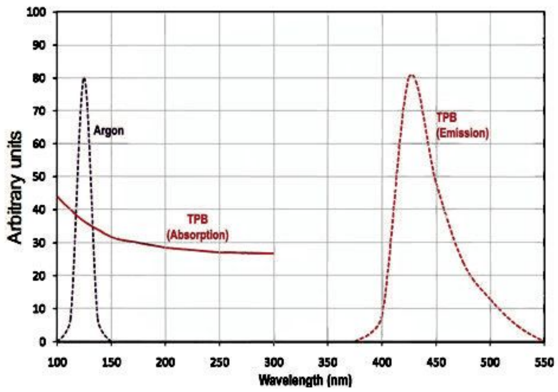
  ➢ Detector geometry

  ➢ Reflectivity of inner surfaces

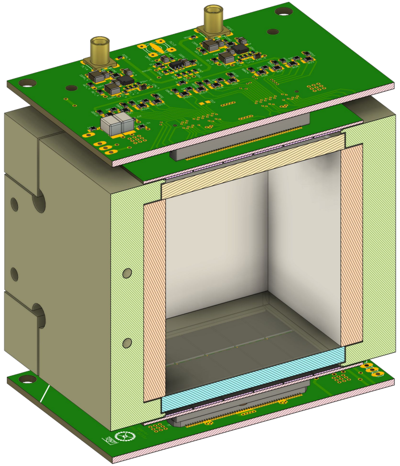
  ➢ Wavelength shifting efficiency of wavelength shifters

- **Therefore, there's always a scope for improving the light collection efficiency of the detector.**

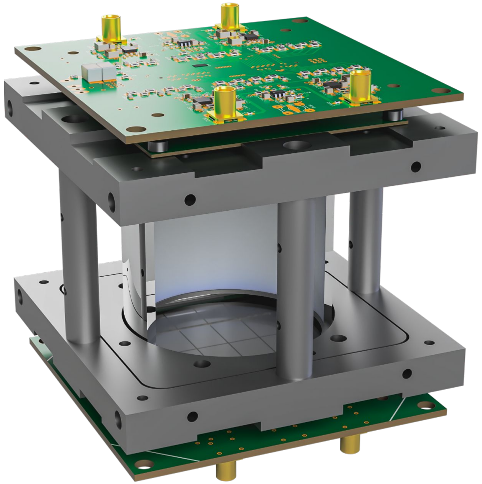




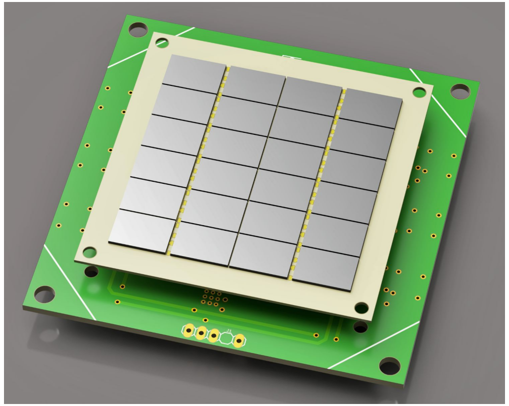
Detector setup



Cubic chamber



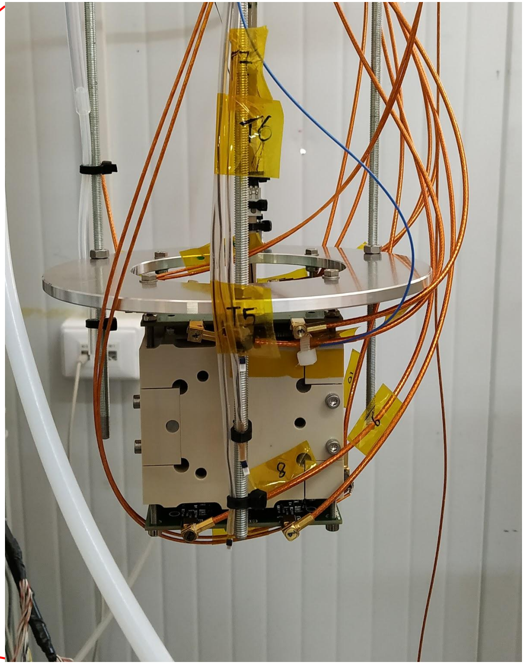
Cylindrical chamber



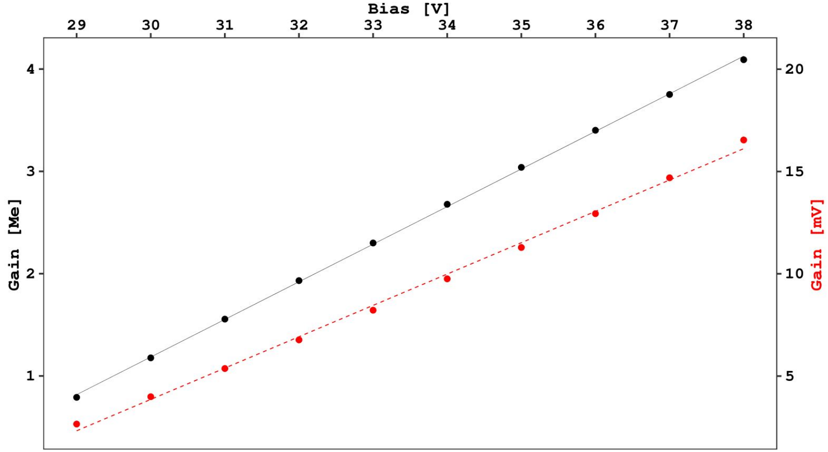
SiPM array

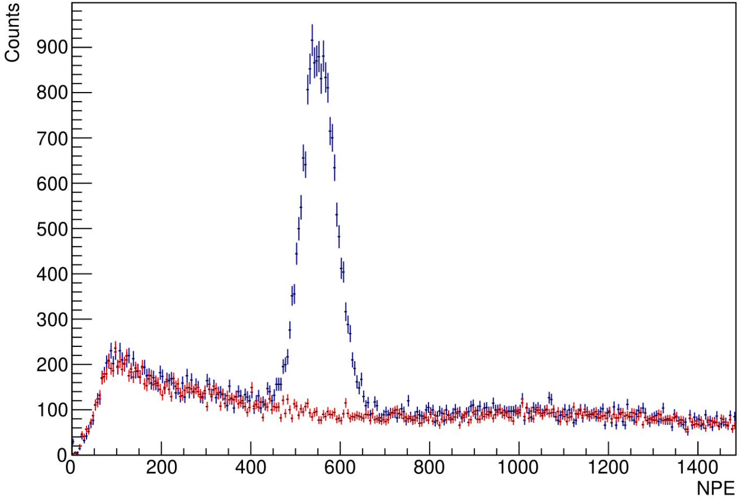
- Inner surfaces of side walls lined with reflector materials
- Fused silica windows installed on the top and bottom surfaces
- All internal surfaces have wavelength shifter coated/attached
- Wavelength shifted photons detected by 2 SiPM arrays at the top and the bottom of the chamber

