High-performance Dichroic Filters for Large-Scale Neutrino Detector

CPAD 2024, Knoxville

Outline

- Introduction on dichroic interference filters
- Technique of Atomic Layer Deposition
- Filter Performance
- Status of R&D for production

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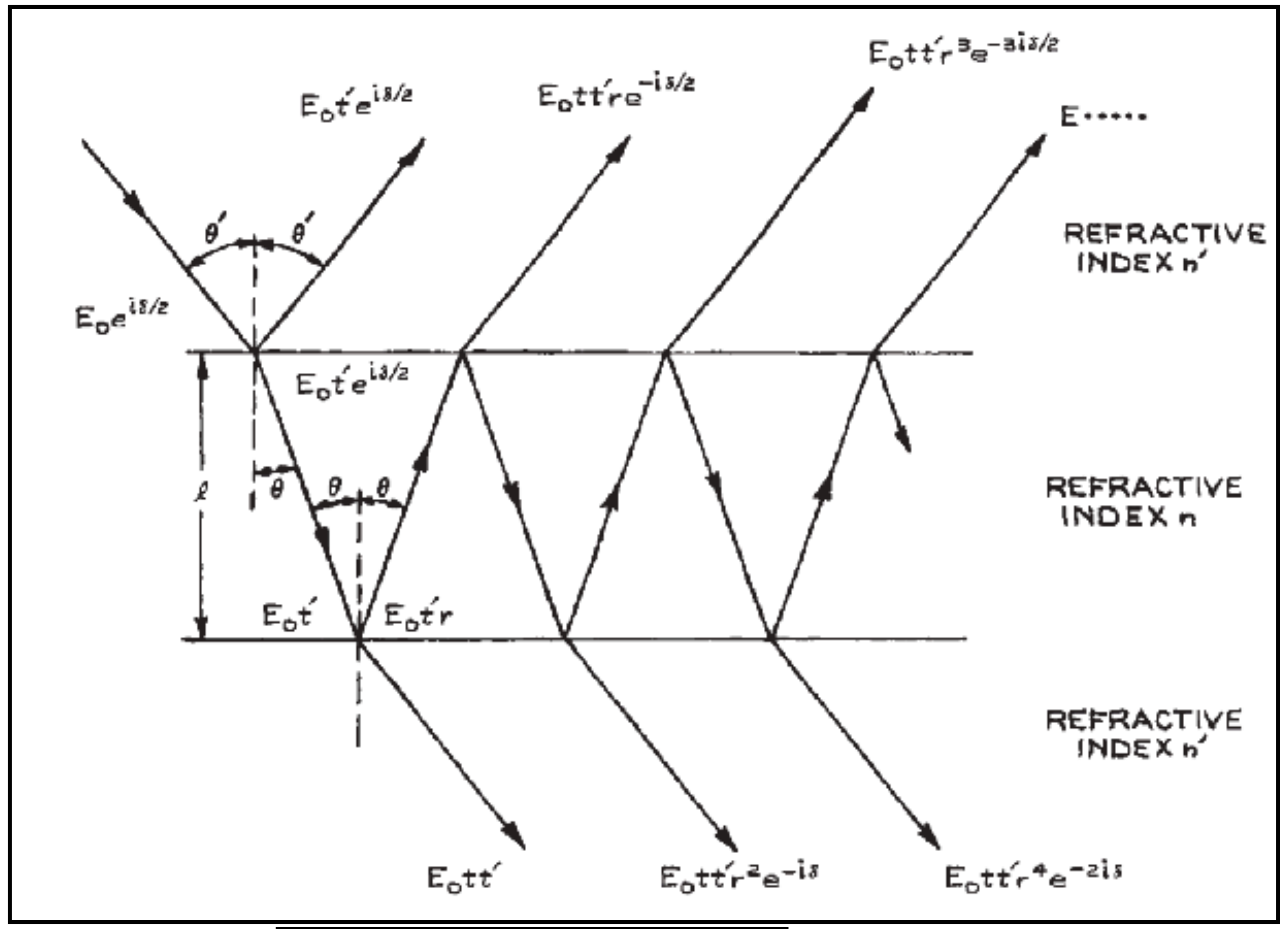
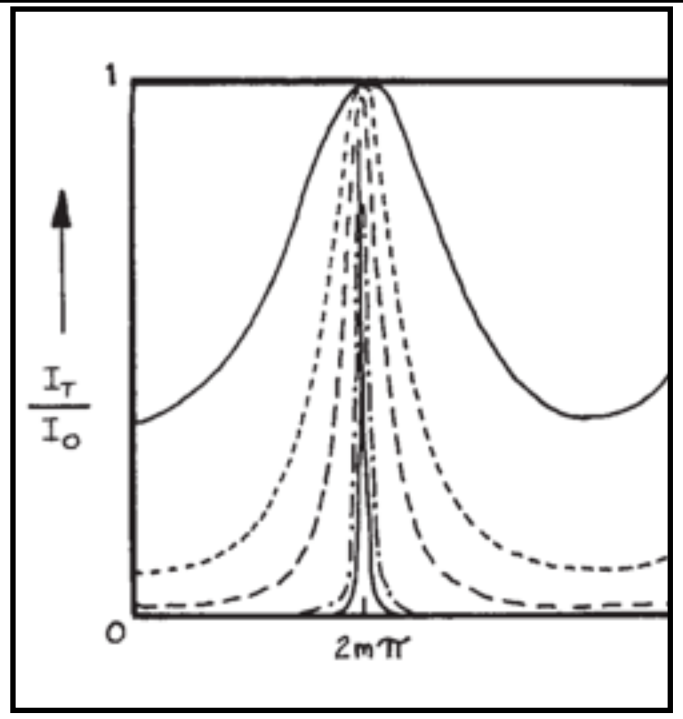
Thanks to

RAYTUM Photonics

Reminder of interference filters

Basics of an etalon or two parallel mirrors.





Moore, Coplan, Davis

- If phase shift and absorption is neglected on interfaces.

$$\frac{I_T}{I_0} = \frac{1}{(1 + \frac{4R}{(1-R^2)} \sin^2 \delta/2)}$$ where R is the reflectivity and

$$\delta = 2kl\cos\theta$$

- Transmission maxima happen when

$$l = \frac{m\lambda}{2\cos\theta}$$

- For a fixed thickness, max wavelength will move lower with angle.
- There will be transmission peaks at l/m values.
- A stack of etalons can be modeled by software to create a bandpass filter. Each etalon is made of a high quality dielectric layer with different index of refraction.

How does one deposit the layers ?

There are many techniques; but the state of the art is consider atomic layer deposition.

Unique Advantages of ALD vs Physical vapor deposition(PVD)

1. Precise and easy thickness control in a monolayer scale over established PVDs for high performance optical filter fabrication
2. Excellent uniformity (<0.1-1%) for fabricating large area optical components.(up to sub-meters)
3. Super conformity on Non-planar optical surface and components.
4. Low temperature process on plastics by energetic ALD.
5. Continuous and pin hole free.
6. Diversity of materials for DF designs.
7. Low maintenance cost and high volume manufacture is established.

https://www.veeco.com/products/savannah-thermal-ald-for-rd/

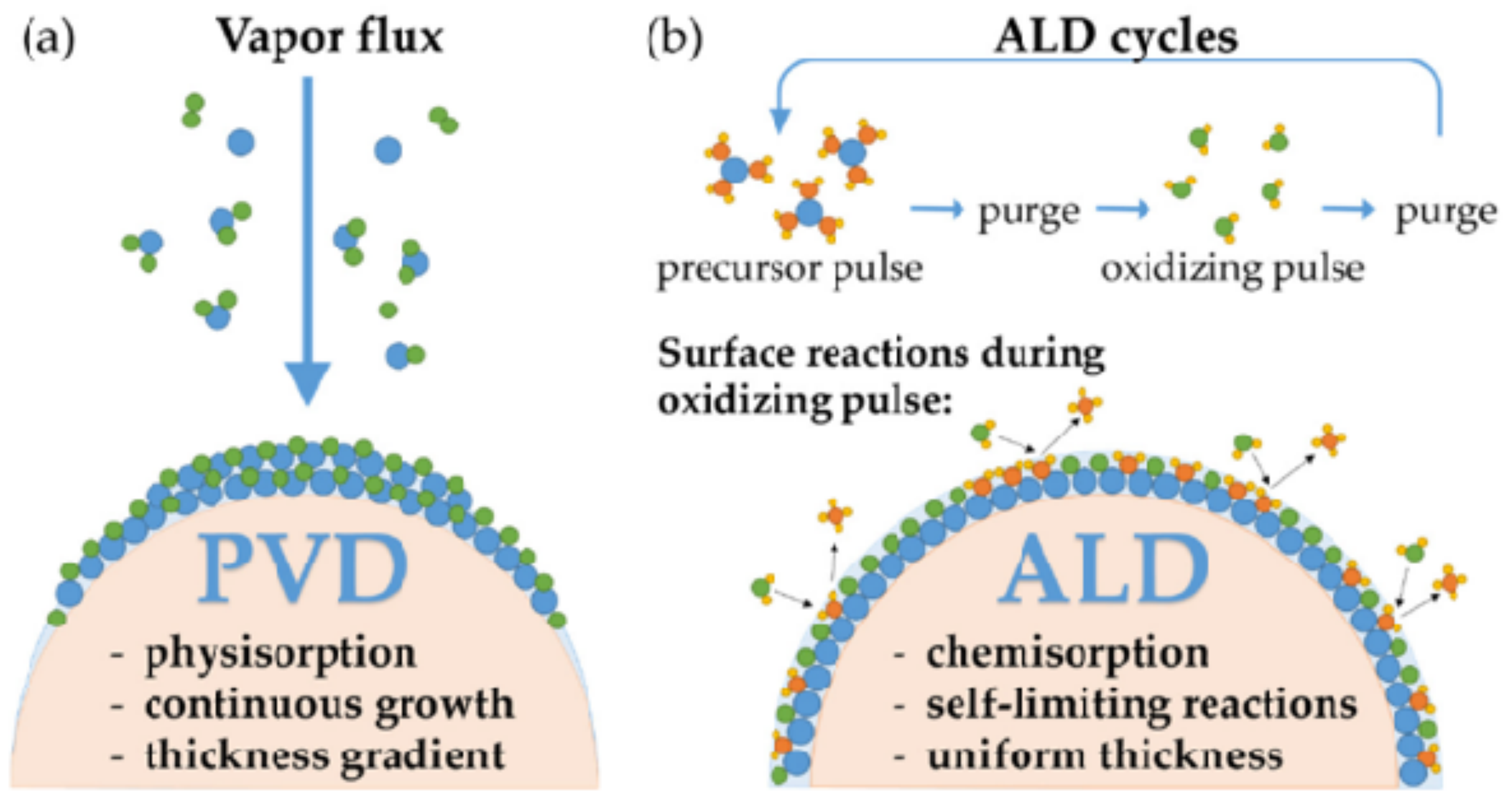
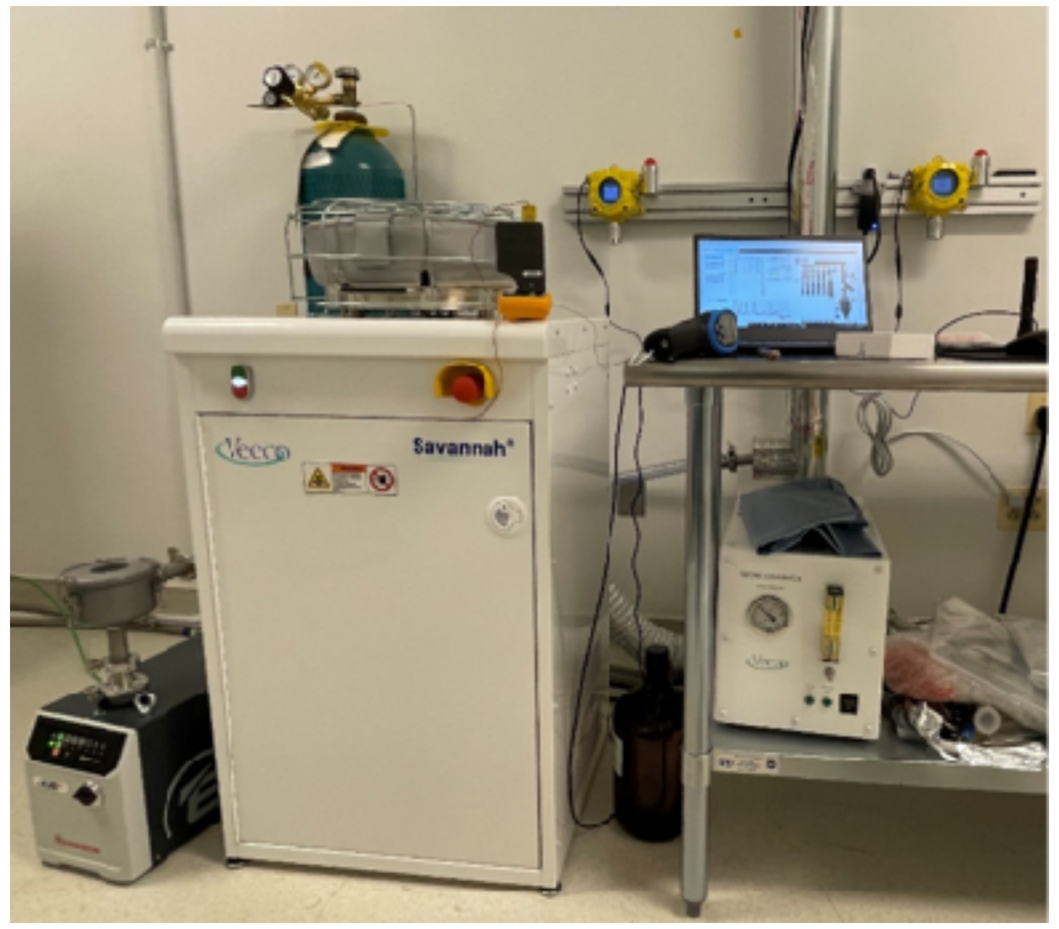


