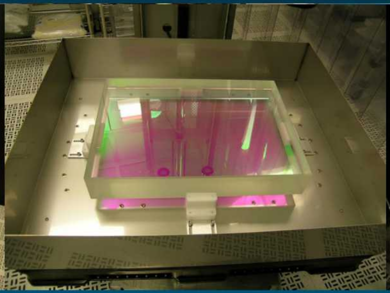
SAND2019-6557PE

Sandia National Laboratories

Overview of Large Optics Coatings Capabilities at Sandia National Laboratories



PRESENTED BY

Ella Field

ELI Meeting, June 24, 2019

ENERGY NNSA

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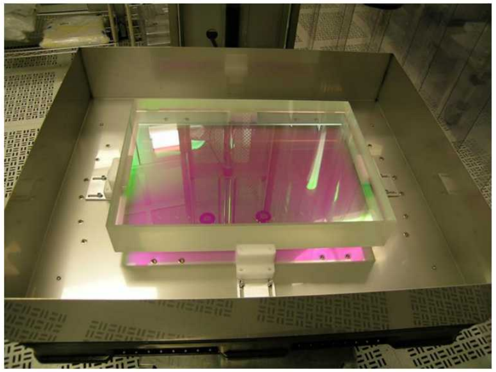
Agenda

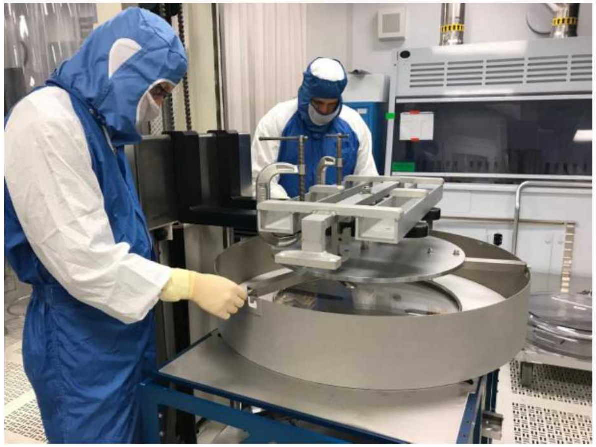
1. Introduction to Sandia's optical coating operation
2. Dual-wavelength coatings for high reflection (1054 nm) and high transmission (527 nm)
3. Broad bandwidth high reflection coatings
4. Optic cleaning, contamination, and storage concerns



Sandia's Optical Coating Operation

Mission:

Provide optical coatings with high laser-induced damage thresholds (LIDT) to support Z-Backlighter laser operations at Sandia National Laboratories



Team:

Ella Field (engineer), Damon Kletecka (lead technologist) and Robert Speas (technologist)

- P. Rambo, et al., "Sandia's Z-Backlighter Laser Facility," SPIE Proceedings Volume 10014, Laser-Induced Damage in Optical Materials 2016; 100140Z (2016).
- J. Bellum, et al., "Production of optical coatings resistant to damage by petawatt class laser pulses," Lasers—Applications in Science and Industry, InTech Open Access Publisher, Rijeka, Croatia (2011).

Optical Coating Capabilities

- 2.3 m X 2.3 m X 1.8 m coating chamber in a Class 100 clean room
- E-beam deposited coatings (mostly hafnia/silica layer pairs) with or without ion-assisted deposition (IAD)
- 3-planet option accommodates up to 94 cm optic per planet
- 2-planet, counter-rotation option holds up to 1.2 m (diagonal) optic per planet
- 3 e-beam sources for thin film materials
- Process control based on crystal sensor monitoring of thin film layers
- Production: 50 – 100 anti-reflection (AR) coated debris shields & vacuum windows needed by backlighting operations per year, plus high reflection (HR) and polarizer coatings

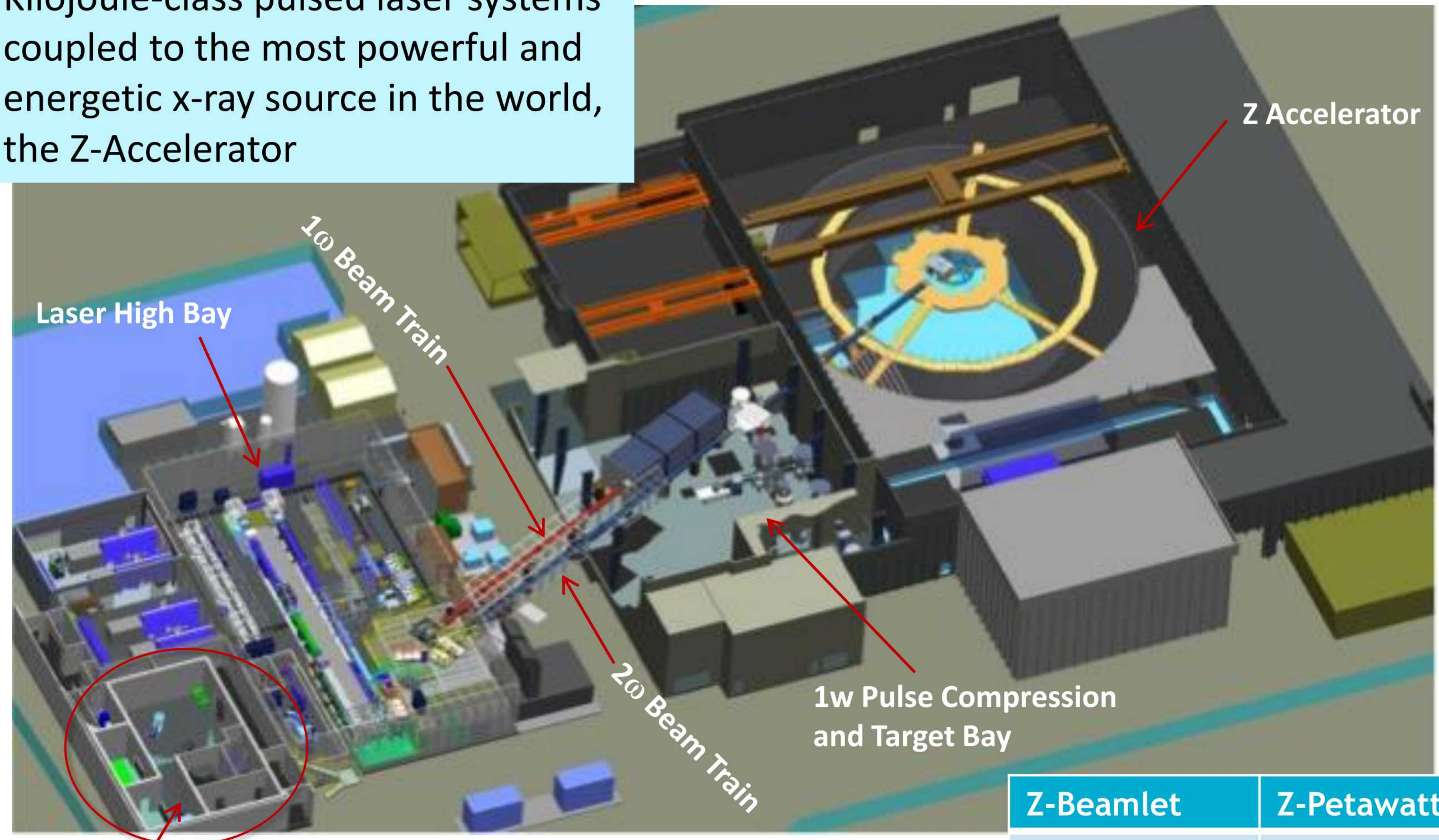
Coating system in class 100 (ISO 5) clean room

Ion-assisted deposition

A mirror, 76 X 55 X 12 cm^3

Sandia's Z-Backlighter Laser Facility

Kilojoule-class pulsed laser systems coupled to the most powerful and energetic x-ray source in the world, the Z-Accelerator



