Dichroic Filters using Atomic Layer Deposition (ALD)

DUNE Far detector 3-4 miniworkshop, Stony Brook University

Milind Diwan June 25, 2023 https://indico.fnal.gov/event/59908

Thanks to

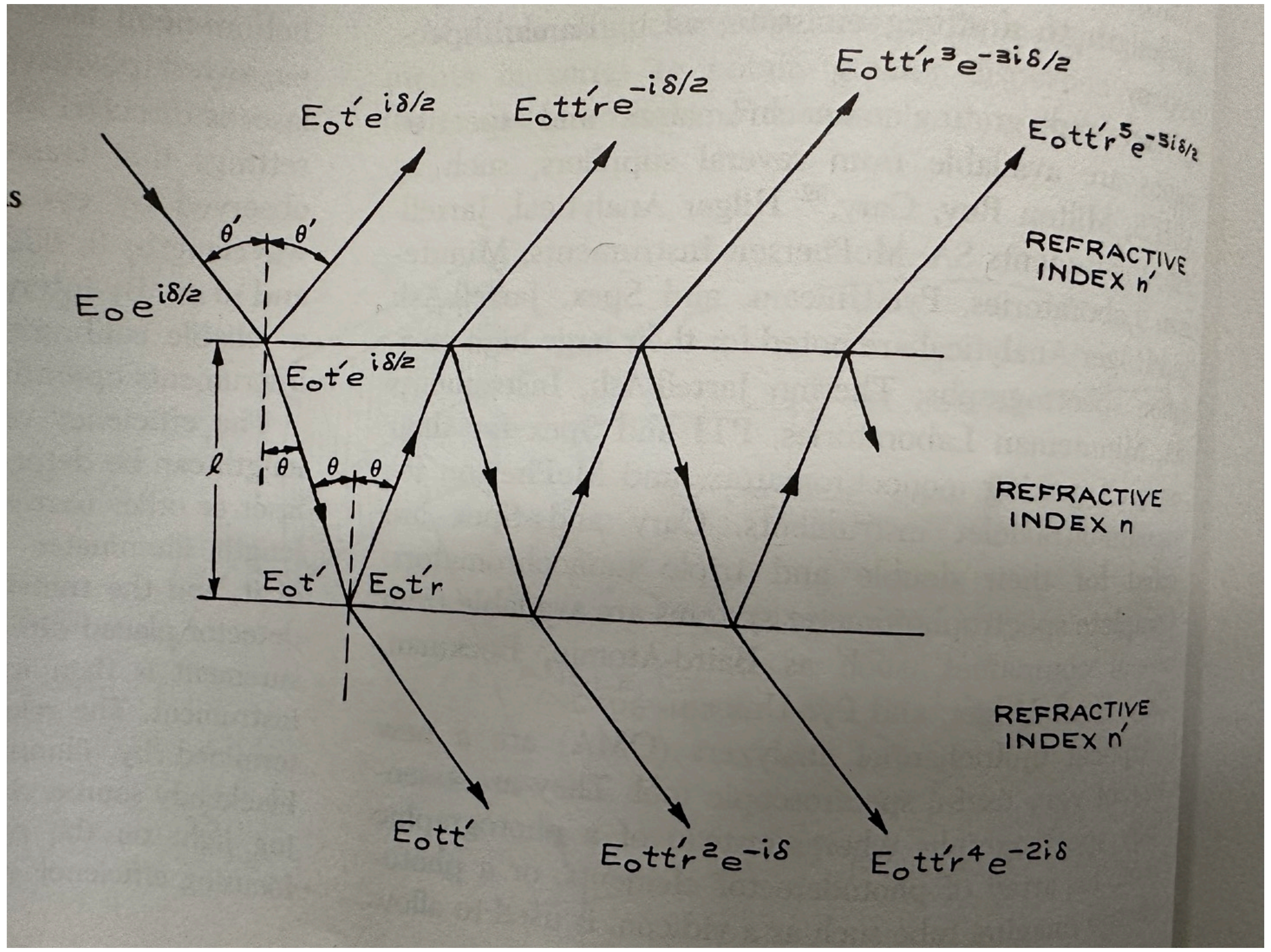
RAYTUM Photonics

Outline

- Background introduction
- Introduction to ALD. Why ALD ?
- R&D project timeline and scope
- Specifications from DUNE for the current project.
- Progress report
- Expectations in the near future.

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

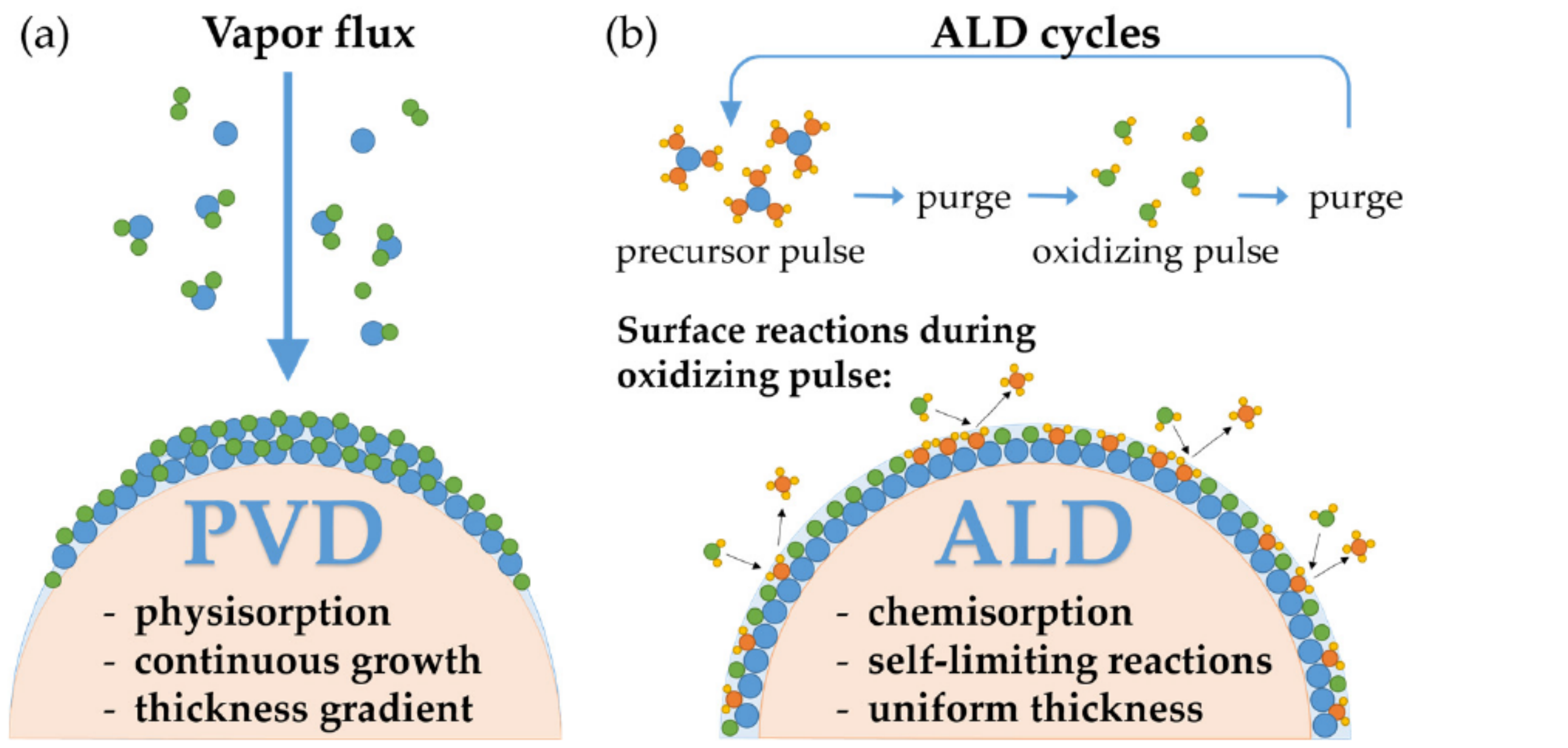


Figure 1. Illustration of (**a**) physical vapor deposition (PVD) deposition and (**b**) atomic layer deposition (ALD) on a hemispherical lens.

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

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*	*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.***

R&D project timeline and scope

BNL and Raytum collaboration

- R&D project was proposed in 2021 and first phase was successfully executed with DOE funding. The Raytum laboratory is in Virginia.
- A second phase with 2 year timeline was started in FY23
- The total scope includes
    - ✓ 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.

