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U.S. DEPARTMENT OF ENERGY

Photon Detection System R&D for DUNE FD3 with Industrial WLS Coating

From industrial pTP deposition to integrated liquid argon validation

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Motivation: WLS coating at DUNE FD3 scale

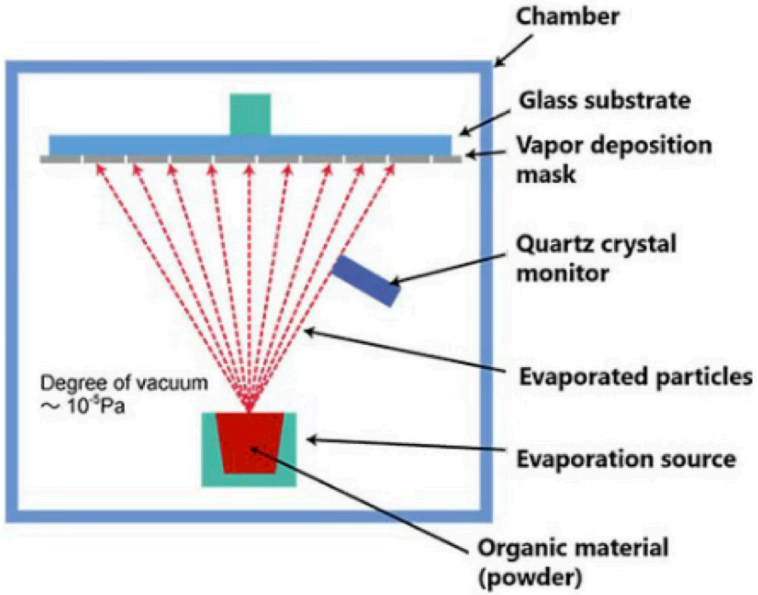
WLS coating requirement for DUNE PDS

- DUNE PDS must shift 127 nm LAr scintillation light; the first WLS layer is p-Terphenyl deposited on a substrate (B33 glass)
- Coated area: ~350 m² for Phase-I FD1/FD2,
  ~2,000 m² for Phase-II FD3 (APEX-design)

Production bottleneck

- Phase-I plan: vacuum deposition, **>1 year per FD** (428-day schedule for 48,000 units, 370 m², for FD1)
- Same approach for FD3/APEX: **>6 years of work**

Can we do it faster, cheaper and better, using industrial deposition processes developed for OLED display manufacturing?



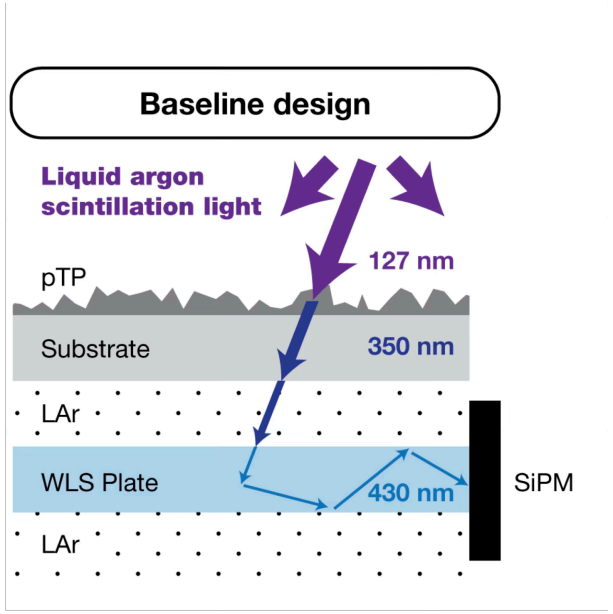


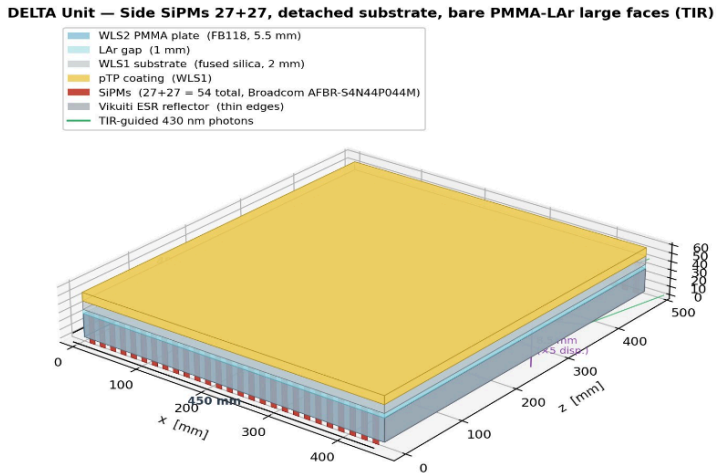
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X-ARAPUCA: light-trap baseline for DUNE PDS

Two-stage wavelength shifting

- 127 nm → **pTP** → 350 nm → **WLS Plate** → 430 nm → SiPM
- The WLS plate acts as a light guide via **total internal reflection** (TIR); 430 nm photons escaping the bar are reflected back by the Vikuiti reflector.
- Photon detection efficiency (PDE) of **~4%**, established by both simulation and measurement





APEX DELTA simulation: Flavio Cavanna

FD3 (APEX) light-trap design is still being optimized -> DELTA

See Flavio Cavanna's DELTA talk earlier today!

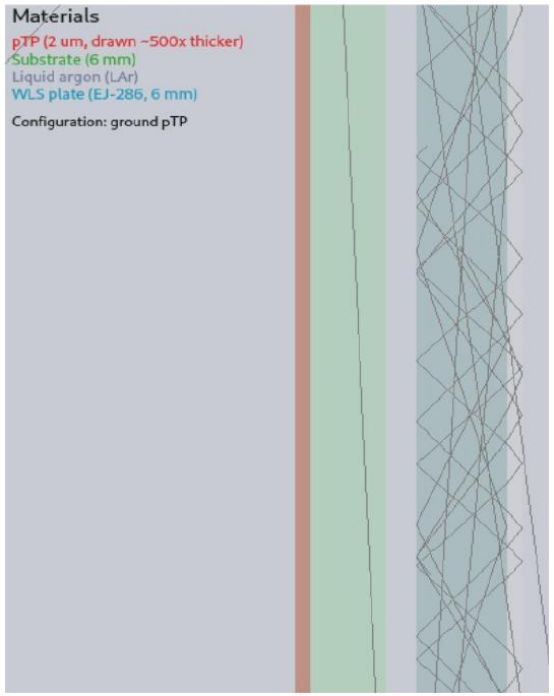
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Opportunity: a smooth pTP layer could trap light itself

