Evaluation of Polymer Membrane Deformable Mirrors for High Peak Power Laser Machining Applications

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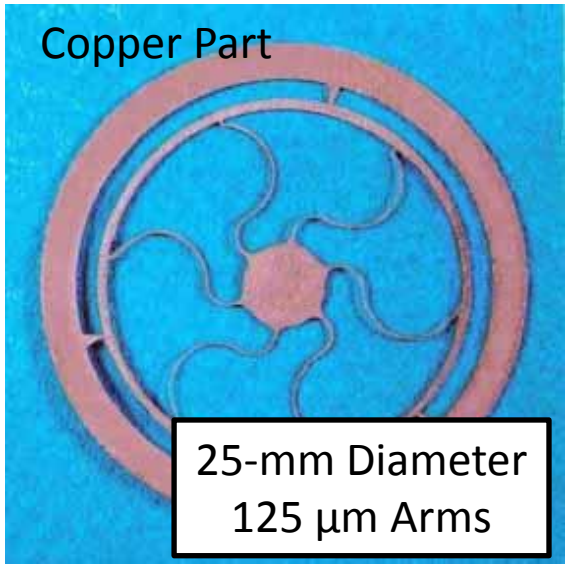
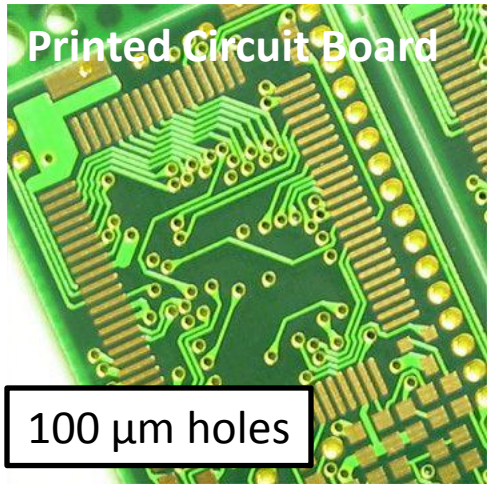
Outline

- Introduction and Motivation
- Polyimide Membrane Deformable Mirror
  - DM Design
  - Humidity Comparison
  - Ultimate Deformation Evaluation
  - Laser Damage Evaluation
- Beam Shaping Demonstration
  - Fiber Laser Beam Shaping
  - Compact Beam Shaping System
- Conclusions & Future Work

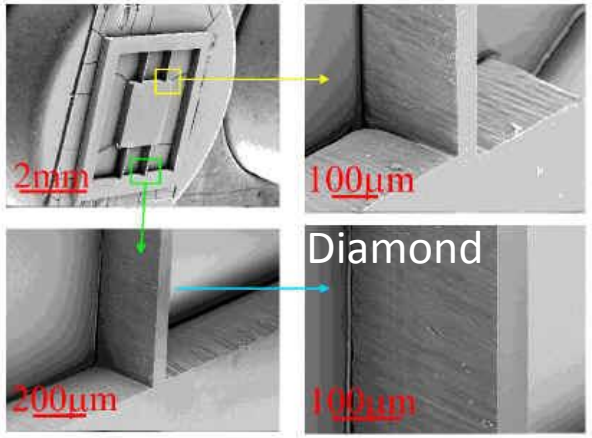
Laser machining is enabling and being widely used in manufacturing. AO can help make it better.



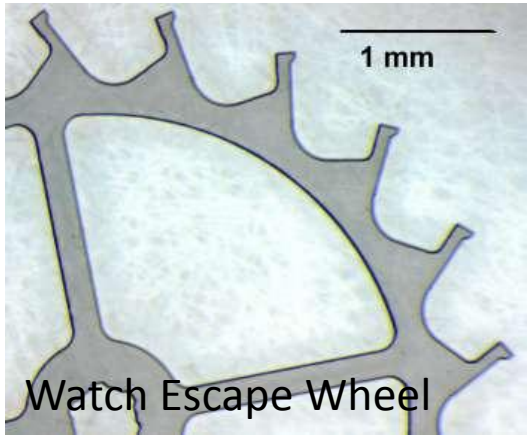


http://www.tp-electronics.com

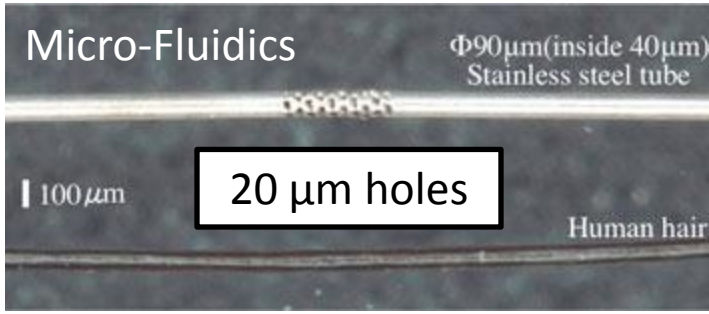
http://www.stencilsunlimited.com/laser-cutting.php