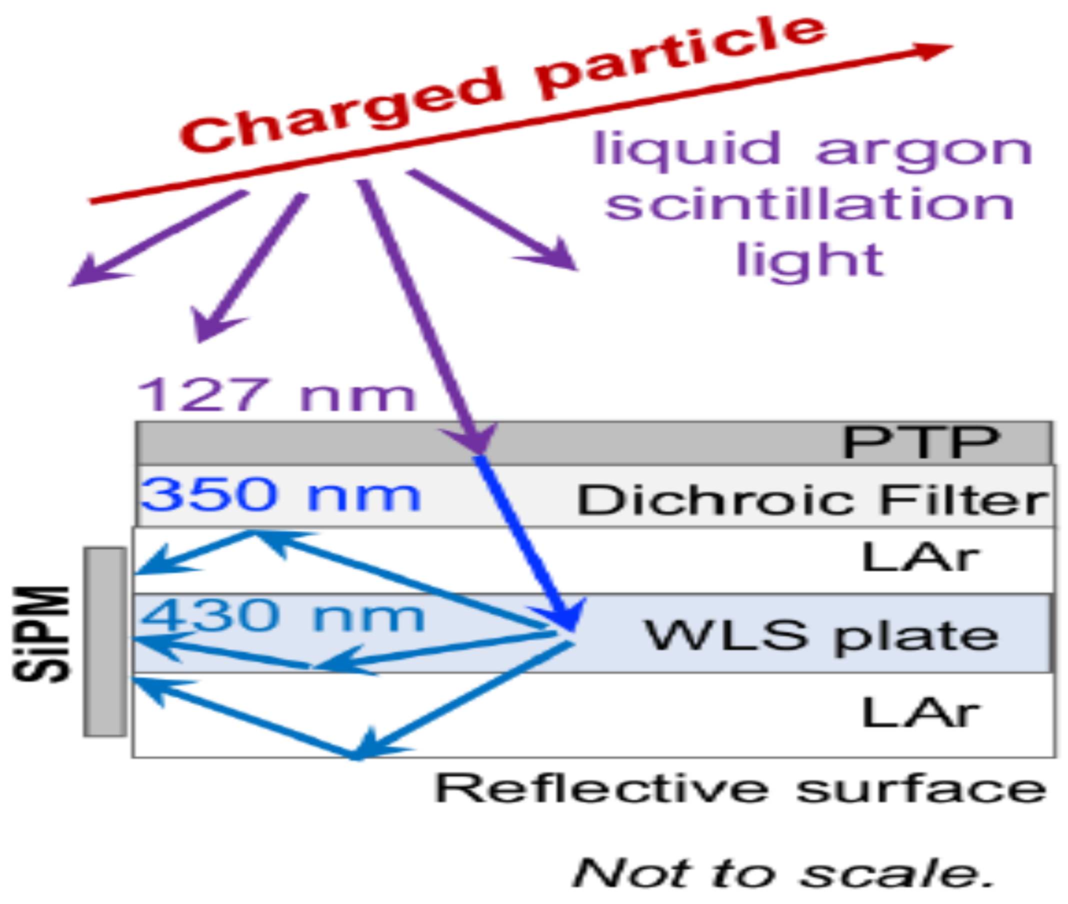
Specifications for first batch of units. For testing only.

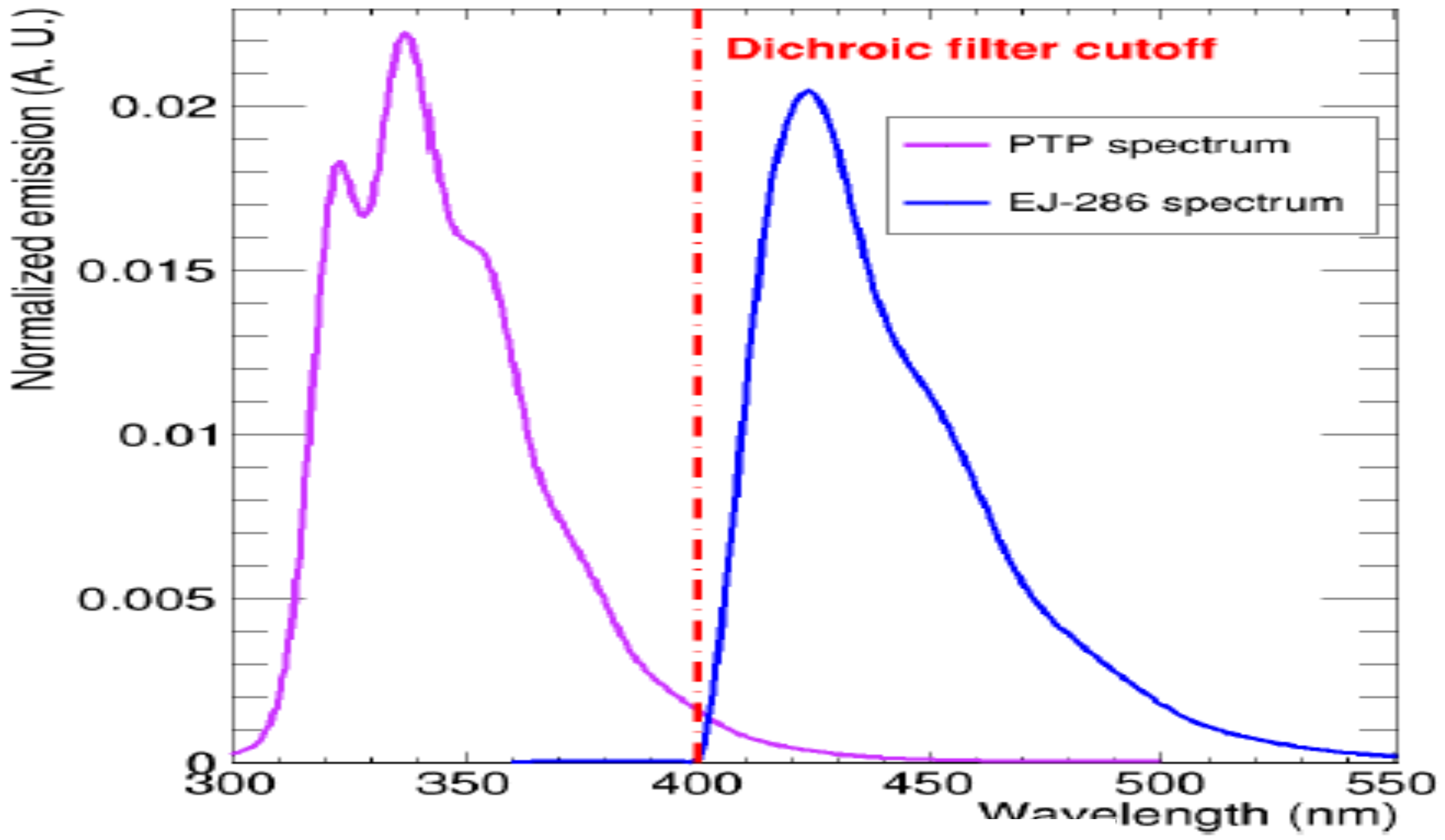
	DUNE 1	THEIA-short-pass	THEIA-long pass
Type of filter needed	Low wavelength pass	Low wavelength pass	High wavelength pass
wavelength of interest	400 nm	450 nm	450 nm
Transparent	320-400 nm	320-450	450-600
Reflective	400-500 nm	450-600	320-400
Medium for the filter to operate	Liquid argon	Water	Water
Max tranmission efficiency	> 90 %	> 90 %	> 90 %
Max reflection efficiency	> 95 %	>95 %	>95 %
width of edge region	<10 nm	< 10 nm	< 10 nm
angle of incidence optimize	20 deg - 70 deg	40-80 deg	0-60 deg
Optimize for	45 deg	60 deg	40deg
movement of edge within angle	< 10 nm	< 10 nm	< 10 nm
Preferred Substrate	B270	B270	B270
Substrate polish	Not needed	not needed	not needed
Second substrate (option)	Fused Silica	Fused Silica	Fused silica
Substrate thickness	1 mm	1 mm	1 mm
Thickness tolerance	0.1 mm	0.1 mm	0.1 mm
Shifter	PTP	N/A	N/A
Size of filter	77 x 100 mm^2	80 mm X 80 mm	80 mm X 80 mm
Filter dimensional tolerance	0.1 mm	0.1 mm	0.1 mm
WLS plate type	EJ286	N/A	N/A
Numbers of items for first test	8	8	8

