MagLITe – a multilayer approach to wavelength shifter thin films

Sep 22nd, 2022

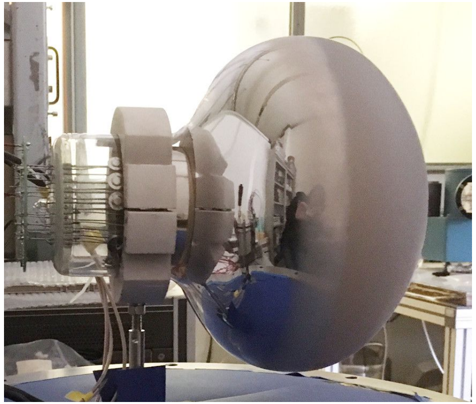
Bruno Passarelli Gelli

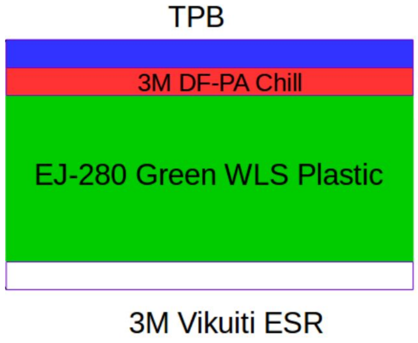
WLS coated photodetection devices

We all know the **importance** in the use of wavelength shifters when detecting **high energy photons**.

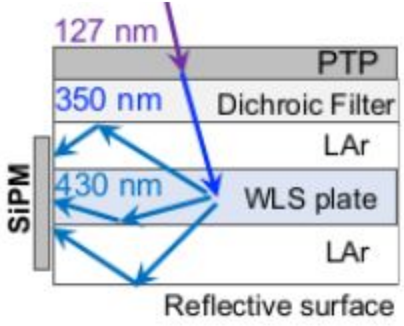
They allow for an easier detection of the scintillation light by converting it to a **less energetic spectrum**.

Not only that, but by combining it with other optical elements, it is possible to create **light-traps**, a technique which is **fundamental** for the new generation of kton-scale experiments.





Auger, M., et al. (2018). ArCLight—A Compact Dielectric Large-Area Photon Detector. Instruments, 2(1), 3.



Souza, Henrique & et al. (2021). Liquid argon characterization of the X-ARAPUCA with alpha particles, gamma rays and cosmic muons.

By having the coating exposed to the external world many problems can manifest.

This is the case for **solubility**. It was shown in previous works that **liquid nobles** are capable to **dissolve TPB**.

- Loss of thickness → efficiency decrease
- **Bulk fluorescence**

The **low resistance** of the external coating to **mechanical** and **chemical stresses**.

Finally, the **isotropic emission** of the WLS coating implies a big loss of efficiency.

- **Factor of 0.5 in efficiency**

ELSEVIER
Thin Solid Films
Volume 600, 1 February 2016, Pages 65-70

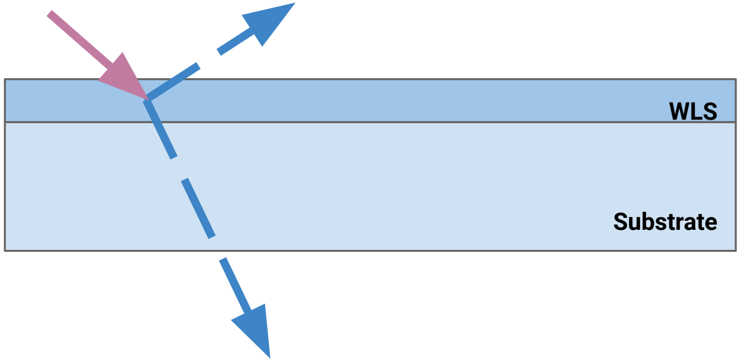
Stability of tetraphenyl butadiene thin films in liquid xenon

Journal of Instrumentation

Emanation and bulk fluorescence in liquid argon from tetraphenyl butadiene wavelength shifting coatings

J. Asaadi[1], B.J.P. Jones[1], A. Tripathi[1], I. Parmaksiz[1], H. Sullivan[1] and Z.G.R. Williams[1]

Published 18 February 2019 • © 2019 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 14, February 2019
Citation J. Asaadi *et al* 2019 *JINST* **14** P02021



MagLITe

The **MagLITe** (**Mag**nesium **F**luoride **L**ight collection **I**mproving **Te**chnique) is a technique in development by our group, and it consists in **coating the external WLS with a protective thin film**.

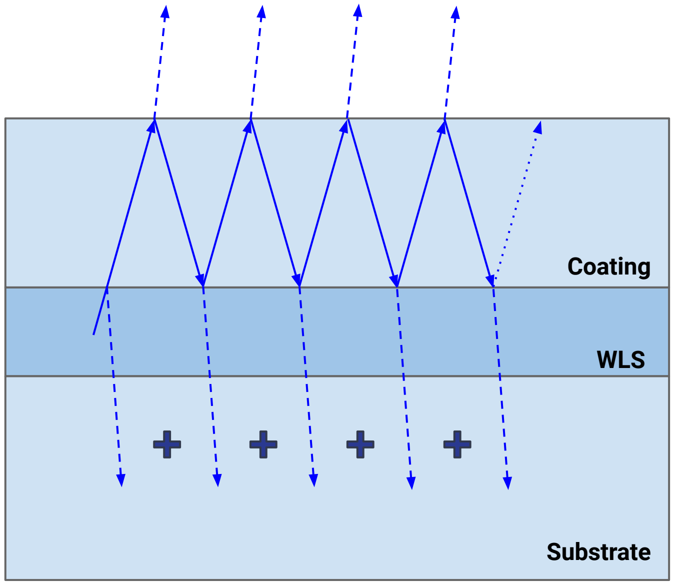
This technique can help with **all drawbacks** discussed!

The **emanation problem** can be solved. By having a **physical barrier** between the organic compounds and the noble liquid.

It also helps to **protect the organic films** from mechanical and chemical damage.

And finally, it can also help with the loss of efficiency.

By choosing a material with the **right refractive index** and choosing the right coating thickness, the film can also **act as an anti-reflective coating**.



For this technique to work, there are **important properties** of this coating needs to present.