http://www.laserod.com/thin.shtm



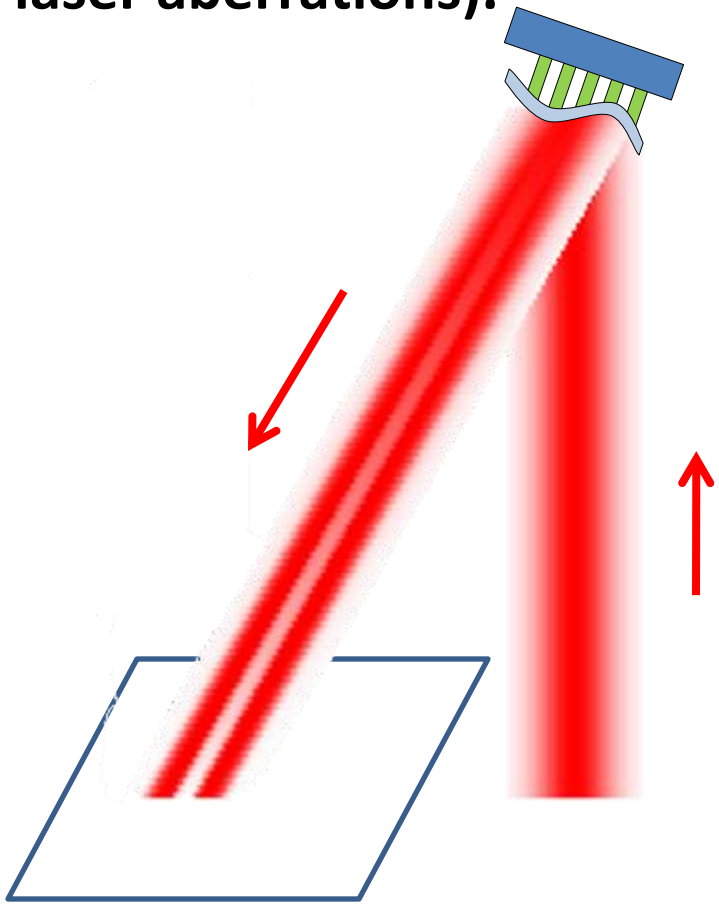
http://www.cvd-diamond.com



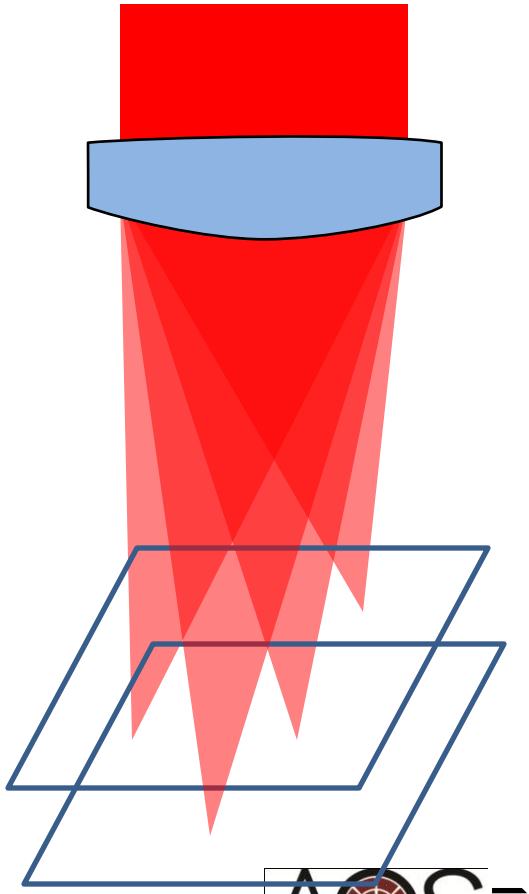
http://www.aist.go.jp/aist_e/latest_research/2009/20090430/20090430.html

How can AO help Laser Machining?

AO enables beam shaping and self-healing (compensation of laser aberrations).



AO also enables scanning in all three axes.



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Laser Machining Requirements for AO

- Appropriate Power Handling
  - Generally Two Modes
    - High Peak Power / Mid Avg. Power
    - High Average Power
  - Truly Continuous Surfaces & High Reflectivity Coatings Preferred
- Good Switching Speed –
  - ~500 Hz
- Relatively Small Size –
  - Systems are typically 1 to 2 meters on each side.
- Industrialized & Robust

http://sureshindulaser.tradeindia.com/Exporters_Suppliers/Exporter7574.280310/Industrial-CO2-Laser-Cutting-System.html

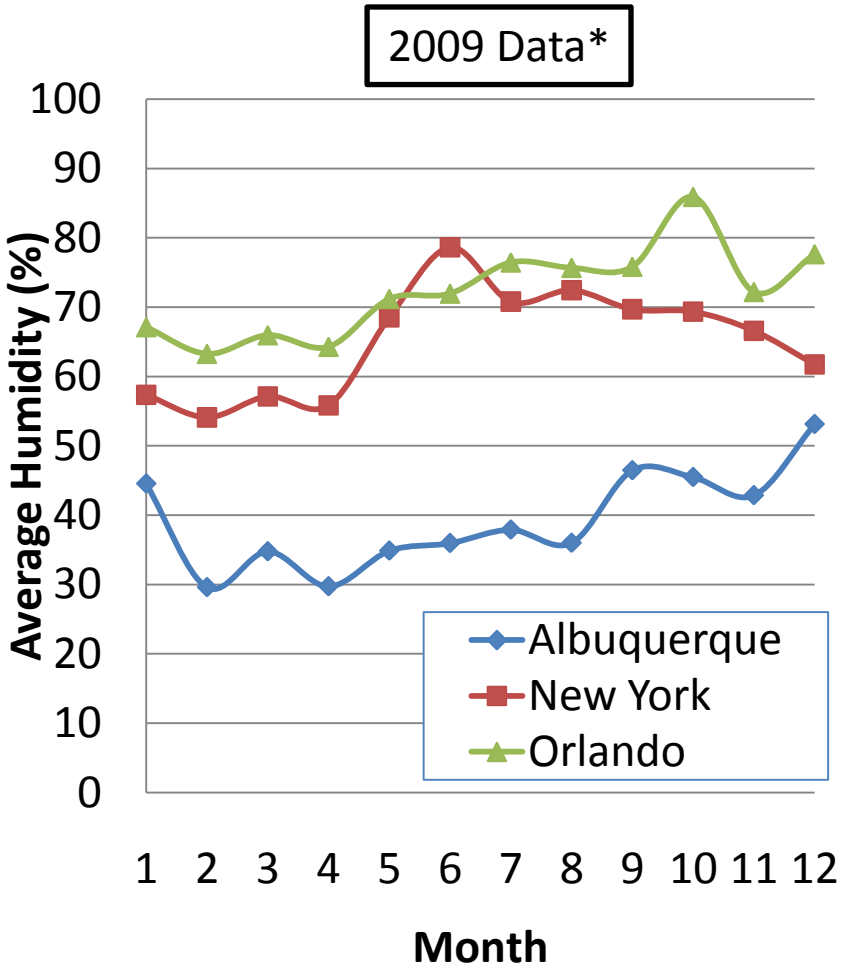
We addressed some of the key challenges to laser machining adoption in our prior work.