DUNE

THEIA

Liquid Argon ARAPUCA detector concept and roles of DFs

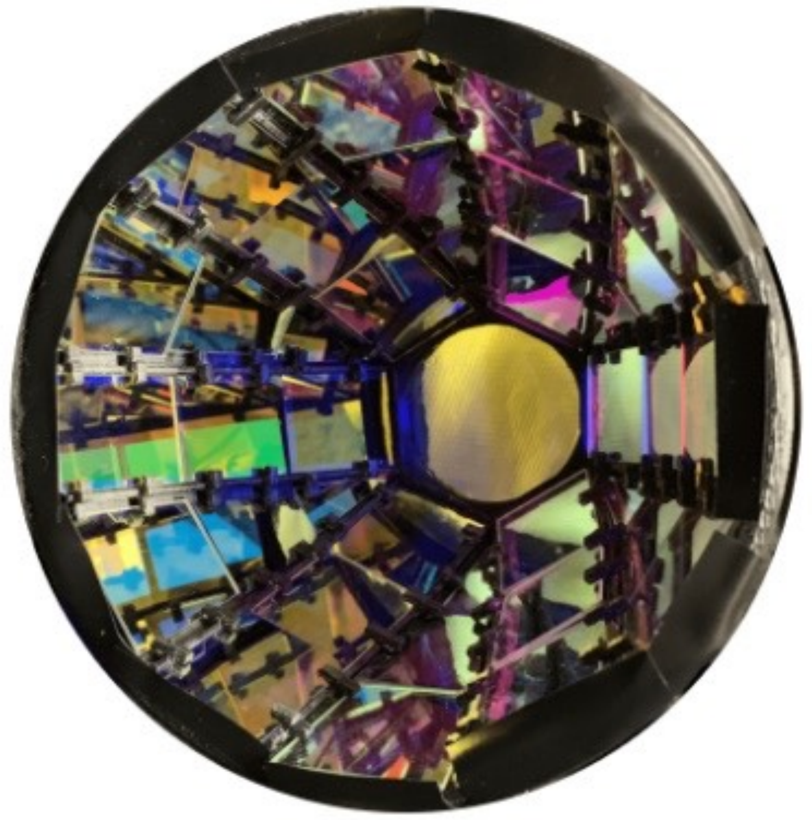


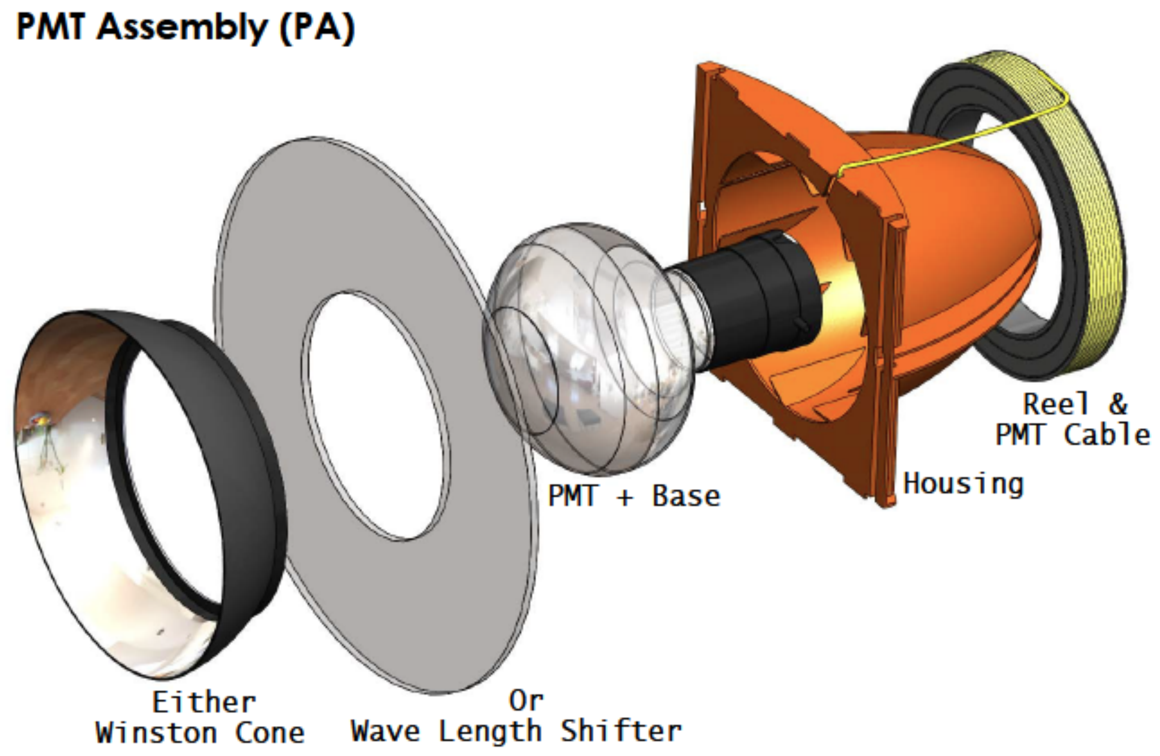


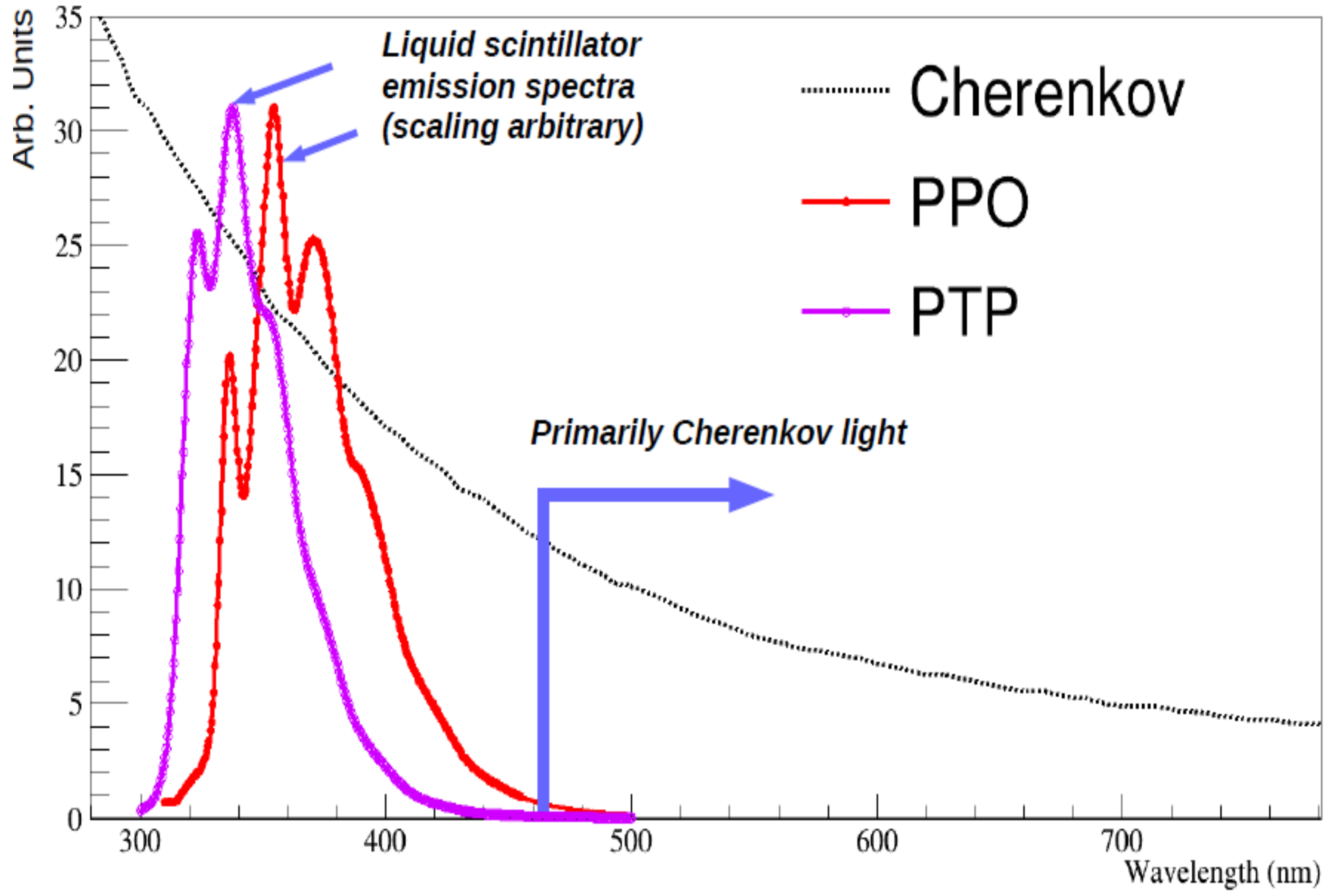
(Polymer EJ-286 WLSP)