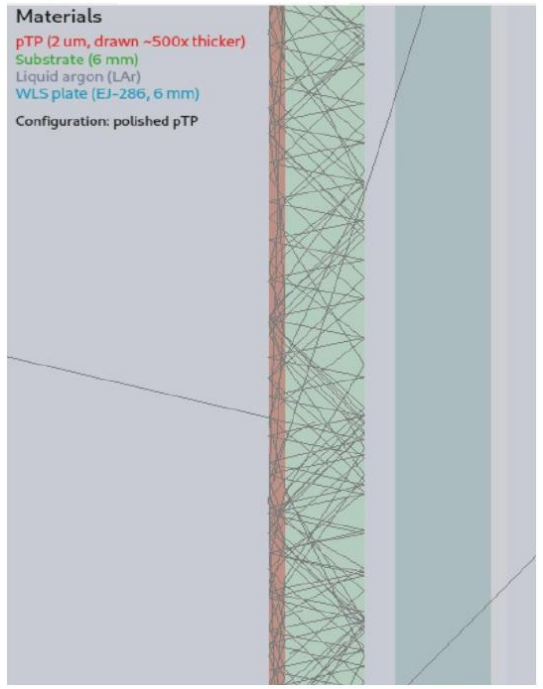
Simulation insight

- If the pTP coating is optically smooth ("polished"), **TIR can occur already in the first WLS layer**
- A single-layer light trap reduces the number of optical interfaces
- Significantly higher photon collection efficiency, at reduced cost and time

Can we deposit WLS uniformly and smoothly enough to enable TIR in the first layer?



pTP surface: ground



pTP surface: polished

pTP physical vapor deposition (PVD) procedure

After lengthy R&D and small-sample tests, our **industrial partner LaserFiberOptics (LFO)** deposited pTP on FD2-size substrates (14.4 cm × 14.4 cm)

Procedure optimized to produce uniform, optically smooth pTP films (target: 1-2 um)

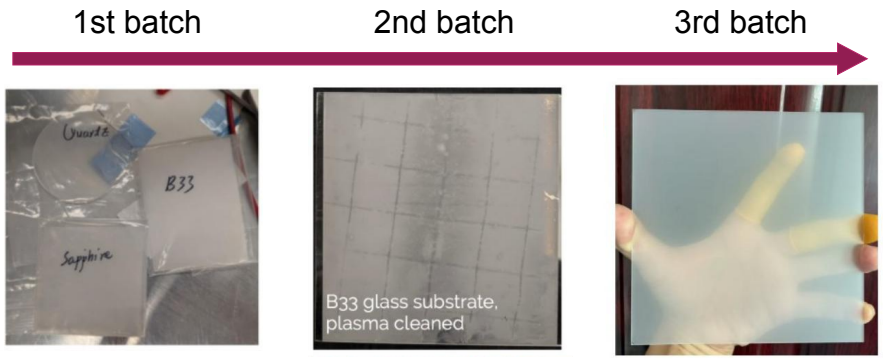
1 **Substrate preparation** — ultrasonic solvent baths and deionized-water rinses

2 **Plasma surface treatment** — $N_2/O_2/CF_4$ plasma for ~15 min, for adhesion and surface cleanliness

3 **In-situ Ar-ion bombardment** — ~10 min on the rotating dome; improves film nucleation and mitigates poor wetting from trace organics

4 **pTP deposition** — 1.6 × 10^{-4} Torr, source boat at ~195 °C, 5 Å/s

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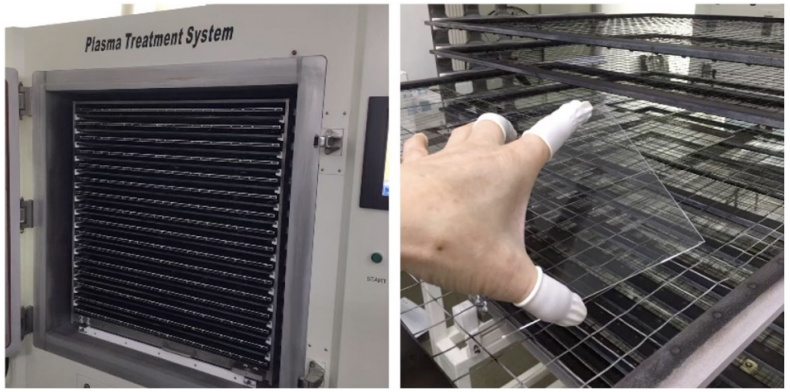


Figure 2. Plasma-treatment system and substrate placement. Mesh shadowing during treatment produced observable thickness modulation in early trials.

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Industrial PVD process demonstrated at large scale

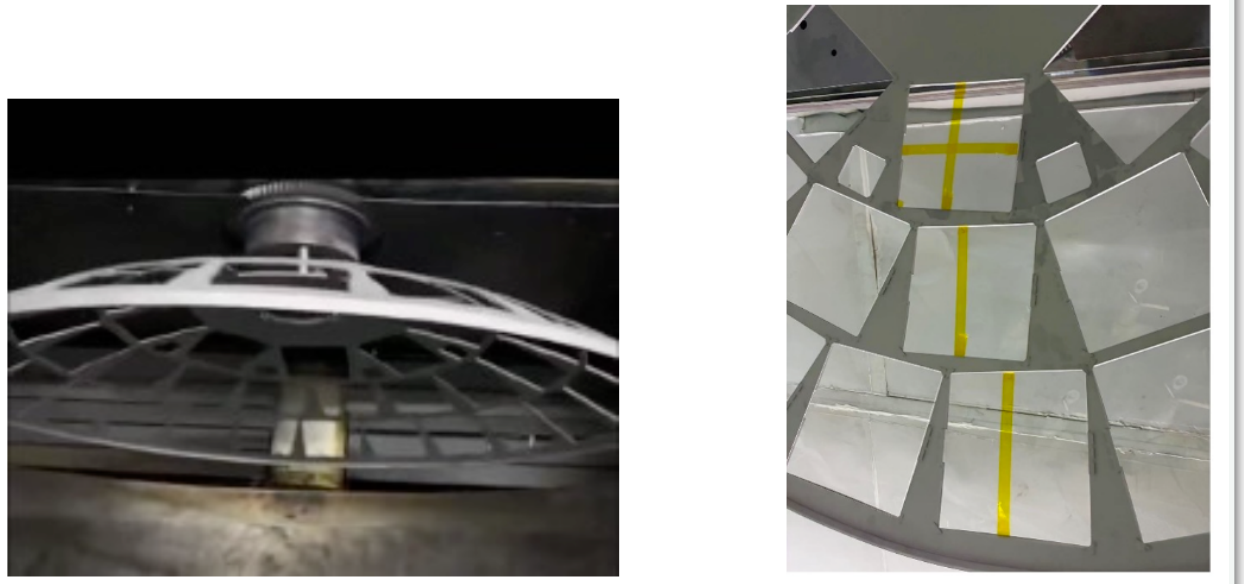
Custom rotating dome

- 34 substrates per batch
- 143.75 mm × 143.75 mm B33 substrate size
- High-purity pTP used in the controlled third campaign

Throughput projection

- **~5.4 m²/day** with two coaters and a four-person crew
- Matches annualized capacity of **~2,000 m²**

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(a) Three-tier rotating dome

(b) Dome loaded prior to deposition

Figure 4. Throughput scaling with a rotating substrate dome.