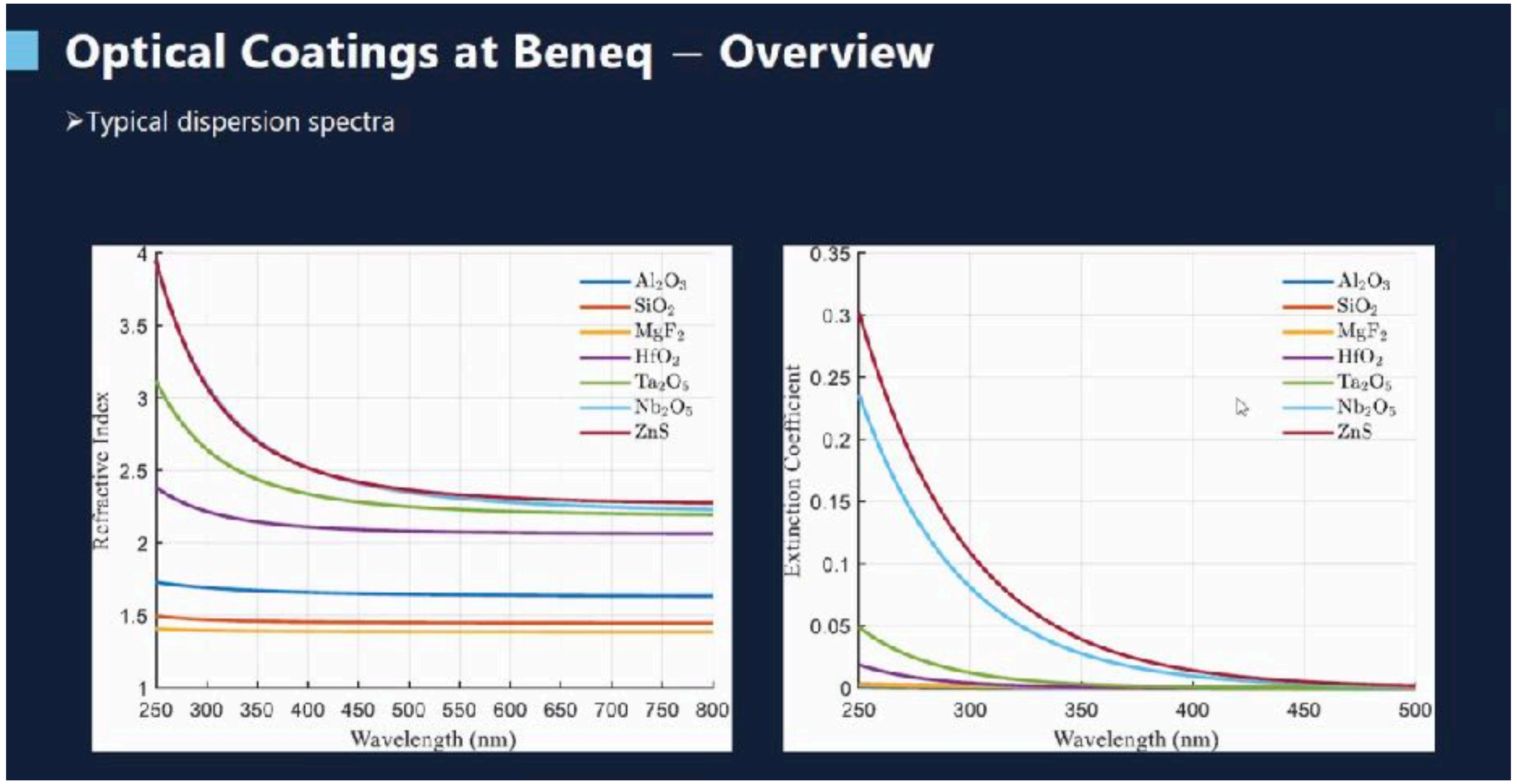
Figure 1. Illustration of **(a)** physical vapor deposition (PVD) deposition and **(b)** atomic layer deposition (ALD) on a hemispherical lens.



Key technical issues

Coating materials (high and low index), Substrate and stresses.

Materials	Coefficient of line expansion(×10-6/°C at RT)	Refractive index at 500nm
TiO2	9.19(//C); 7.14(^C)	2.54
Al2O3(sapphire)	6.7((//C); 5.0(^C)	1,77
SiO2(fuse silica)	0,55	1,46
Si	4,2	
N-BK7	7,1	1,52
Borofloat (borosilicate from SCHOTT)	3,25	1,52
Soda lime glass	8,1 4	1,528



- *There are other optical materials also, but practical list is limited.*
- *Substrate has to be chosen so that the CTE is reasonably matched to both coatings.*
- *The problem with fused silica is the mismatch of CTE. But this is getting resolved.*

R&D Project Timeline and Scope

BNL and Raytum collaboration

- R&D project was proposed in 2021 with Understanding the scientific requirements.
    - A miniworkshop was organzied with both liquid argon and water based liquid scintillator experts Oct 17, 2022
  - Development of test samples from Raytum adapting ALD technology.
  - Testing of samples in real conditions for
    - Material compatibility, Handling issues, Detector performance
  - Understanding requirements for large scale production.
  - Preliminary development of production techniques.

The entire scope has been accomplished. However, it would be best to use the produced filters in a real detector setup.

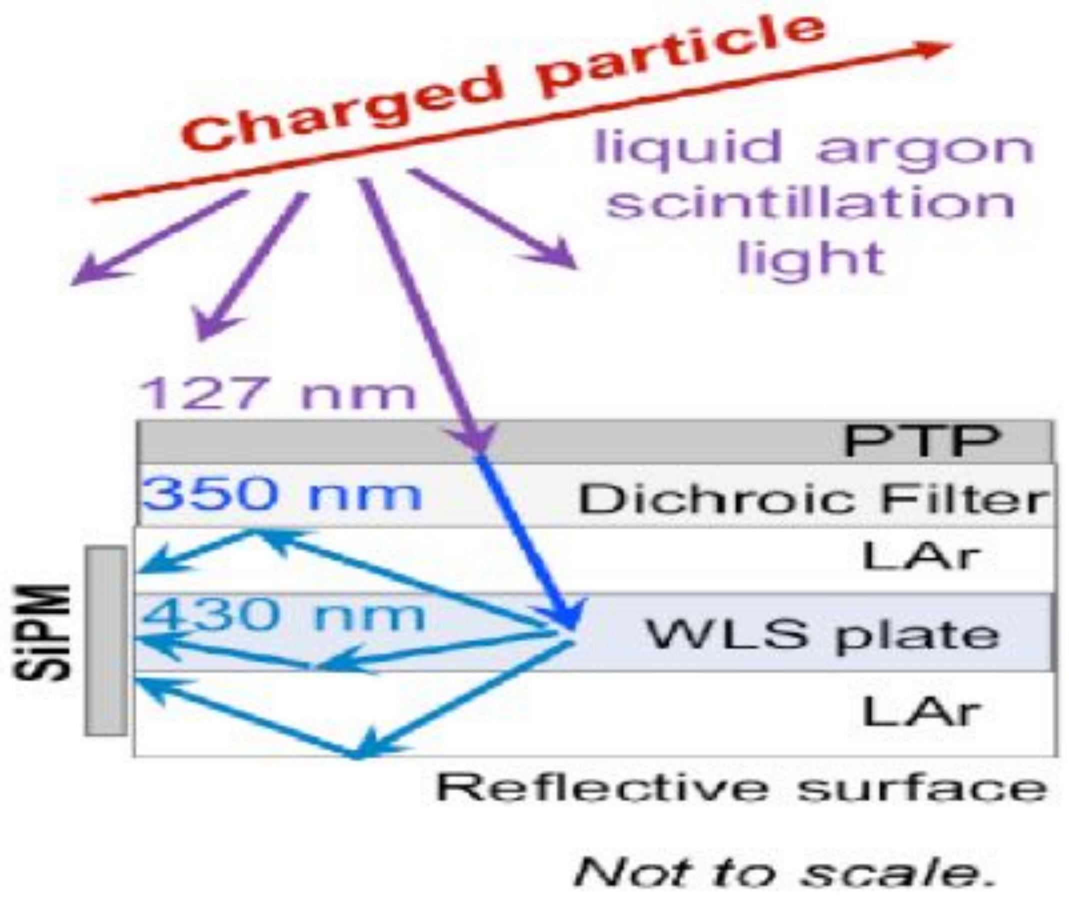
Design/ variations/ and production technique are all in hand