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

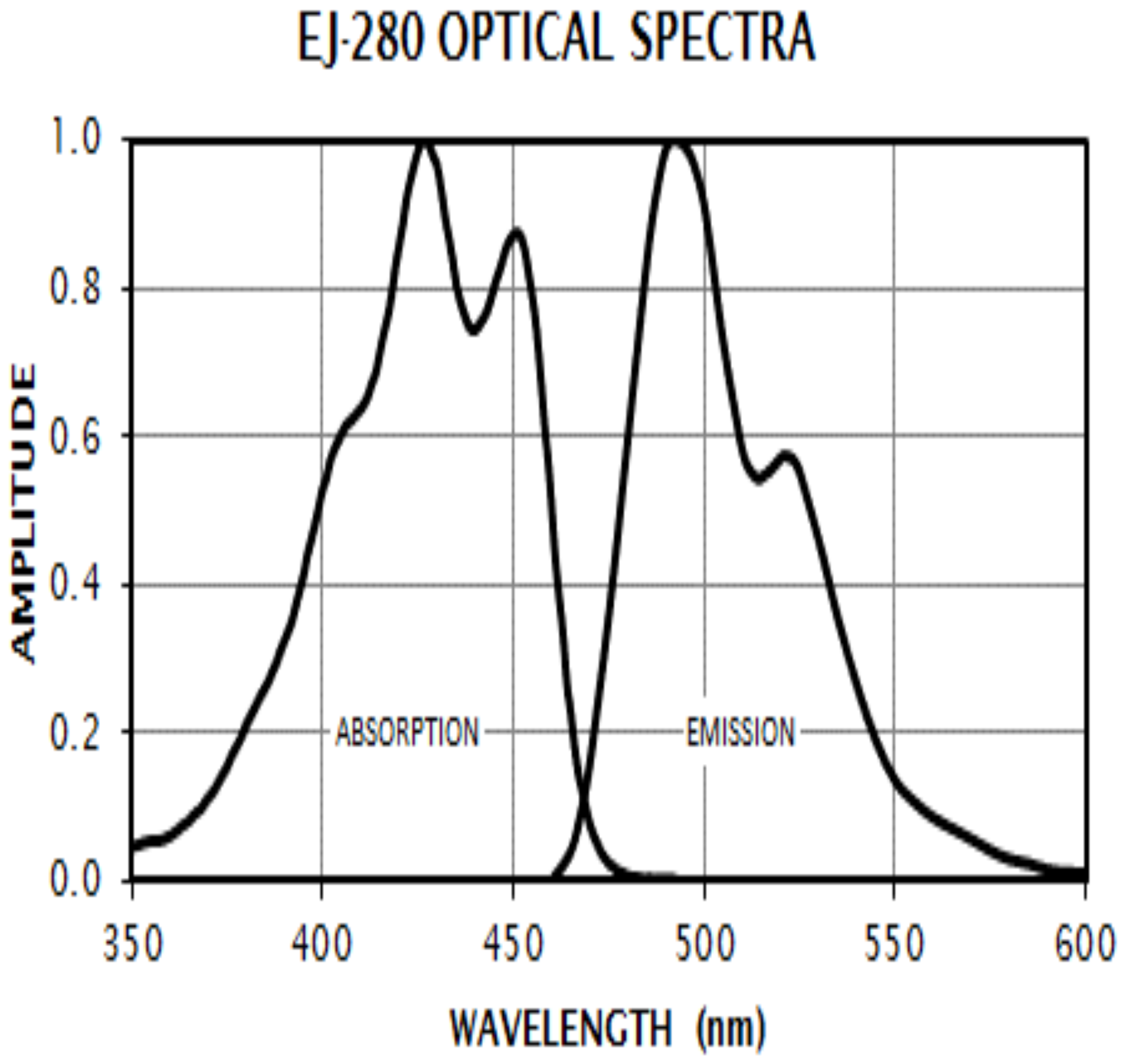
Winston cone(WC) /wavelength shifting plates(WLSP) type of detector concept and roles of DFS







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.

Advantages of ALD and Our Core Innovations in Fabricating Optical Filters

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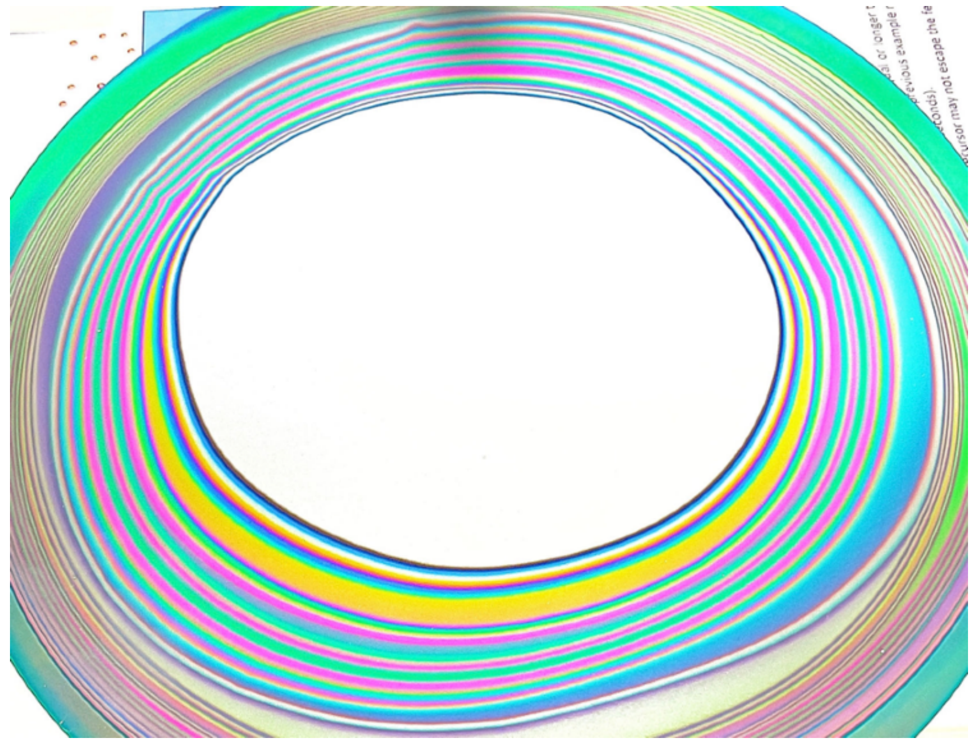
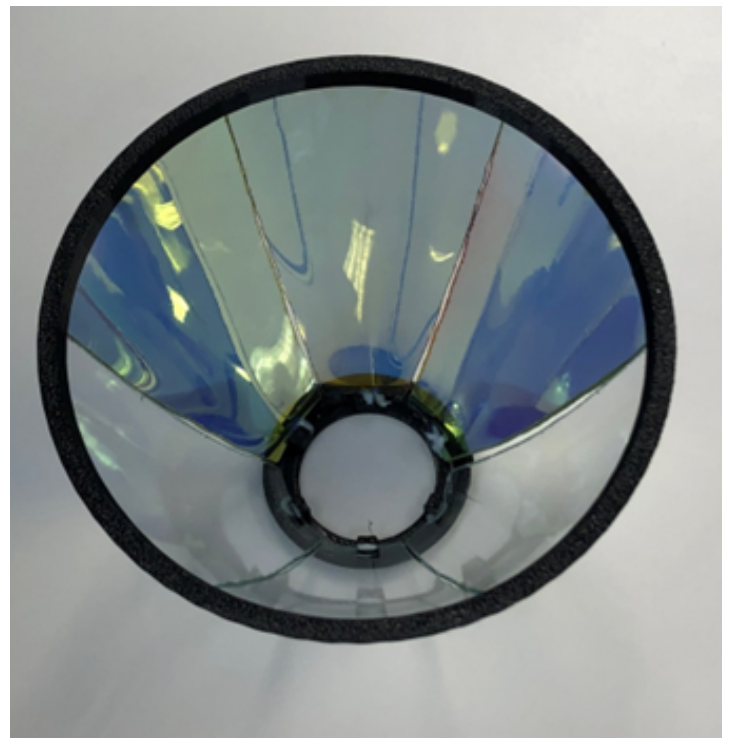
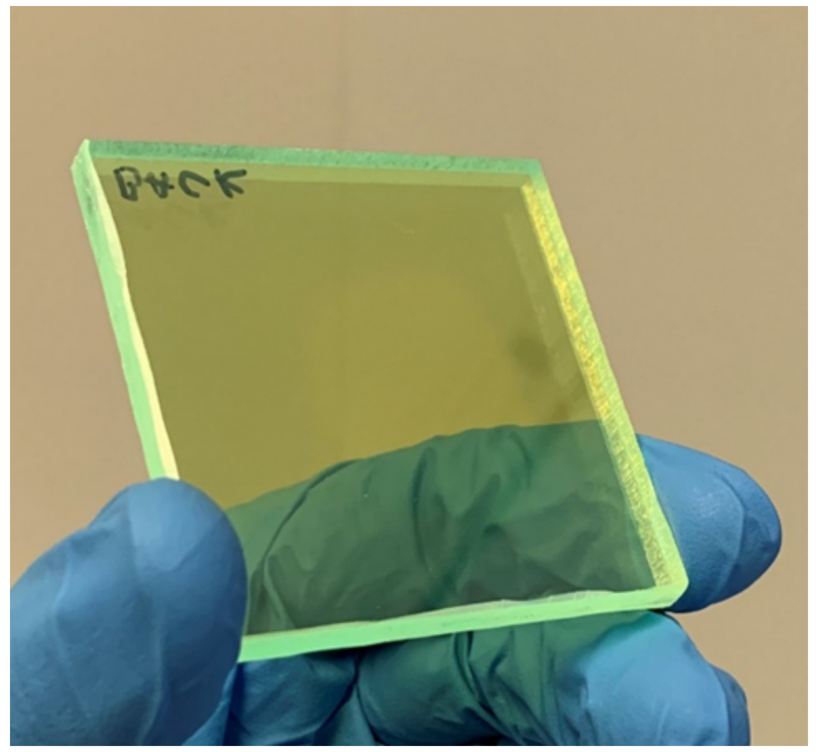
- Unique dichroic-filter coating designs optimized for large area dichroic application (various angle of incidents, liquid argon or water compatible).
- Low and near room temperature coating over temperature sensitive material like wavelength shifting plate EJ287.
- Superior conformity, flexibility, large area coating uniformity (<0.1%) on various substrates shapes like Winston cones.
- Precise and easy control of thickness and composition due to the self-limiting nature, critical for fabricating high-performance filters with excellent thickness tolerance leading to precise wavelength positioning and sharp cutoff.