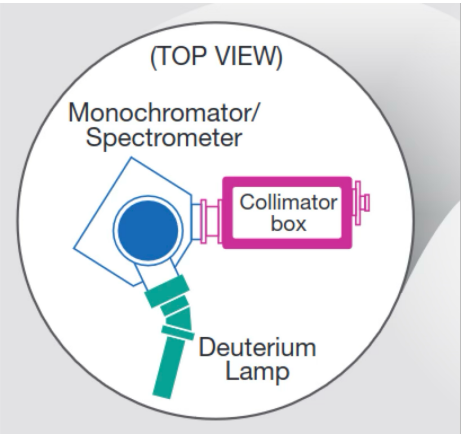
Emission spectra match laboratory-made references

Room-temperature measurement

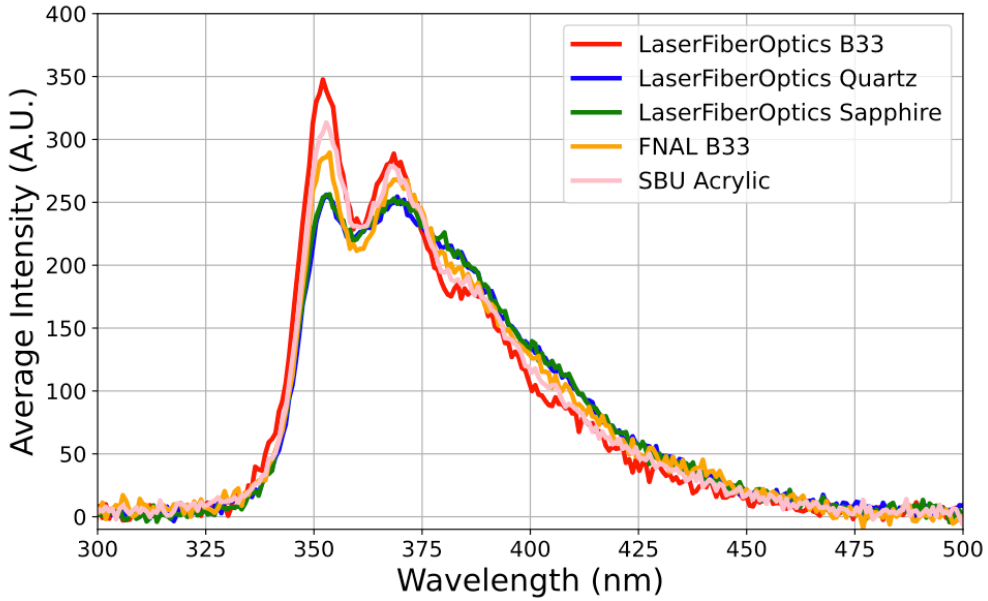
- Spectrometer with **deuterium-lamp UV source** (266 nm excitation)
- References: FNAL (B33, PVD) and SBU (acrylic, chemical deposition), both Thermo Fisher pTP

Results

- Batch-3 LFO samples (Thermo Fisher pTP, B33) closely match the FNAL/SBU spectral shape
- Batch-2 (generic pTP, Quartz/Sapphire): shape differences, but the same peak position
- Peak variation < 5 nm across all samples: **neither substrate nor plasma pre-treatment alters the optical response**



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Cryogenic stress tests: no coating degradation

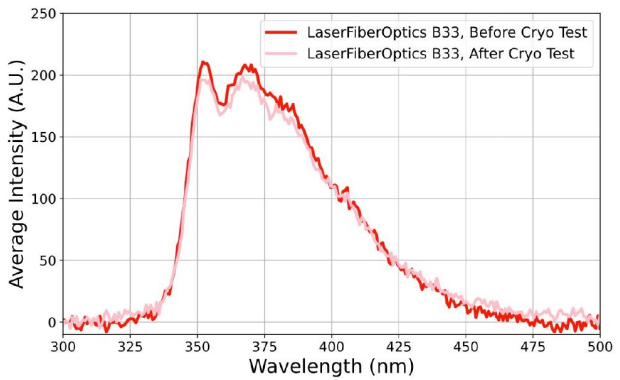
Round 1: open LN_2 dipping

- Vertical and horizontal dipping, multiple cool-down/warm-up cycles, all three substrates
- B33: spectral shape and light yield remain stable
- Minor visual changes on quartz/sapphire traced to condensation during warm-up, not degradation in the cold

Round 2: closed LAr system

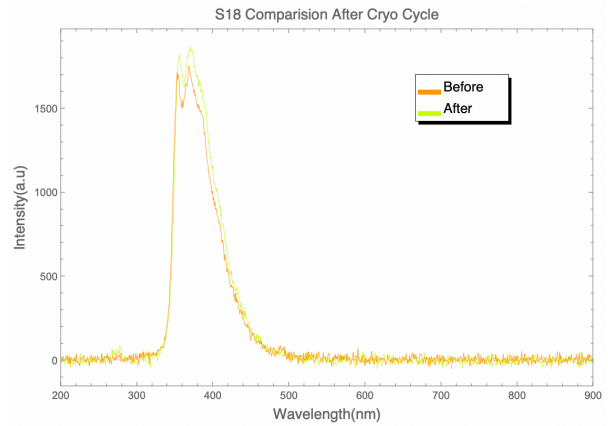
- Mitigates moisture ingress during warm-up
- **No visible degradation and no change in emission spectrum**