- **Hard and stable** coating
- **Transparent to VUV photons**
- Compatible properties
  - Adequate **refractive index**
  - Thermal expansion coefficients
  - Young's modulus
- Easy production → **Scalability**

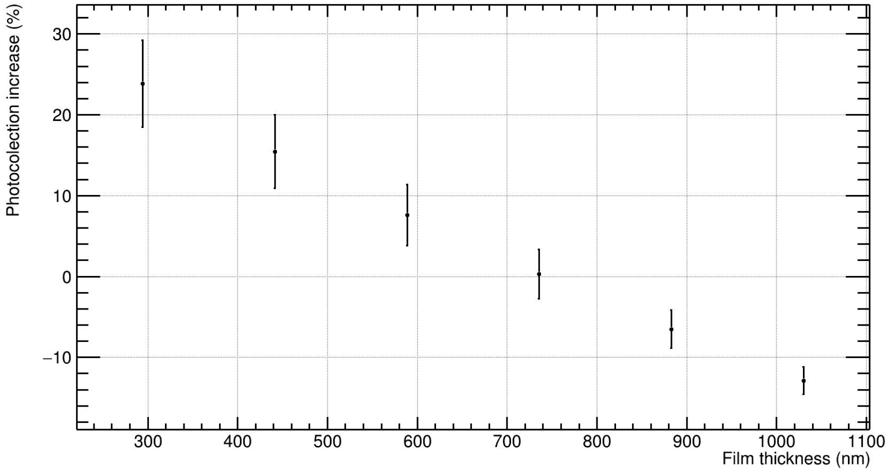
The two **most promising** compounds are **MgF_2** and **Al_2O_3**

	LiF	CaF_2	CeF_3	LaF_3	MgF_2	SrF_2	Al_2O_3
Hardness (Knoop)	102	158	-	-	415	154	2000
$n(128)$	1.57	1.58	2.18	2.07	1.64	1.89	2.55
$n(175)$	1.49	1.55	1.76	1.73	1.50	1.60	1.94
$n(350)$	1.40	1.45	1.66	1.60	1.39	1.50	1.72
$n(420)$	1.40	1.44	1.64	1.59	1.38	1.49	1.70
$n(450)$	1.39	1.44	1.64	1.59	1.38	1.49	1.69
$\alpha(128)$ (μm^{-1})	-	-	1.94	2.62	0.78	21.6	37.8
$\alpha(175)$ (μm^{-1})	-	-	0.60	0.30	0.17	2.89	0.73
$\alpha(350)$ (μm^{-1})	-	-	0.24	0.04	0.04	0.46	0.54
$\alpha(420)$ (μm^{-1})	-	-	0.16	0.03	0.02	0.31	0.57
$\alpha(450)$ (μm^{-1})	-	-	0.13	0.03	0.02	0.26	0.56

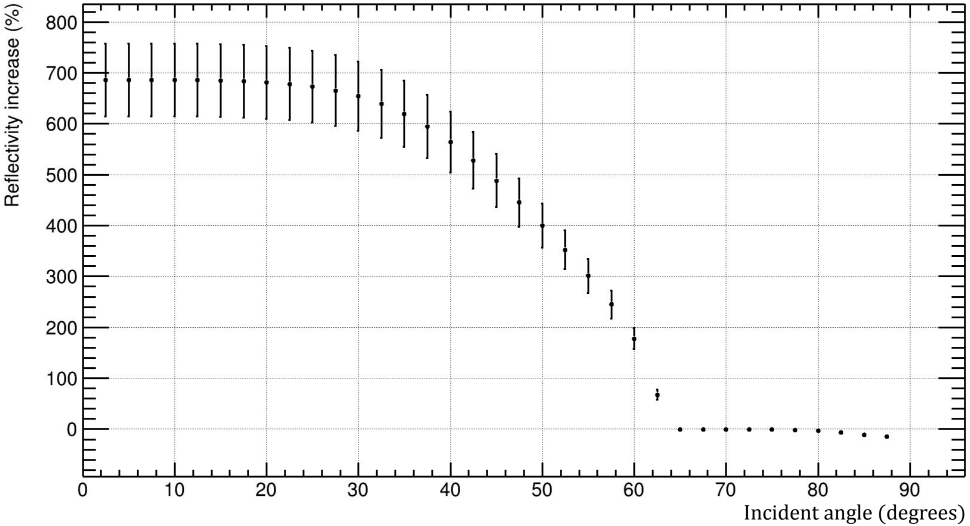
Rodríguez-de Marcos, et all, "Self-consistent optical constants of MgF2, LaF3, and CeF3 films," Opt. Mater. Express 7, 989-1006 (2017)
I.H.Malitson; J.Opt.Soc.Am. Vol52, p1377, 1962
Handbook Optical Constants, ed Palik, V2, ISBN 0-12-544422-2

$$I(d) = I_0 e^{-\alpha d}$$

The **Al_2O_3** is a **hard material** commonly used in coatings for optical elements. Although it is **not transparent to LAr light**, it is **transparent to LXe light**.



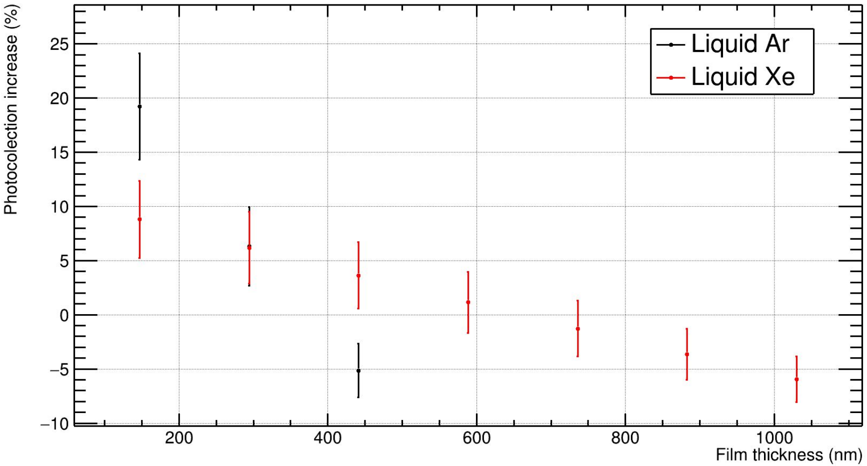
	n(128)	n(175)	n(420)	$\alpha(128)$ (μm^{-1})	$\alpha(175)$ (μm^{-1})	$\alpha(420)$ (μm^{-1})
Al_2O_3	2.55	1.94	1.70	37.83	0.73	0.57