Prior Work Challenges	New Approach
Humidity reduces nitrocellulose mirror tension	Polyimide Membranes
Need good laser power handling	Dielectric Coatings
Established reliability	Test Large Deformation
Lab-Scale System Size	System Miniaturization

EFFECT OF HUMIDITY ON MEMBRANE TENSION

Effect of Humidity on Membranes

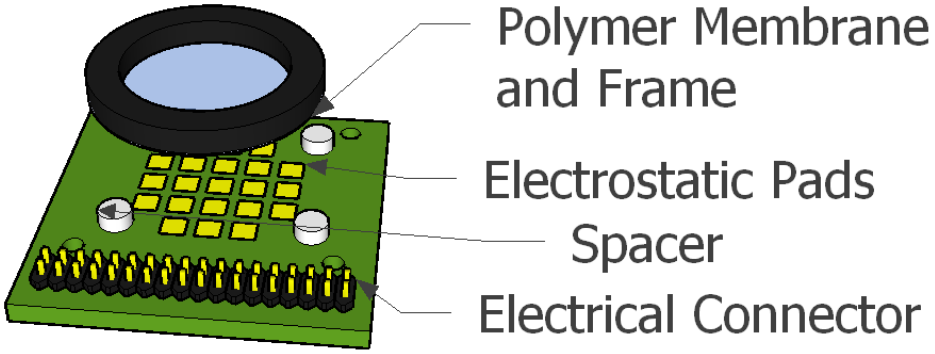
- We have previously published some indication that the nitrocellulose membrane tension was affected by humidity.
  - We had not observed this in Albuquerque due to the fairly low average humidity.
  - East-coast customers in the spring and summer reported on this phenomenon.
- Some manufacturer literature indicated less of an effect of humidity on polyimide, so we wanted to try to quantify this effect for both nitrocellulose and polyimide.



*Data from http://www.wunderground.com/

Polyimide Membrane Deformable Mirror Architecture

- Large membrane mirrors have been made out of CP1 polyimide material.*
  - Very expensive material!
- We commissioned development of another variety of polyimide membranes and integrated them into our existing nitrocellulose DM architecture.



1" 32-Channel MDM Package

Integrated Kinematic Mount

* Surya Chodimella et al., "Design, fabrication, and validation of an ultra-lightweight membrane mirror", Proc. SPIE, Vol. 5894, 589416 (2005).

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Polyimide Materials Parameters

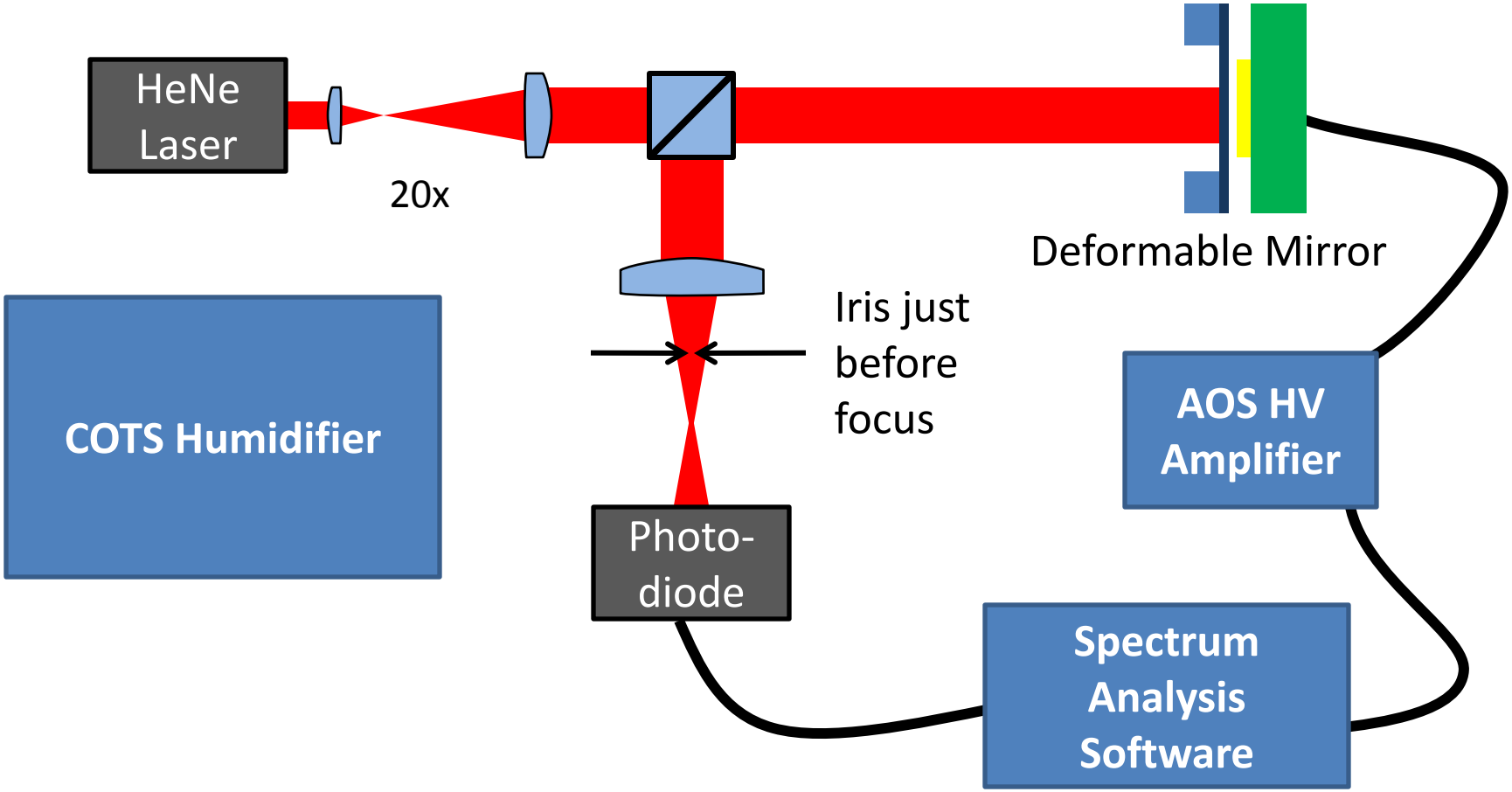
- Polyimide is a well characterized plastic material that has been demonstrated as a reflective optical element.*
- Relative to polyimide, nitrocellulose
  - has a smaller operating temperature range (-40° C to 125°C)
  - is more dangerous to use (combustion hazard)