SiPM Test setup in ARgon (STAR)

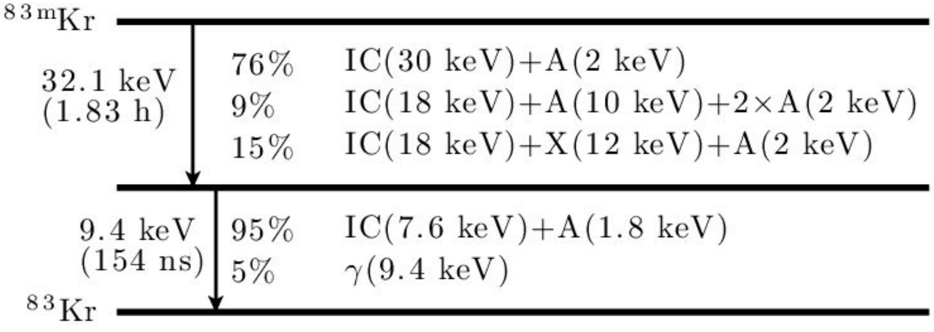


Characterization of detector energy response





$$^{241}_{95}\mathrm{Am} \xrightarrow{432.2\mathrm{y}} {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\alpha^{2+} + \gamma 59.5409\mathrm{keV}$$



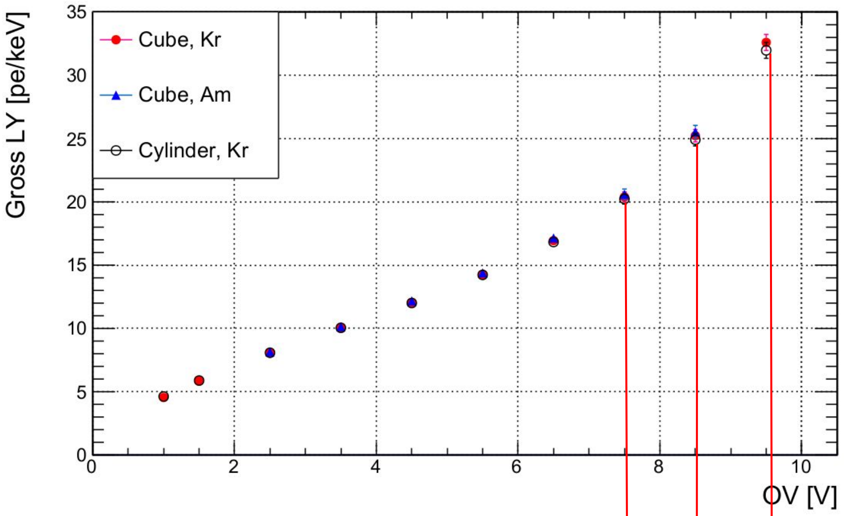
Gross light yield vs. OV

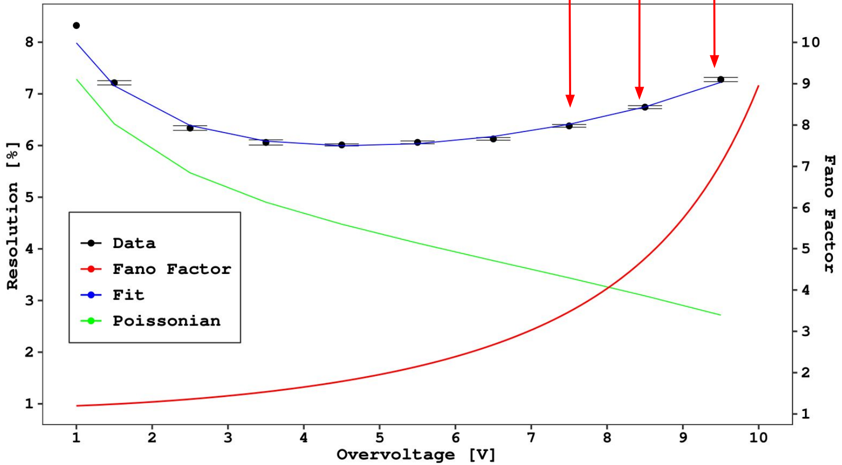
The gross light yield (LY_G) is given by the ratio of the number of detected photoelectrons and the energy deposited in the medium by the source in use.

The LY_G increases from 5 pe/keV at 1.5 VoV to 32 pe/keV at 9.5 VoV. However, the energy resolution, although found to improve initially, worsens at higher OV values.

This increasing trend of the LY_G is not only due to the change in the PDE, but also because of change in noise contributions, both increasing with the OV.