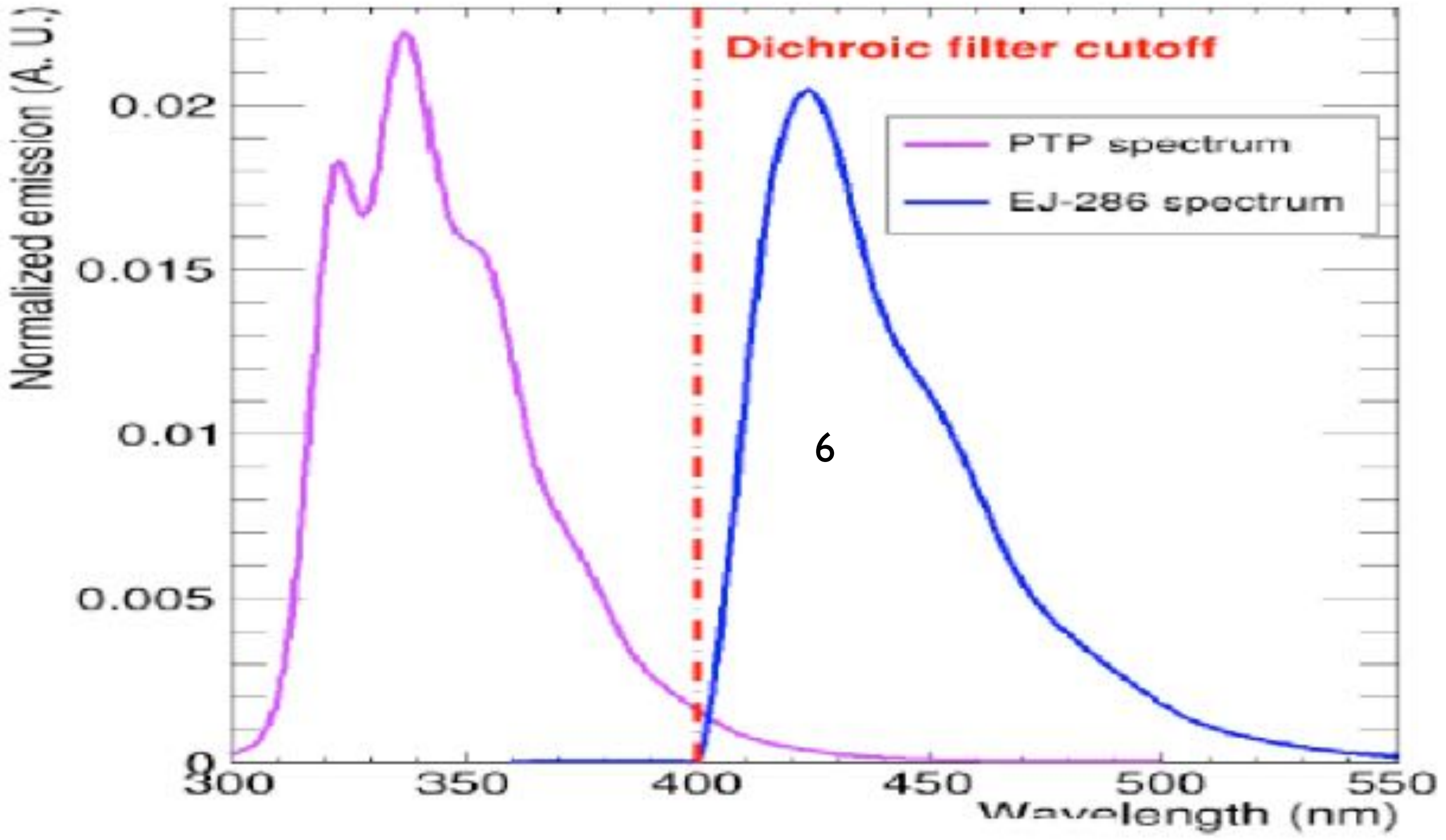
Technical Challenges

1. Down-select ALD materials (low index(L), high index(H) with optical properties like n, k, optical loss as well as mechanical properties comparable with or better than well-qualified optical coating material by PVD.
2. Demonstrate a single layer ALD process with excellent uniformity on larger area using our innovative step rotation mechanism.
3. Fabricate multilayer filters based on our design with precise thickness monitoring and stress management.
4. Evaluate small optical absorption and scattering loss and filter performance setup and modelling refinement and process optimization.
5. Identify or modify an ALD tool from R&D for future volume production at low cost, such as spatial ALD or larger batch process ALD.

DUNE

Liquid Argon ARAPUCA detector concept and roles of DFs



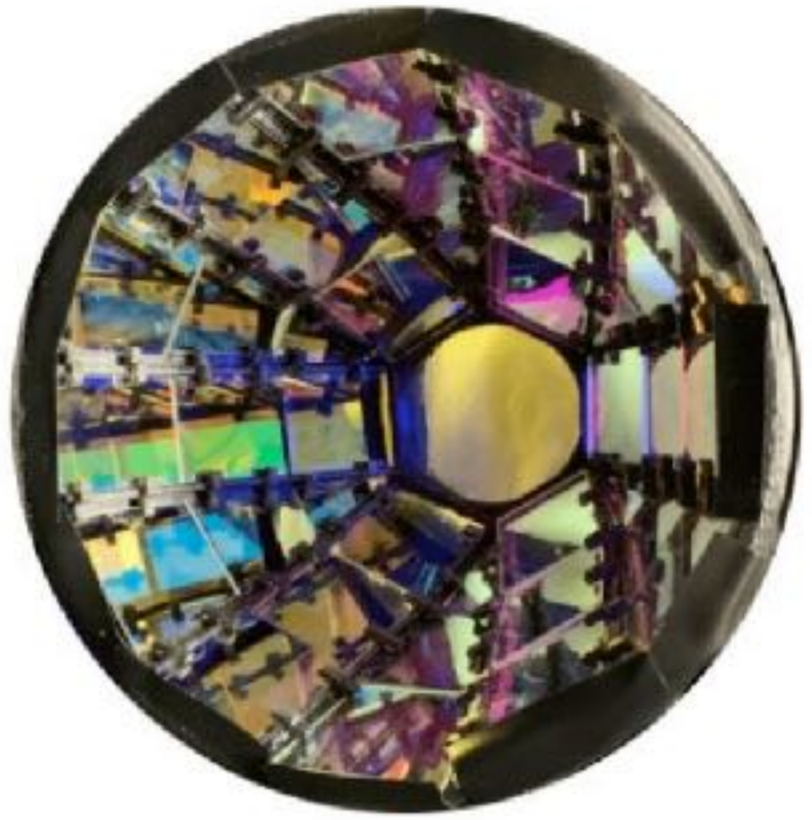


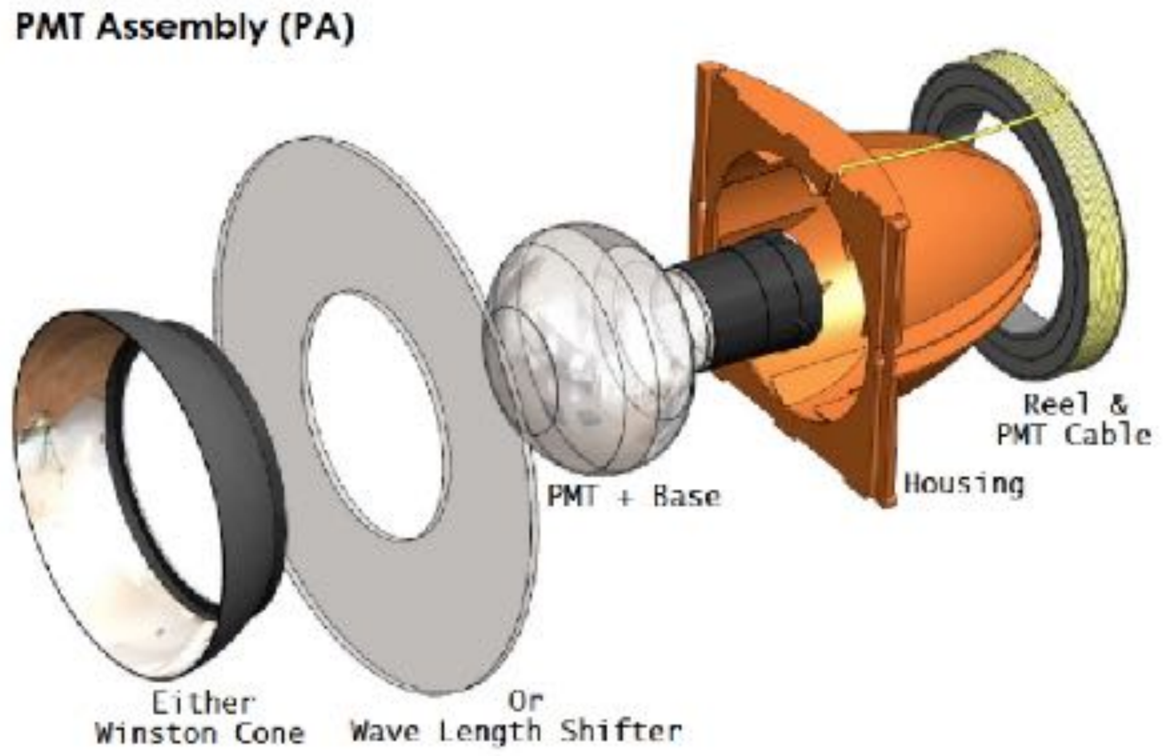
(Polymer EJ-286 WLSP)