Polyimide	
Density	1430 kg/m^3
Young's modulus	3200 MPa
Tensile strength	75-90 Mpa
Elongation @ break	4-8%
notch test	4-8 kJ/m
Glass temperature	>400 °C
melting point	None
Vicat softening point	220(?) °C
Thermal conductivity	0.52 W/(m·K)
Coefficient of thermal expansion	55 ppm /K
Specific heat capacity	1.15 kJ/(kg·K)
Water absorption (ASTM)	0.32
Dielectric constant at 1 MHz	3.5

* Surya Chodimella et al., "Design, fabrication, and validation of an ultra-lightweight membrane mirror", Proc. SPIE, Vol. 5894, 589416 (2005).

http://en.wikipedia.org/wiki/Polyimide

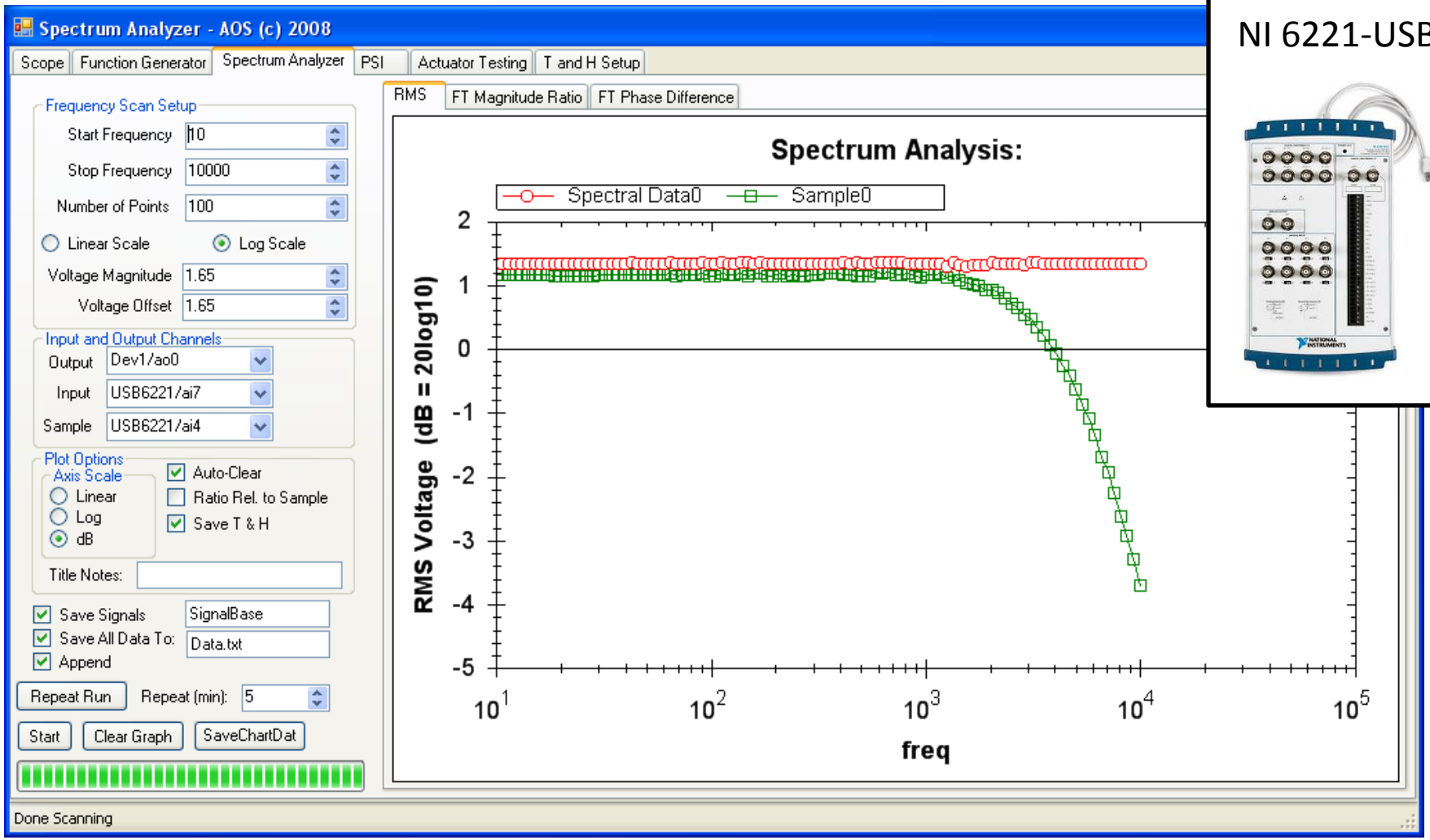
Experimental Setup



Effect of Humidity on Polymer DMs

- We measured the frequency response by
  - driving the DM with varying frequency sinusoidal signals and
  - examining its response on a photodiode where an iris has been put in the beam just before the tightest focus to create a zero-dimensional curvature sensor.
- This was implemented with a USB NI 6221 and an AOS high-speed amplifier.
- Humidity and temperature were monitored throughout the test.
  - No humidity control, just measurements
- The humidity was increased in the laboratory using a COTS vaporizer/humidifier.

We wrote software to make the NI 6221 into a spectrum analyzer.



NI 6221-USB

Humidity reduces tension and decreases high frequency response

- We know that the absorption of water reduces the mirror tension.
- This can be observed in the frequency response.
- We fit our measured data to a typical first resonance gain curve and extracted a corner frequency.