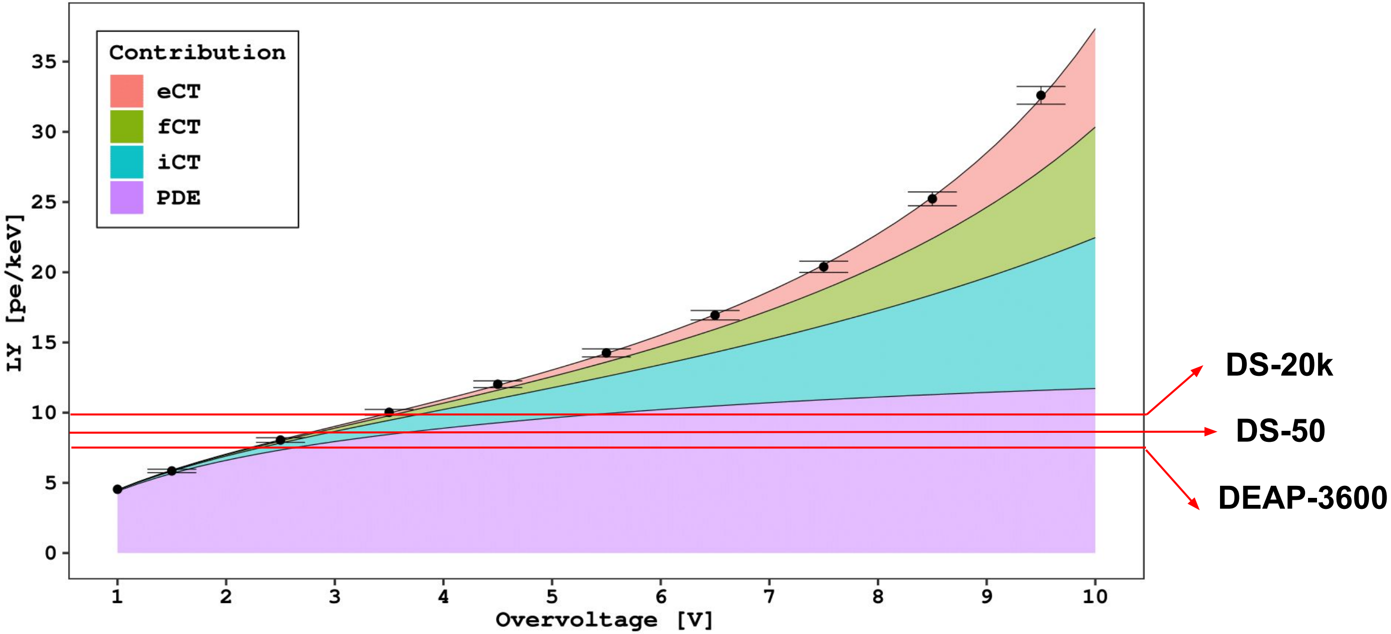
It is essential to characterize noise contributions in order to estimate the true light yield of the system.





Net light yield and optical crosstalk components

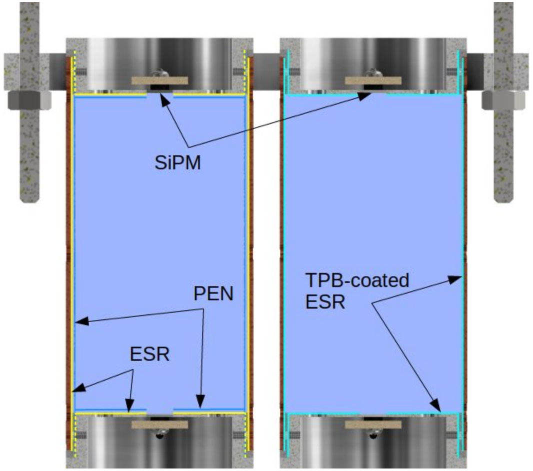
An analytical model was developed to model the contributions of crosstalk components to the gross light yield of the system:

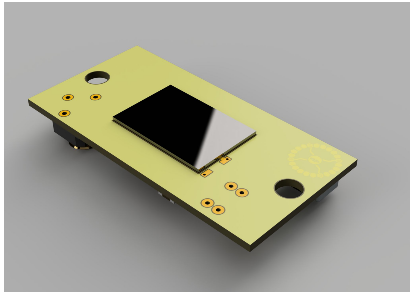


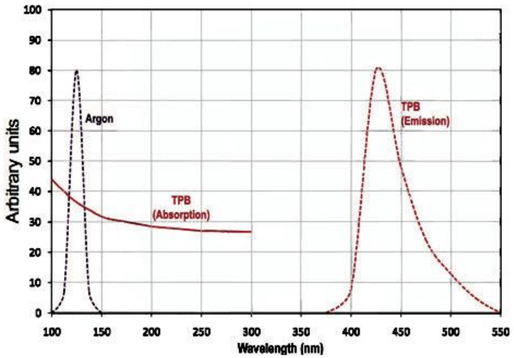
The net LY was found to be ~12 pe/keV at the maximum operating OV, which is one of the highest LY values obtained in a LAr setup with a SiPM-based readout.

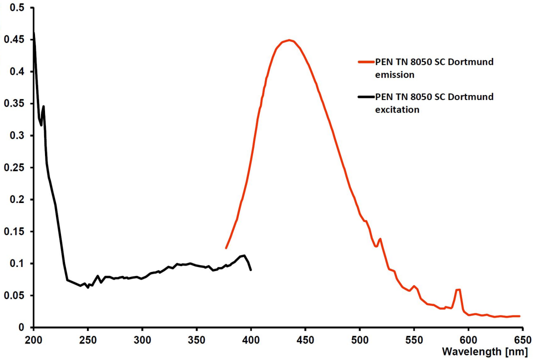
The 2PAC system

- TetraPhenyl Butadiene (TPB) is the standard WLS used in all LAr detectors owing to its high wavelength shifting efficiency (WLSE).
- TPB is coated on detector surfaces through a vacuum evaporation process which is cumbersome to scale to large surface areas.
- PolyEthylene Naphthalate (PEN), which is a polymeric film available in large footprints, has been proposed as an alternative to TPB.
- This work makes a direct comparison of the LY obtained in two identical LAr detectors, employing either PEN or TPB as their WLS.