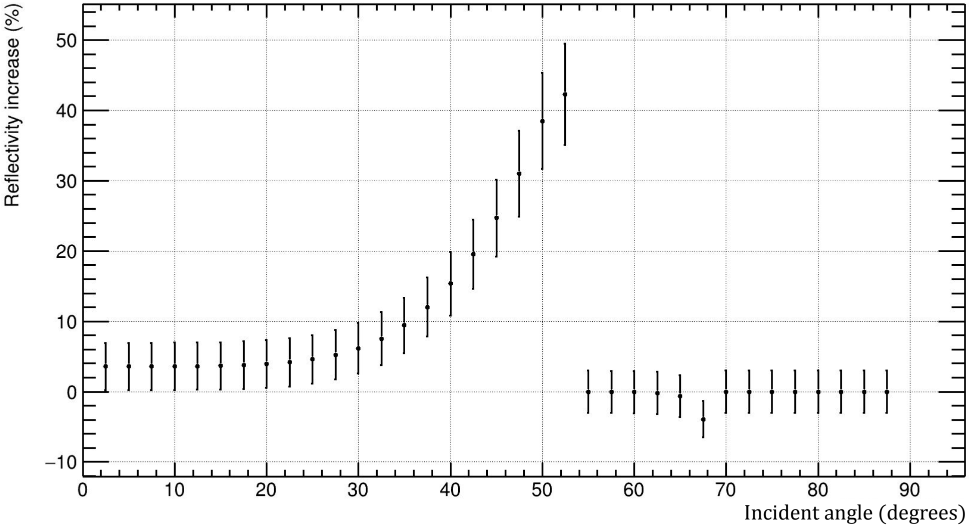
$$E = \frac{e^{-\alpha d}\left(\frac{1}{2} + R_{coating}\right)}{\left(\frac{1}{2} + R_{Lnoble}\right)}$$

$$\Omega_i = \int_{\theta_i}^{\theta_i+\Delta\theta} 2\pi sin(\theta) d\theta$$

Now for **MgF_2**. This material is **highly used** in combination with VUV photons, from optical elements to hard coatings. It is transparent to both **LAr** and **LXe** scintillation light



	n(128)	n(175)	n(420)	$\alpha(128)$ (μm^{-1})	$\alpha(175)$ (μm^{-1})	$\alpha(420)$ (μm^{-1})
MgF_2	1.64	1.50	1.38	0.78	0.17	0.02



$$E = \frac{e^{-\alpha d}\left(\frac{1}{2} + R_{coating}\right)}{\left(\frac{1}{2} + R_{Lnoble}\right)}$$

$$\Omega_i = \int_{\theta_i}^{\theta_i+\Delta\theta} 2\pi sin(\theta) d\theta$$

Running the calculation for **other combination** of wavelength shifters and coatings we get:

If you are interested in **LAr**, sapphire is not the best. But **MgF_2** could get you:

- **19%** increase for **TPB;**
- **20%** increase for **BisMSB;**
- **26%** increase for **pTP;**
- Or go for ~ *300 nm* coating **without losing any efficiency**

Now if you are interested in **LXe,** both coatings will work for you!
For **MgF_2** and **Al_2O_3** , respectively, we get:

- **9%** increase for **TPB**
- **9%** increase for **BisMSB**
- **19%** increase for **pTP**
- Or a ~ *600 nm* coating **without losing any efficiency**

- **24%** increase for **TPB**
- **25%** increase for **BisMSB**
- **24%** increase for **pTP**
- Or a ~ *700 nm* coating **without losing any efficiency**

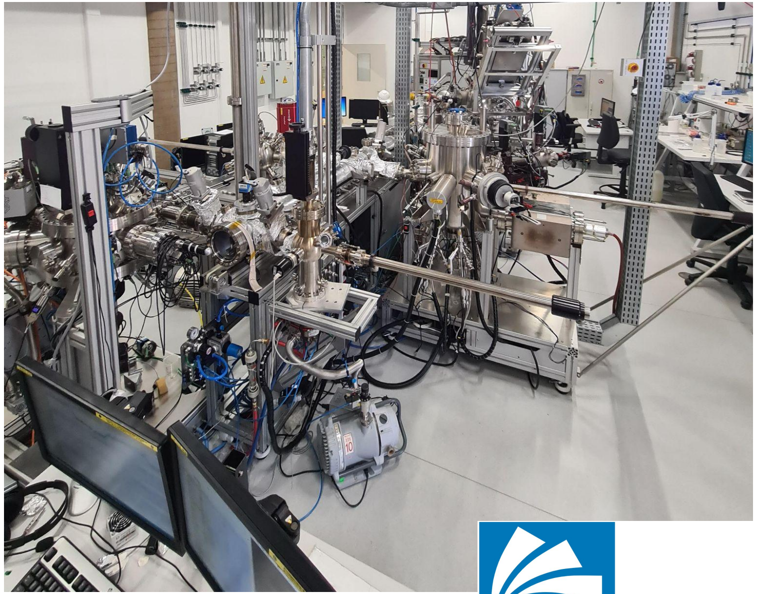
Depositing

We are currently in depository phase! Although both compounds can be deposited using **vacuum thermal evaporation**, to grow the first samples we decided to use an **specialized deposition facility** (LCIS), in the new **Sirius synchrotron light laboratory** in Brazil.

This laboratory permits us to grow samples using **several techniques** (PLD, MBE), while also **characterizing them *in situ*** (RHEED, STM, Sincrotron Light).

We decided to use **PLD** (Pulsed laser deposition) for our first tests.

- **0.009 nm/shot**
- Up to 10Hz
- < 0.1 nm surface roughness



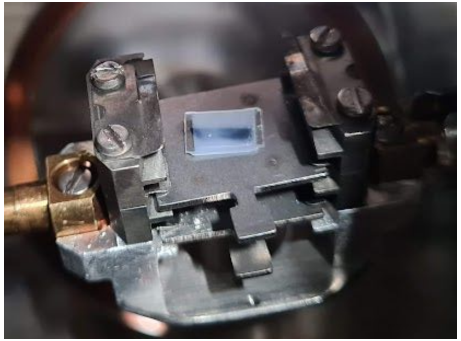
LNLS sirius Brazilian Synchrotron Light Laboratory

Using this facility we are growing samples ranging from a **few nanometers** up to several micrometer. Covering all the thicknesses for **constructive** and **destructive** interference.

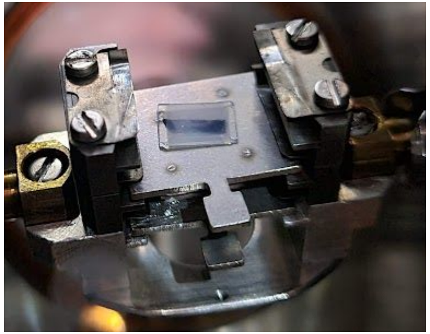
The preliminary results are promising!

- **No alteration to the refractive index**
  - From ellipsometry: **Δn = (0.01 ± 0.02)**
- **No fracture or peeling in the cryogenic stress tests**
  - Under optical microscopy → AFM is on the way!
- **No loss of material in the Chemical stress tests**
  - From ellipsometry: **ΔT = (3 ± 8) nm**

*Results for 2.7 μm TPB covered with 130 nm - 300 μm <100> Quartz substrate.



130 nm of Al_2O_3



Conclusion

In conclusion, the use of external wavelength shifters is **fundamental** for current generation of detector. But it comes with **several drawbacks**. **MagLITe is a promising technique** to help fix most of those.