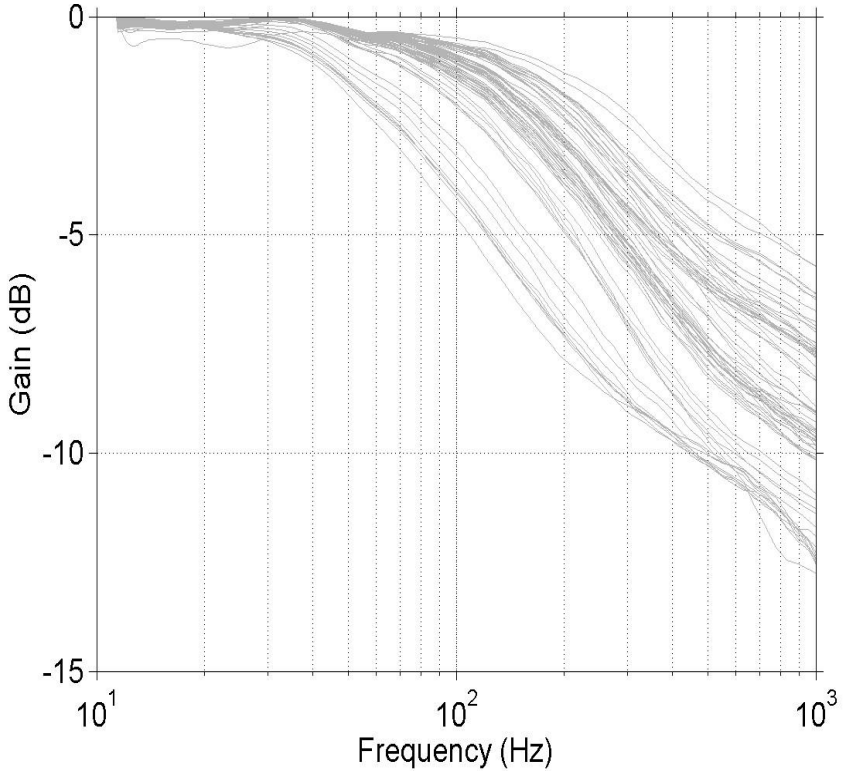
$$f_1 = \frac{0.766}{D}\sqrt{\frac{T}{\sigma}}$$

$$Gain(f) = \sqrt{\frac{1}{1+\left(\frac{f}{f_c}\right)^2}} = \frac{V_{PD}}{V_{drive}}$$

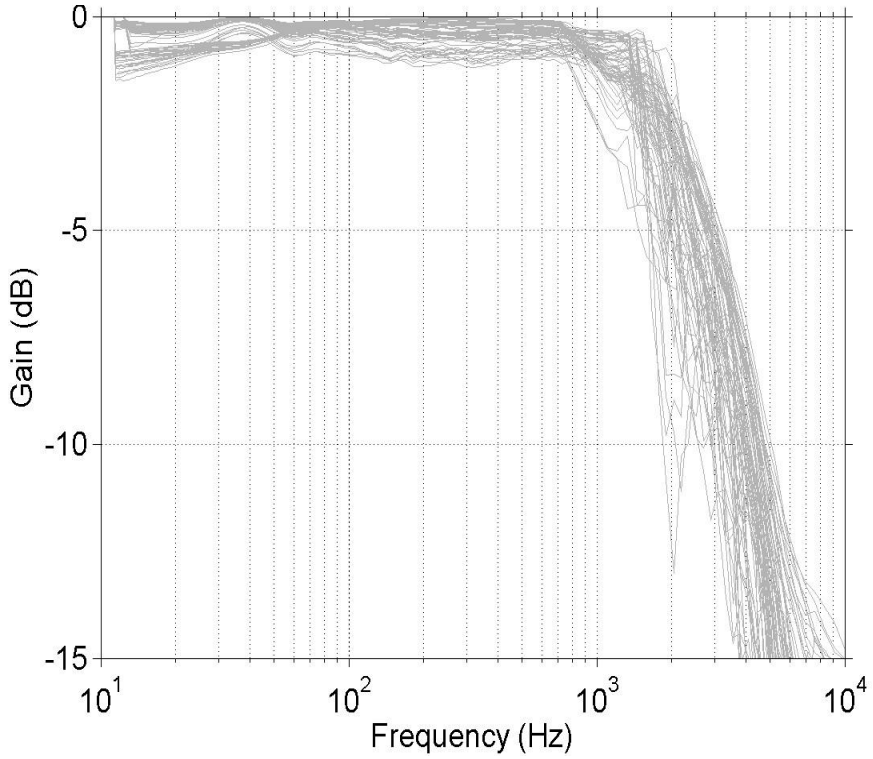
$$dB_{GAIN} = 20 \cdot \log_{10}(Gain)$$