Optical Support Facility and Large Optics Coater
(Class 100 Clean Area)

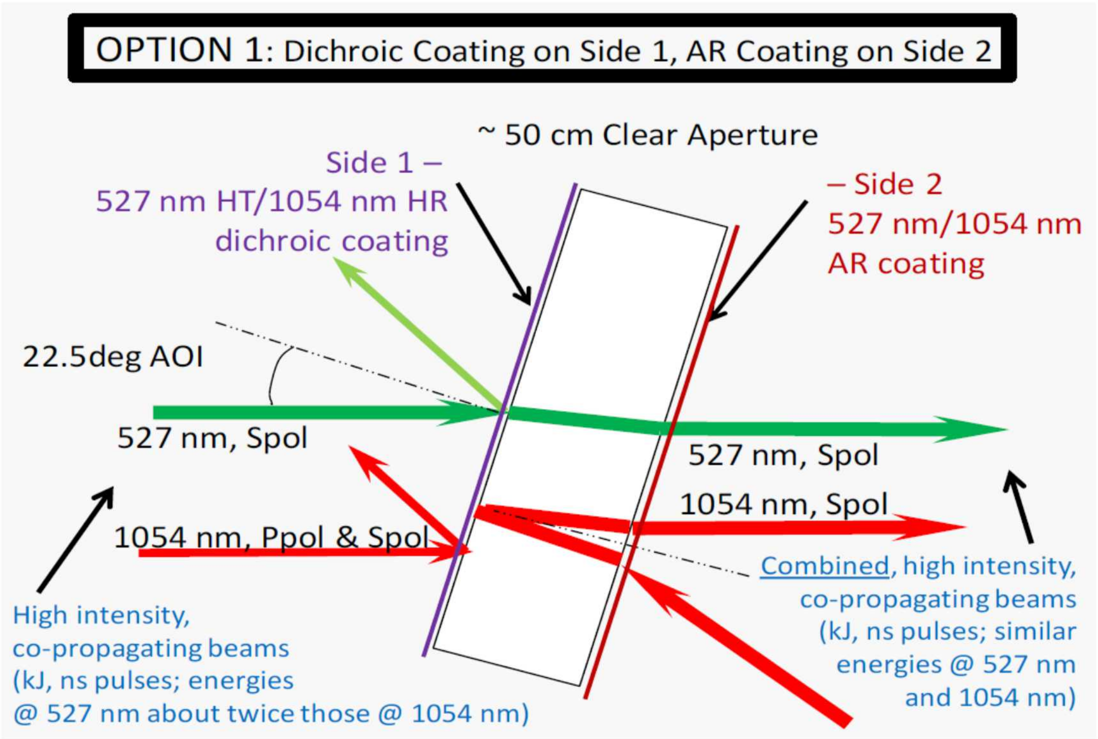
Z-Beamlet	Z-Petawatt
λ = 527 nm	λ = 1054 nm
τ = 0.3 – 6 ns	τ = 500 fs
I = 10^{16} W/cm^2	I = 10^{20} W/cm^2
E = 4 kJ	E = 500 J

Dual-wavelength coatings for high reflection (1054 nm) and high transmission (527 nm)

J. Bellum, et al., “Design and laser damage properties of a dichroic beam combiner coating for 22.5-deg incidence and S polarization with high transmission at 527 nm and high reflection at 1054 nm,” Optical Engineering, 56(1), 011020 (2016).

E. Field, et al., “Strategies for improving the laser-induced damage thresholds of dichroic coatings developed for high-transmission at 527 nm and high reflection at 1054 nm,” SPIE Proceedings Volume 10713, Pacific-Rim Laser Damage 2018: Optical Materials for High-Power Lasers; 107130A (2018).

Dual-wavelength coating for combining 527 nm and 1054 nm Z-Backlighter laser beams



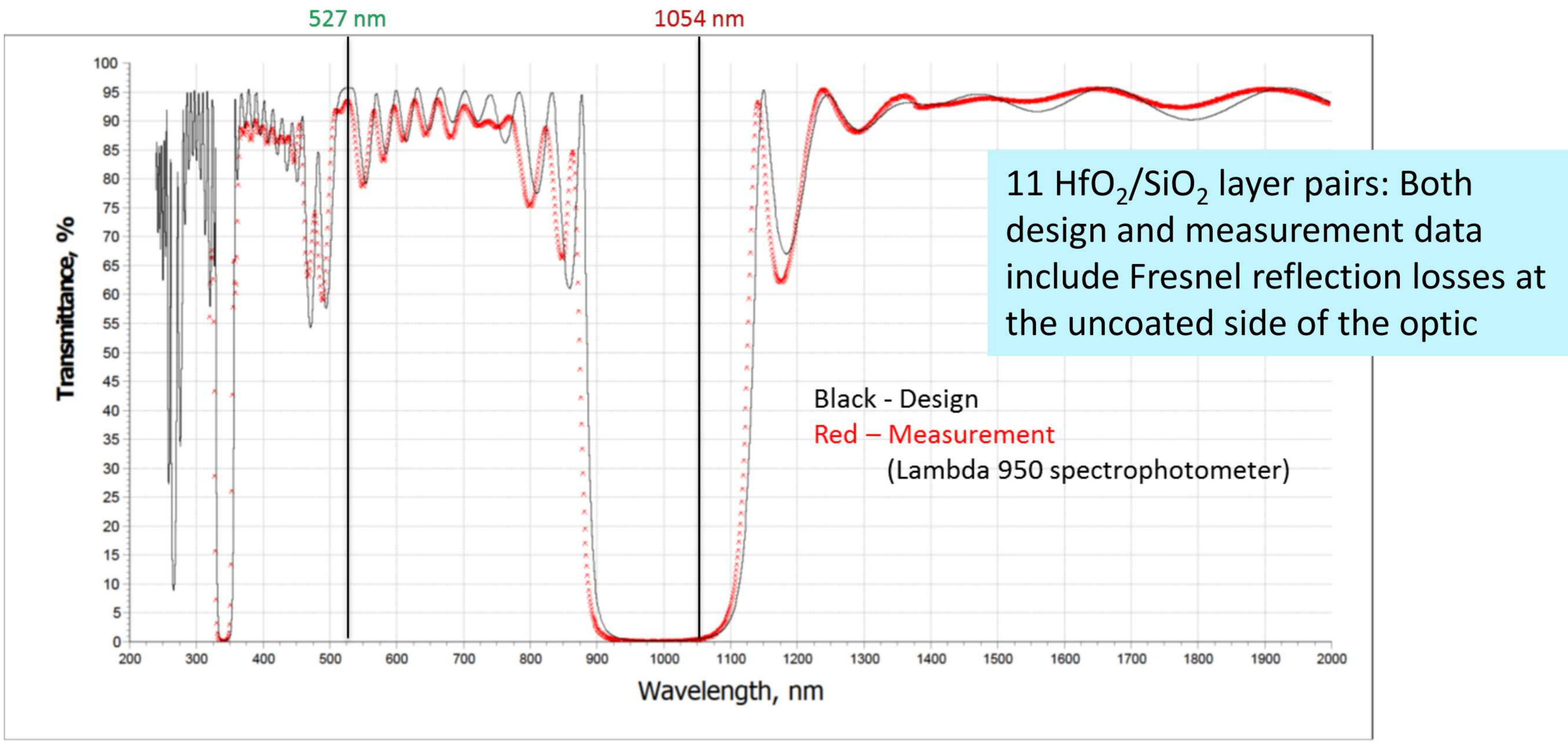
Coating Requirements:

- 22.5° angle of incidence (AOI)
- High transmission (HT) for 527 nm, S polarization (Spol)
- High reflection (HR) for 1054 nm, Spol
- High laser-induced damage threshold (LIDT)