Using just one additional layer, It can **increase the collection efficiency of photodetection devices by up to 25%**, while also protecting the thin films from mechanical and chemical damages.

New measurements on this technique are coming! We will soon be testing it using **synchrotron light** to precisely characterize all important parameters the **UV and VUV range**.

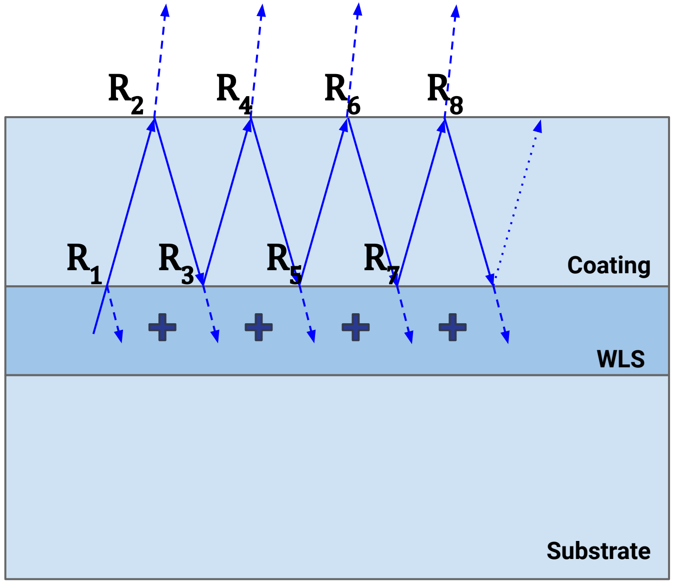
We will test **other protective materials** (CaF_2, LiF) as well as **other wavelength shifter** (pTP, BisMSB, PEN, Quantum Dots).

Obrigado!

Calculating the reflectivity

$$R_s = \left[\frac{n_1 cos(\theta_1) - n_2 cos(\theta_2)}{n_1 cos(\theta_1) + n_2 cos(\theta_2)}\right]^2 \quad R_s = \left[\frac{n_1 cos(\theta_2) - n_2 cos(\theta_1)}{n_1 cos(\theta_2) + n_2 cos(\theta_1)}\right]^2 \quad \theta_2 = asin\left(\frac{n_1 sin(\theta_1)}{n_2}\right)$$

$$R_T = R_1 + (1 - R_1)R_2(1 - R_3)A + [1 - R1 + (1 - R_1)R_2(1 - R_3)A]R_4(1 - R_5)A + \ldots$$

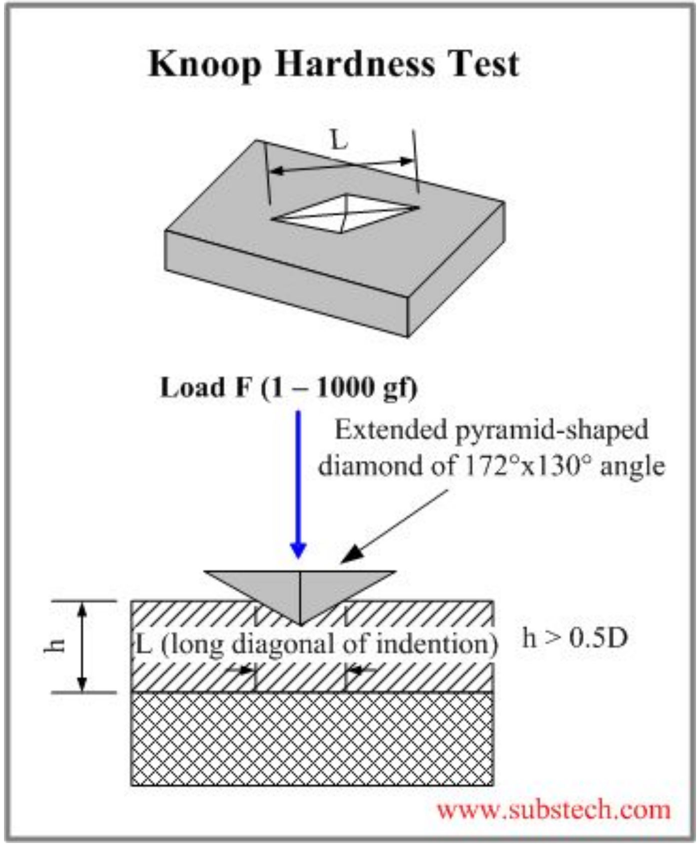


$$R_T = R_1 + T_1^2 R_2 A + (T_1 + T_1^2 R_2 A)R_2 T_1 A + \ldots$$

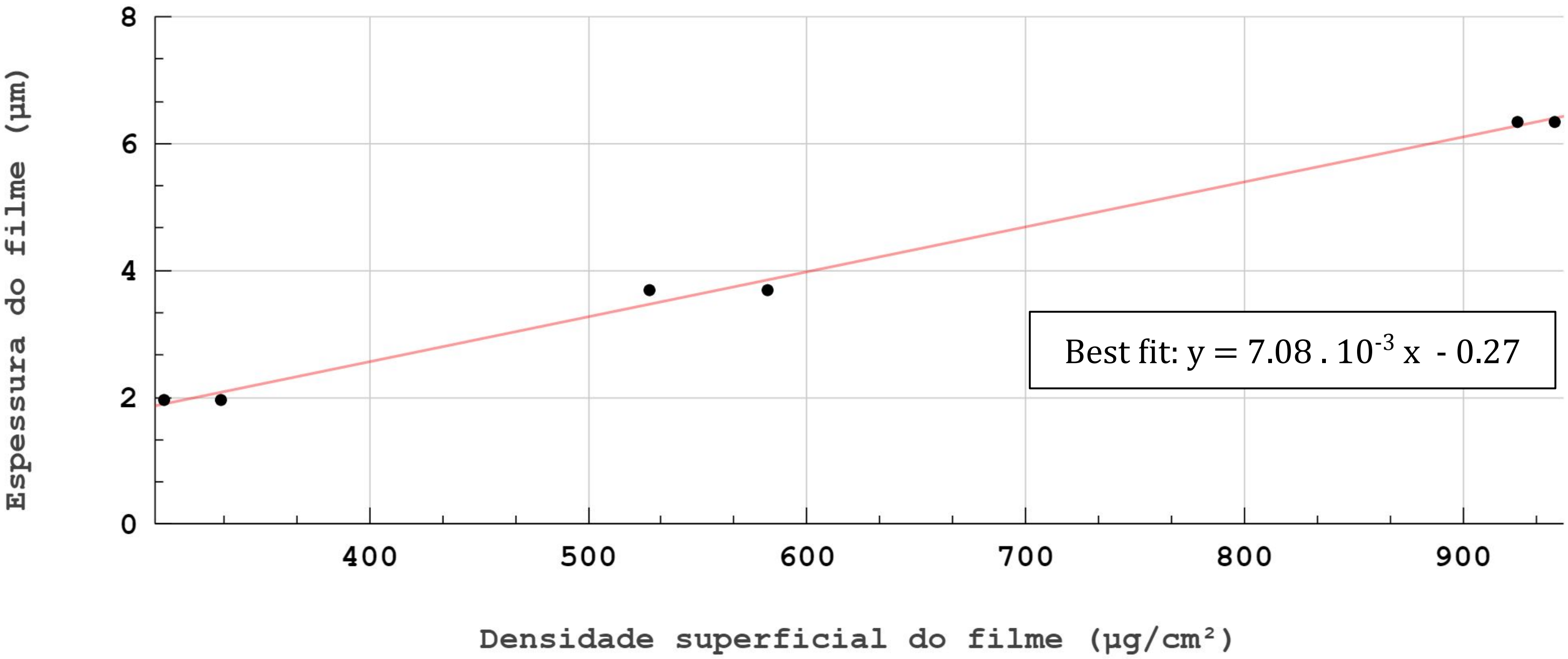
$$R_T = R_1 + 2T_1^2 R_2 A + T_1^3 R_2^2 A^2 + \ldots$$