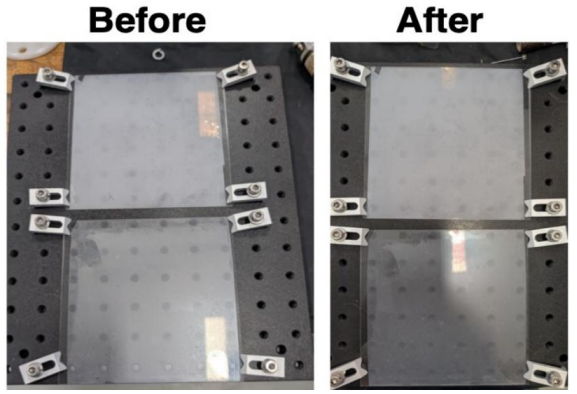
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Round 1: before/after cycling with open LN2 dipping





Round 2: before/after cycling with closed LAr system

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Coating thickness and uniformity

Stylus profilometry

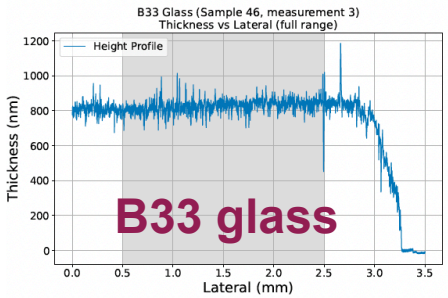
- 2 nm resolution
- 3.5 mm scans from the uncoated edge into the coating; 0.5–2.5 mm interval used for uniformity



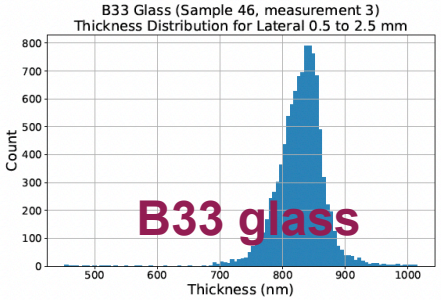
Results

- All coatings reach the 1–2 μm target with < 10% variation over the scanned region
- **B33 gives the lowest spread**: σ = 40–60 nm
- Quartz: < 100 nm variation
- Sapphire: apparent slope from substrate bow, not coating non-uniformity

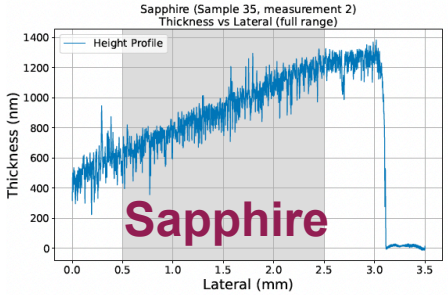
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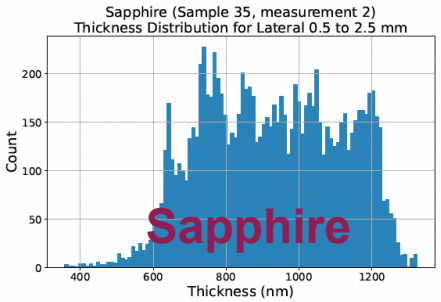
(a) Thickness vs. lateral distance (B33)



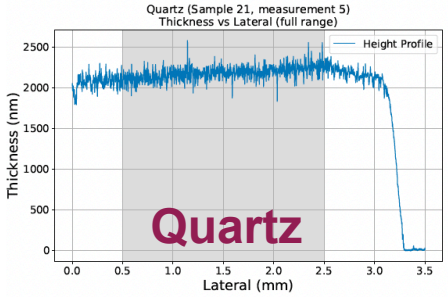
(b) Thickness distribution (B33)



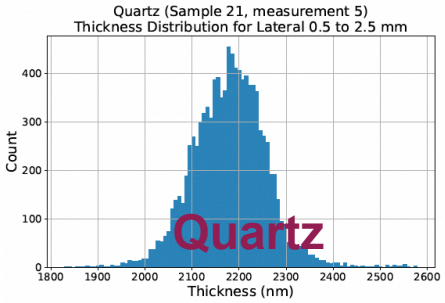
(c) Thickness vs. lateral distance (Sapphire)



(d) Thickness distribution (Sapphire)



(e) Thickness vs. lateral distance (Quartz)



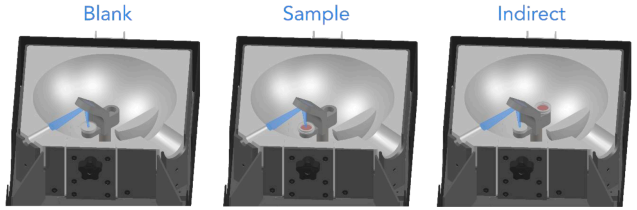
(f) Thickness distribution (Quartz)

Photoluminescence quantum yield of the pTP film



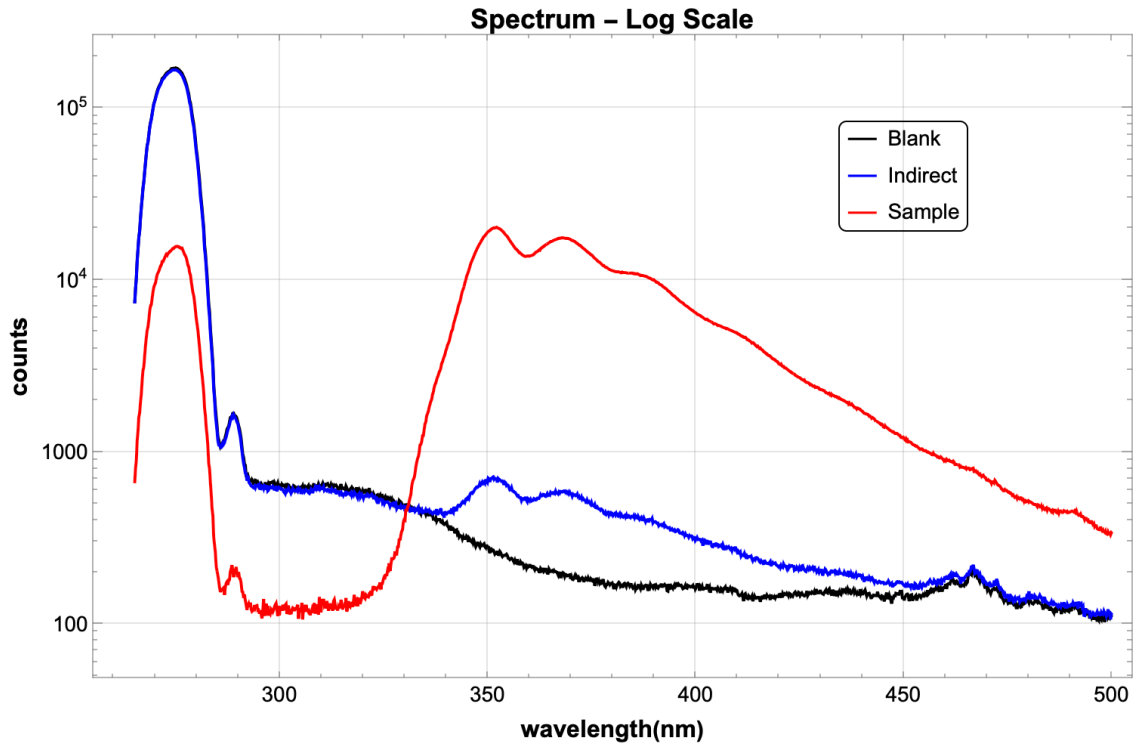
Integrating-sphere measurement

- Edinburgh Instruments FS-5 spectrometer with SC-30 integrating-sphere module
- **Three-scan method** (blank, sample, indirect): removes the contribution of indirect excitation on the sphere wall. Adv. Mater., 9: 230-232 (1997)