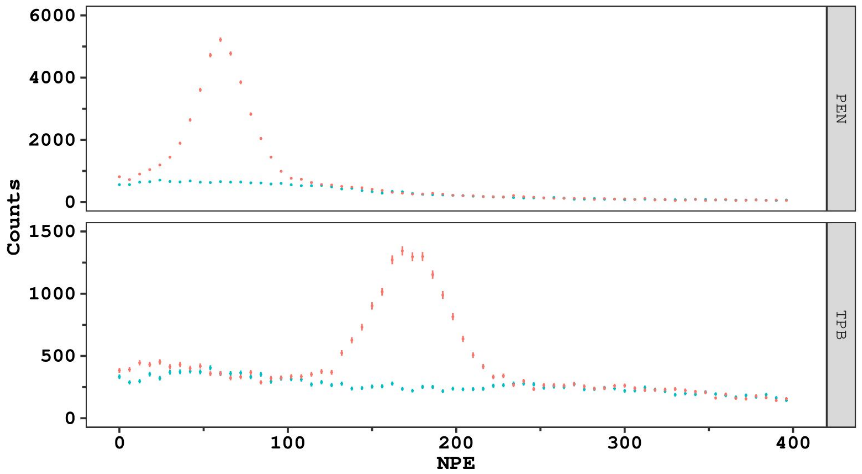


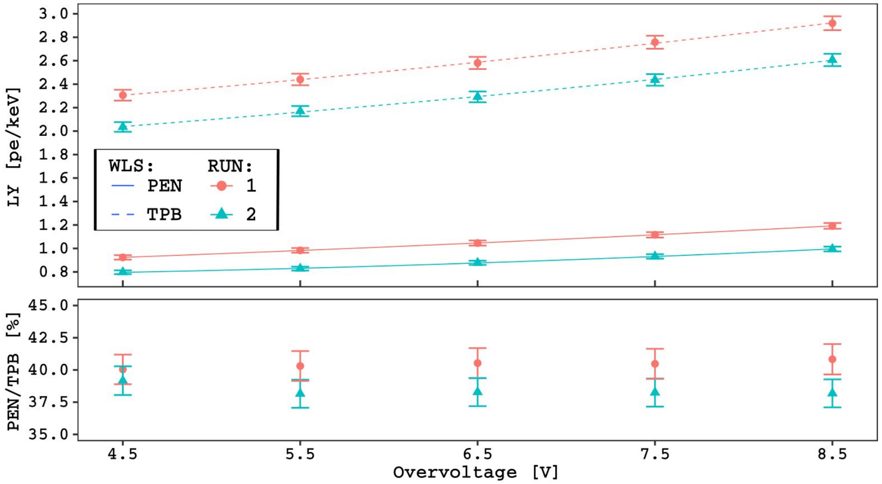




Analysis

- Both detectors were operated over a range of OVs, data was collected at each point and then analyzed to estimate the LY_G of both detectors.
- Two detector runs carried out to check the consistency of PDE of SiPMs and to validate the reproducibility of results.
- The correlated noises were estimated and subtracted from the LY_G to estimate the net LY of the system.
- The weighted average of the ratio of the LY of the PEN chamber to that of the TPB chamber, from all over-voltages, was found to be 39.4 ± 0.4(stat) ± 1.9(sys) %.





Paper Submitted to EPJ C: *"Direct comparison of PEN and TPB wavelength shifters in a liquid argon detector"*
https://arxiv.org/abs/2106.15506

Estimation of relative WLSE of PEN

$$LY \propto LCE \propto \begin{cases} \text{WLSE of WLS} \\ \text{Effective reflectivity of ESR/WLS} \end{cases}$$

A MC model was developed to decouple these two effects.

$$WLSE_{PEN} / WLSE_{TPB} = \frac{\left(LY_{PEN}^{exp.} / LY_{TPB}^{exp.} \right)}{\left(LY_{PEN}^{sim.} / LY_{TPB}^{sim.} \right)}$$

Using the above expression, the WLSE of PEN relative to that of TPB was estimated to be (47.2 ± 5.7)%, where the uncertainty is dominated by the systematic error.

This result for the preselected PEN foil is significantly higher than the previously projected results for other PEN grades, thus motivating its use as an alternative WLS in large LAr detectors.

Conclusions

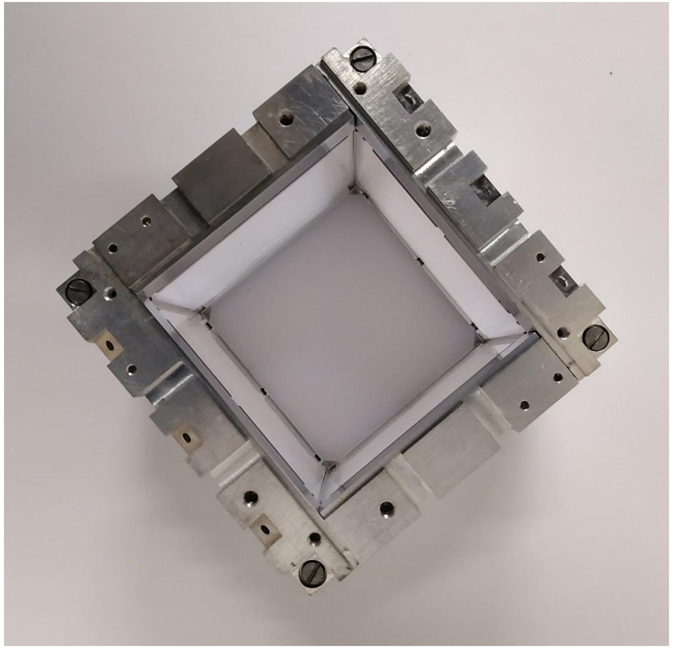
- Two detector geometries, a cubic chamber and a cylindrical chamber, were designed and utilized the same reflector and WLS materials.
- The gross LY obtained with both geometries was estimated to be ~32 pe/keV at the maximum operating OV. However, after removing the contributions of different noise sources, the net LY was estimated to be ~12 pe/keV.
- The 2PAC system was developed for comparing the performances of PEN and TPB WLS.
- The WLSE of PEN relative to that of TPB was found to be (47.2 ± 5.7) %
- This is a significant result which motivates the use of PEN as an alternative WLS in large-scale future LAr detectors.

Work in progress

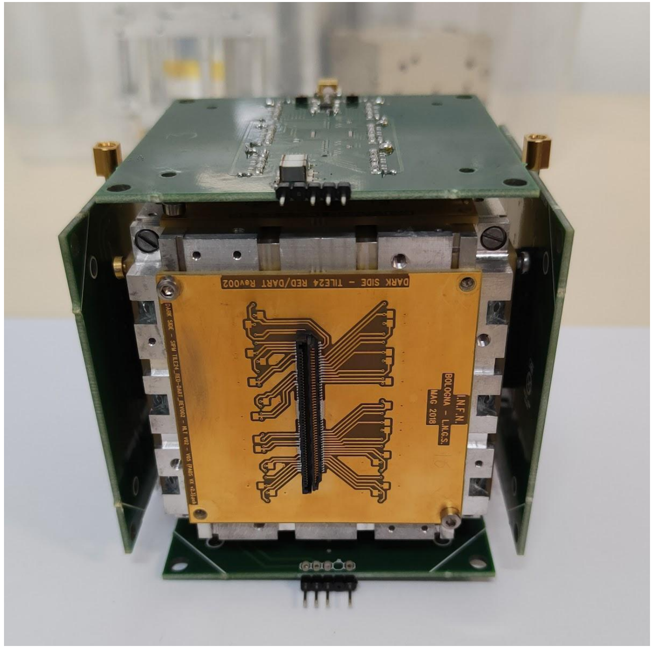
&

Future plans

The 4-pi detector



TPB coated fused silica windows on all inner faces



SiPM tiles and FEB on all six faces

Thank you!