Dichroic Coating History at Sandia

11 HfO_2/SiO_2 layer pairs → **LIDT: 7 J/cm²** (532 nm, 22.5⁰ Spol, 3.5 ns NIF-MEL protocol). 7 J/cm² LIDT was attributed to the E-field intensity peaks in the outer two HfO_2 layers. Therefore, the outer two hafnia layers were replaced with a higher bandgap material Al_2O_3. The coating with Al_2O_3 layers did not show notable improvement (**LIDT 7 – 10 J/cm²**). [1]

[1] J. Bellum, et al, "Use of Al_2O_3 layers for higher laser damage threshold at 22.5° incidence, S polarization of a 527 nm/1054 nm dichroic coating" in SPIE Proceedings Volume 10014, Laser-Induced Damage in Optical Materials, 2016. doi: 10.1117/12.2257607



Strategies for Increasing Laser Damage Threshold

Defects became the suspected cause of low LIDT because the E-field characteristics were already optimized in the 22-layer HfO_2/SiO_2 coating

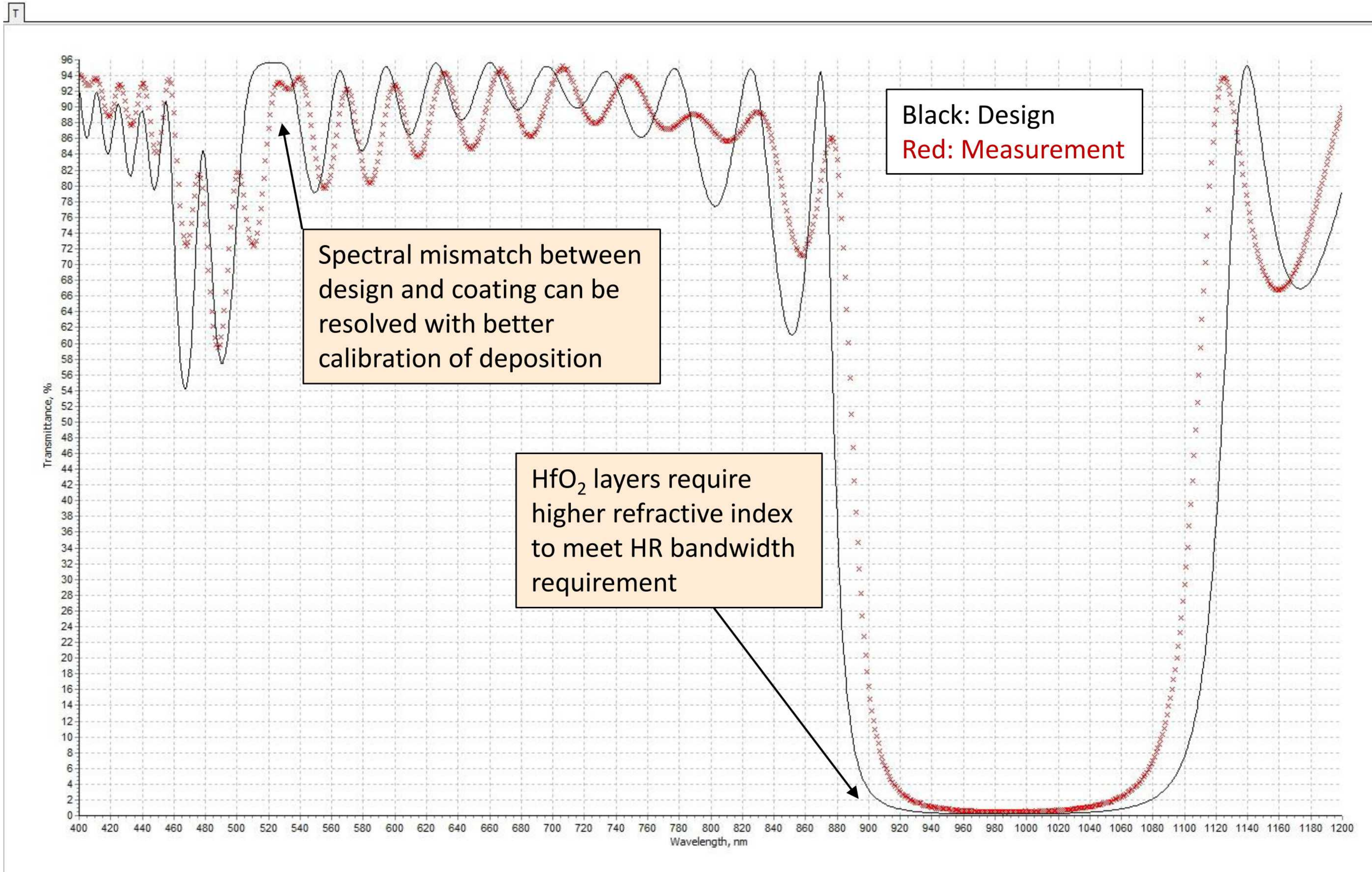
→ Therefore, our coating efforts focused on minimization of defects…

We used the same 22-layer HfO_2/SiO_2 coating design as before, but introduced the following changes in the deposition process:

- 100 nm silica adhesion layer → provides better foundation for first HfO_2 layer
- Slower hafnia deposition rate (from 3 Å/s to 2 Å/s) → minimizes spitting
- No-IAD → minimizes roughness; our lower density coatings tend to have higher LIDT

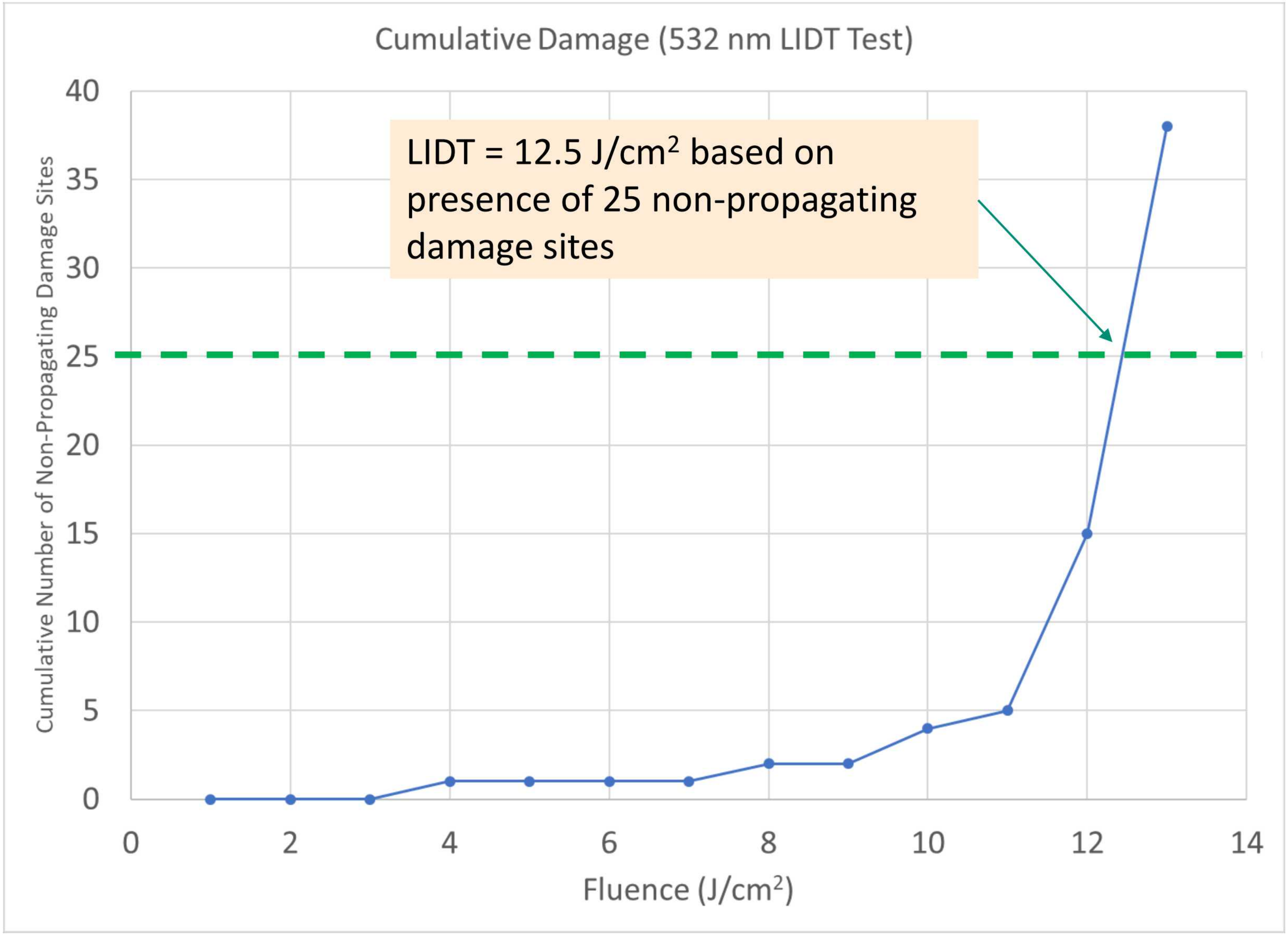
Note: All of the above changes to the deposition process were performed in the same coating. We prefer to address each variable one at a time, in separate coatings, but due to scheduling constraints this was not accomplished.