Quantum-yield result

$$\text{PLQY} = \frac{N_{\text{emitted}}}{N_{\text{absorbed}}} = 59.4\% \quad \text{(three-scan)}$$



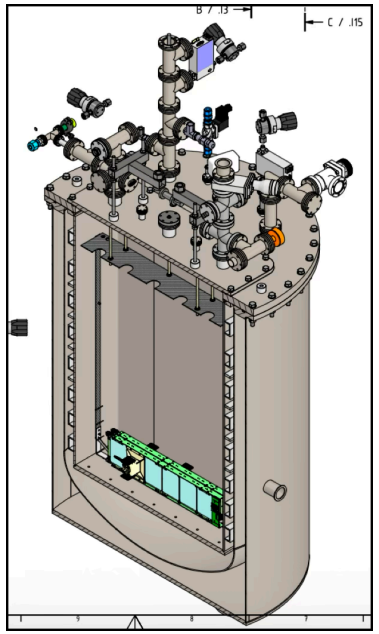
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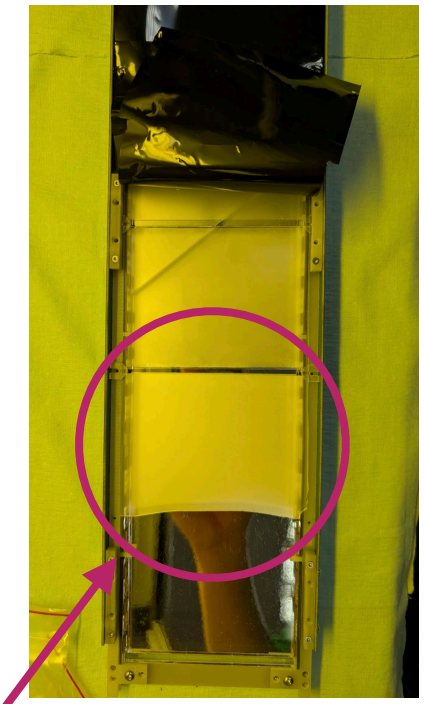
Test Setup @ CIEMAT

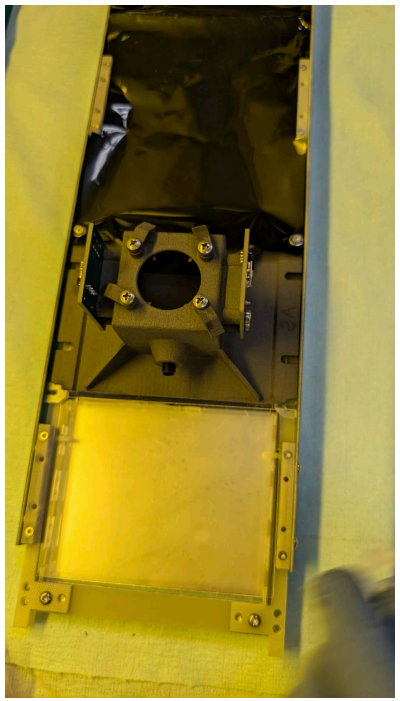
GOAL: detector-level performance validation of our industrial PVD-deposited pTP coatings using the FD1/FD2 baseline photodetector.

- A **BNL/LFO coating was mounted in one X-ARAPUCA supercell** (FD1), alongside reference/baseline coatings in the same setup.
- The filter was **cut down to fit the supercell**; cut edges may contribute.





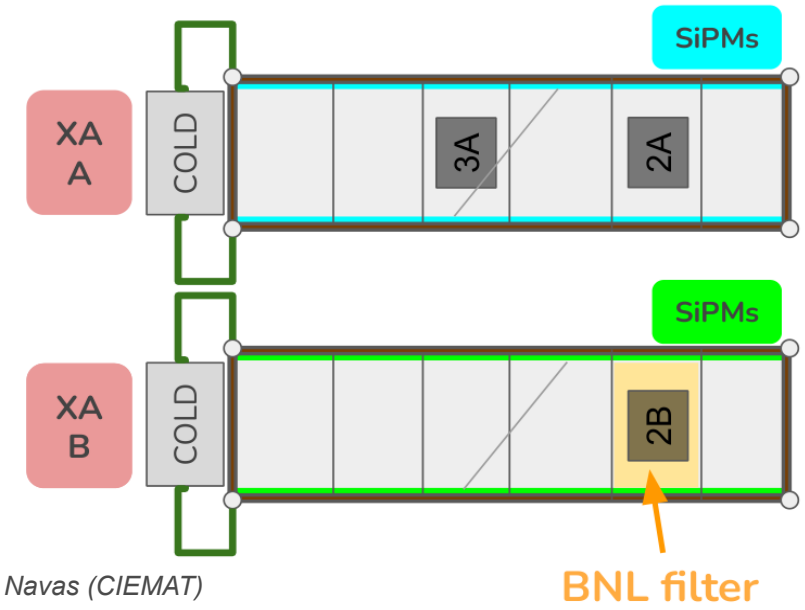




The CIEMAT measurement isolates the comparison at module level

XA HD: Measurement Layout

- Individual XA read-out (possible to compare directly based on collected #PEs).
- The **PDE** is measured **in LAr** with the **scintillation light from ^{241}Am α-source**
- **Characterization boxes** positioned in **2 distinct** XA positions (1 equivalent position).
- Each box mounts **1 α-source** & **2 reference VUV4 SiPMs** with known PDE.
- BNL filter is mounted in one XA (XA-B) just below the characterization box



Credit: Diana Navas (CIEMAT)

Readout and calibration

- Two X-ARAPUCA channels
- Reference VUV4 SiPMs with known PDE
- ^{241}Am α source in each characterization box

Comparison logic

- Same LAr run, comparable geometry, independently calibrated channels.