Measured Frequency Responses while Varying Humidity

Low Tension Nitrocellulose



Polyimide



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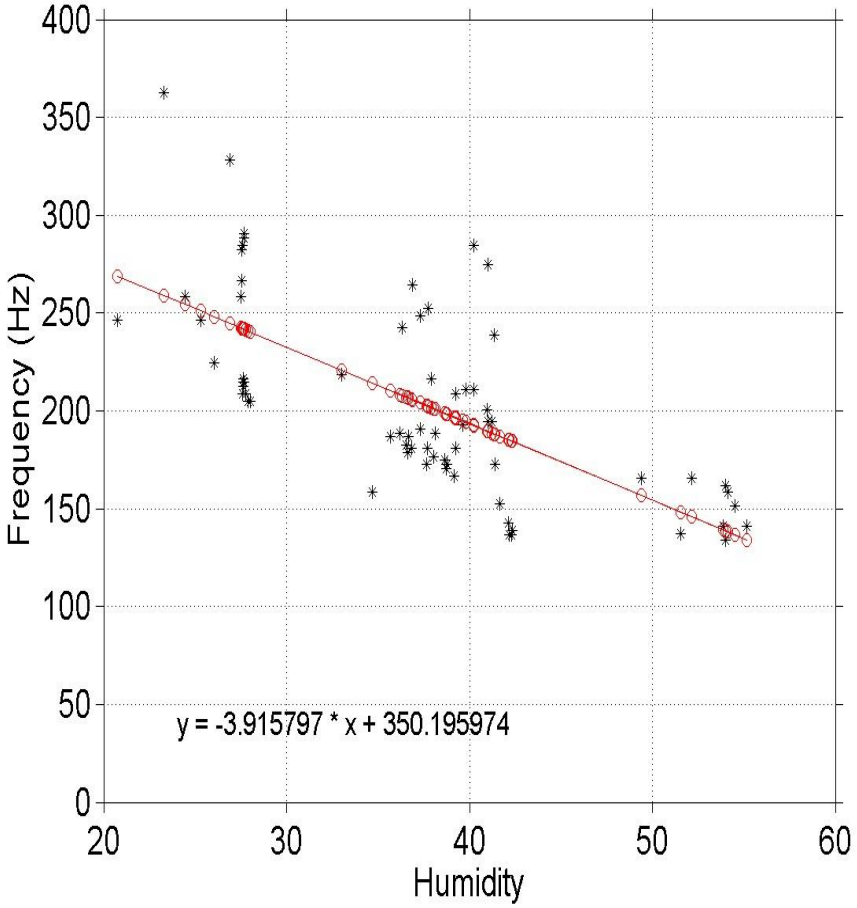
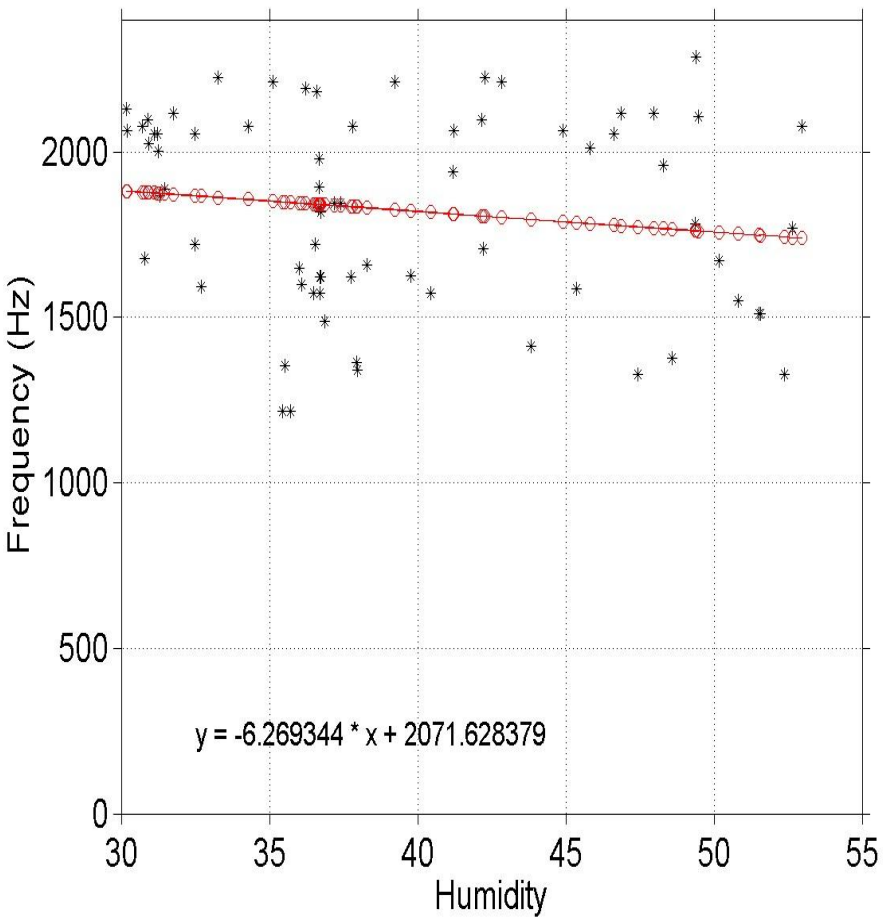
NC and Polyimide Corner Frequency Comparison

Low Tension Nitrocellulose



Polyimide



Humidity Conclusions

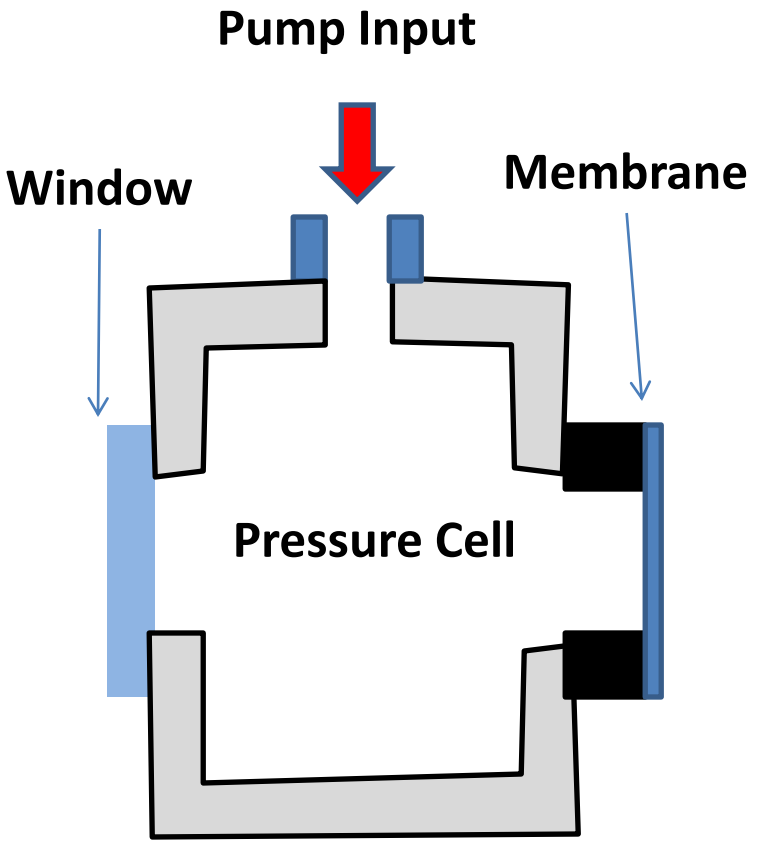
- Nitrocellulose showed a significant variation in frequency response with varying humidity, but the polyimide membranes did not.
- Unfortunately, since nitrocellulose is available as a standard material, it is less expensive to use, so we will continue to offer it in a high tension form for $1.5k.
- We are now offering a polyimide membrane deformable mirror as well, but it is more expensive ($2k).

How far can we push a membrane before it ruptures?