Spectral Characteristics

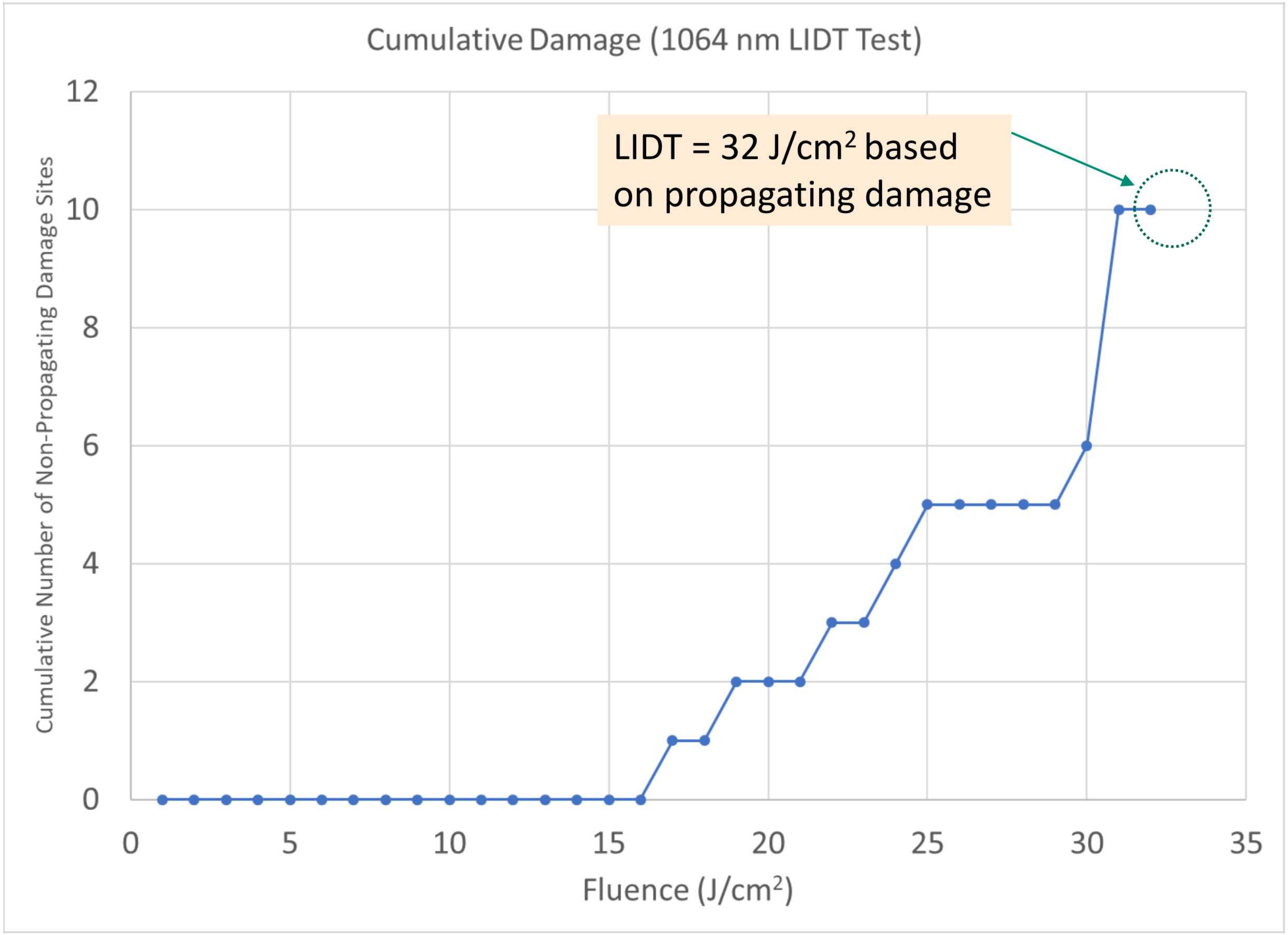


Both design and measurement data include Fresnel reflection losses at the uncoated side of the optic

Laser Damage Performance: 532 nm



Laser Damage Performance: 1064 nm



Conclusions

At 532 nm, the LIDT of 12.5 J/cm^2 is the highest we have achieved so far for a dichroic coating, however…

- The LIDT was based on the accumulation of defects rather than intrinsic damage. We expect to see even higher LIDTs when more of the defects are mitigated. The source(s) of the defects have yet to be determined.

- More investigation is needed to understand how each variable contributed to this positive result (lower hafnia deposition rate, addition of 100 nm silica adhesion layer, and no IAD).

- The refractive index of HfO_2 needs to be increased to meet the HR bandwidth requirement. However, the lower refractive index of HfO_2 in the current coating may be responsible for increasing the LIDT.

Next Steps:

- Damage testing of dichroic coating with HfO_2 refractive index correction (in process, expect results in a couple weeks)
- Deposit the dichroic coating on a large piece of float glass to determine if there are coating stress issues.

Broad bandwidth high reflection coatings

J. Bellum, et al., "Reactive ion-assisted deposition of e-beam evaporated titanium for high refractive index TiO_2 layers and laser damage resistant, broad bandwidth, high-reflection coatings," Applied Optics Vol. 53, Issue 4, pp. A205-A211 (2014).

E. Field et al., "Laser damage comparisons of broad-bandwidth, high-reflection optical coatings containing TiO_2, Nb_2O_5, or Ta_2O_5 high-index layers," Optical Engineering, 56(1), 011018 (2016).

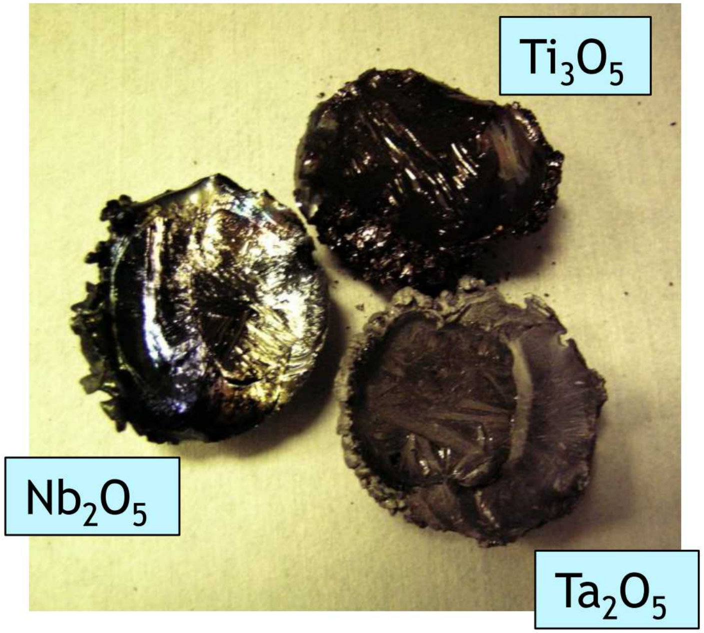
J. Bellum, et al., "Analysis of laser damage tests on coatings designed for broad bandwidth high reflection of femtosecond pulses," Optical Engineering, 56(1), 011012 (2016).