The test provides a detector-level acceptance reference for the industrial coatings

Preliminary PDE results in LAr

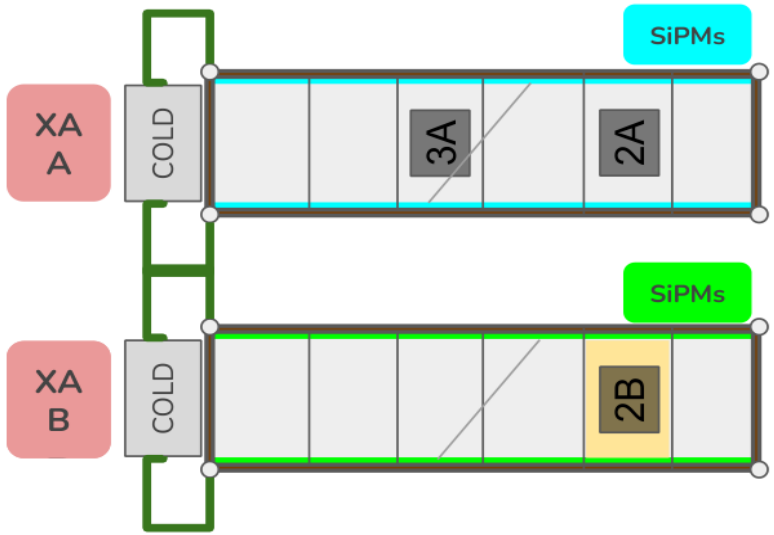
Absolute PDE results

- PDE results stable across all the data taking (2 days)
- BNL filter reduces PDE by -17±1% for the 3 OV
- This was just one sample; edges were cut to fit.

PRELIMINARY

	XA-0		BNL filter
OV	Position 2	Position 3	Position 2
3V	(4.4±0.4) %	(4.1±0.4) %	(3.7±0.3) %
2.5V	(4.1±0.4) %	(3.8±0.4) %	(3.4±0.3) %
2V	(3.7±0.3) %	(3.4±0.3) %	(3.1±0.3) %

Credit: Diana Navas (CIEMAT)

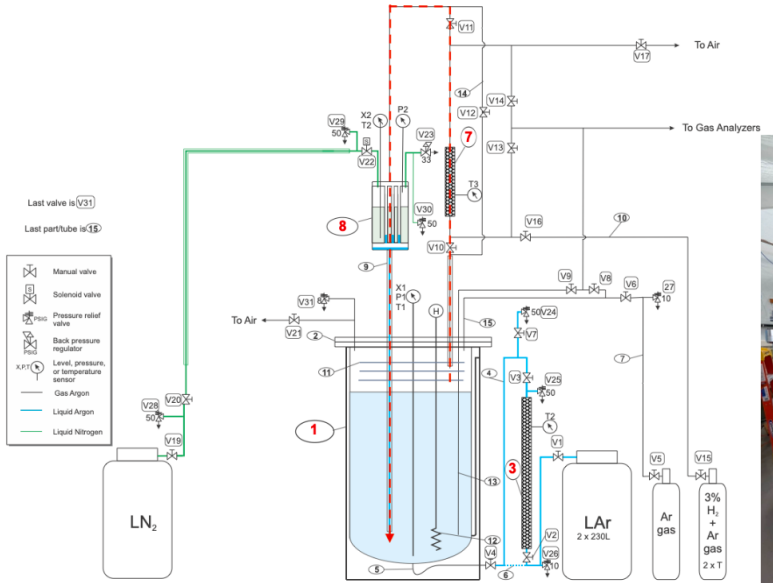


Successful detector-level validation, with only marginal PDE difference from baseline FD1/FD2 coatings

Next: Establish similar LAr setup at BNL

Why the 260-L stand

- Medium-scale LAr volume (260L) for detector-component R&D
- Pump-free gas purification and direct electron-lifetime monitoring.
- Complete operational cycle in about seven days.

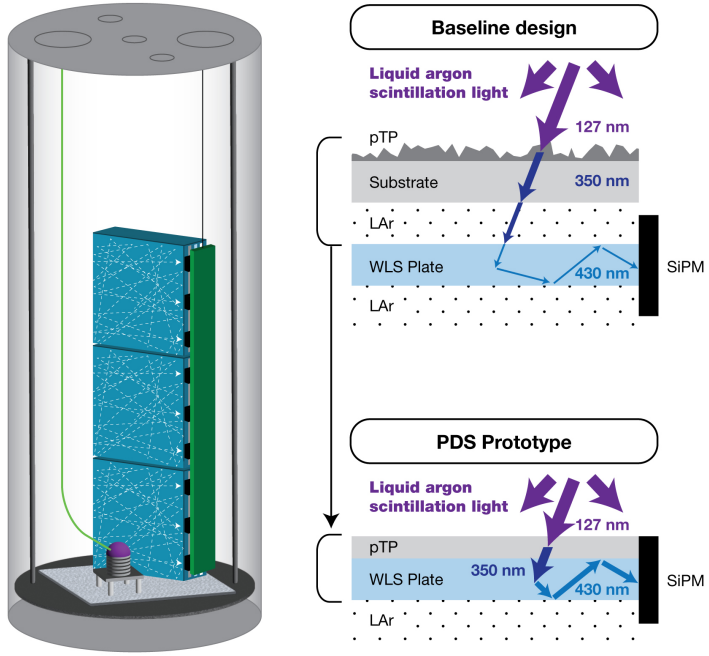




JINST 21 P09021 (2026)

Planned PDS program

- Establish one **R&D platform for DELTA**
- Perform detector-level characterizations in XA-like setups, comparisons of samples and geometries.



Not to scale.