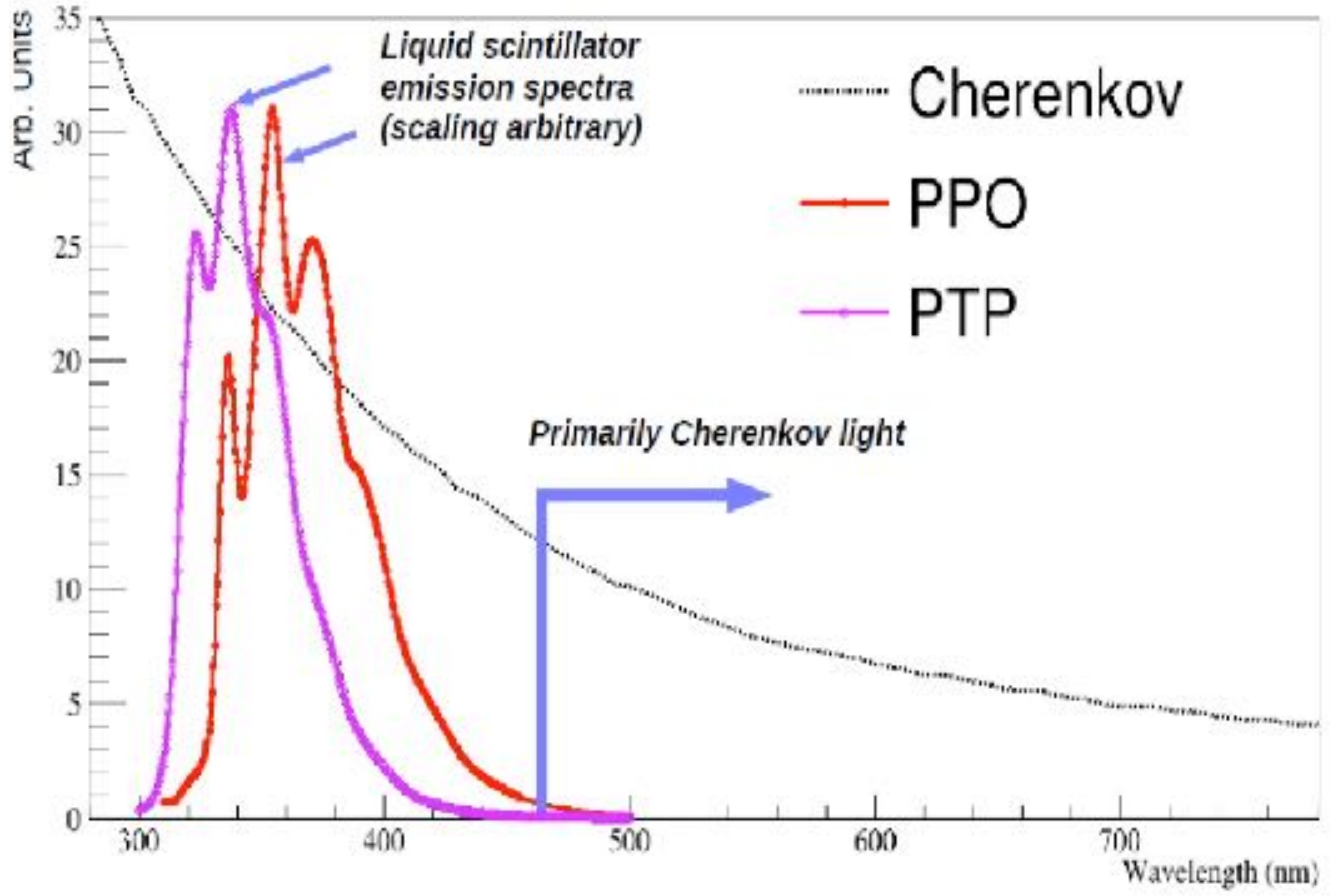
The dichroic cutoff (red dashed line), the PTP (purple) and the EJ-286 emission spectra. (b) X-ARAPUCA principle of work, with total internal refl ection and the refl ective cavity trapping photons.

THEIA

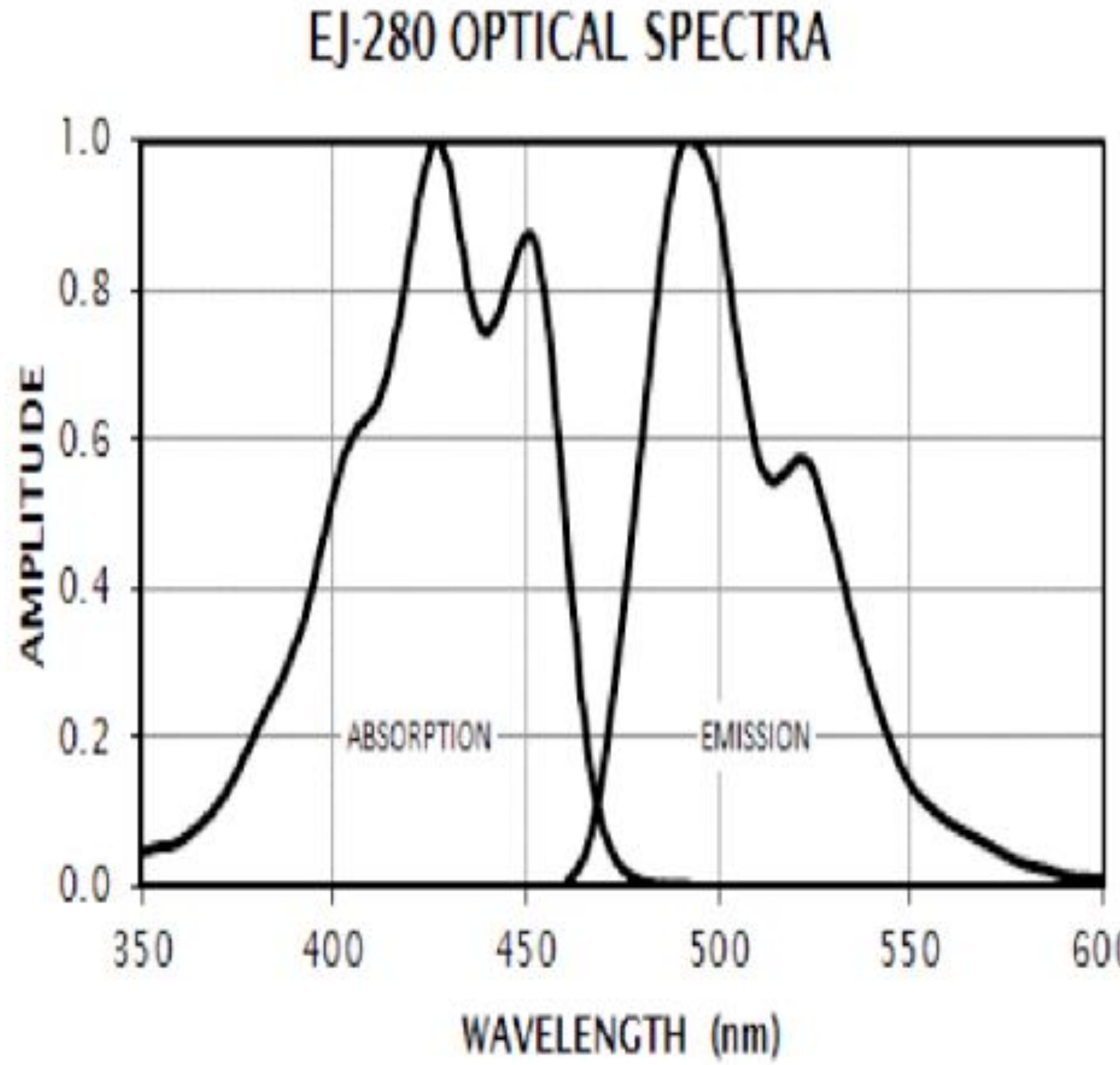
Winston cone(WC) /wavelength shifting plates(WLSP) type of detector concept and roles of DFS







Goal is to achieve Cherenkov and scintillation separation while losing as few total photons as possible.



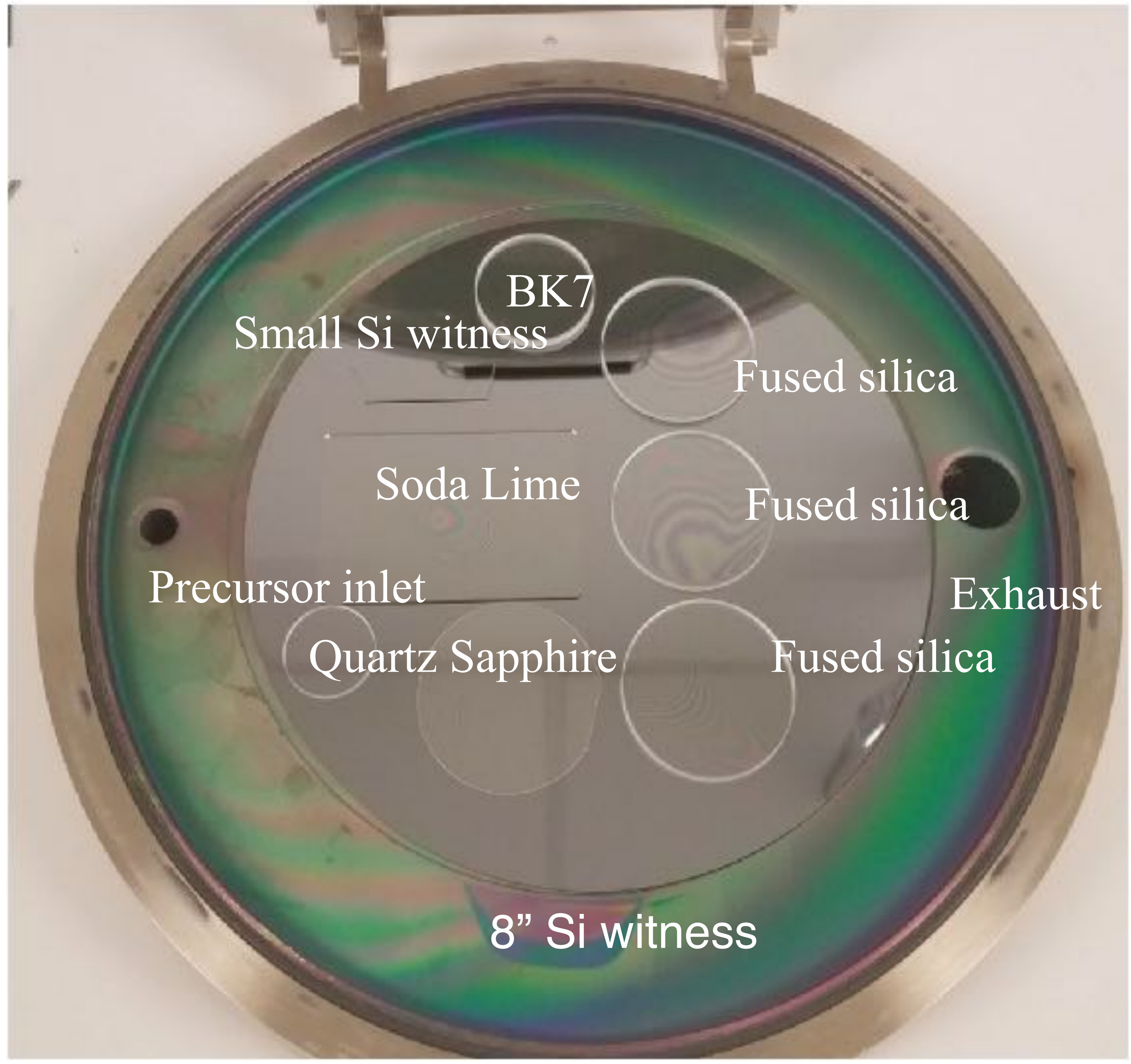
The SP filters tile the barrel of the Winston cone and a central LP filter is placed at the aperture. A small amount of black electrical tape is used to block a small gap between the filters and the holder at the top of the dichroicon .