ALD coating on | **8″ Sample** | **Winston cone** | **EJ280**

Significant Technology Breakthrough from Raytum Photonics

RAYTUM Photonics

- Large Area Coating using ALD Technology has been achieved. Long 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 short pass filter is on the way.

Long-pass Filter Fabrication using ALD

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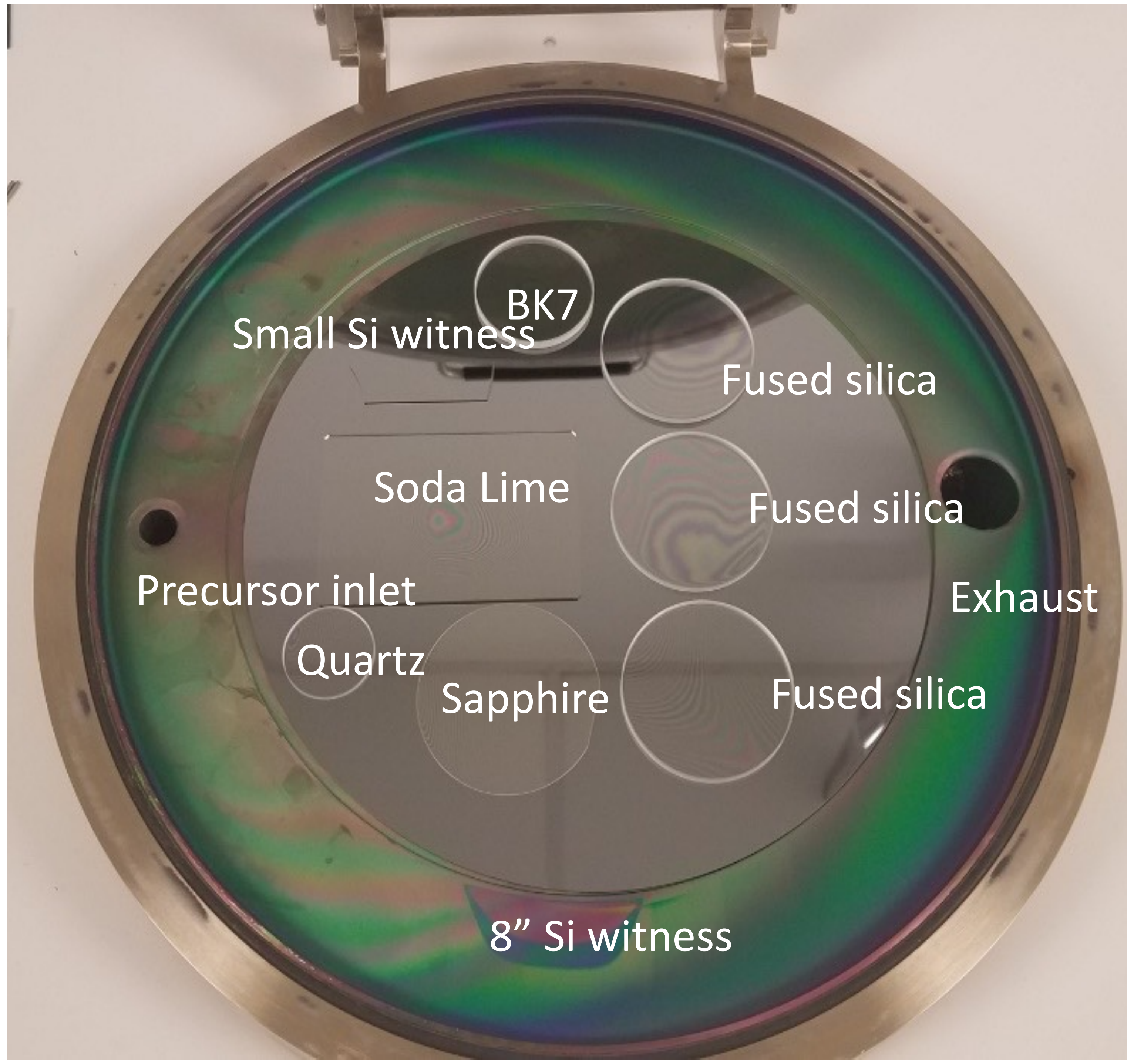
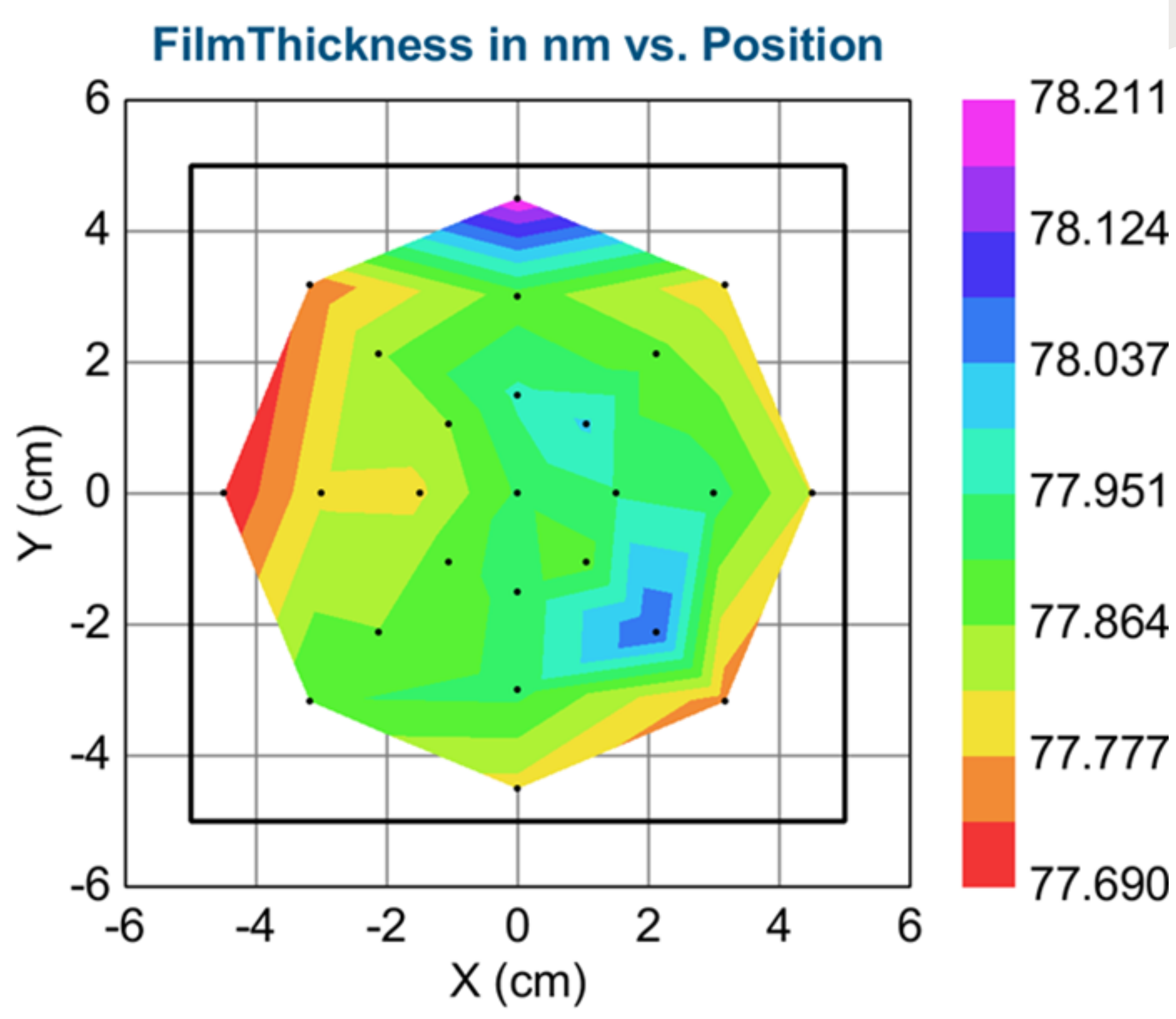