MAXIMUM DEFORMATION TESTING

Experimental Setup: Pressure Cell

- Designed a pressure cell with a 0.5” nitrocellulose membrane deformable mirror in the relief path.
- Used a commercial hand-pump to pressurize the cell.
- Examined the rupture strength of the nitrocellulose membrane under extreme pressure loading



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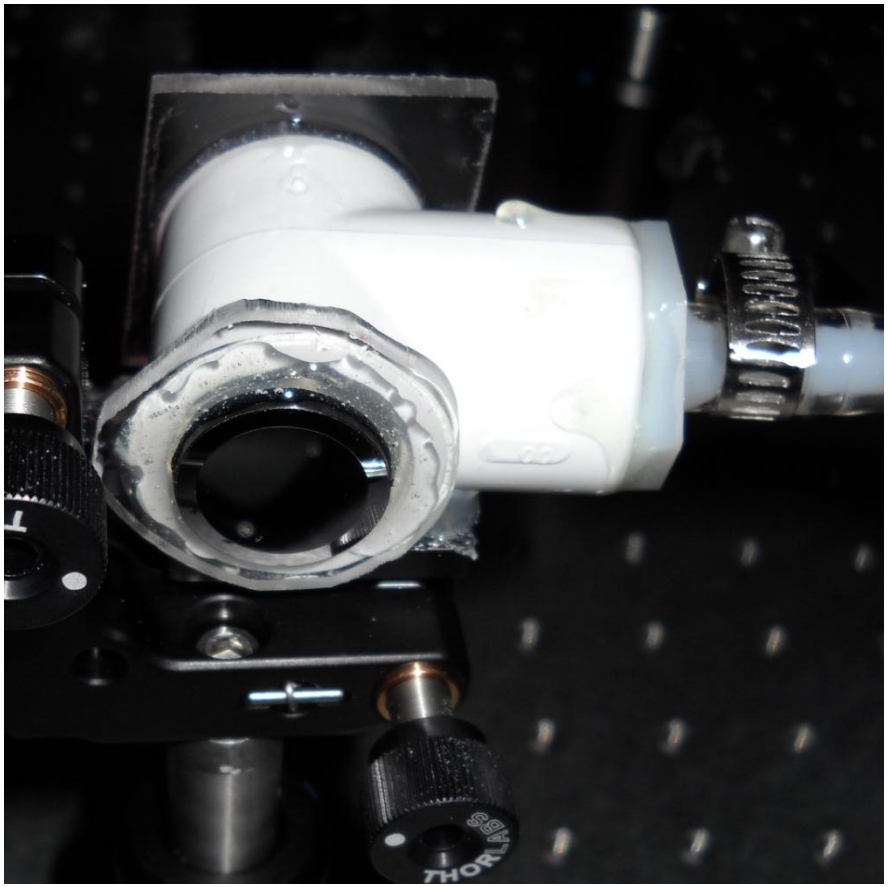
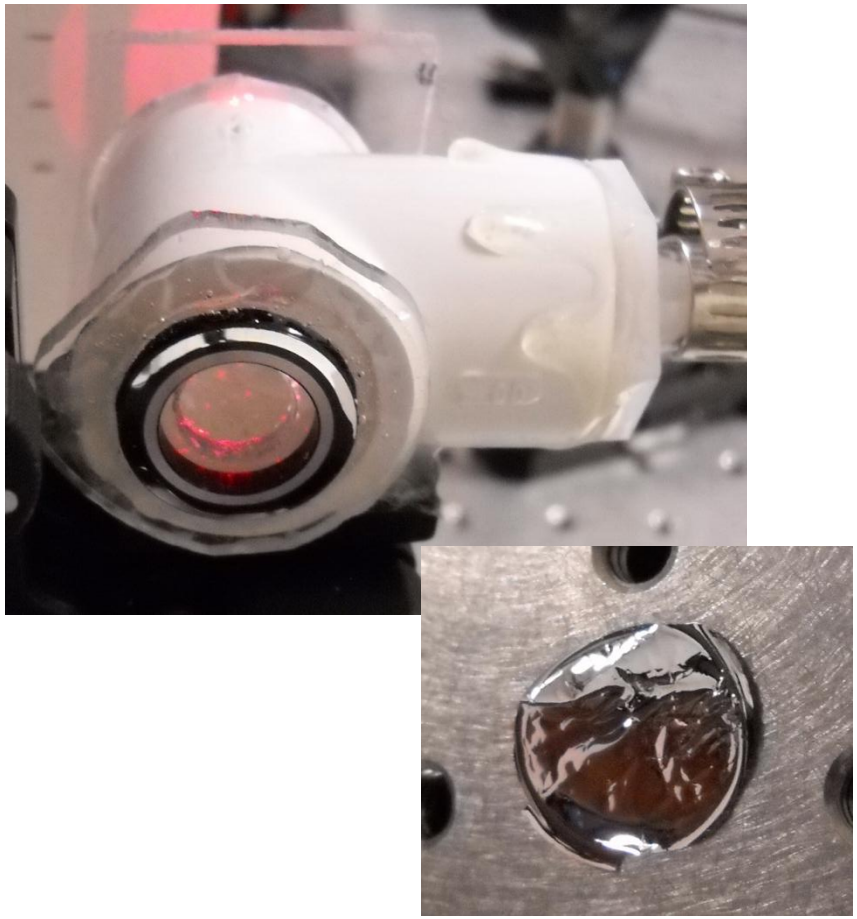
Pressure Cell Pictures