Significant Technology Breakthrough from Raytum Photonics, What has been achieved.

RAYTUM Photonics

- Large Area Coating using ALD Technology has been achieved. Long/Short pass filters in UV band are successfully demonstrated over different substrates. The results match with the design very well.
- Extremely low absorption, only tens of ppm for 68 layers of coating , was confirmed by PCI technique.
- The uniformity as low as 0.12% has been achieved.
- By optimizing the coating process, the production rate could be greatly improved.
- The fabrication of Long/Short pass filters been performed. And I will provide some results.

Long-pass Filter Fabrication using ALD



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Coated samples sitting inside the chamber of ALD coater

The transparency of a coated sample is fully evident, indicating the remarkably low absorption of the coating.

ALD coating layers

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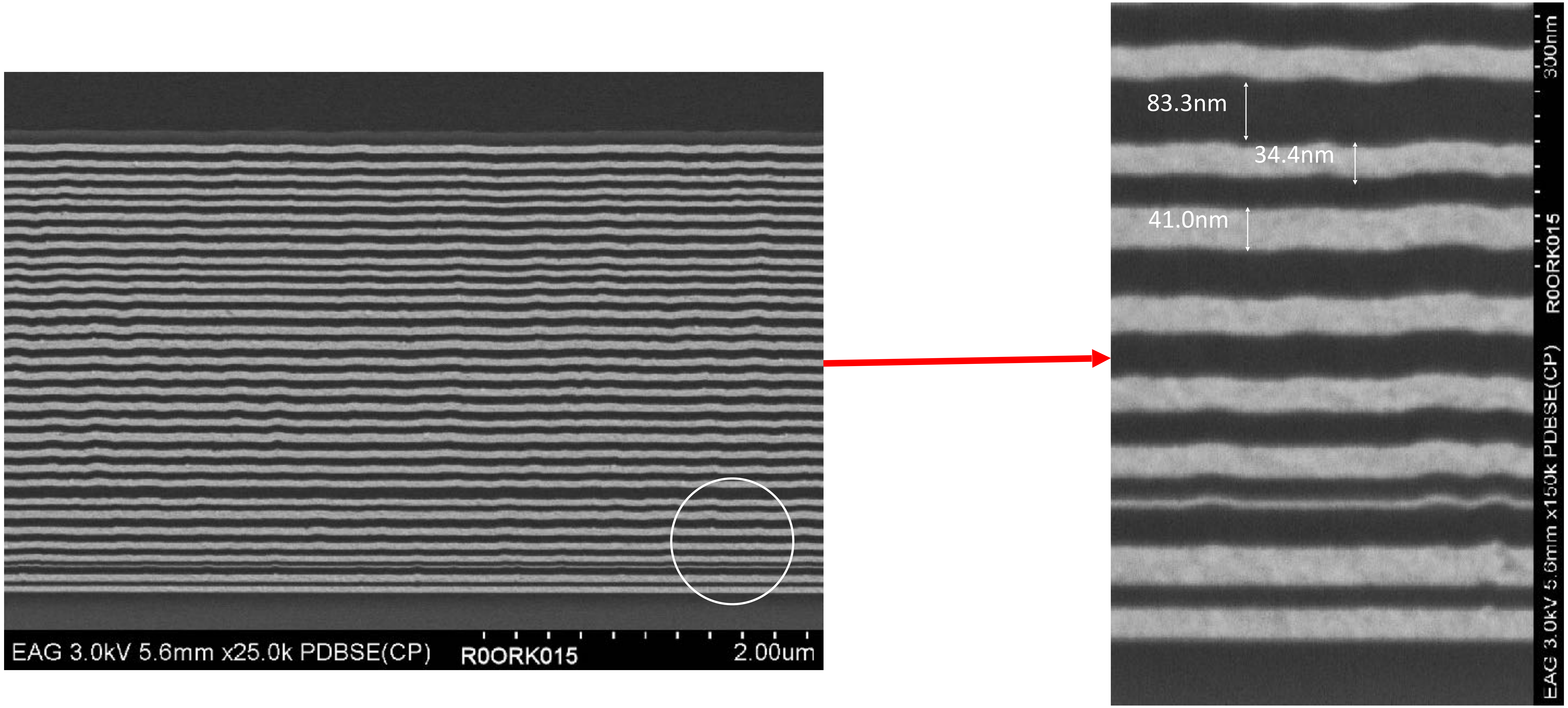
Cross sectional SEM imaging of a full long pass Dichroic filter consisting of 64 total layers