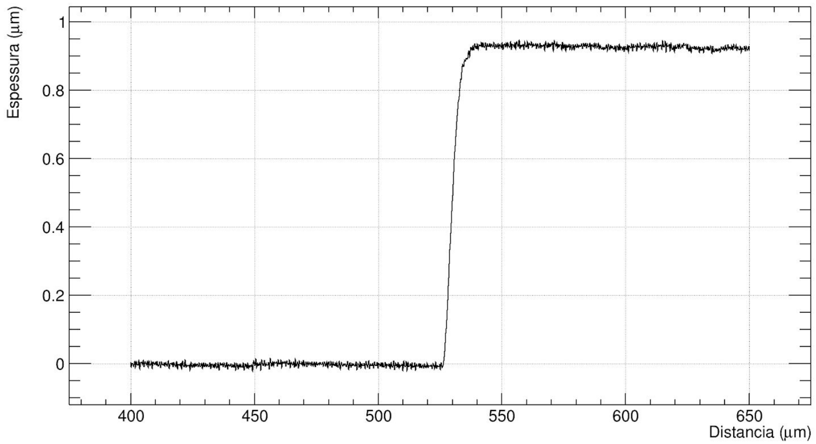
Knoop vs Vickers

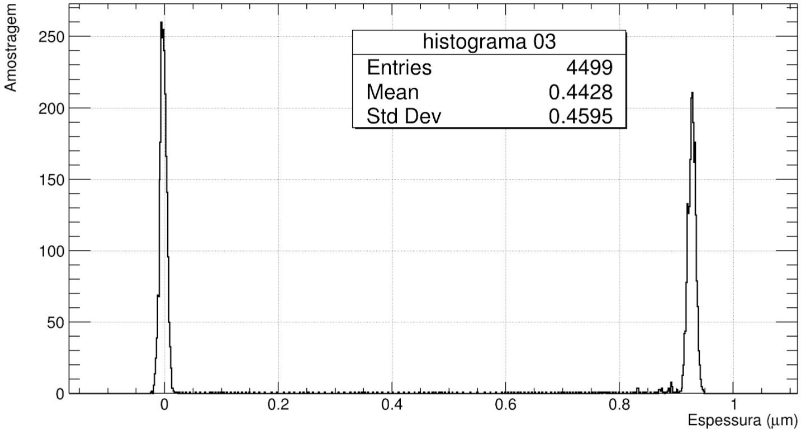
Both standards are used to measure the **surface hardness** of thin films. The Knoop standard is desirable due its resistance to form **surface cracks.**