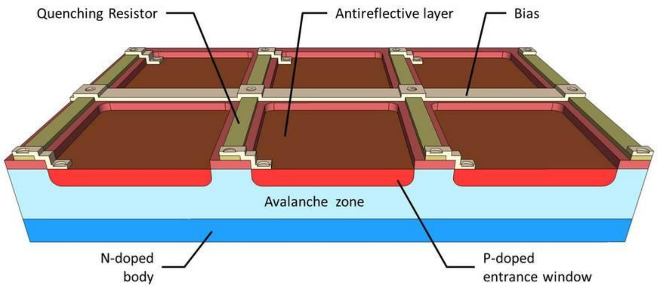
Backup slides

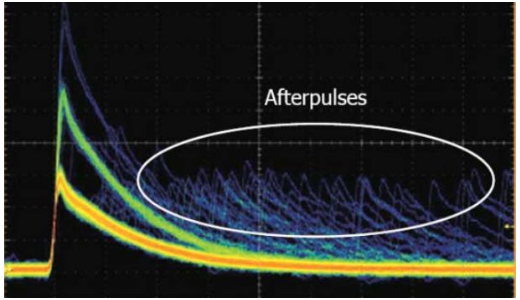
SiPM Noises

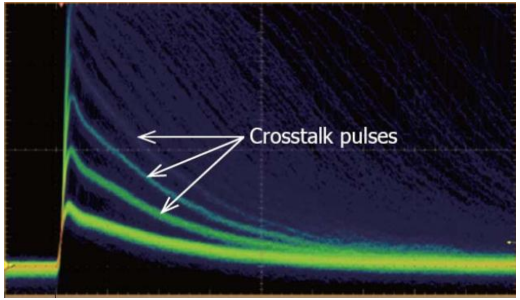
Electrons generated in the active region of a SiPM by thermal agitation can initiate avalanches, thereby producing real photon-like signals. These signals are known as dark counts.

During an avalanche process, some carriers get trapped in the impurity energy levels and are released after short delays (within 1-10 ns). These carriers generate new avalanche pulses which appear with varying delays after the genuine pulses, and are referred to as afterpulses.

A Geiger discharge in a microcell of a SiPM emits isotropically about a few tens of photons that have enough energy to create an e-h pair, These photons can can create an e-h pair in the avalanche region of a nearby microcell, which can then trigger a secondary avalanche, known as crosstalk.



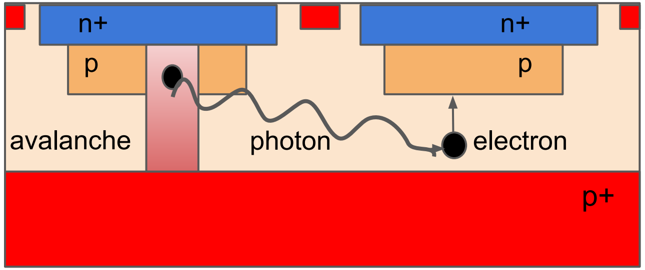




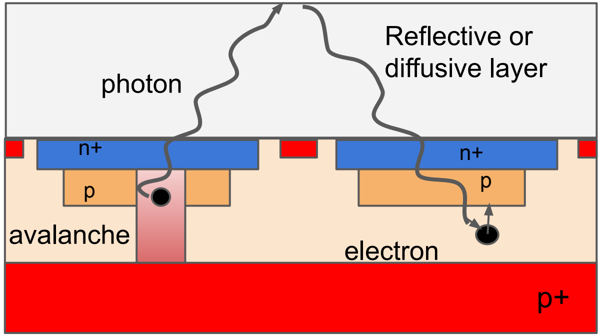
Types of crosstalk

- If the photon remains confined in the Si bulk and generates an avalanche in a neighbouring cell, we speak of internal crosstalk (iCT).
- Alternatively, if the photon escapes the Si bulk and produces an avalanche in other SiPMs of the setup, we speak of external crosstalk (eCT).
- Finally, if the photon is reflected back and absorbed by the same photodetector that emitted it, we speak of feedback crosstalk (fCT).
- The three effects described above, are collectively termed optical crosstalk (oCT).

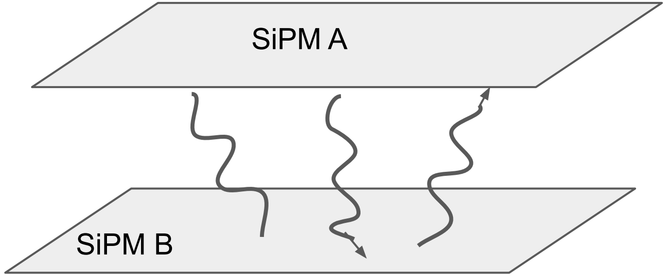
iCT



fCT



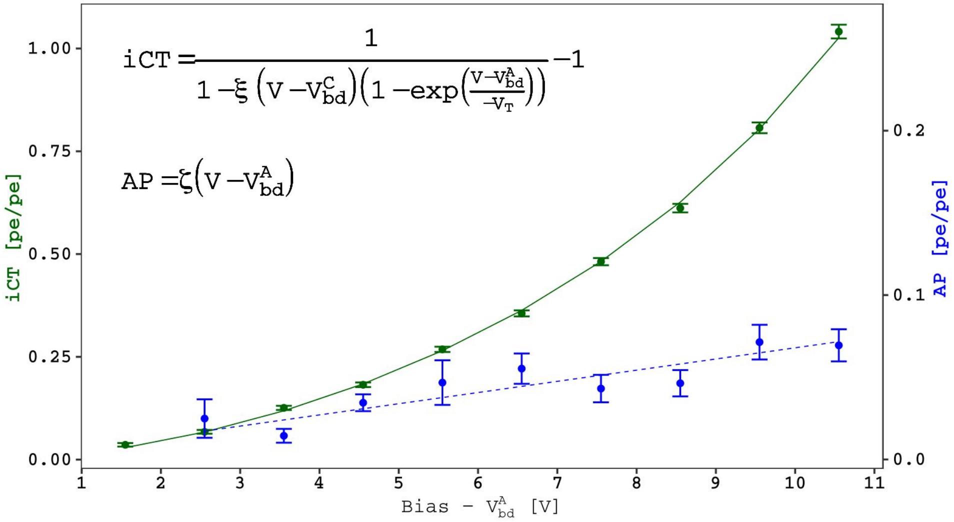
eCT



Dark Counts, internal CrossTalk (iCT) & Afterpulse

Measurements performed with a dedicated liquid nitrogen setup in a stable, low noise environment:

- DCR was found to be less than 20 cps per photosensor at cryogenic temperatures. Therefore, its contribution to the liquid argon scintillation can safely be neglected.
- Using a laser source, the iCT probability was estimated by assuming a Poisson distribution of the laser photons. The results were fitted with a geometric chain model.
- The afterpulse probability was estimated by measuring the relative charge of single photoelectron events in a time window of 7 µs following the primary pulse.