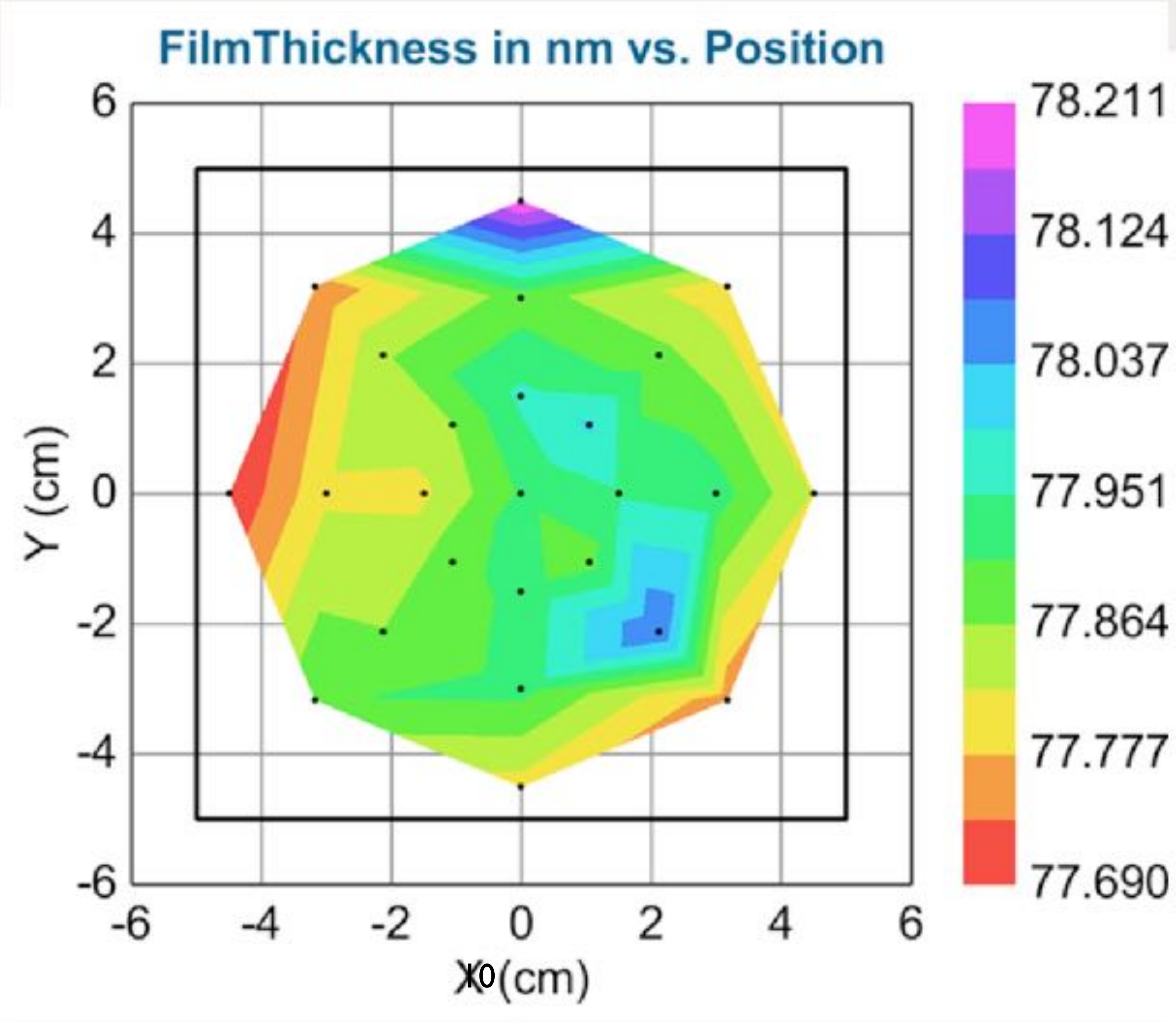


Dark band: dielectric material #1

Light band: dielectric material #2

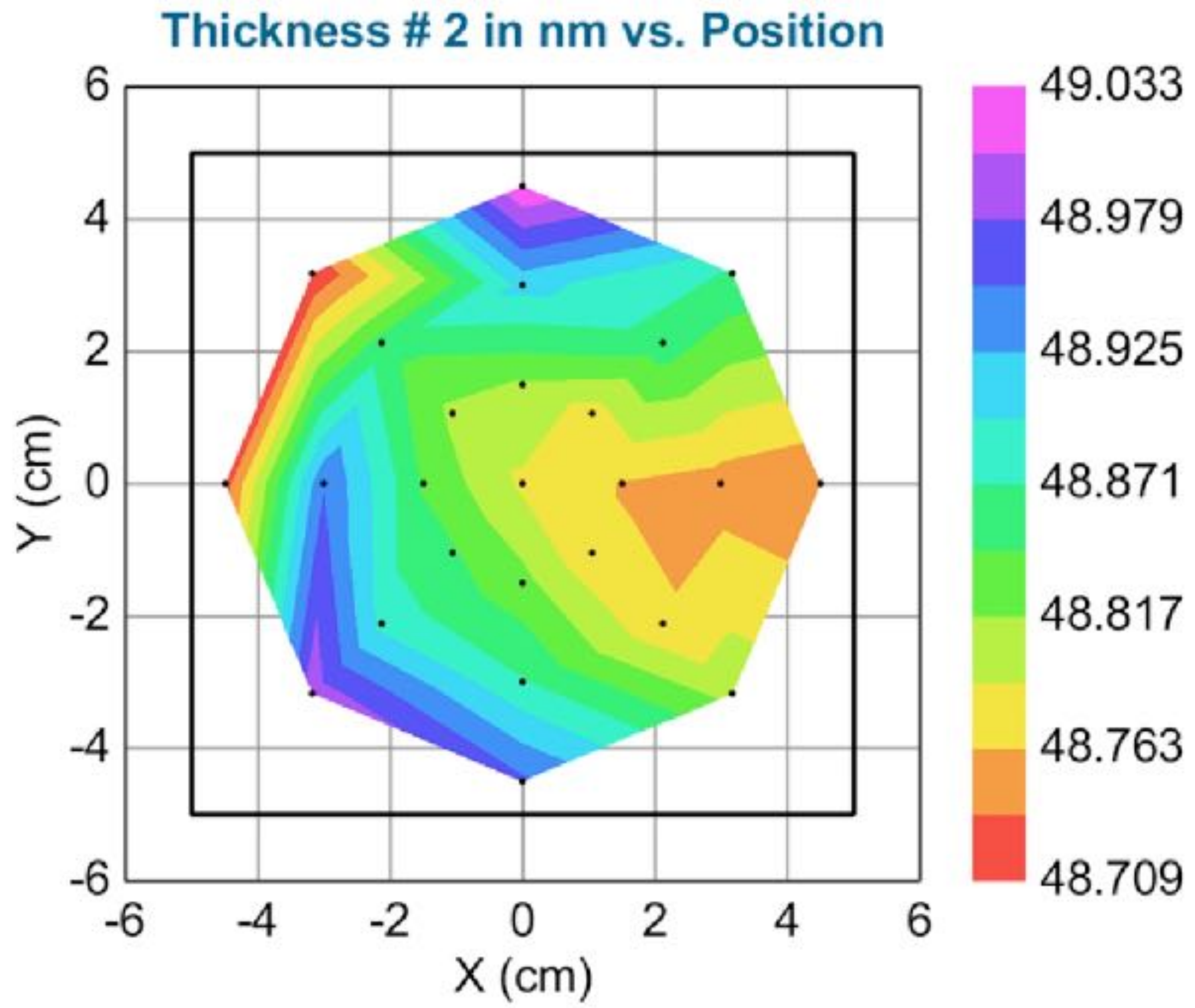
Measurements are calibrated by a standard sample, estimated measurement error (±1nm).

Coating Uniformity Measurement



Parameter	Average	Std. Dev.	Slope	Min	Max	Range
Thickness in nm	77.88561	0.10829	0.12%	77.69048	78.21082	0.52035

Low Index Material



Parameter	Average	Std. Dev.	Slope	Min	Max	Range
Thickness in nm	48.83677	0.08485	0.17%	48.70925	49.03308	0.32383

High Index Material

Performance of Long-pass Edge Filters Made by ALD

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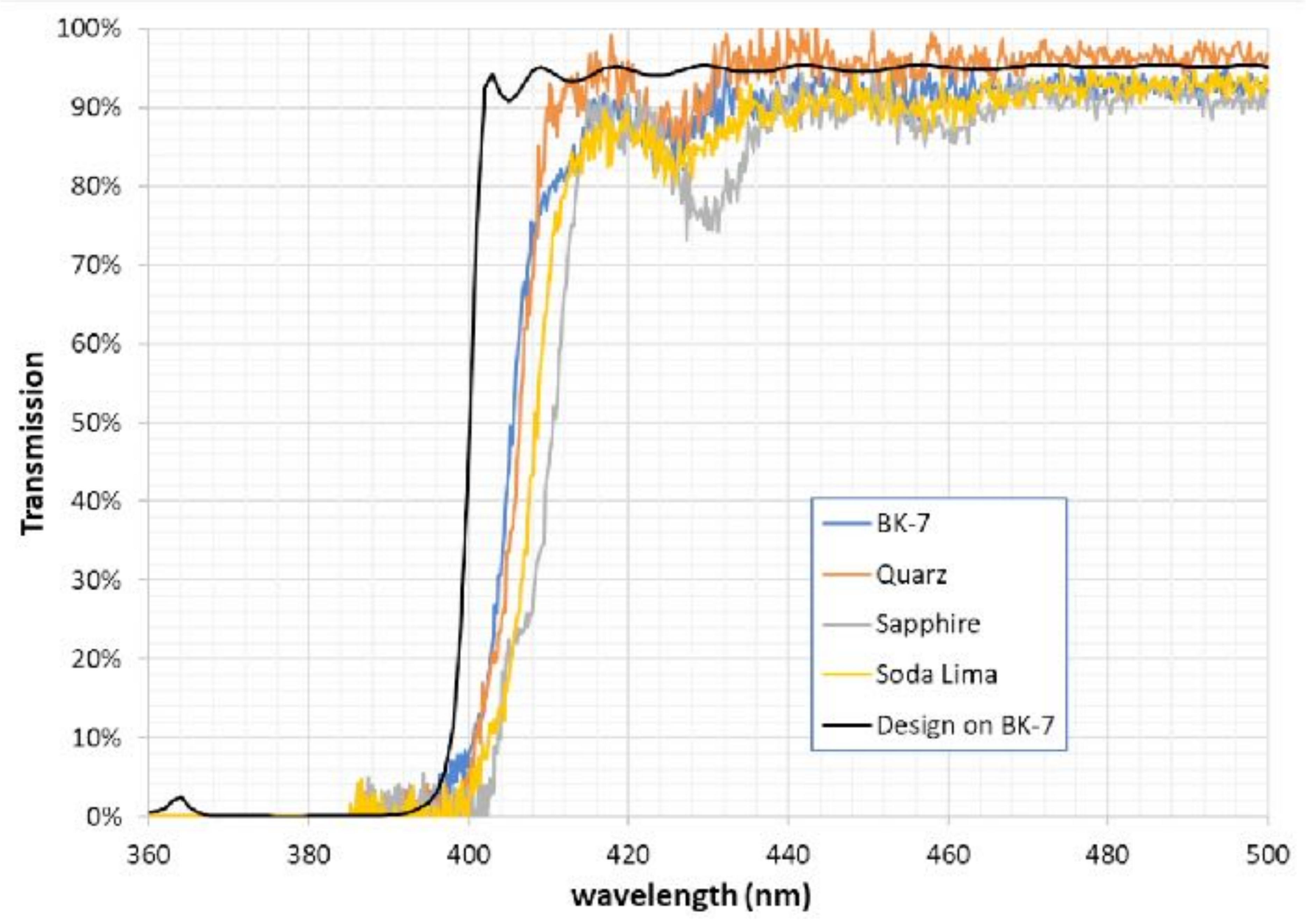
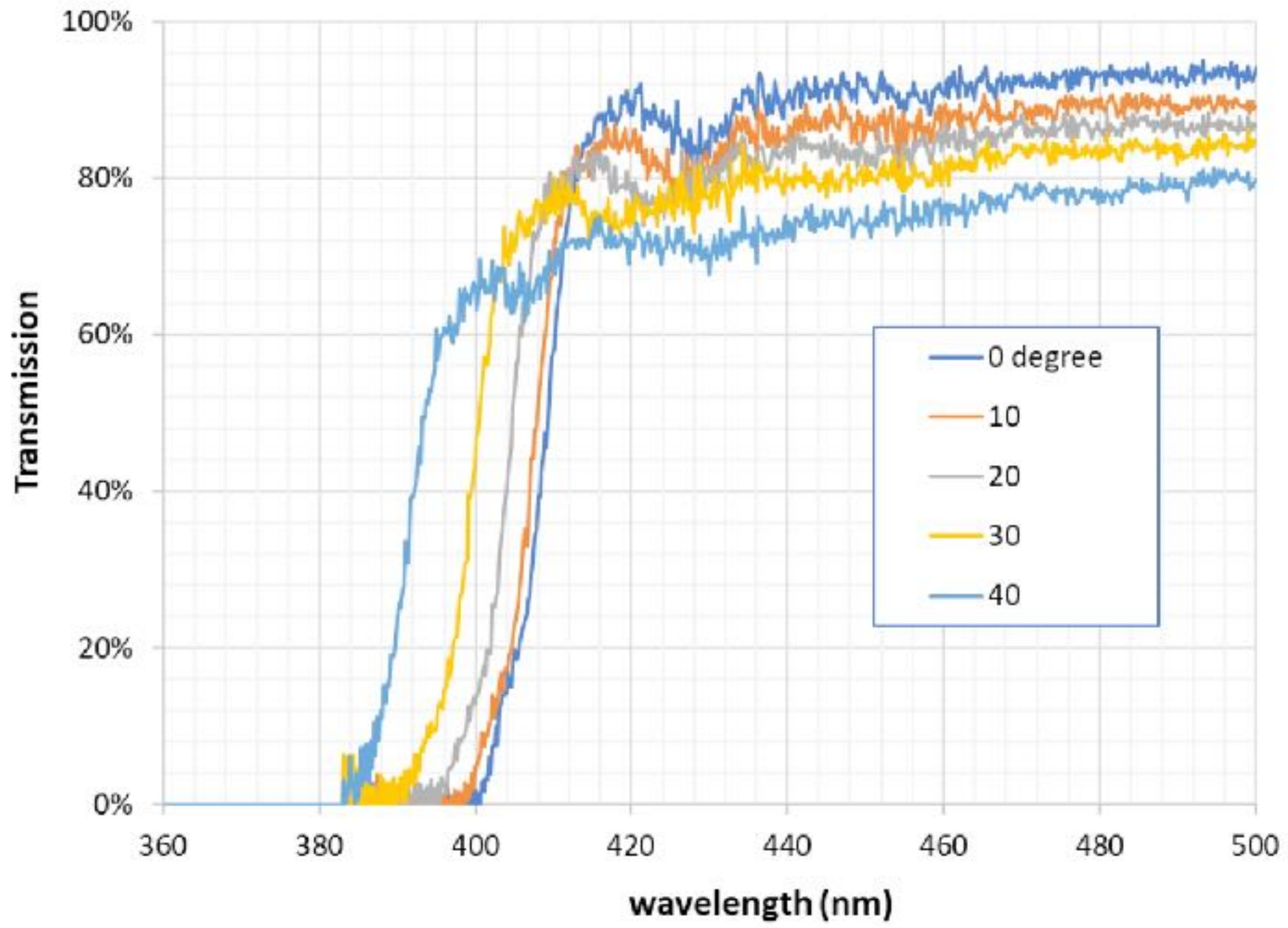
0 ° AOI measurement, coated over different substrates



