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Repair of a Mirror Coating on a Large Optic for High Laser Damage Applications using Ion Milling and Over-Coating Methods

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Introduction

About Sandia's Large Optics Coating Operation:

- We deposit optical coatings consisting of HfO_2/SiO_2 layer-pairs on large optics for Sandia's Z-Backlighter Lasers using e-beam evaporation. HfO_2 is deposited by reactive evaporation of Hf in O_2 back pressure; sometimes we use ion-assisted deposition (IAD). The coatings must have high laser damage resistance.

About Sandia's Z-Backlighter Lasers:

- The kilojoule class pulsed laser system is coupled to the most powerful and energetic x-ray source in the world, the Z-Accelerator

Z-Beamlet	Z-Petawatt
λ = 527 nm	λ = 1054 nm
τ = 0.3 – 8 ns	τ = 500 fs
I = 10^{17} W/cm²	I = 10^{19} W/cm²

http://www.z-beamlet.sandia.gov/

A case study: how to salvage a substrate with an incorrect coating

- This study was conducted because a coating was incorrectly deposited on a 65 cm diameter mirror substrate (BK7)
  - The coating was a 42-layer quarter wave high reflection design for 1054 nm and 45 degrees, Ppol, consisting of SiO_2 and HfO_2 layers.
  - The SiO_2 layers were deposited via e-beam evaporation of SiO_2 granules, and the HfO_2 layers were deposited via e-beam evaporation of Hf in an oxygen environment.
  - The coating was unsuccessful because at layer 35, there was no oxygen in the chamber to react with Hf and form HfO_2. Hence, layer 35 was Hf metal and not suitable for high laser damage thresholds.

Our usual protocol is to repolish and recoat optics when the coating is unsuitable, but in an effort to save time and money, we performed ion milling and recoating experiments to see if any of those methods would be an appropriate alternative.

Exploring alternatives to removing or repairing high reflection coatings from large substrates

- **Alternative options that we tested:**
  1. **Deposit a new coating on top of the original coating –** the incorrect coating would be buried under the correct coating and therefore diminish the negative impact that the incorrect coating would have on the laser-induced damage threshold.
  2. **Remove the entire coating with ion milling –** recoat the optic with the correct coating following the complete removal of the incorrect coating.
  3. **Remove select layers from the coating with ion milling –** remove the outer layers through to the incorrect layer and recoat them correctly, leaving the underlying coating intact.
- **Evaluation Criteria:**
  - Laser-induced damage threshold (LIDT)
  - Spectral requirements

Repair Method 1: bury the incorrect coating under a new coating

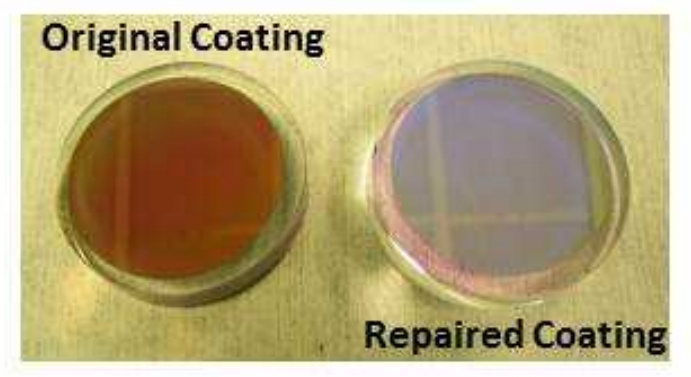
- **Concept:** the electric field magnitude of a high reflection coating quenches rapidly, such that much of the field diminishes within the outermost layers of the coating. Depositing a correct mirror coating on top of the incorrect mirror coating would not allow much light to penetrate into the incorrect coating, and therefore the incorrect coating may be prevented from greatly impacting the LIDT.
- **Outcome:** we deposited a 35-layer correct coating on top of a 34-layer incorrect coating that had an Hf layer intentionally placed at layer 27. The LIDT was just 7 J/cm², far below the 70 J/cm² LIDT of the 35-layer coating itself.
- **Other concerns:**
  - crazing and delamination on large optics
  - This method best suited for high reflection coatings

Repair Methods 2 and 3: ion milling to remove entire coating or select outer layers