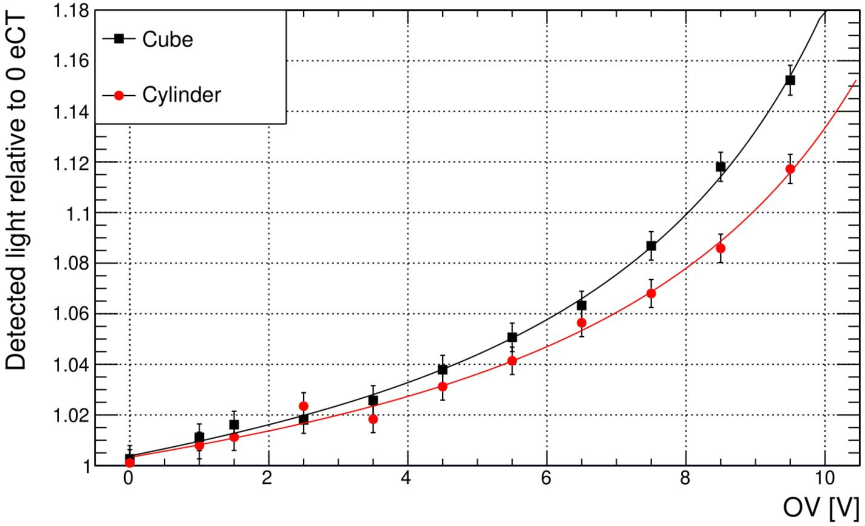


external CrossTalk (eCT) & feedback CrossTalk (fCT)

The eCT was estimated by acquiring data for one photodetector, maintained at a constant bias voltage (target), while the other photodetector (source) was operated at different over-voltages.

The gross LY of the target photodetector was estimated from the mean of the photoelectron spectrum obtained with ^{83m}Kr source after background subtraction.

Most of the fCT happens at the boundaries of the TPB coated fused silica windows in front of the SiPMs: TPB acts as a diffusive layer, reflecting a large part of crosstalk photons.



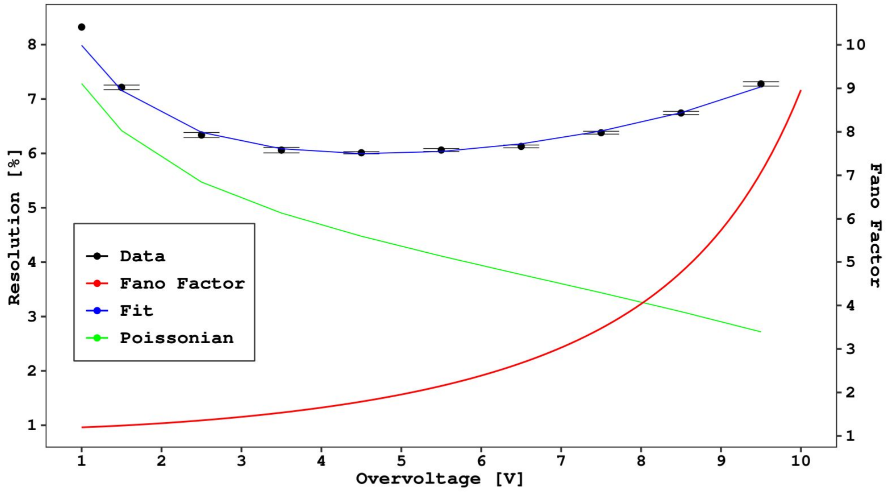
Detector energy resolution

The detector energy resolution is expected to follow a Poisson distribution.

However, the presence of CT noises cause a departure from the Poisson limit. This manifests in the form of a Fano Factor larger than unity.

The analytical model accurately describes the detector resolution at different over-voltages.

- At low OVs, the detector gain is low and the resolution is dominated by electronic noise.
- At high OVs, the resolution is affected by increased contributions from CT noises.



Investigation of wavelength shifters

2PAC MC Simulation

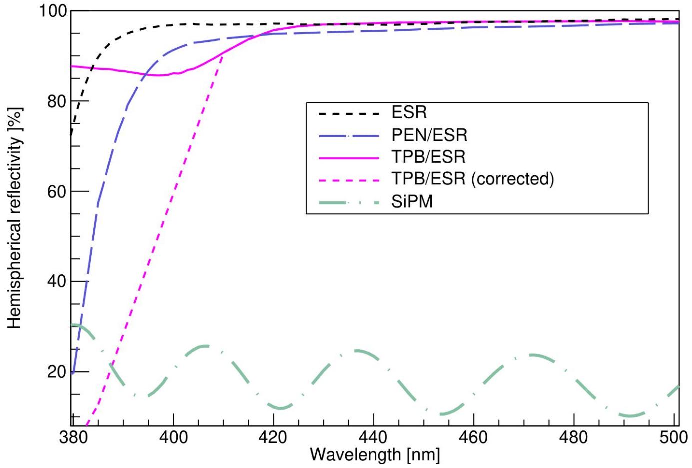
LY = Scint. yield x PDE x Light Collection Efficiency (LCE)

WLS photons undergo multiple reflections before reaching the photodetectors owing to the small SiPM coverage.

Therefore, in addition to the WLSE, LCE also sensitive to the effective reflectivity of the ESR/WLS.