J. Bellum, et al., "Low Group Delay Dispersion Optical Coating for Broad Bandwidth High Reflection at 45° Incidence, P Polarization of Femtosecond Pulses with 900 nm Center Wavelength," Coatings 2016, *6*(1), 11.

Development of High Index Layers for Broad Bandwidth High Reflection Applications

Materials Explored:

Material	Index of Refraction at 500 nm
TiO_2 (from Ti metal)	2.42
TiO_2 (from Ti_3O_5)	2.41
Nb_2O_5	2.37
Ta_2O_5	2.19



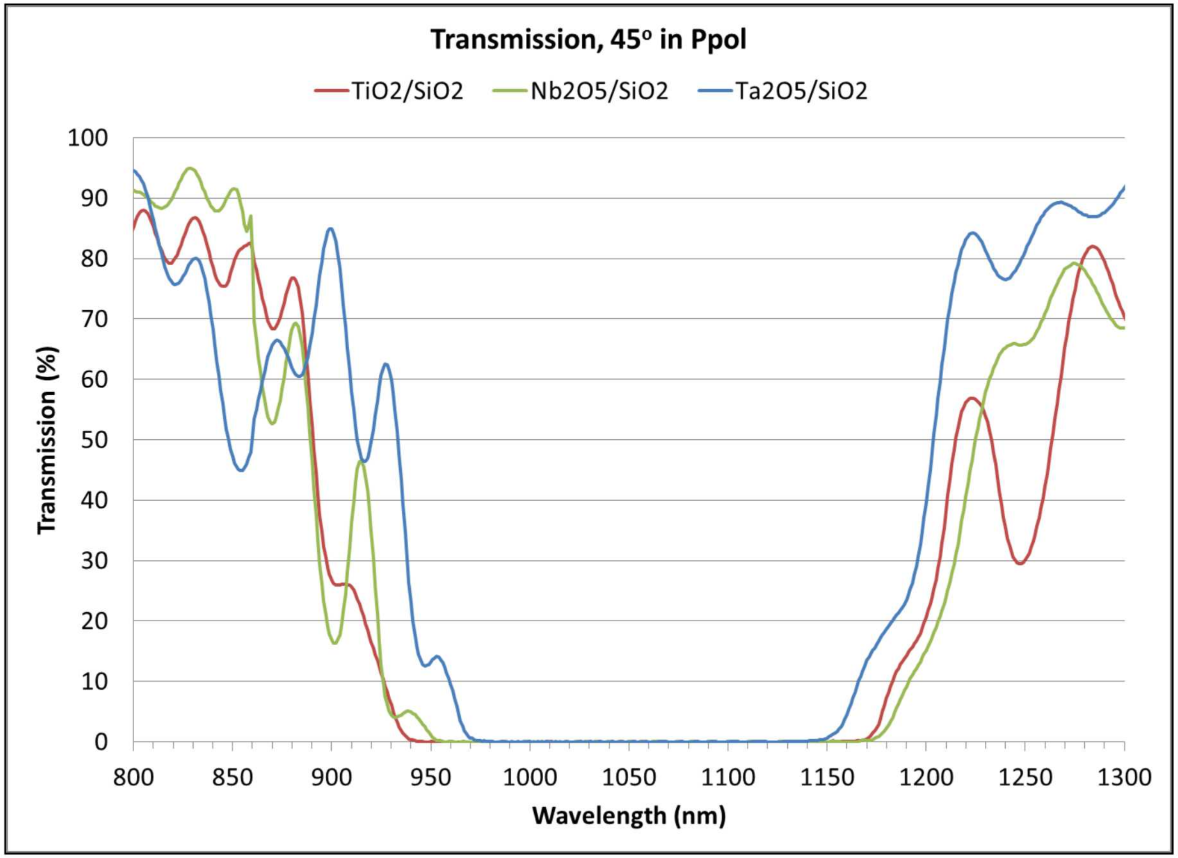
HR Coating designs:

- 42-layer quarter wave stacks for 1054 nm, 45^o Ppol
- High index materials paired with SiO_2
- Explored using both HfO_2 and TiO_2 layers within the same coating

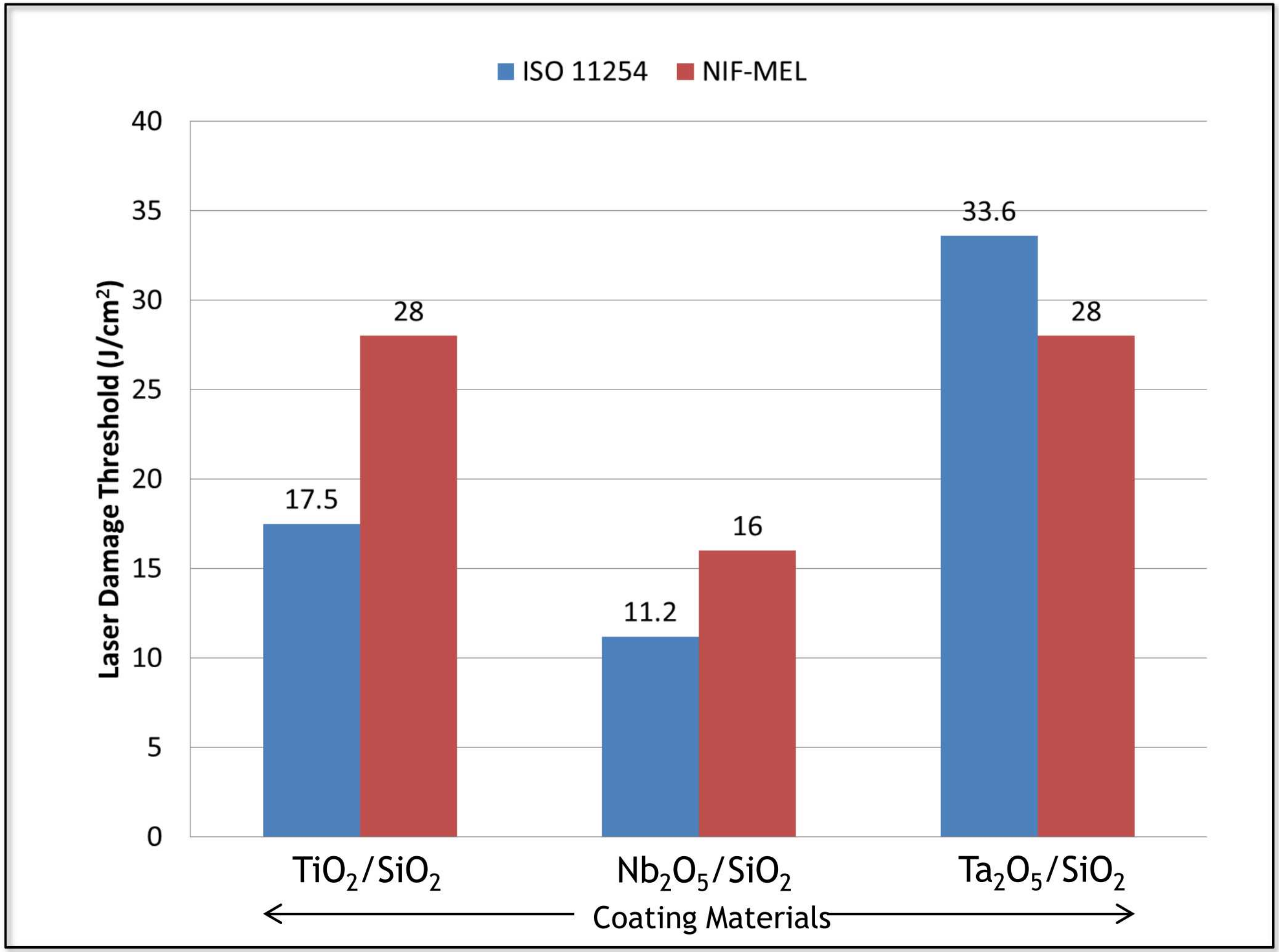
HR Bandwidths for Coatings Containing TiO_2 (from Ti_3O_5), Nb_2O_5, and Ta_2O_5 Layers