transmission of filter over Soda-lima, different AOI

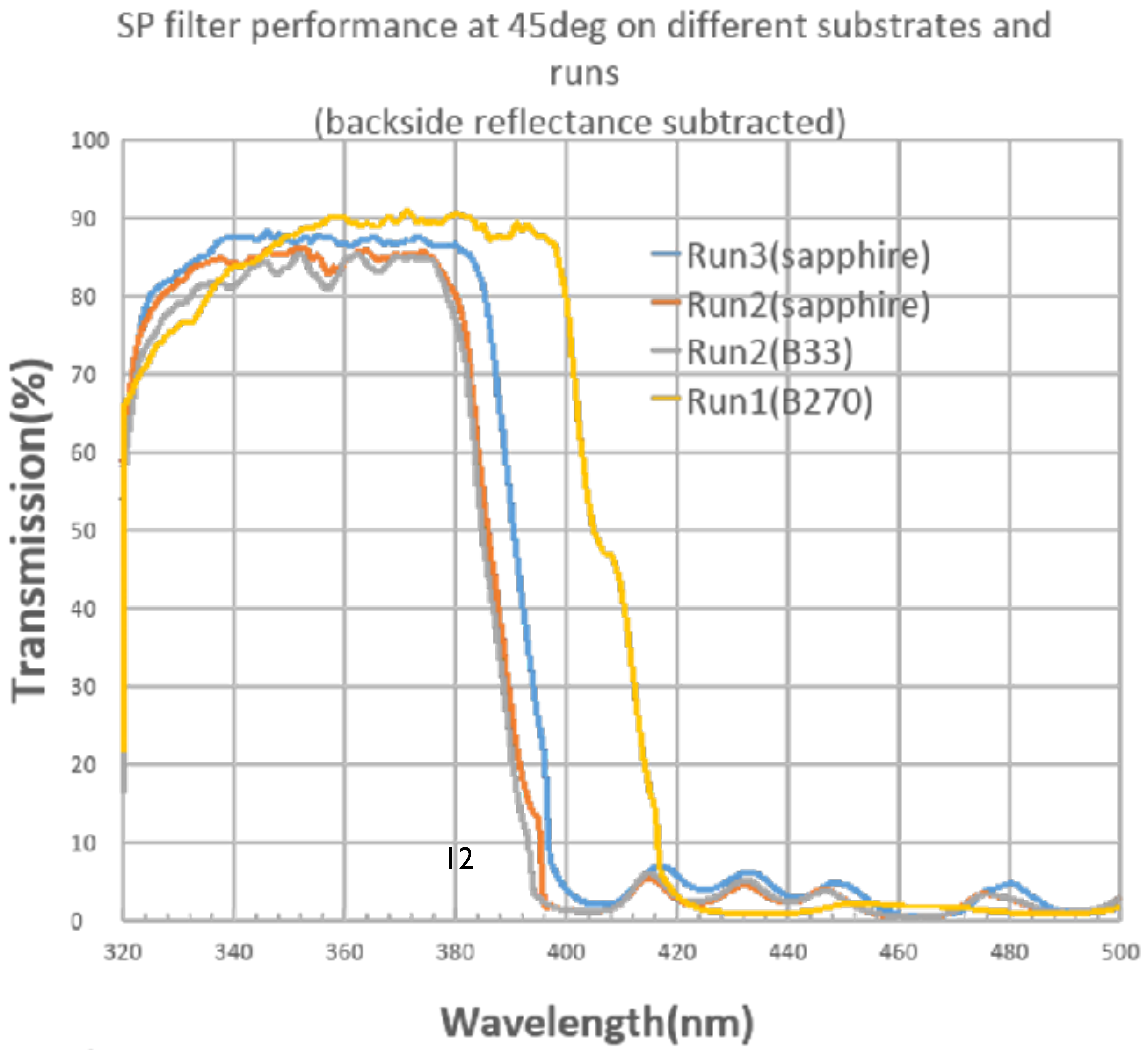


1. Difference in edge shape is related to index of different substrates.
2. Transmission of >90% in passing band (400-500nm) matches the design specification, indicating extremely small absorption.
3. The blocking band <400nm show a small percentage of transmission. Shorter wavelength noise is attributed to the source used.
4. The width of edge area is less than 10nm.
5. With larger AOI, the filter edge shifts toward blue.

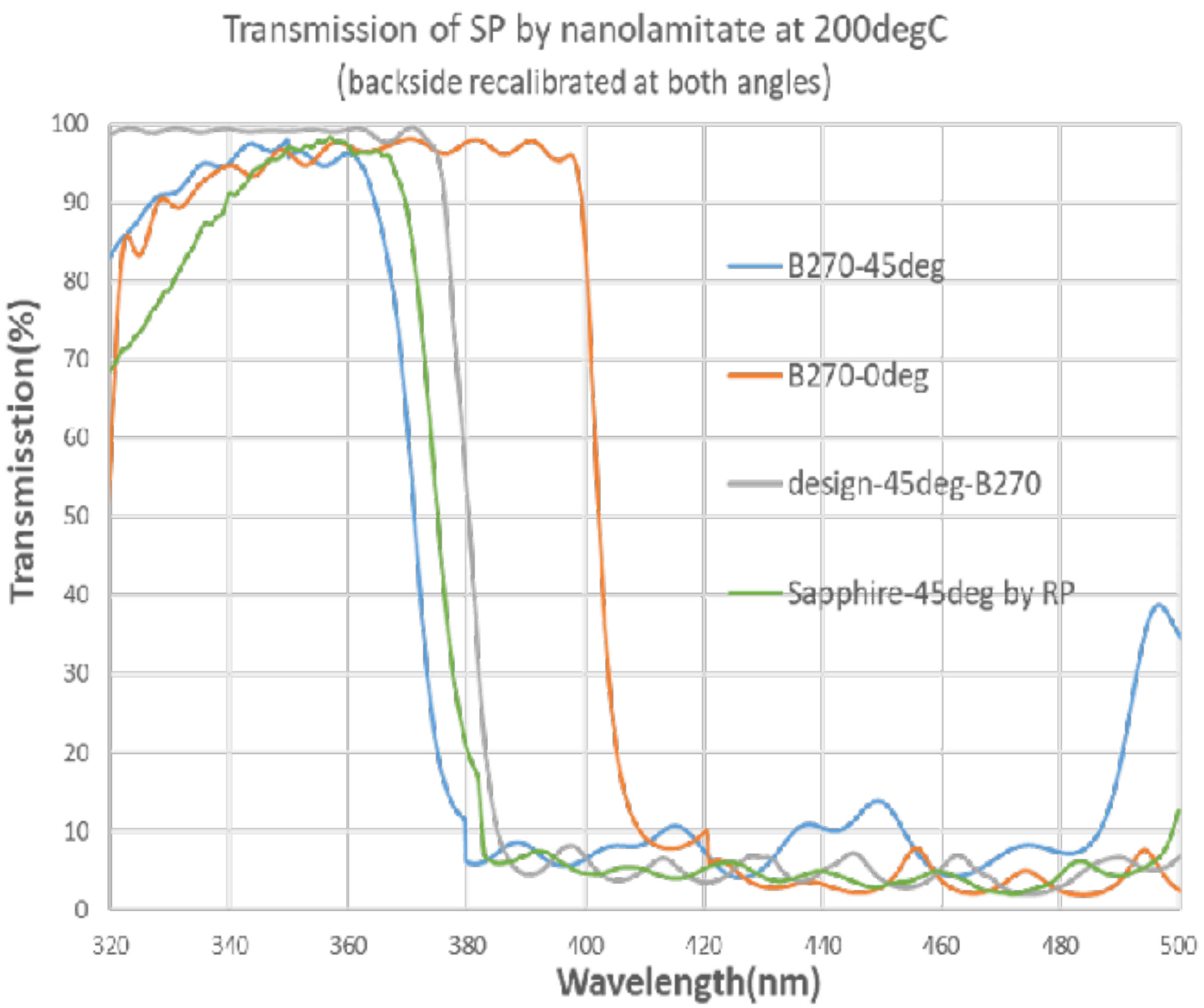
Performance of Short-Pass Edge Filters Made by ALD