Coated samples sitting inside the chamber of ALD coater

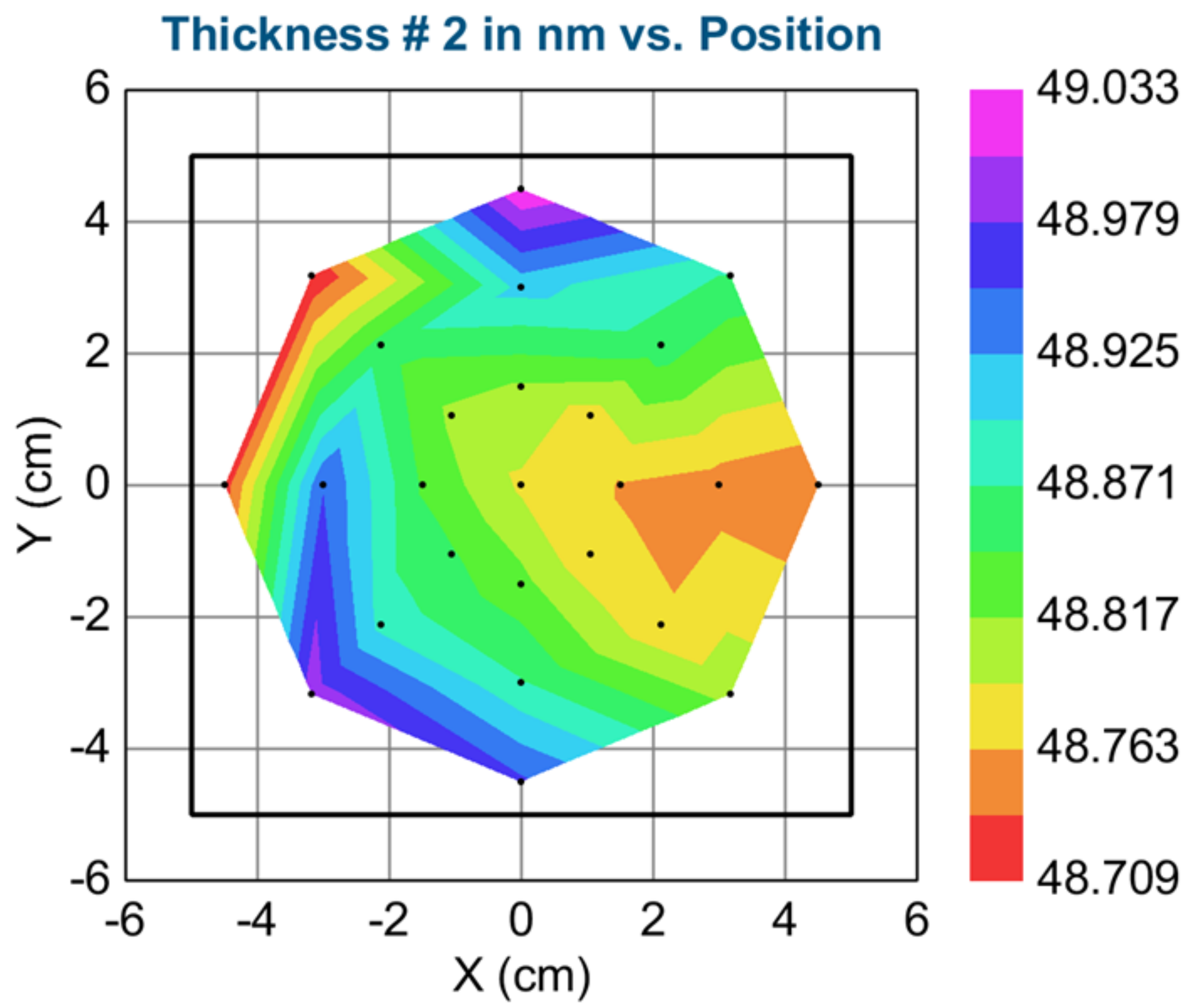
The transparency of a coated sample is fully evident, indicating the remarkably low absorption of the coating.

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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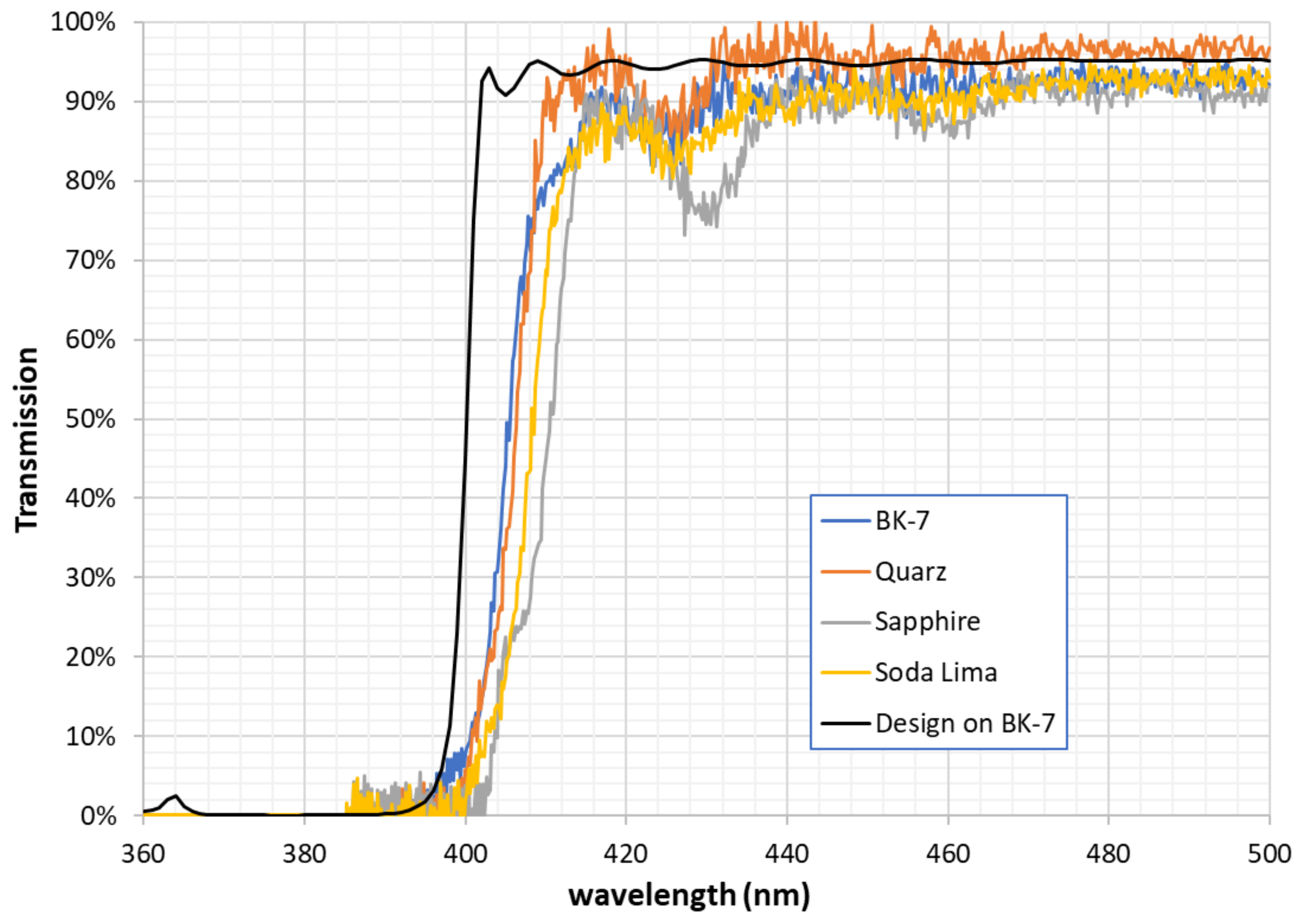
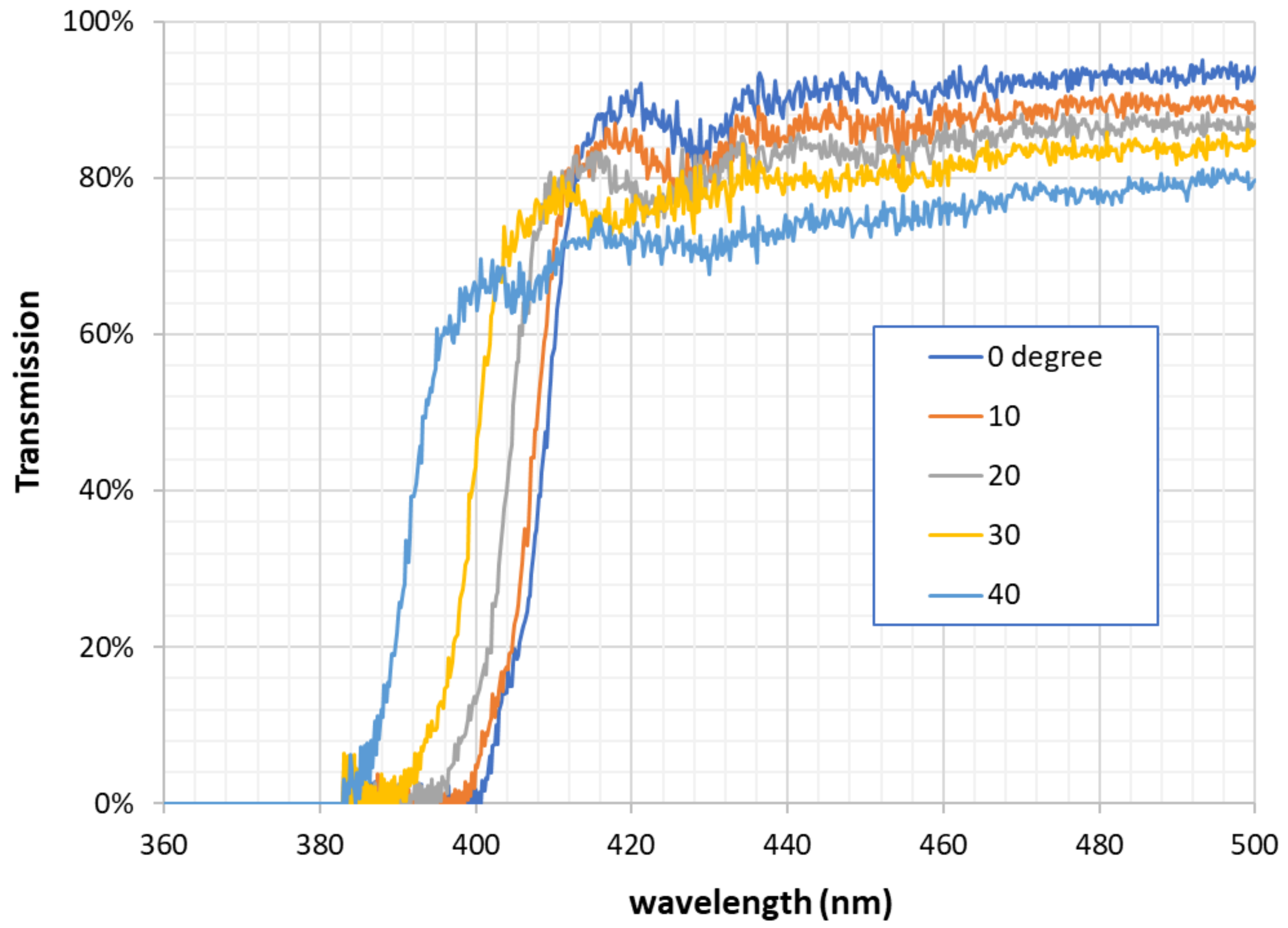
0° AOI measurement, coated over different substrates