- HR bandwidth taken where transmission < 0.5%
- The 42-layer coatings all exhibit higher bandwidth than predicted

Coating Materials	HR Bandwidth, Ppol, 45°	
	Predicted (nm)	Actual (nm)
TiO_2/SiO_2	221.3	231
Nb_2O_5/SiO_2	218.7	221
Ta_2O_5/SiO_2	158.7	177



Laser Damage Thresholds: TiO_2 (from Ti_3O_5), Nb_2O_5, and Ta_2O_5 HR Coatings

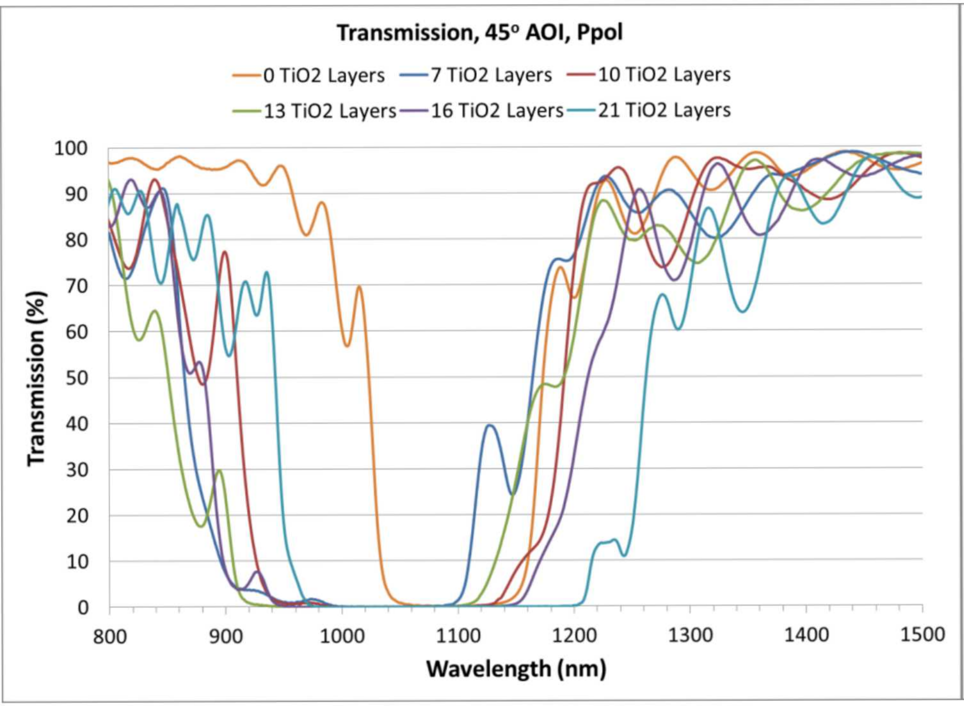


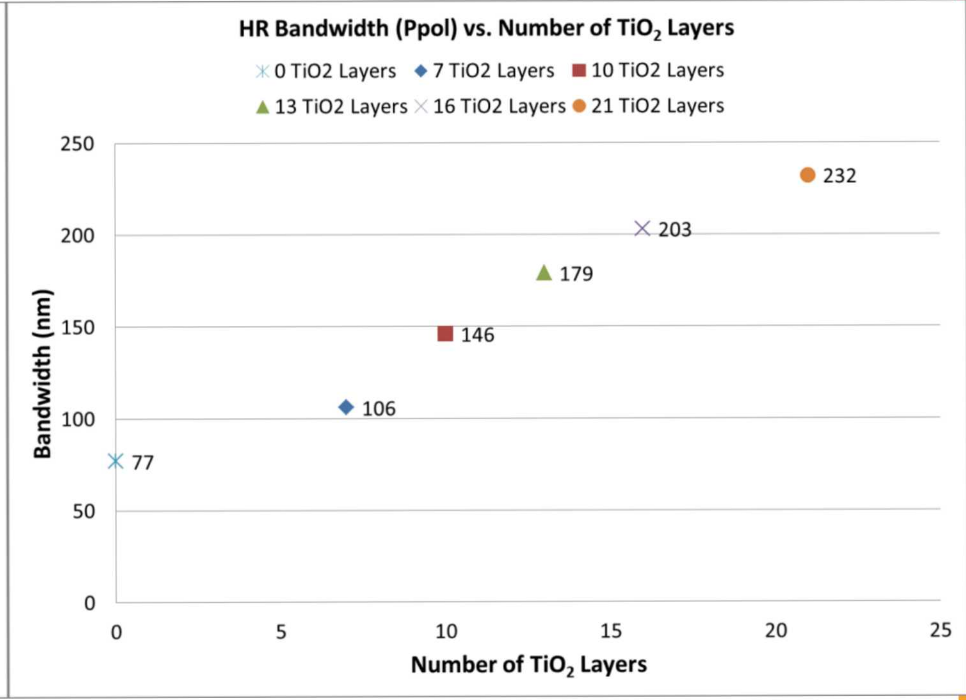
Test Protocols at 1064 nm, 45° AOI, Ppol:

- Spica: NIF-MEL Method with 3.5 ns laser pulses
- Quantel: ISO Damage Frequency Method (ISO Standard 11254-1) with 10 ns pulses

Another broad bandwidth study: Replacing Inner HfO_2 Layers with High Index TiO_2 Layers in 42-Layer Coatings to Increase HR Bandwidth at Expense of LIDT

- Studied 42-layer coatings for HR at 45° AOI, Ppol
- Replaced inner HfO_2/SiO_2 layer pairs with 7, 10, 13, 16 and 21 TiO_2/SiO_2 layer pairs
- TiO_2 layers: higher index, lower band gap increases HR bandwidth but decreases LIDT;
  - Material: reactive deposition from Ti metal and oxygen gas
- HfO_2 layers: lower index, higher band gap increases LIDT but decreases HR band gap
  - Material: reactive deposition from Hf metal and oxygen gas