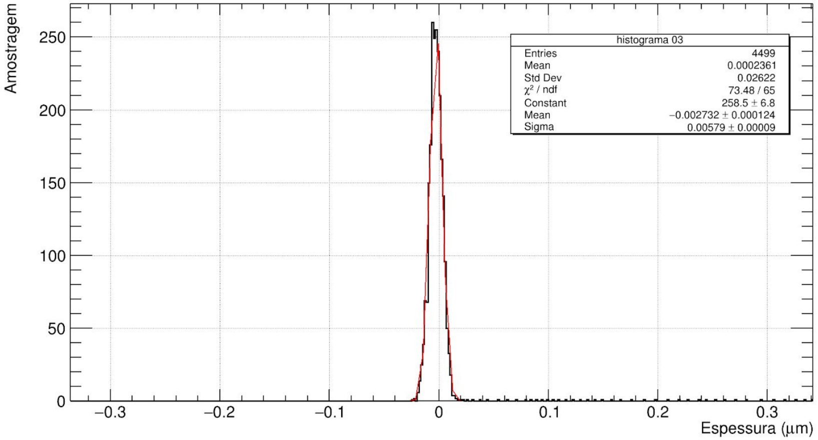


Surface density vs thickness – TPB



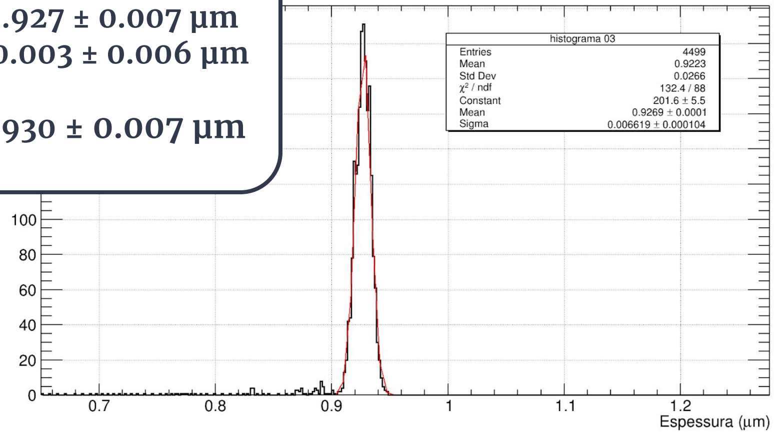




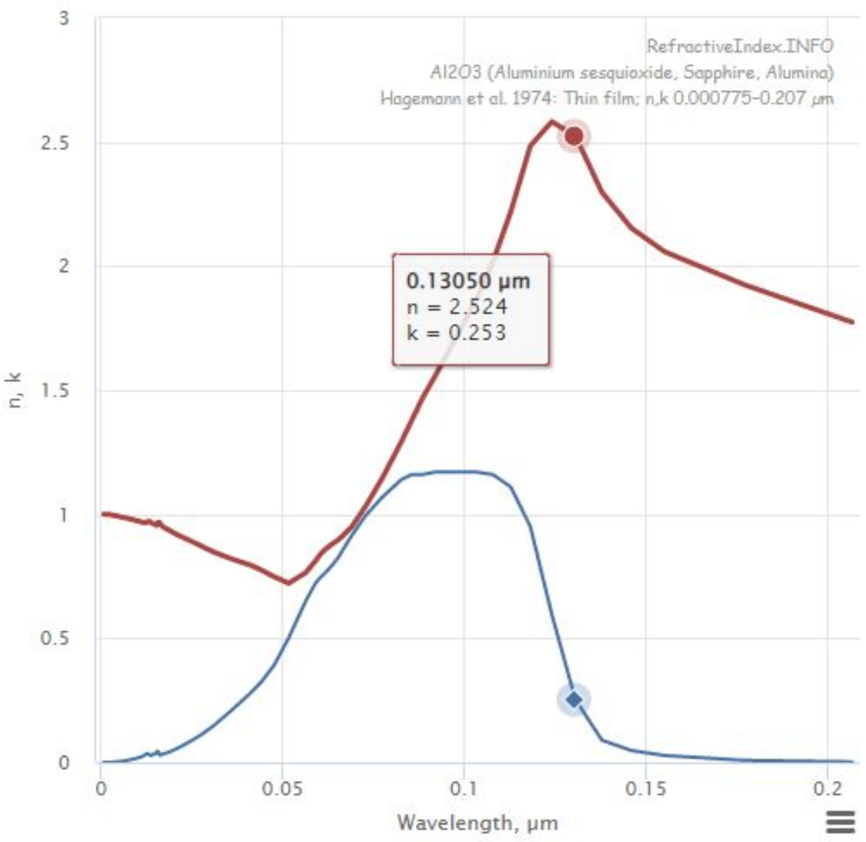


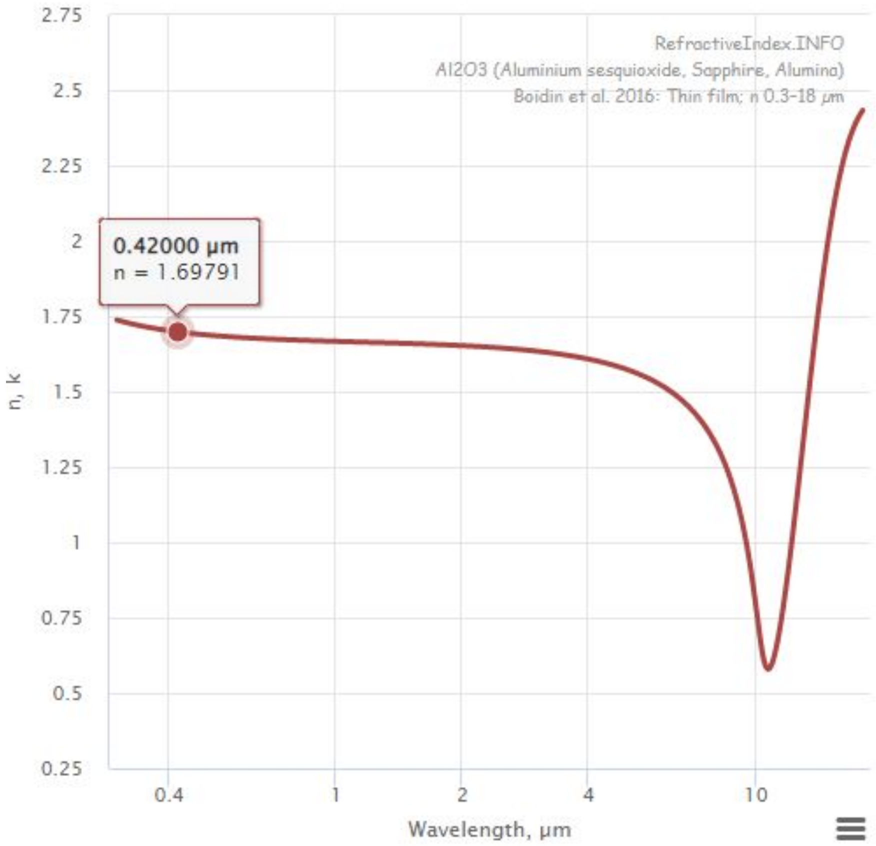
T = 0.927 ± 0.007 µm
B = −0.003 ± 0.006 µm