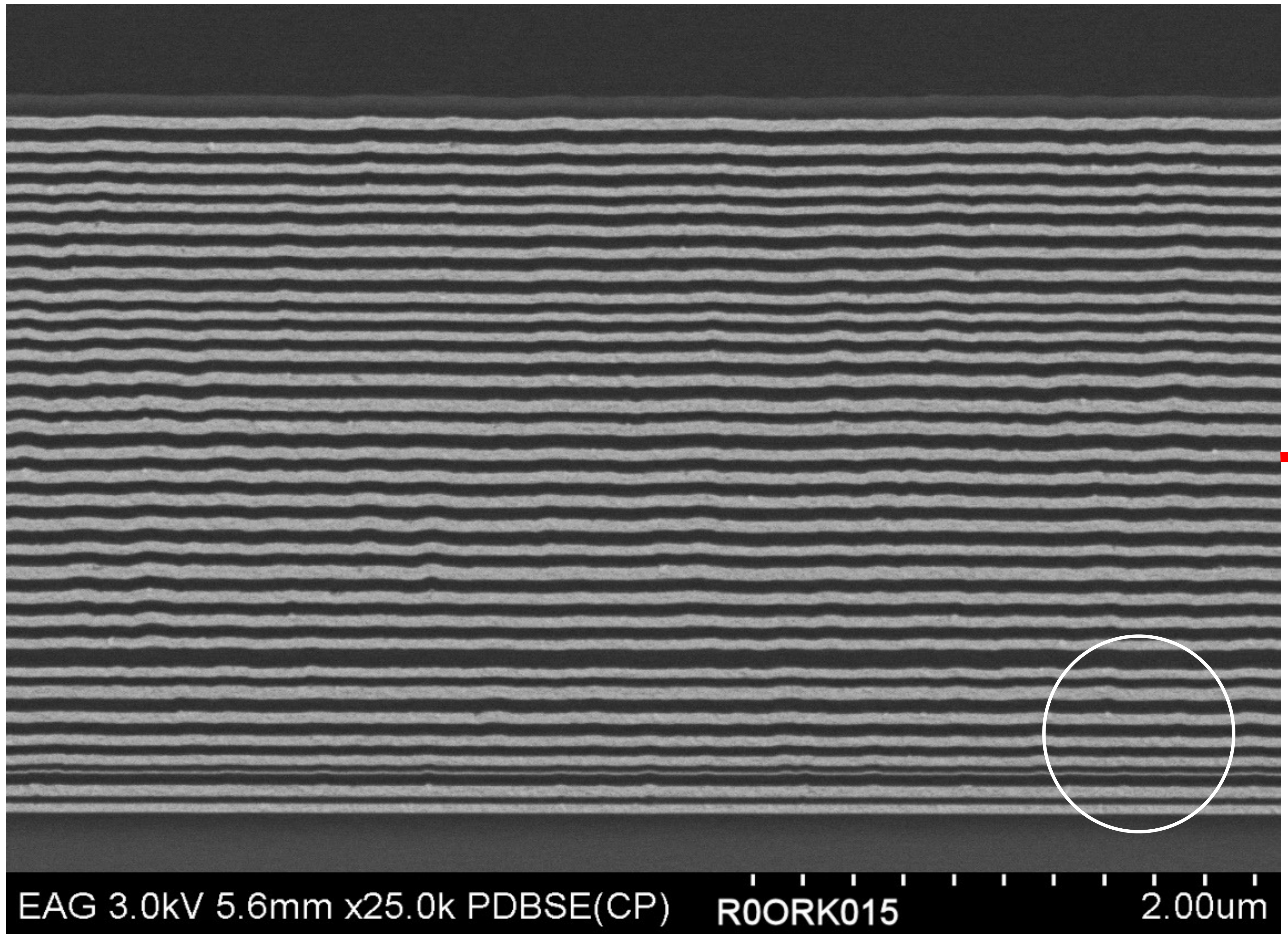


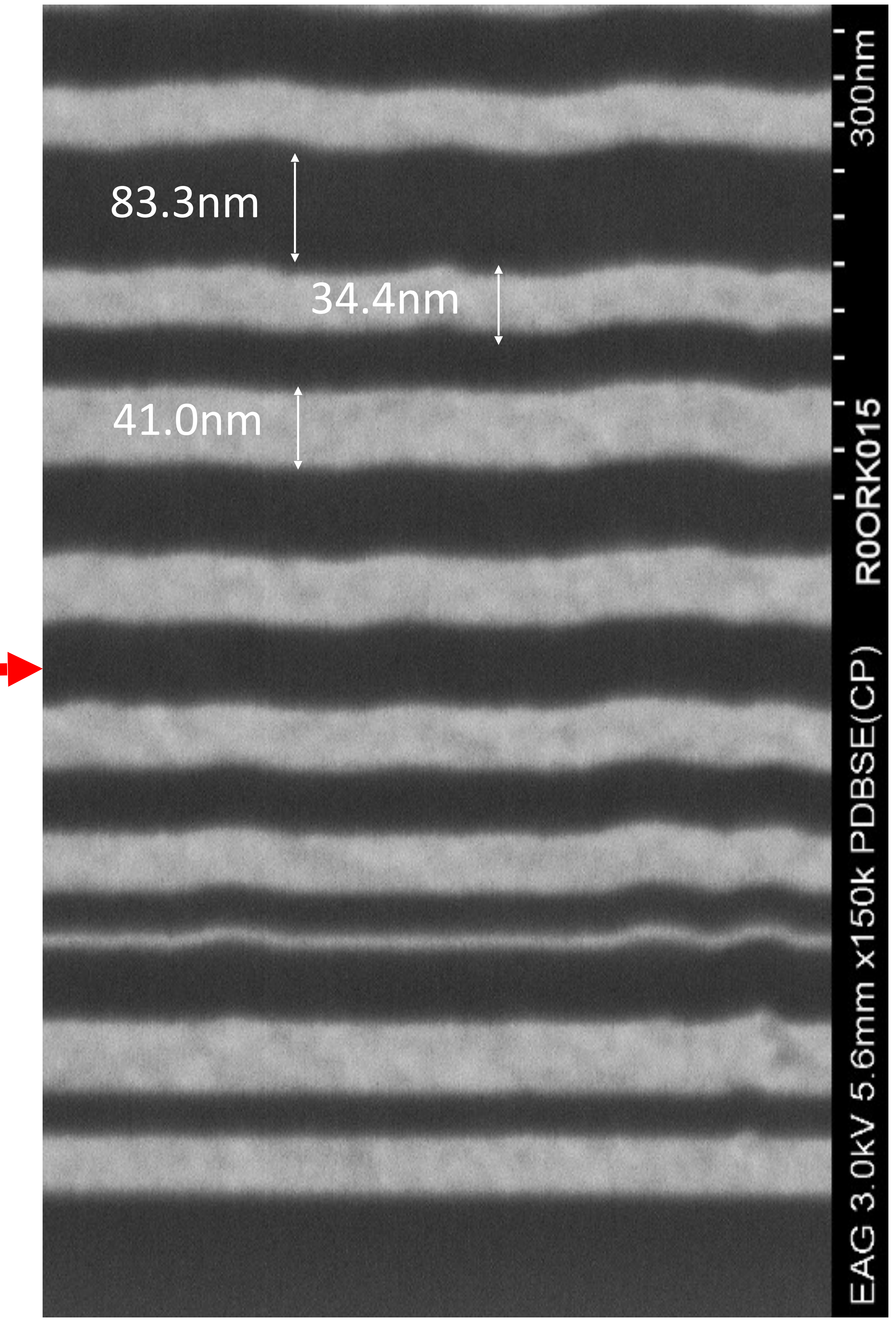
transmission of filter over Soda-lima, different AOI



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.

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





Dark band: dielectric material #1

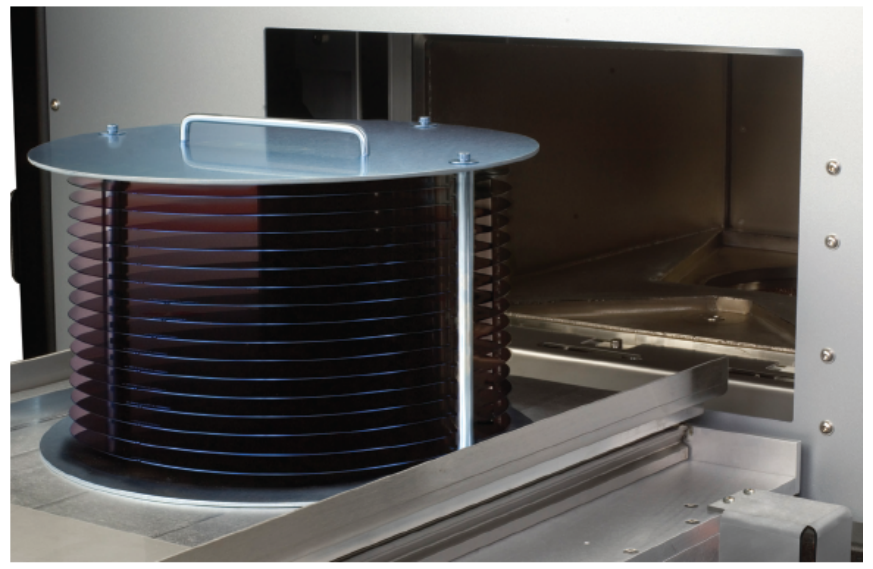
Light band: dielectric material #2

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

Possibilities for size scale up

Size of the filters needs to be known well before designing an ALD system

- Batch ALD production systems are available in industry. Using them will require definite specifications and contract management.
  - Batch ALD system
  - Large numbers of wafers ~50-100 possible
  - Large objects can be done with modifications to the chamber
  - Deposition temperature is flexible 85-285 C.



Testing facility status

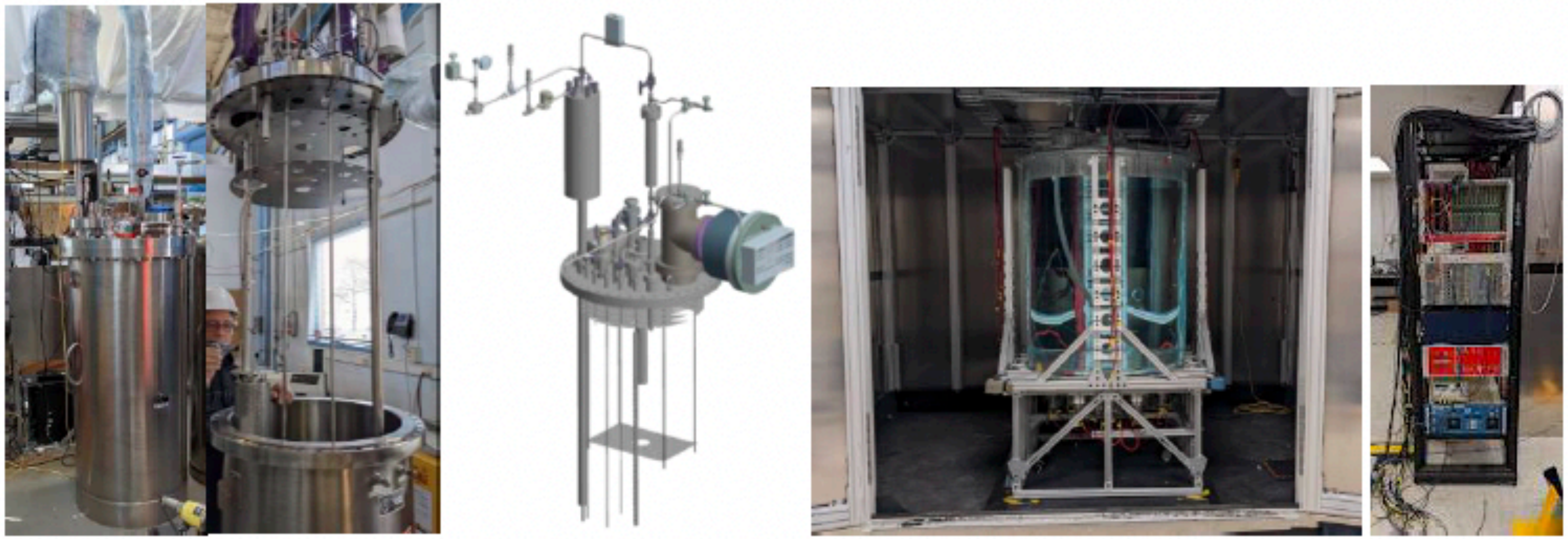


Fig 20: Left: LArFCS system and 3D model for top flange assembly. Right: the 1 ton WbIS system and DAQ.

Both of these facilities are now functional. The LARFCS system has gone through commissioning, for photon detector R&D some design in the volume will be needed.   The 1 ton WbIS is currently taking data 24/7 with 1% WbLS solution.

Photos of the actual 1-ton detector

Questions that need to be answered in collaboration with DUNE

- What are the correct requirements for FD3 FD4 ?
- What measurements are needed in the medium in real conditions
- What is the requirement for the angle ? What is the movement of the cut wavelength with angle.
- Can we do angle-resolved measurements in the real fluid ?
- How do the layer stresses get annealed ? Does the annealing affect the cut wavelength. What are the thermal changes in LAR ?
- What is the best way to limit the movement of the cut wavelength with temperature.
- Measurements may be needed on stoichiometry of the high index material (ratio of oxygen to the metal). It may affect the index of refraction across the surface

This kind of full quality control program will require project support.

Conclusion

- A project using atomic layer deposition ALD for carefully tuned high quality dichroic filters is in progress.
- An important break-through in achieving high transmission from high index layers has been achieved.
- Design of filters needed for DUNE or THEIA has been demonstrated.
- Timeline for preproduction prototypes is known.
- Further collaboration on testing is welcome.
- ***A caution: The optical performance is quite complicated and needs a proper physics simulation. Naive modeling of transmission and reflection will not work.***