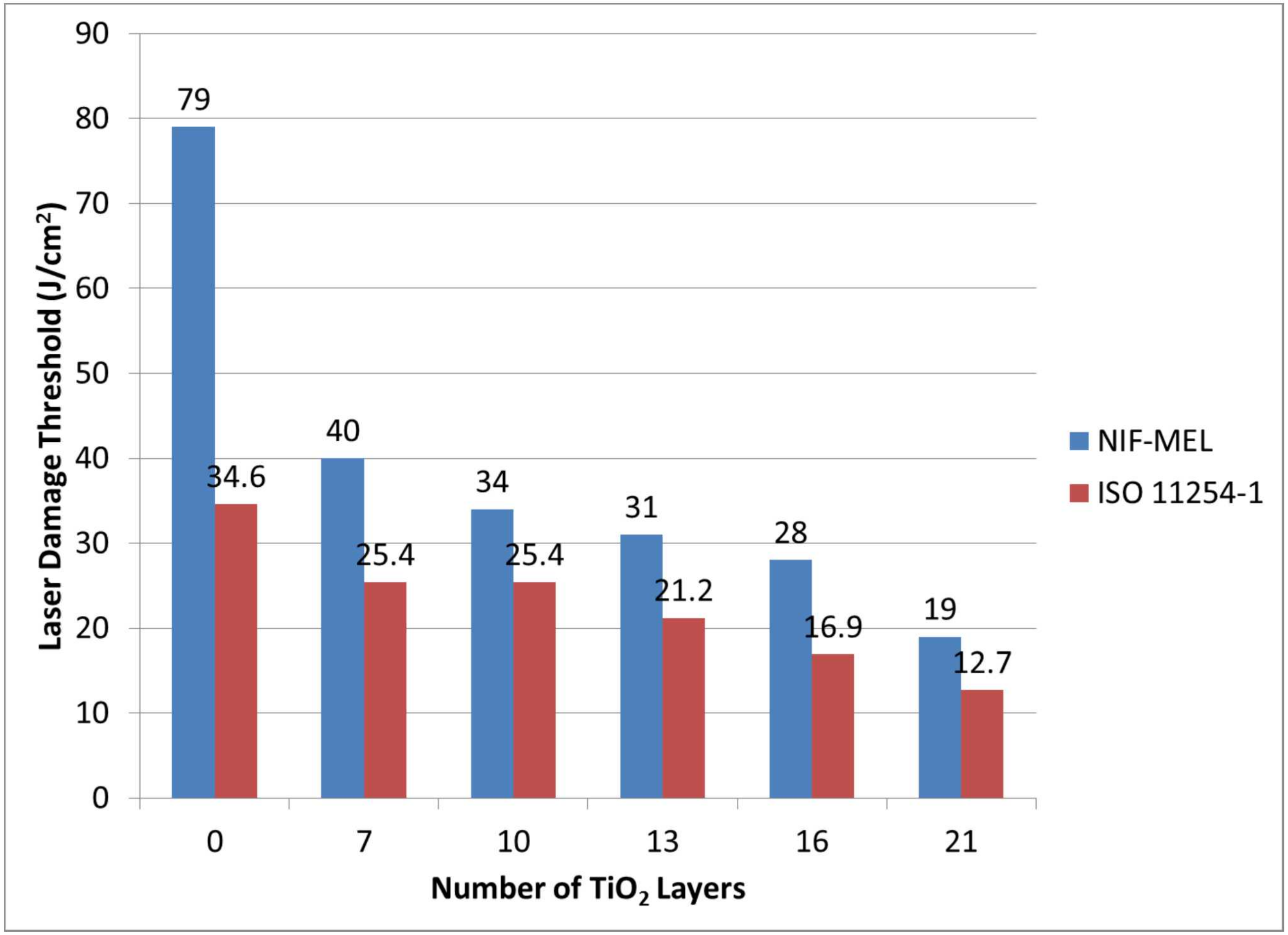




Bandwidth measured across T < 0.5%

Replacing Inner HfO_2 Layers with High Index TiO_2 Layers in 42-Layer Coatings to Increase HR Bandwidth at Expense of LIDT

LIDT Results



Test Protocols at 1064 nm, 45° AOI, Ppol:

- Spica: NIF-MEL Method with 3.5 ns laser pulses
- Quantel: ISO Damage Frequency Method (ISO Standard 11254-1) with 10 ns pulses

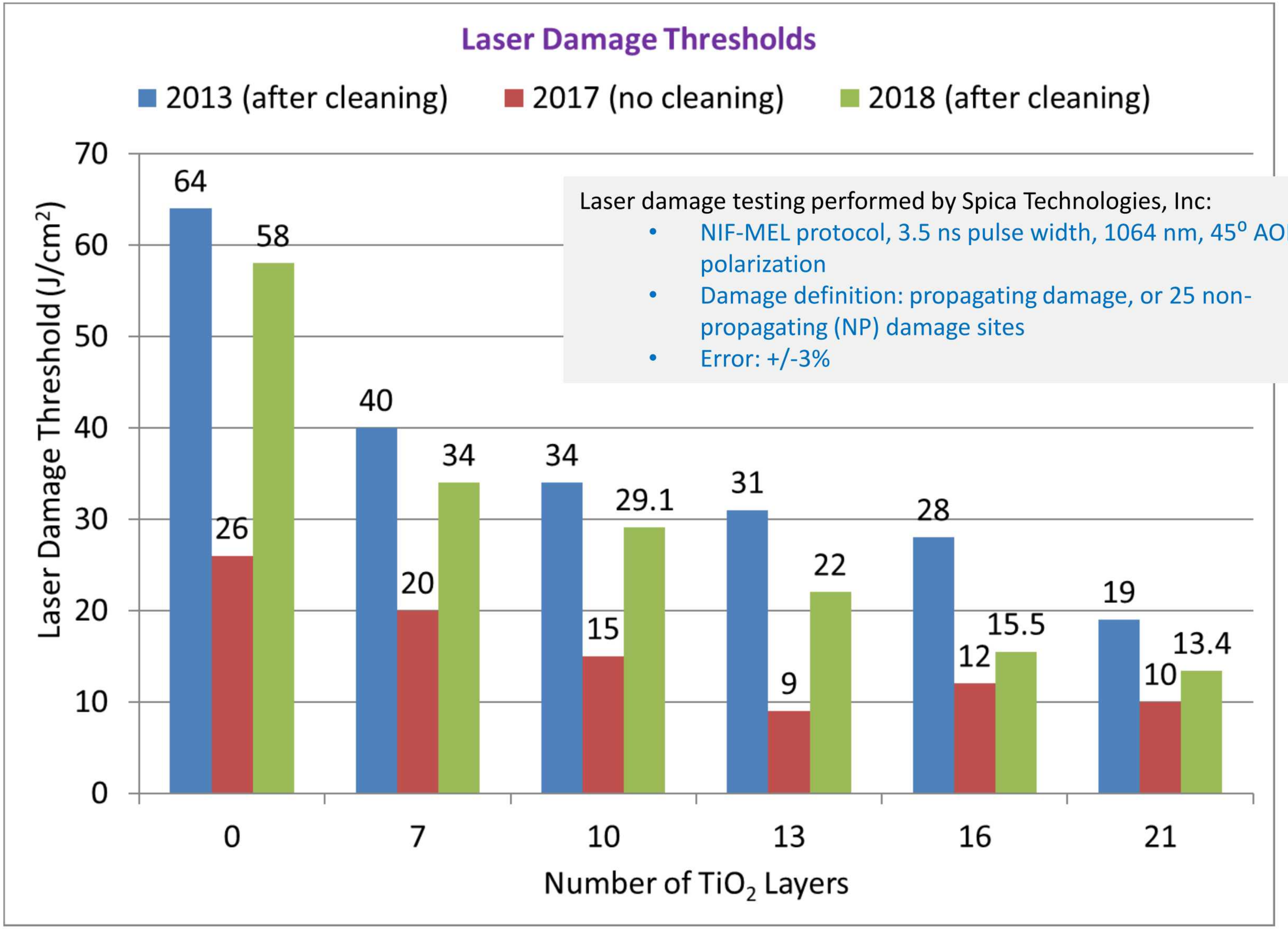
Optic cleaning, contamination, and storage concerns

E. Field, et al., “Impact of different cleaning processes on the laser damage threshold of antireflection coatings for Z-Backlighter optics at Sandia National Laboratories,” Optical Engineering, 53(12), 122516 (2014).

E. Field, et al., “How reduced vacuum pumping capability in a coating chamber affects the laser damage resistance of HfO2/SiO2 antireflection and high-reflection coatings,” Optical Engineering, 56(1), 011005 (2016).