R&D plan forward

Current goal

- Thorough characterization of LFO samples: robust cryo tests, better uniformity measurements
- Comparable PDE (2–3%) with LFO coating + XA baseline: **proves industrial PVD of pTP is suitable for DUNE PDS**

Intermediate goal

- FD3/DELTA **light-trap optimization**: different WLS, substrate and reflector materials, SiPM geometries to maximize PDE

Future goal

- New light-trap geometries for much-improved DELTA PDE: **single-layer light trap**, better WLS–light guide–photon detector coupling

Next steps: transmittance and light-yield measurements, PDE in an XA-like setup in LAr, light-trap geometry R&D

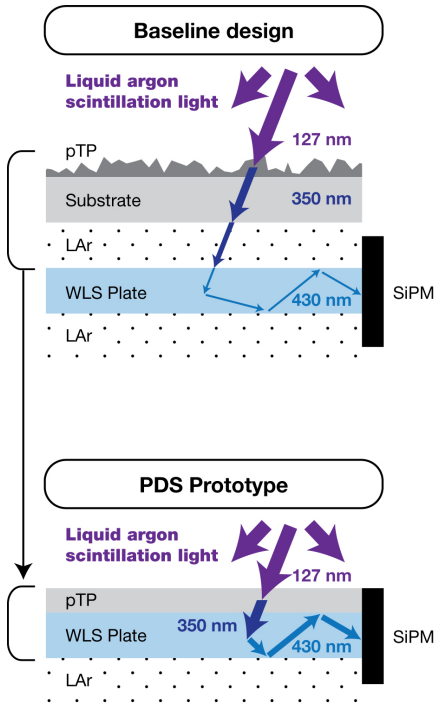
Summary

Industrial PVD provides a credible production path for FD3/ DELTA WLS coatings

- pTP successfully deposited by an industrial vendor on FD2-size B33 glass, quartz and sapphire substrates
- Films are uniform and adherent: **1–2 µm with < 10% thickness variation**, emission spectra matching lab references, no degradation after LN_2/LAr cycling, QY ≈ 59%
- **Projection**: ~2,000 m² needed for FD3/APEX within ~1 year of production
- Full module **PDE measurement at CIEMAT**: industrially-coated filter operated in a FD1 X-ARAPUCA shows comparable results.

- Various R&D activities within **DELTA** to **optimize the light-trap geometry** and maximize PDE at BNL, utilizing available equipments and 260L LAr test-stand.





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Thank you!

Vacuum vs. chemical deposition

	Vacuum deposition (this work)	Chemical deposition
Pros	• Strong thickness / areal-density control • Clean process (no solvent, fumes or residue) • QA-friendly: in-situ monitoring	• Scales via automation and parallel stations • Equipment can be simpler and lower-cost • High throughput potential with robotics • Flexible with various geometries
Cons	• Needs specialized infrastructure and a vendor • **Throughput/capacity is the main risk** **→ industrial partner with dedicated equipment: cost-effective production model for 2,000 m²/year**	• Requires solvent handling / ventilation • Typically higher QC mapping burden • **Uniformity and surface finish are process-sensitive; can be rougher without optimization** **→ automation/optimization with a robotic station being planned**

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Why a double-layered WLS light trap?

- Light trapping and guiding via **total internal reflection (TIR)** in the WLS plate is essential.
  - Direct SiPM exposure to the active volume would require ~10× more sensors to collect the same number of photons.
- TIR relies on a well-defined interface between a high-refractive-index plate and low-refractive-index liquid argon.
  - Evaporated WLS layers result in irregular boundaries, compromising TIR.
- Two wavelength shifts are (almost) unavoidable due to the rapid absorption of LAr scintillation light in most materials.

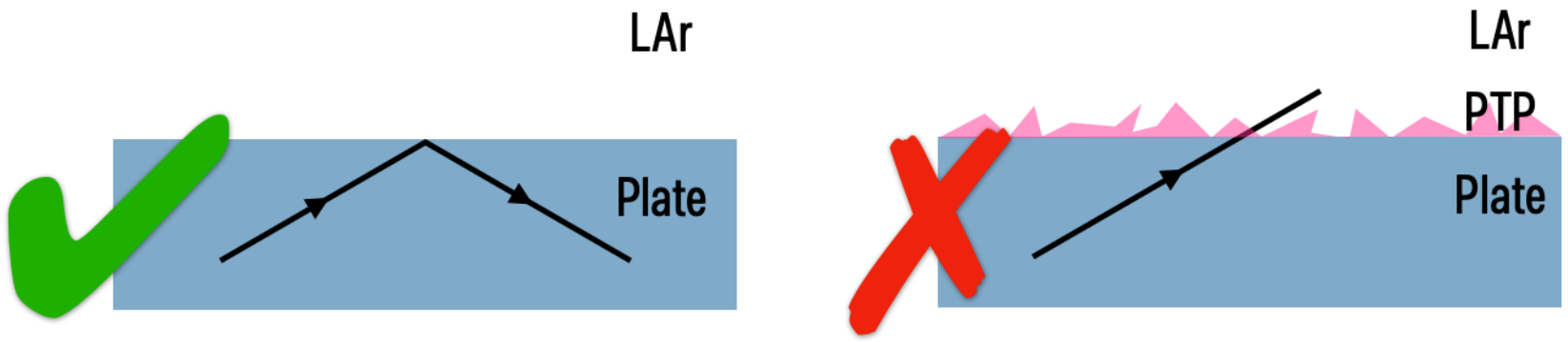


Figure: J. Martín-Albo

Industrial pTP samples produced by LaserFiberOptics

After lengthy R&D and small-sample tests, our industrial partner LaserFiberOptics (LFO) deposited pTP on FD2-size substrates (14.4 cm × 14.4 cm)

Three production batches

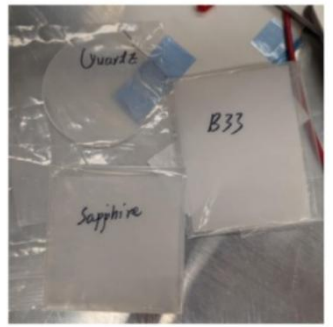
1 **Batch 1** — small samples on three substrates (generic pTP)

2 **Batch 2** — FD2 size on three substrates, with/without plasma cleaning, better-optimized thermal deposition control (generic pTP)

3 **Batch 3** — FD2 size on B33, plasma cleaned, fully optimized deposition (high-purity Thermo Fisher pTP)