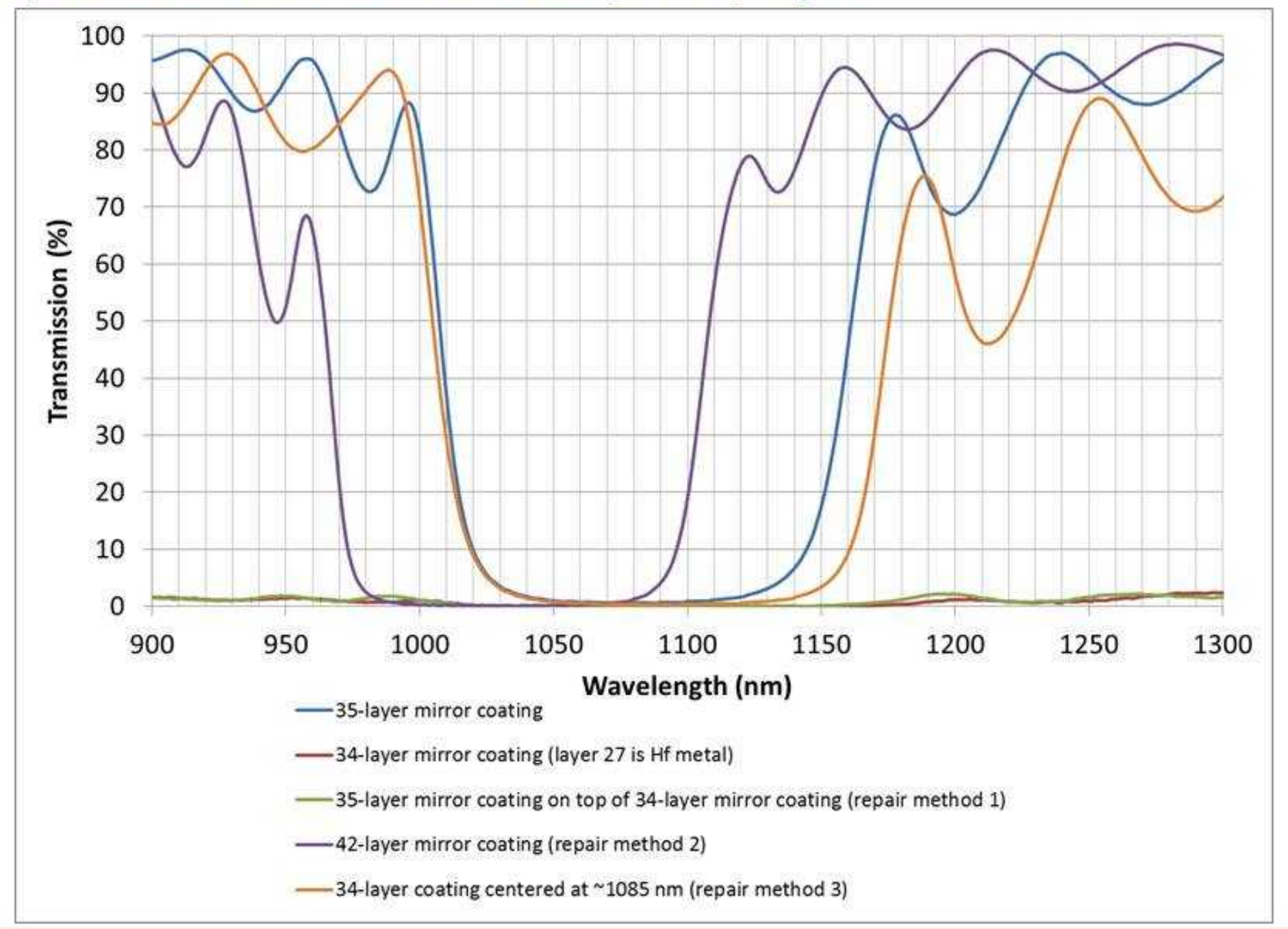
- **Concept:** ion milling can be used to etch away the coating all the way down to the bare substrate. The bare substrate can then be recoated with the correct coating. Or, select outer layers can be etched and recoated.
- **Ion milling parameters:**
  - Gridded RF ion source, 16 cm diameter grid, beam oriented diagonally across chamber at optic center
  - Ion beam voltage and current: 750 V and 750 mA
  - Gas flows: oxygen 5 sccm, argon 35 sccm, argon neutralizer 7 sccm
- **Etch rates:** SiO2: ~100 nm/hr, HfO2: ~60 nm/hr
- **Etch indicators:** SiO_2 layers appear dark and HfO_2 layers appear white during the ion milling process – must turn off lights to see these colors.