E. Field, et al., “The impact of contamination and aging effects on the long-term laser-damage resistance of $SiO_2/HfO_2/TiO_2$ high-reflection coatings for 1054nm,” SPIE Proceedings Volume 10805, Laser-Induced Damage in Optical Materials 2018: 50th Anniversary Conference; 108051T (2018).

Optics stored in PETG containers for a few years in a class 100 clean room still accumulate contamination that lowers LIDT by a factor of 2 or more. Optics must be cleaned after long storage periods to restore the high LIDT.

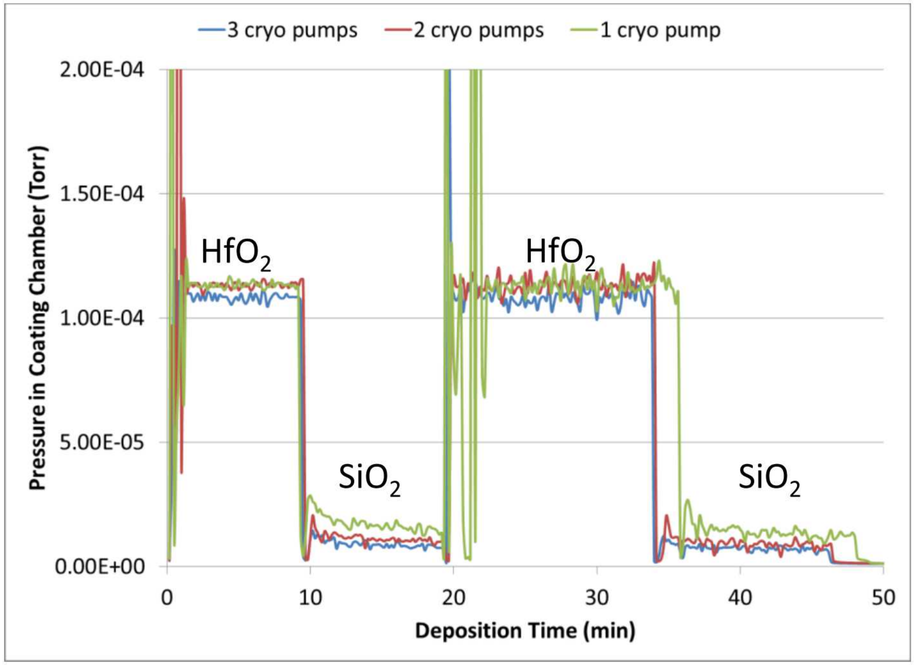


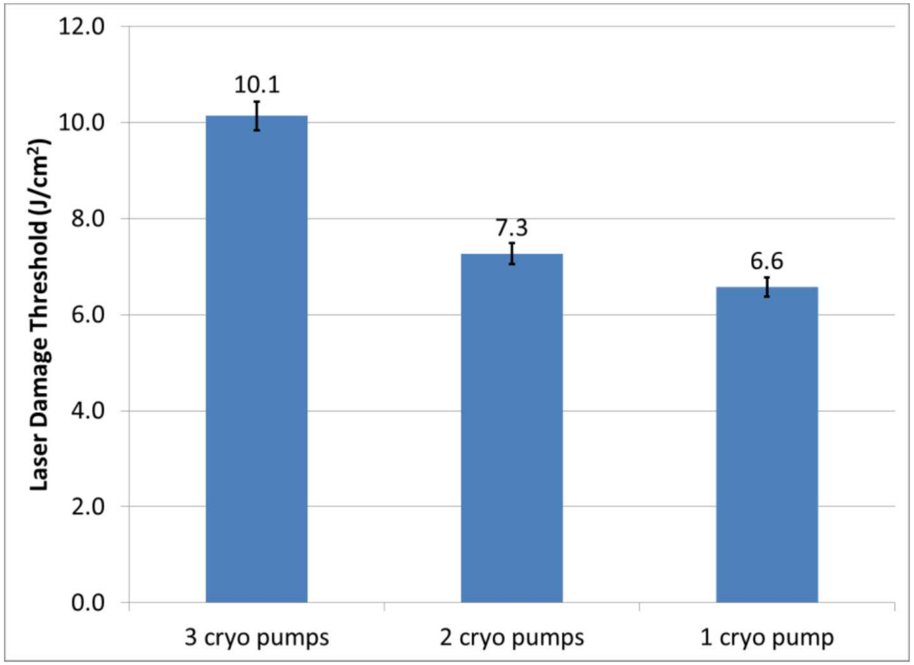
Laser damage testing performed by Spica Technologies, Inc:

- NIF-MEL protocol, 3.5 ns pulse width, 1064 nm, 45° AOI, P-polarization
- Damage definition: propagating damage, or 25 non-propagating (NP) damage sites
- Error: +/-3%

LIDT is also reduced by lower vacuum pumping speeds during the coating process

AR Coating (4 layers):





Fewer vacuum pumps lead to higher pressure during deposition, especially in SiO_2 layers

Fewer vacuum pumps ultimately lead to lower LIDTs

NIF-MEL Damage testing protocol:

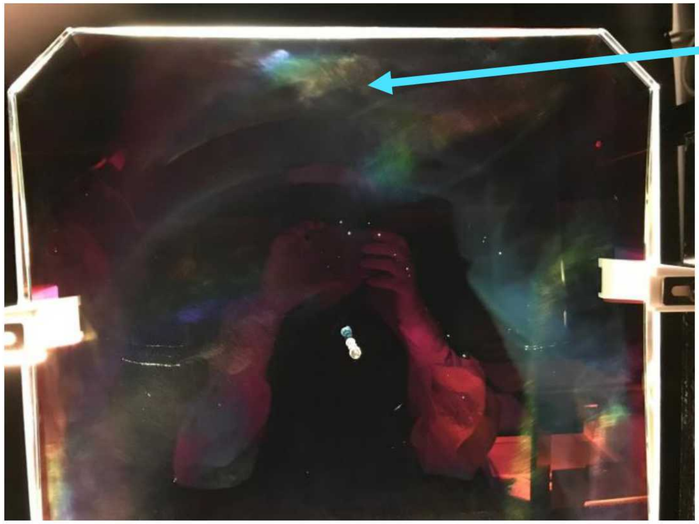
*3.5 ns pulse width, 0°, 532 nm, +/- 3% error

*Damage definition: propagating damage, or 25 non-propagating (NP) damage sites

*Performed by Spica Technologies Inc.

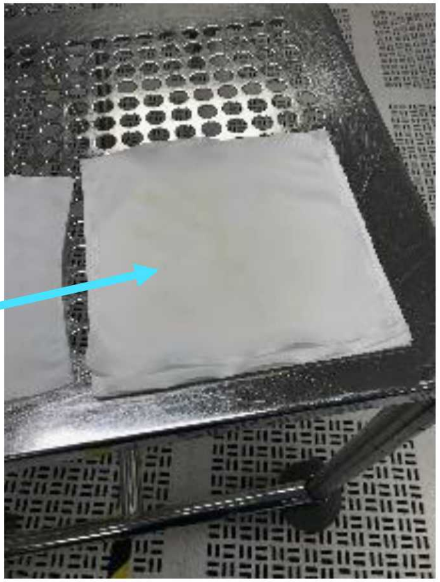
Contamination in the beam lines

In some of the beamlines, there are motorized stages that contain grease. This grease has contaminated some of our lenses. Periodically, we remove the lenses and clean them with acetone. Transmission through the lenses improves after cleaning.



Oily haze on lens

Oil seen on a wipe with acetone



Note: e-beam deposition results in coatings that are porous. This means the coatings can be very difficult to clean once they have been contaminated. We have been able to successfully clean this grease with acetone, but hours of manual labor are required. At a larger laser facility with more optics to clean, I imagine this type of manual cleaning would not make sense. Reducing contamination is a better option.

Thank You! Questions?