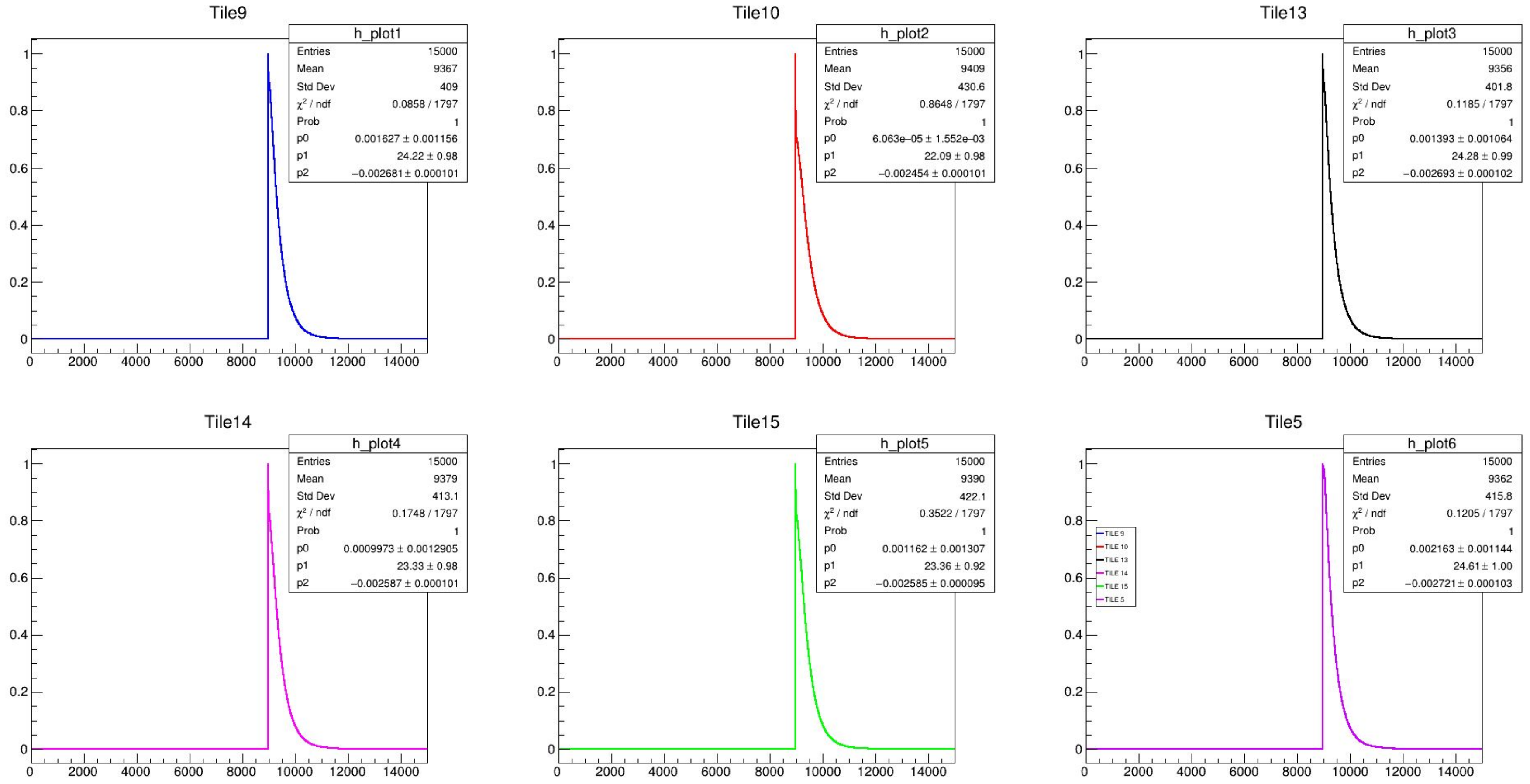
MC model implemented in Geant4 to decouple both effects and evaluate the PEN WLSE:

- Values of some optical parameters were taken from literature whereas, some others were measured.
- TPB WLSE fixed at 100% since the relative performance of both detectors is of main interest.
- A LY of (2.6 ± 0.5) pe/keV predicted for the TPB chamber, consistent with the corresponding measurement value of (2.5 ± 0.05) pe/keV.