Ion milling outcomes

- **Removing the entire coating (method 2)**
  - Good laser damage thresholds achieved (49 to 61 J/cm²)
  - ~10 days required to remove 42 layers from the 65 cm diameter optic
  - Dense pitting on substrate surface
  - Non-uniform etch rate: material removed fastest from center of optic compared to edges, substrate surface may now have slight curvature, though this has not effected the performance of the mirror, which is now in the Z-Backlighter beam train.
- **Removing select layers (method 3)**
  - LIDT compromised by poor spectral mismatch
  - Same etch non-uniformity leads to simultaneous exposure of multiple coating layers in bands across large optics
  - We removed 10 layers from a 34-layer analogue of the original 42-layer coating. Layer 27 was intentionally an Hf metal layer. We etched through layer 25 and recoated 10 layers on top of it to form a repaired 34-layer coating free of Hf metal.

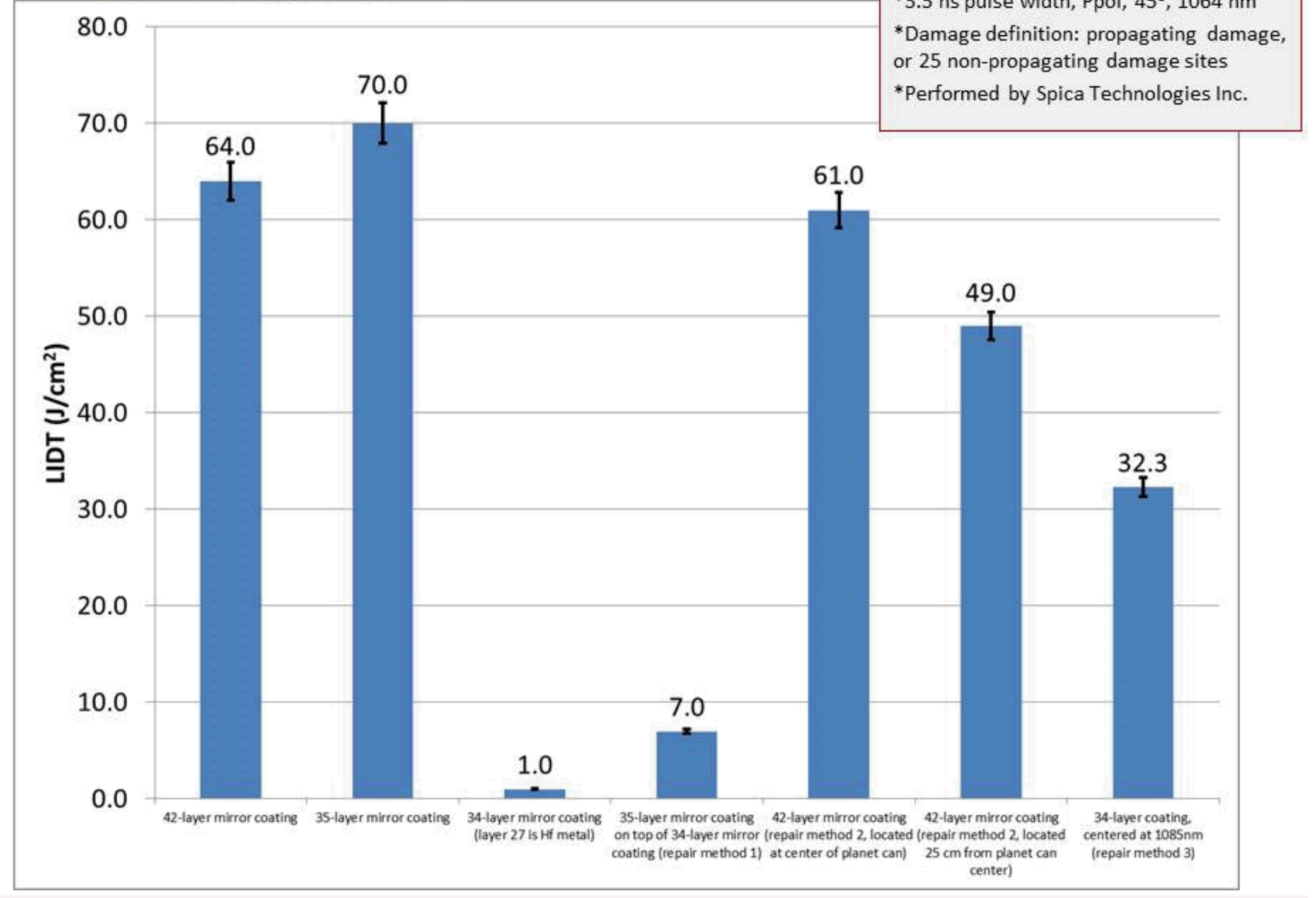


Spectral characteristics, 45°, Ppol

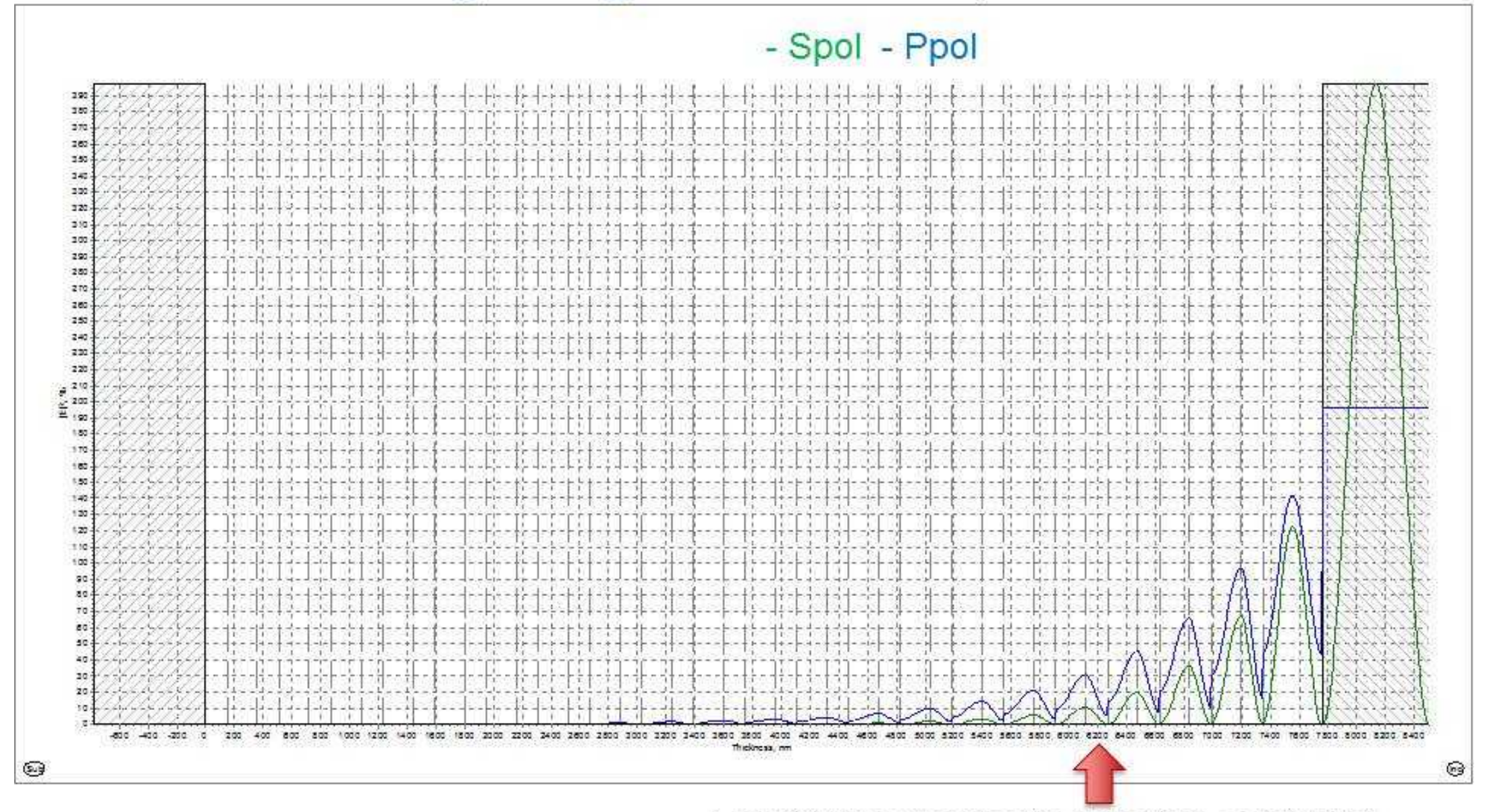


Laser damage results

NIF-MEL Damage testing protocol:
*3.5 ns pulse width, Ppol, 45°, 1064 nm
*Damage definition: propagating damage, or 25 non-propagating damage sites
*Performed by Spica Technologies Inc.



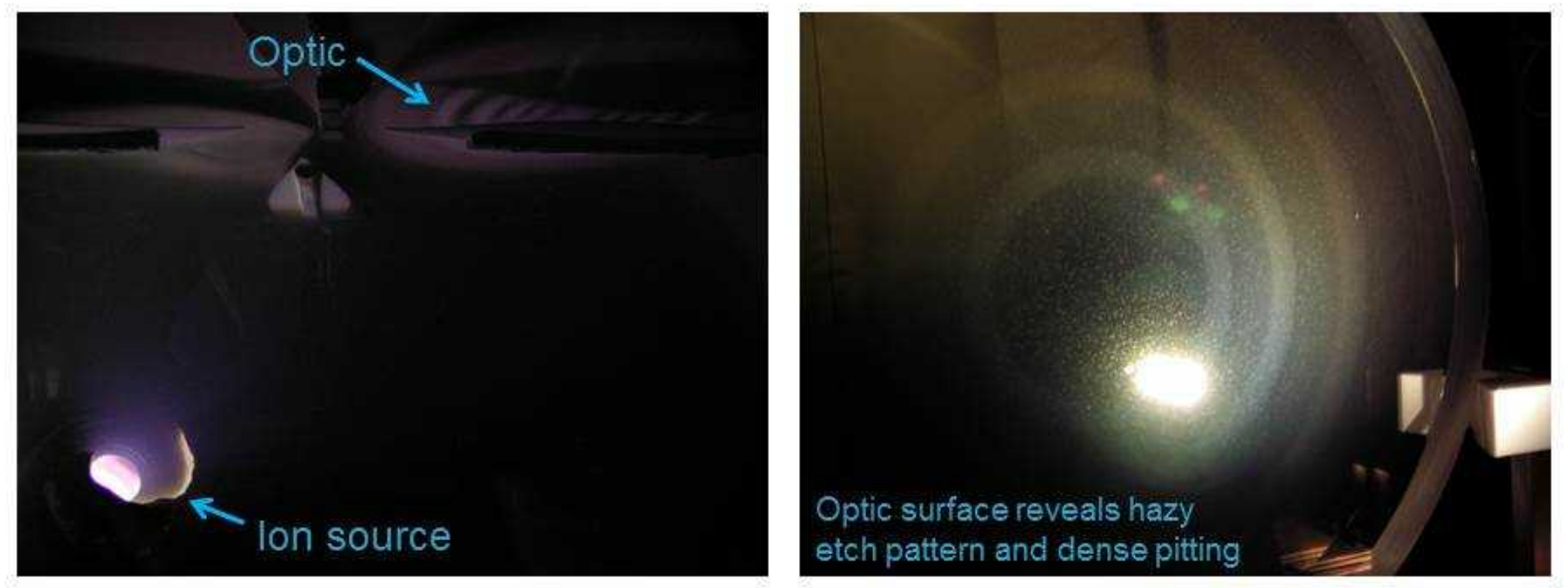
Electric field characteristics of 42-layer mirror coating design at 1054 nm, 45°