E = 0.930 ± 0.007 µm

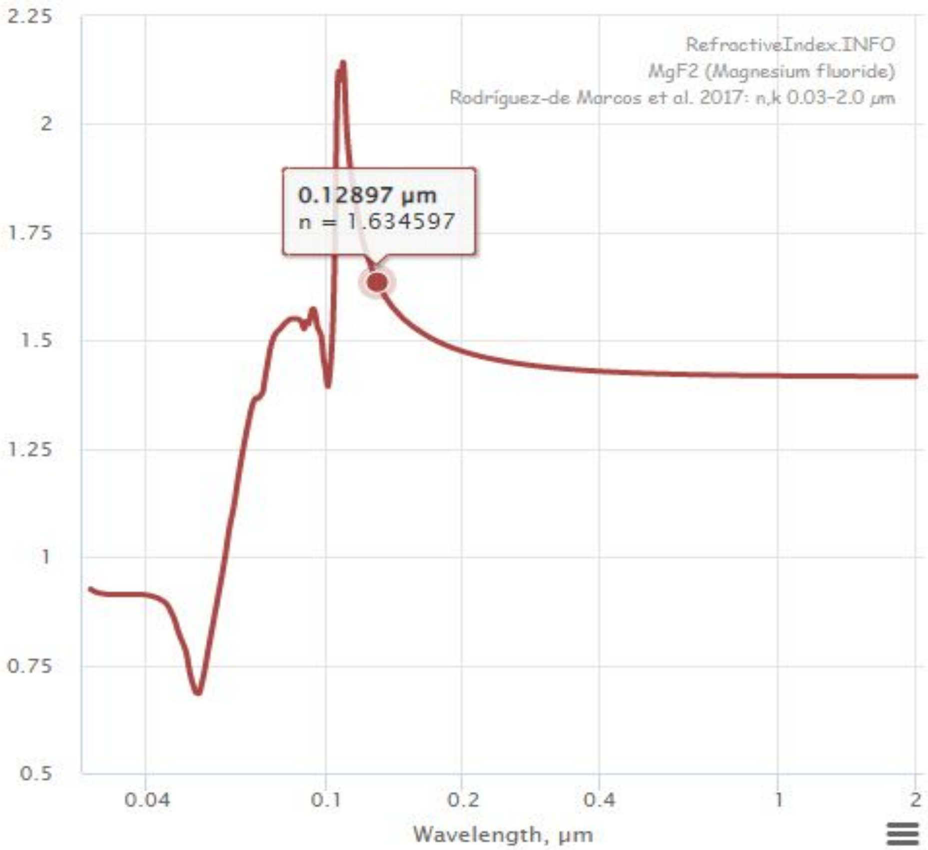


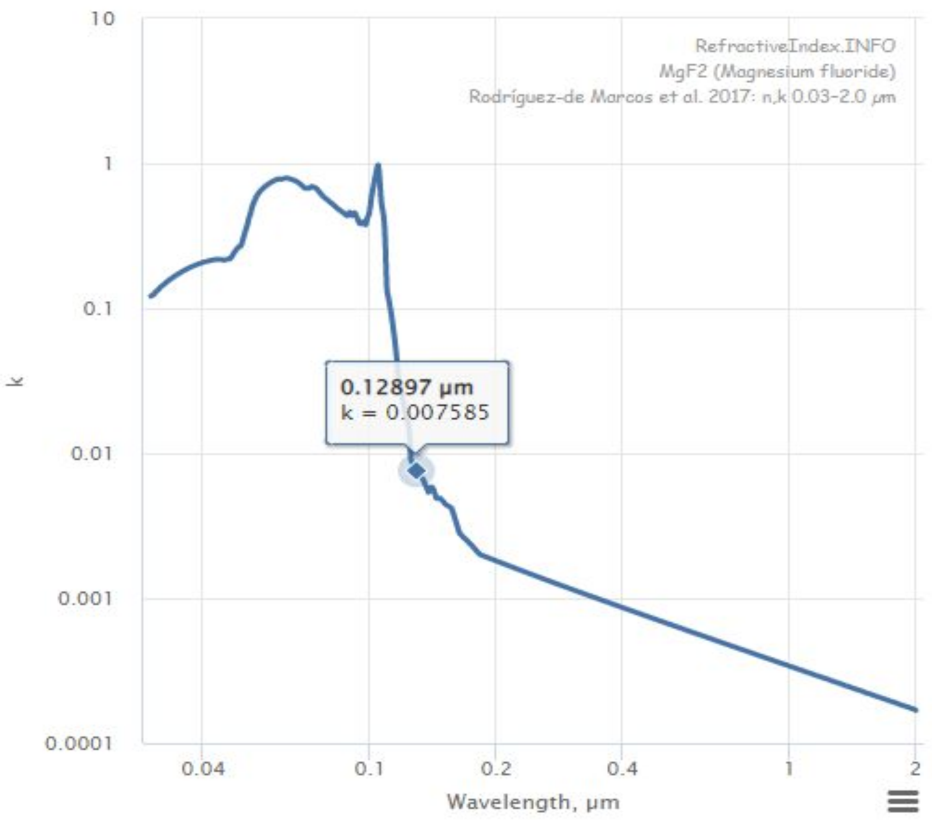
Aluminium Oxide

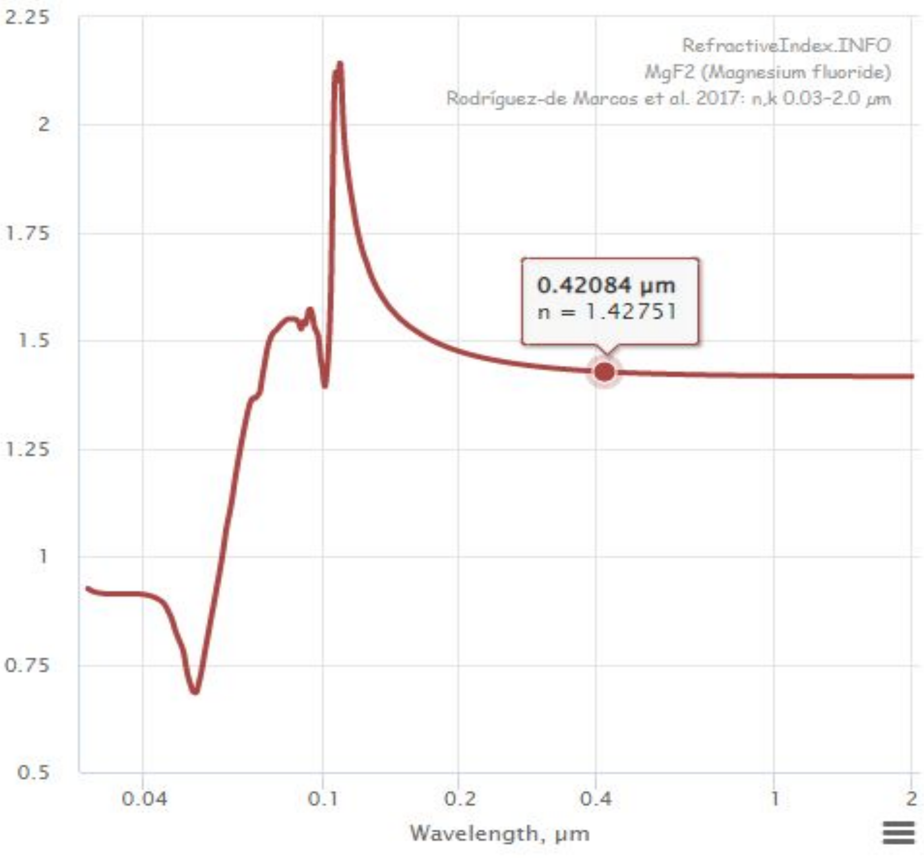


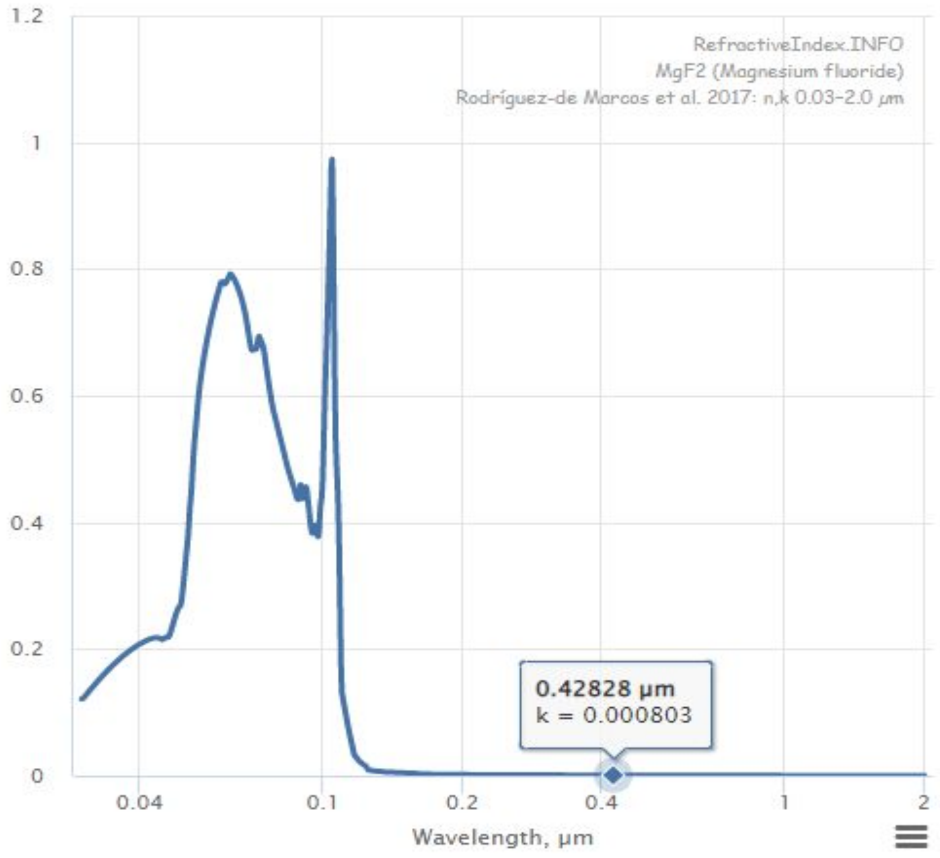


Magnesium Fluoride






RefractiveIndex.INFO
MgF2 (Magnesium fluoride)
Rodríguez-de Marcos et al. 2017: n,k 0.03-2.0 µm
0.42084 µm
n = 1.42751
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.04
0.1
0.2
0.4
1
2
Wavelength, µm


RefractiveIndex.INFO
MgF2 (Magnesium fluoride)
Rodríguez-de Marcos et al. 2017: n,k 0.03-2.0 µm
0.42828 µm
k = 0.000803
1.2
1
0.8
0.6
0.4
0.2
0
0.04
0.1
0.2
0.4
1
2
Wavelength, µm

Increase in light Collection

OSTI.GOV / Technical Report: *Basic Research Needs for High Energy Physics Detector Research & Development: Report of the Office of Science Workshop on Basic Research Needs ...*

Basic Research Needs for High Energy Physics Detector Research & Development: Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development: December 11-14, 2019

Full Record   Other Related Research

Research Plan

High-priority research activities for the future include the following:

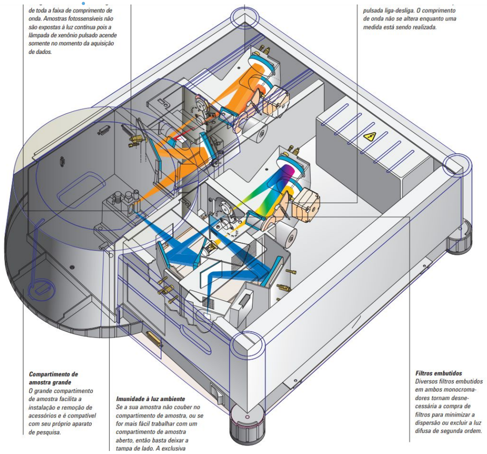
1. Increasing the light collected (most of which is emitted in the VUV range) over many tens to hundreds of square meters and improving the light detection efficiency of sensors, addressed in PRD 5, are crucial. Another important area of research is to enable high-efficiency wavelength-shifting techniques via novel thin films, fluorescent and scintillating structural