RAYTUM Photonics

45 ° AOI measurement, coated over different substrates



Transmission of filter over different AOI

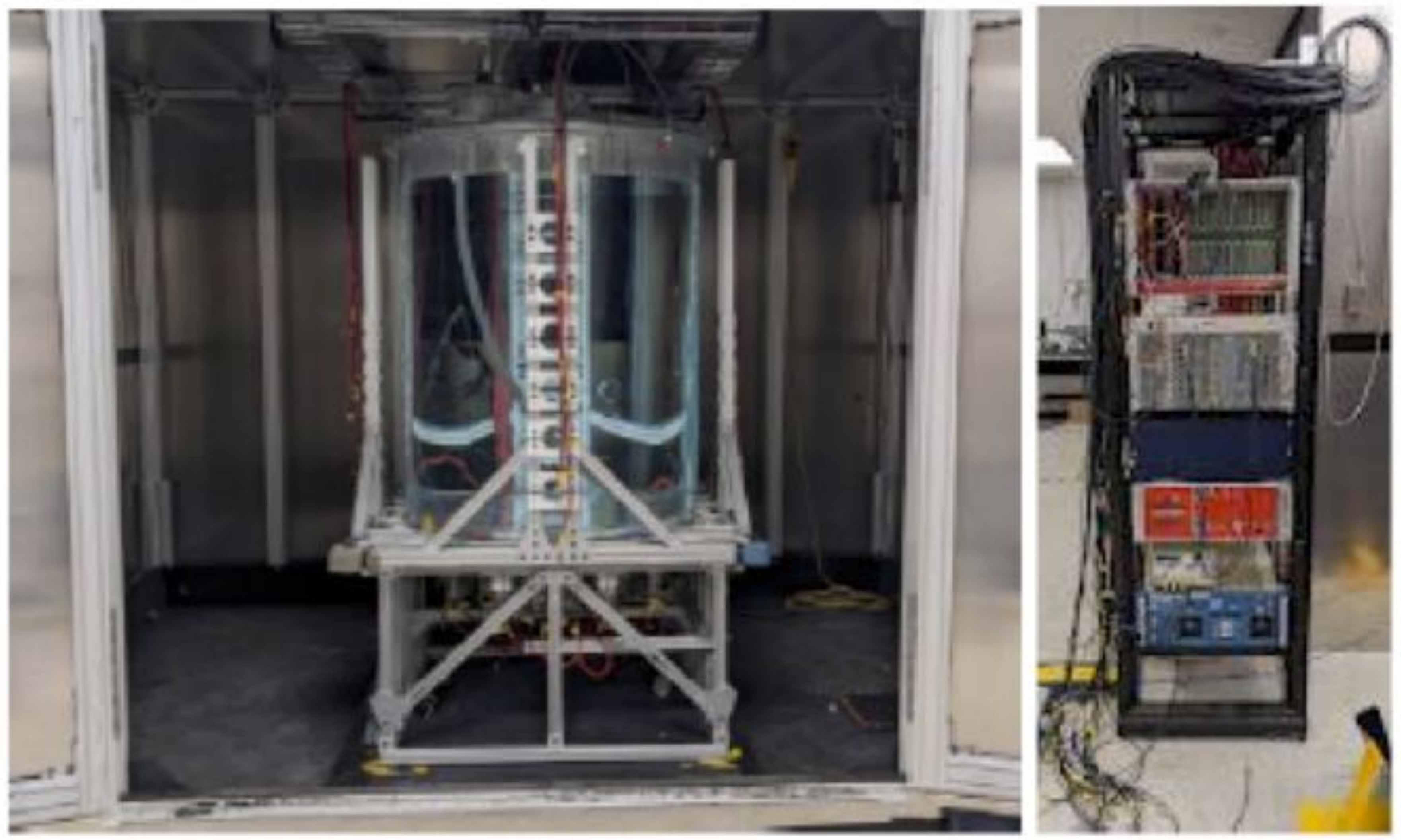


Comments

1. Transmission band >85% regardless substrates. Substrate backside reflectance subtracted (B33=4.8%, B270=5.3%, sapphire=9%).
2. Blocking band <5%.
3. Run1 designed for cutting-off edge at 400nm, later tuned to 380nm for Runs 2 and3.

Testing Facility at BNL

260-L LAr system



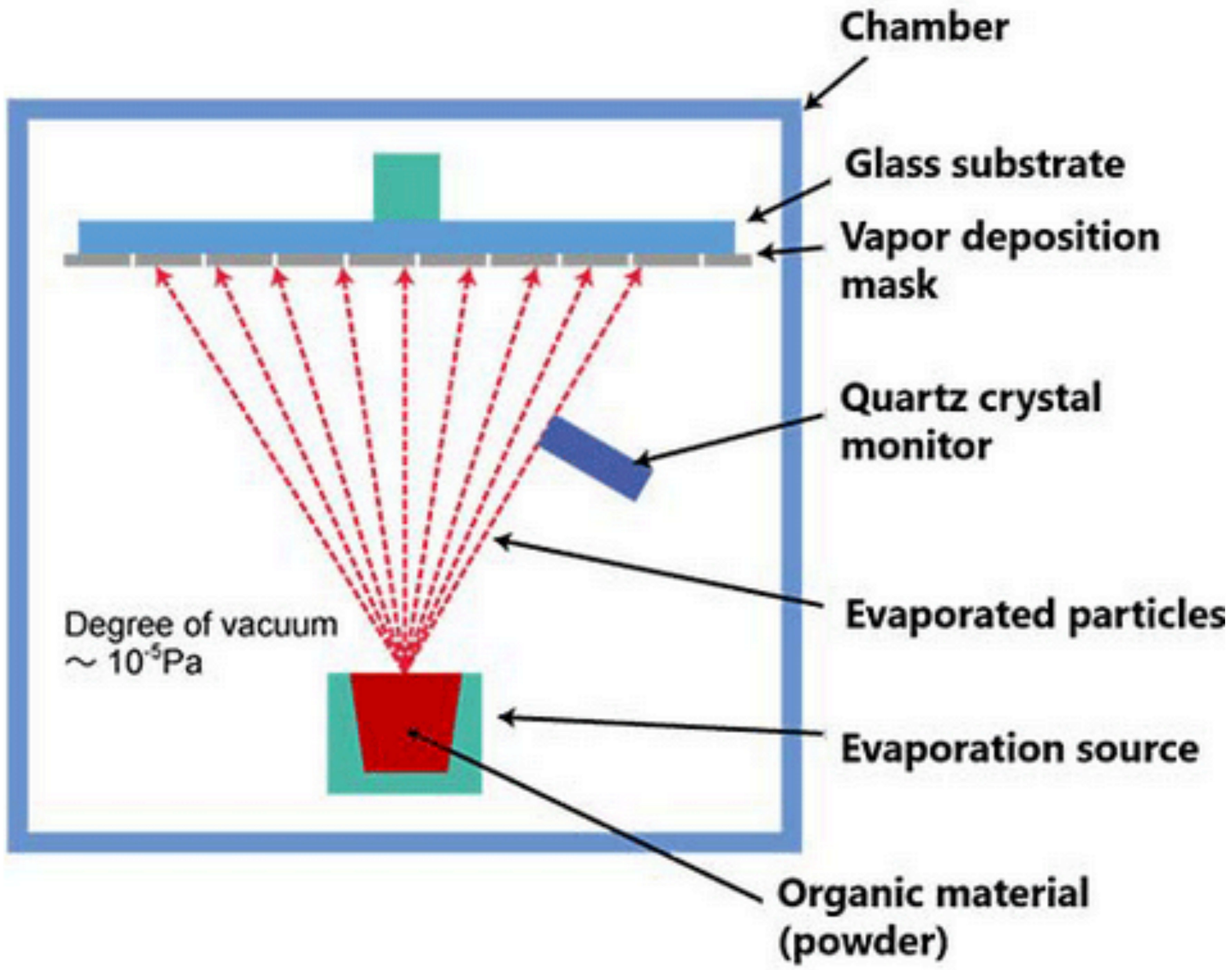
1-ton WbLS system

- 260-L LAr system has simple operating parameters has been operated for several months.
- The 260-L system is ready for charge and and photon measurement with sub-ppt purity in terms of O2 equivalent impurities, ~1 ppm of N2 concentration.
- The 1-ton WbLS is currently taking data 24/7
- Both of these facilities are functional.
- Welcome to contact me to get the designs for both of these installations.

Organic Material Coating?

- Photon detection for LAr scintillation lights requires large area wavelength shifter coating with PTP, an organic material

- We are working on a possible solution using industry vacuum deposition for computer monitors for mass production with quality control and low cost



https://global.canon/en/technology/oled-display-2023s.html

Conclusions

- A project using atomic layer deposition ALD for carefully tuned high quality dichroic filters is complete.
- An important break-through in achieving high transmission from high index layers has been achieved.
- Dichroic filters as specified in the x-ARAPUCA proposal for DUNE have been produced in small batches through ALD.
- The same ALD filter technology can be used for THEIA.
- Solution found for mass production
- For PTP coating, it is technically possible to have a commercial production of any organic coating, we are working on it
- Further collaboration on testing is welcome.

Updated Specifications for variety of projects

	DUNE Module 1	DUNE Module 2	DUNE Module 3 or 4	THEIA
Status	Technical Design Ready (ready for construction)	Technical Design Ready	Pre-concpetual	Pre-conceptual
Size	10000 tons	10000 tons	10000 tons	25000 to 100000 tons
Technique	Liquid Argon Scintillation	Liquid Argon Scintillation	Liquid Argon Scintillation	Water Cherenkov and Water Based Liquid Scintillator
Type of filter needed	Low pass	Low pass	Low pass	Both low and high pass
cut wavelength of interest	400 nm (modified to 380 nm)	400 nm (modify to 380 nm)	380 nm	450-475 nm
Transparent	320-400 nm	320-400 nm	320-400 nm	320-450 (low pass) > 450 (high pass)
Reflective	400-500 nm	400-500 nm	400-500 nm	> 450 (low pass) 320-450 (high pass)
Max tranmission efficiency	> 90 % (dependent on substrate)	> 90 %	> 90 %	> 90 %
Max reflection efficiency	> 95 %	> 95 %	> 95 %	>95 %
width of edge region	<10 nm	< 10 nm	< 10 nm	< 10 nm
angle of incidence optimize	20 deg - 70 deg	20 deg to 70 deg	20 deg to 70 deg	TBD
Optimize for	45 deg	45 deg	45 deg	TBD
movement of edge within angle	< 10 nm	< 10 nm	< 10 nm	< 10 nm
Preferred Substrate	BK270 glass (Fused silica possible ?)	BK270	Still open selection	Open
	~~Try fused silica, BK270 glass, UVT acrylic, B33 glass~~	~~Try fused silica, BK270 glass, UVT acrylic, B33~~	~~Try fused silica, BK270 glass, UVT acrylic, B33~~	~~Try fused silica, BK270 glass, UVT acrylic, B33~~
Shifter	PTP on the uncoated side	PTP on uncoated side	PTP on uncoated side	No shifter is needed on any filter.

Short Pass Filters Delivered and measurements

4 delivered to BNL and 3 to UPenn.

Number	Substrate		Size	Cut wavelength	location
B16	Sapphire	HfO2/Al2O3	77 x 100 x 1 mm	380 @ 45 deg	BNL
B17	Sapphire	HfO2/Al2O3	77 x 100 x 1 mm	380 @ 45 deg	BNL
B20	B33	HfO2/Al2O3	77 x 100 x 1 mm	380 @ 45 deg	BNL
B21	B33	HfO2/Al2O3	77 x 100 x 1 mm	380 @ 45 deg	BNL
NA	Sapphire	HFO2/Al2O3	4 inch circle x 1 mm	380 @ 45 deg	UPenn
B23	B33	HFO2/SiO2	77 x 100 x 1 mm	380 @ 45 deg	UPenn
B15	Sapphire	HFO2/SiO2	77 x 100 x 1 mm	380 @ 45 deg	UPenn

BENEQ   C2R coater

ALD is now extremely important technology for silicon production.

The new gate structures for near future GPU's will be manufactured using ALD for part of the process.

The key leader in this is https://beneq.com/en/

The filters delivered from RAYTUM were made with BENEQ system C2R

"Beneq C2R provides an optimal solution for high performance ALD in industrial applications, such as optical coatings and barriers."