Layer 35 was incorrectly deposited as Hf metal

Ion milling concerns: non-uniform etch rate

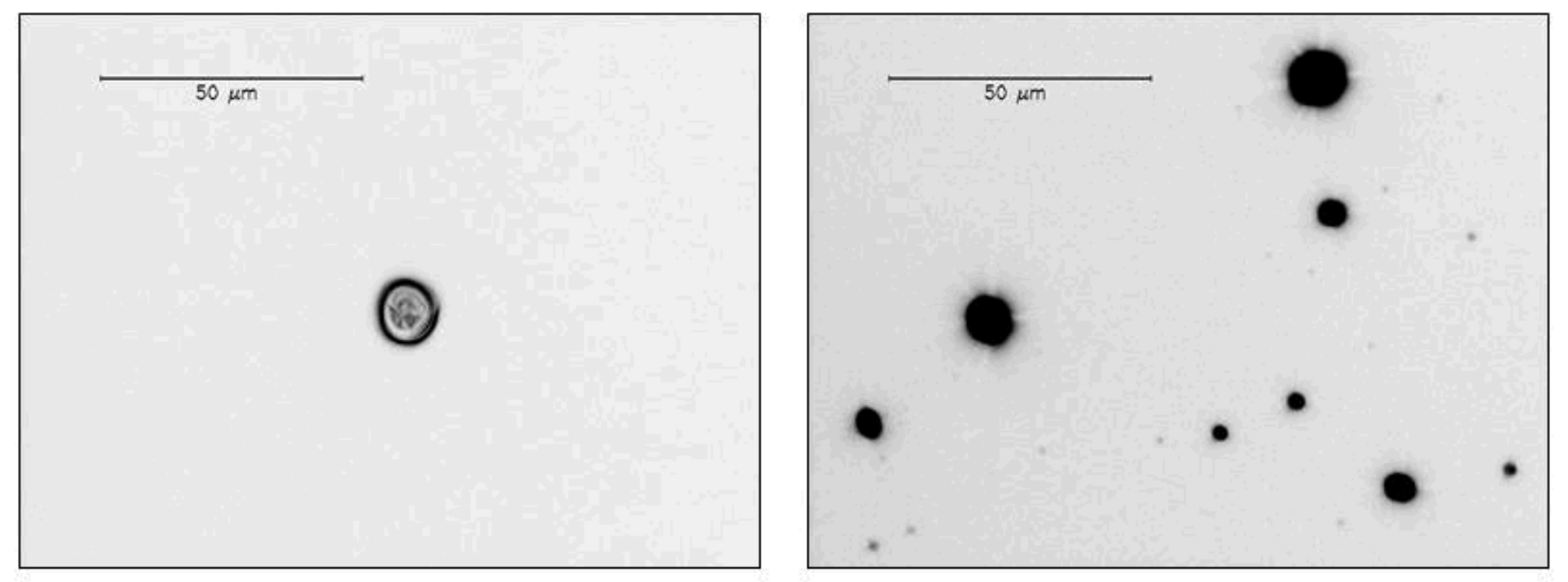
- Not a problem for small optics (~12 cm diameter)
- Faster etch rate at the center of the optic means the coating was completely removed from the center before the edges were finished. This means the bare substrate was etched as well, giving it slight curvature. At worst, we estimate the substrate radius of curvature to be 32 km.



Optic surface reveals hazy etch pattern and dense pitting

Ion milling concerns: pitting on substrate surface

- 5 – 10 micron pits appear over entire optic surface
- Consider trying lower ion energies to reduce pitting, though this will increase the etch time



***Despite the pitting and non-uniformity of the etch, the mirror is performing well in the Z-Backlighter beam train**

Summary of optical coating repair methods

Method	Pros	Cons
1. Deposit a new coating on top of the original coating	• Shortest lead time	• Poor LIDT – negative impact of underlying metal layer still evident • Delamination and crazing may be a concern with large optics
2. Remove entire coating with ion milling	• Achieves the highest LIDT compared to methods 1 and 3 • Good approach for thin, AR coatings • Useful for both small and large optics	• ~1 week required to remove 42 layer HR coating • Minor removal of material from center of substrate due to poor etch uniformity • Pits on substrate surface
3. Remove select layers from the coating with ion milling	• Entire removal of coating not required	• Unsuitable for large optics (>12 cm diameter) because non-uniform etch simultaneously exposes multiple coating layers in bands • Difficulty with spectral mismatch between repaired and underlying layers; could compromise LIDT • Potential for delamination
4. Repolishing	• Returns substrate surface to original condition	• Expensive • Potentially long lead time