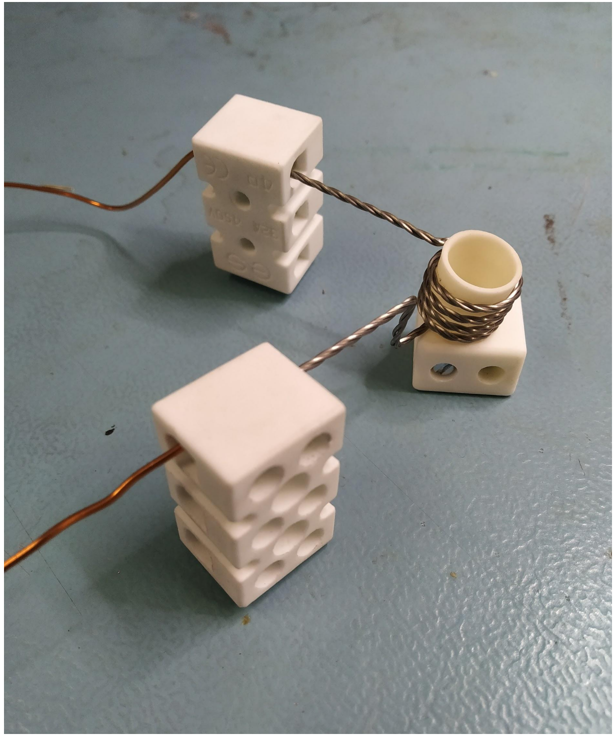


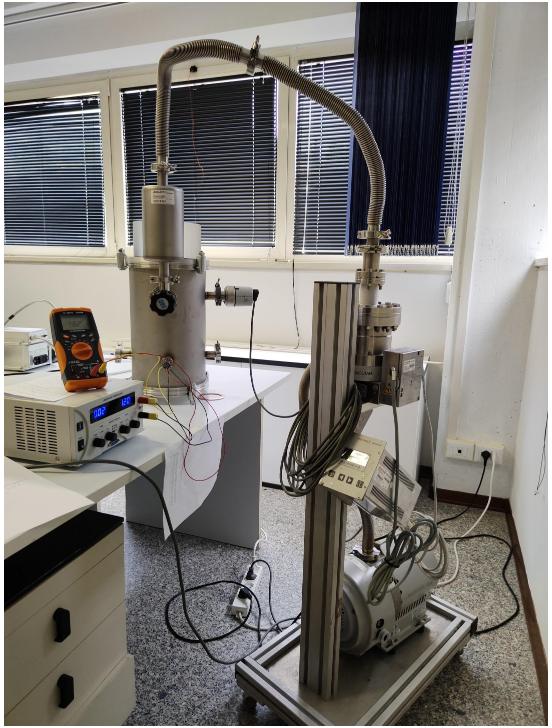
Input	**Allowed range**	$\delta_{syst}/\frac{LY_{PEN}}{LY_{TPB}}$
R calibration (reference)	0.980±0.005	0.07
R correction (slits and bolts)	0.994±0.006	0.08
R in LAr	1.000±0.0035	0.05
TPB R spectrum (spurious component removal)	extrapolate below 415 nm	0.02
SiPM reflectivity	0.171±0.017 (PEN) 0.167±0.017 (TPB)	0.01 0.01
PDE curve shape T dependence	shift by –20 nm	0.02
Total		**0.12**

LAr scintillation mean trace

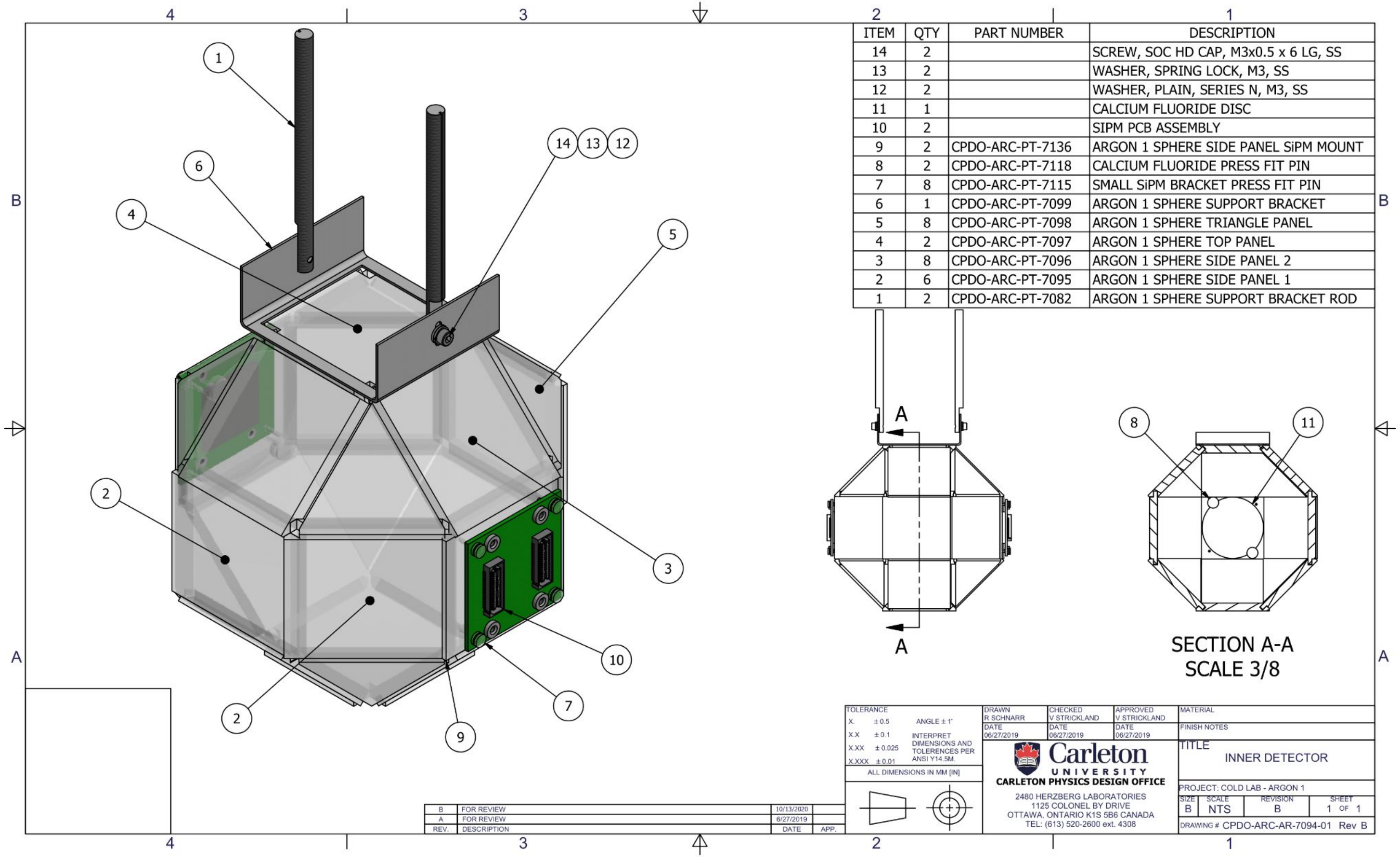


Evaporator for TPB coating





Detector for pulse-shape studies



ITEM	QTY	PART NUMBER	DESCRIPTION
14	2		SCREW, SOC HD CAP, M3x0.5 x 6 LG, SS
13	2		WASHER, SPRING LOCK, M3, SS
12	2		WASHER, PLAIN, SERIES N, M3, SS
11	1		CALCIUM FLUORIDE DISC
10	2		SIPM PCB ASSEMBLY
9	2	CPDO-ARC-PT-7136	ARGON 1 SPHERE SIDE PANEL SiPM MOUNT
8	2	CPDO-ARC-PT-7118	CALCIUM FLUORIDE PRESS FIT PIN
7	8	CPDO-ARC-PT-7115	SMALL SiPM BRACKET PRESS FIT PIN
6	1	CPDO-ARC-PT-7099	ARGON 1 SPHERE SUPPORT BRACKET
5	8	CPDO-ARC-PT-7098	ARGON 1 SPHERE TRIANGLE PANEL
4	2	CPDO-ARC-PT-7097	ARGON 1 SPHERE TOP PANEL
3	8	CPDO-ARC-PT-7096	ARGON 1 SPHERE SIDE PANEL 2
2	6	CPDO-ARC-PT-7095	ARGON 1 SPHERE SIDE PANEL 1
1	2	CPDO-ARC-PT-7082	ARGON 1 SPHERE SUPPORT BRACKET ROD