Target coating thickness: 1–2 µm

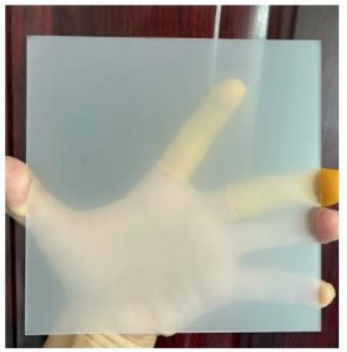
1st batch



2nd batch



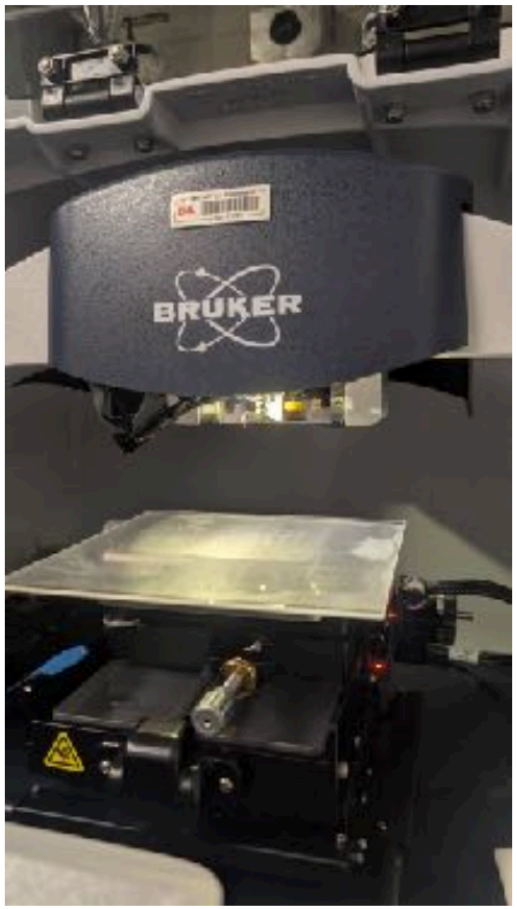
3rd batch



Thickness and uniformity: all scanned samples

Batch	Sample	Substrate	No. scans	Mean thickness (nm)	Scan-to-scan std dev (nm)	Per-scan std dev range (nm)
2	S9	B33	6	1758.5	210.9	50.8 – 396.6
2	S12	B33	6	1585.6	46.6	56.3 – 108.4
2	S15	B33	6	2115.3	165.2	41.6 – 239.4
2	S20	B33	6	1526.2	136.9	54.4 – 147.8
3	S40	B33	3†	987.1	72.6	56.5 – 173.3
3	S42	B33	4	990.5	18.5	50.9 – 131.8
3	S43	B33	4	1001.3	39.4	27.5 – 173.9
3	S44	B33	4	960.3	47.7	61.4 – 140.1
3	S45	B33	2†	965.9	36.4	41.5 – 55.4
3	S46	B33	4	955.1	88.7	33.8 – 137.2
2	S21	Quartz	6	2124.0	160.0	77.9 – 297.0
2	S29	Quartz	6	1336.1	89.1	65.6 – 229.1
2	S2	Sapphire	6	1562.3	187.1	118.1 – 491.8
2	S35	Sapphire	6	1028.6	300.5	119.8 – 514.2

JINST 21 P04044 (2026) — sapphire substrates tend to bow, hard to disentangle from coating uniformity



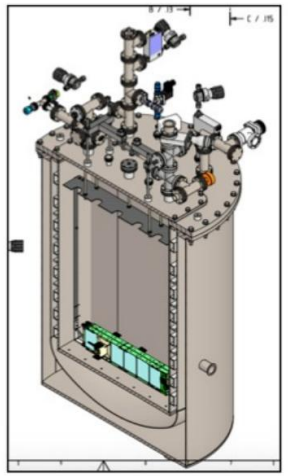
R&D plan: PDS / light-trap prototyping

test TIR with LFO sample + SiPM setup

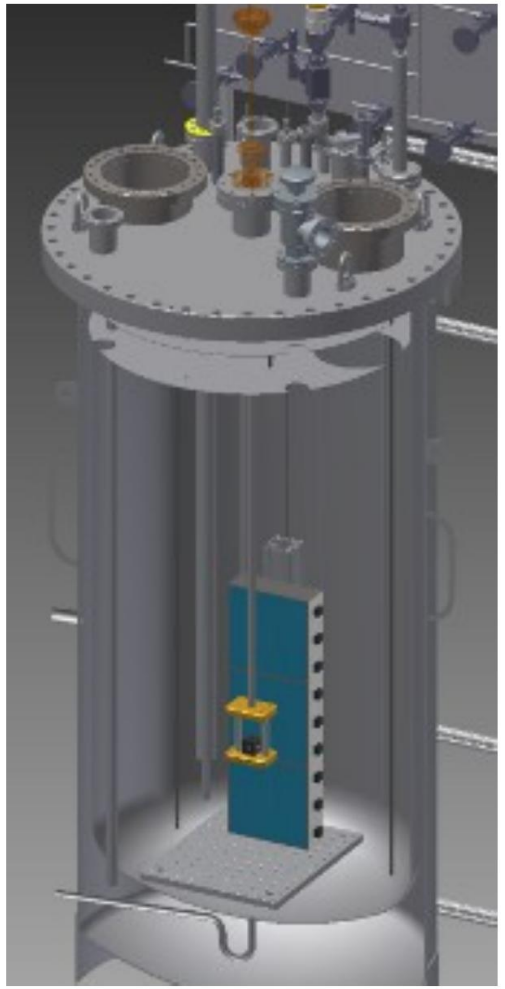
small prototype of XA

measurement of PDE with XA baseline prototype in LAr, cross-check with tests done at CIEMAT

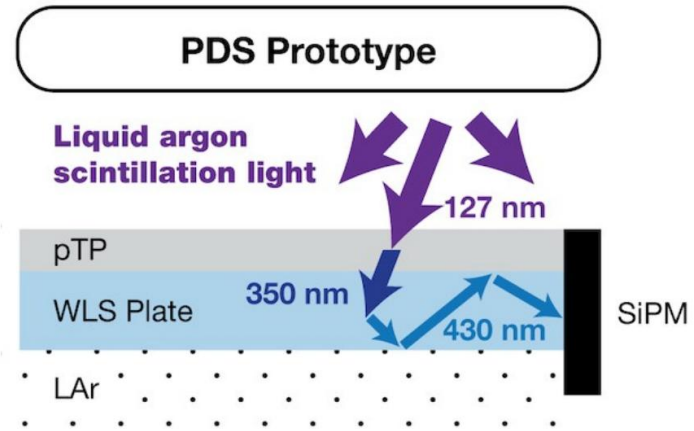
test different geometries for higher PDE







SiPM measurement prototype (in progress)







a prototype made by 3D printing

- filter held in place in groove
- slots on the side for SiPMs mount against the side surface of the filter
- currently testing without 2nd WLS, simply trying to see if the 350nm light can be trapped inside B33 glass substrate

Lessons learned and open challenges

Lessons from multiple batches

- pTP source purity is key to reliable, high-quality emission spectra
- Avoid substrate bow when using a profilometer to quantify uniformity
- Avoid water condensation during cryogenic warm-up cycles
- Thicker layers are possible (up to 4 μm tested)

Challenges

- Profilometer scans only up to 5 cm: no full-sample scan
- Profilometry gives thickness, not optical smoothness: ellipsometry or AFM needed, critical for a single-layer light trap
- Emission tested only at 266 nm; shorter wavelengths are absorbed in air
- No detector-level test setup at BNL yet → CIEMAT test