materials, and dissolved atoms and molecules (the latter overlapping PRD 24 to some extent). In addition, the development of highly reflective surfaces over large detector components promises to greatly improve light collection efficiency.

Fleming et all. 2019. "Basic Research Needs for High Energy Physics Detector Research & Development: Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development: December 11-14, 2019". United States. https://doi.org/10.2172/1659761.

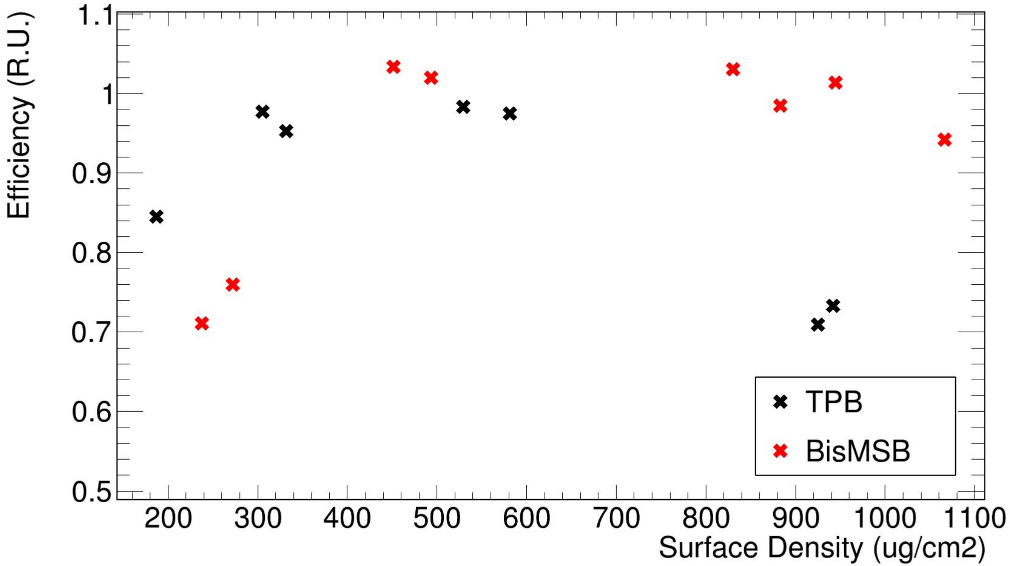
Efficiency vs Surface density – TPB

Using an *Agilent Cary Eclipse Fluorescence Spectrophotometer*:

Agilent Technologies
Innovating the HP Way



Technical University of Munich



Thanks to Gabriela and the group for helping with this measurements!

Refractive index – VUV

Table 1. Fundamental properties of common WLS materials used in LAr detectors: peak emission wavelength (λ_{em}), PLQY, re-emission lifetime (τ), refractive index (n), vapour pressure (p_{sat}), and approximate sublimation temperature (T_m).

Wavelength shifter	λ_{em} [nm]	PLQY @ 128 nm	τ [ns]	n	p_{sat} [mbar]	T_m [°C]	Comment
TPB	430	0.6 [25]–2 [26]	2	1.7	10^{-11}	204	
p-Terphenyl	350	0.82 [27]	1	1.65		213	PLQY @ 254 nm
bis-MSB	440	0.75–1 [28,29]	1.5	1.7		180	PLQY rel. to TPB
pyrene	470	0.64 [30]	155	1.8	$6 \cdot 10^{-6}$	150	PLQY @ 260 nm
PEN	420	0.4–0.8 [31]	20	1.75	–	270	PLQY rel. to TPB

Kuźniak M, Szelc AM. Wavelength Shifters for Applications in Liquid Argon Detectors. Instruments. 2021; 5(1):4. https://doi.org/10.3390/instruments5010004