Pressure Cell



After Rupture



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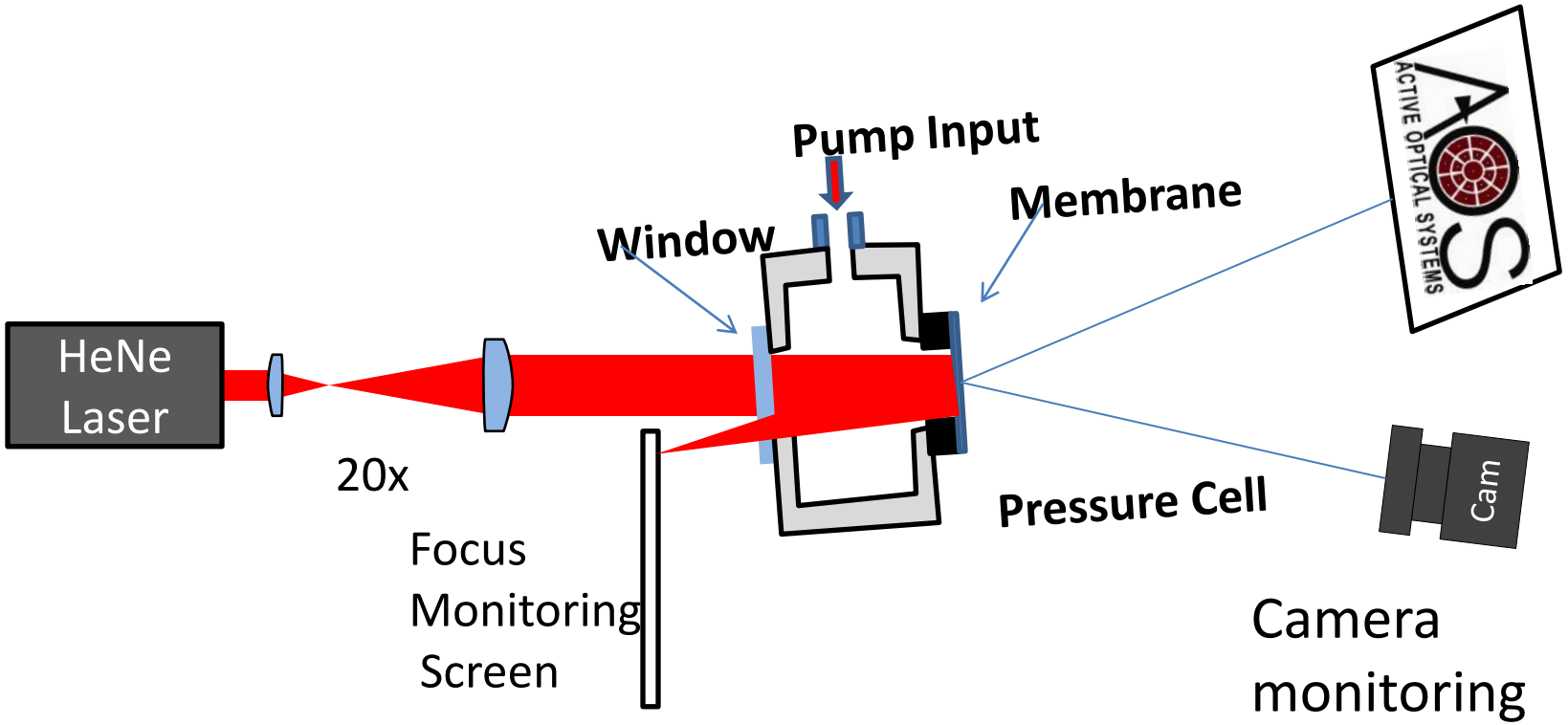
Optical Setup

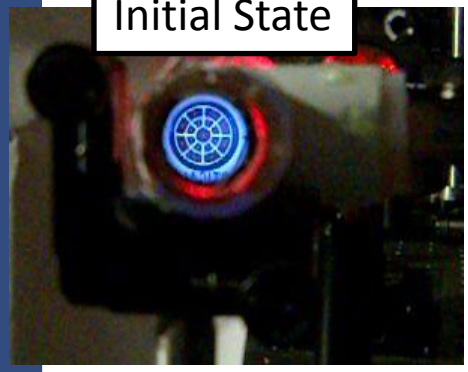


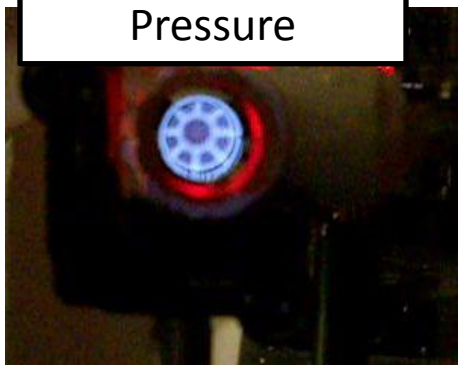
Camera monitoring reflection of the AOS Logo

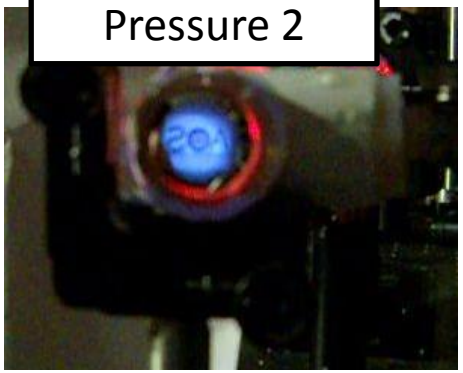
Ultimate Stress Testing Video

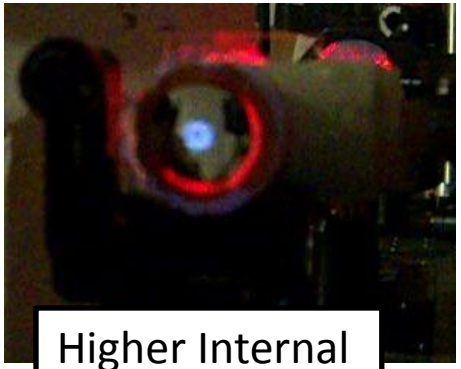
Movie Link

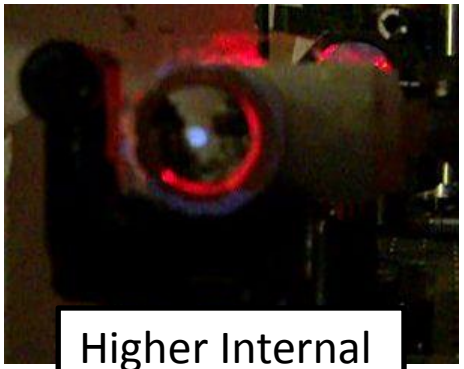
Images from Movie











Ultimate Stress Test Results

- Membrane ruptured when focusing at less than 1” from the mirror surface
  - 2” radius of curvature
  - Corresponds to a deformation of 30 mil (~800 microns) of deflection.
- Saw no damage during relaxation (inelastic stretching)

LASER DAMAGE TESTING

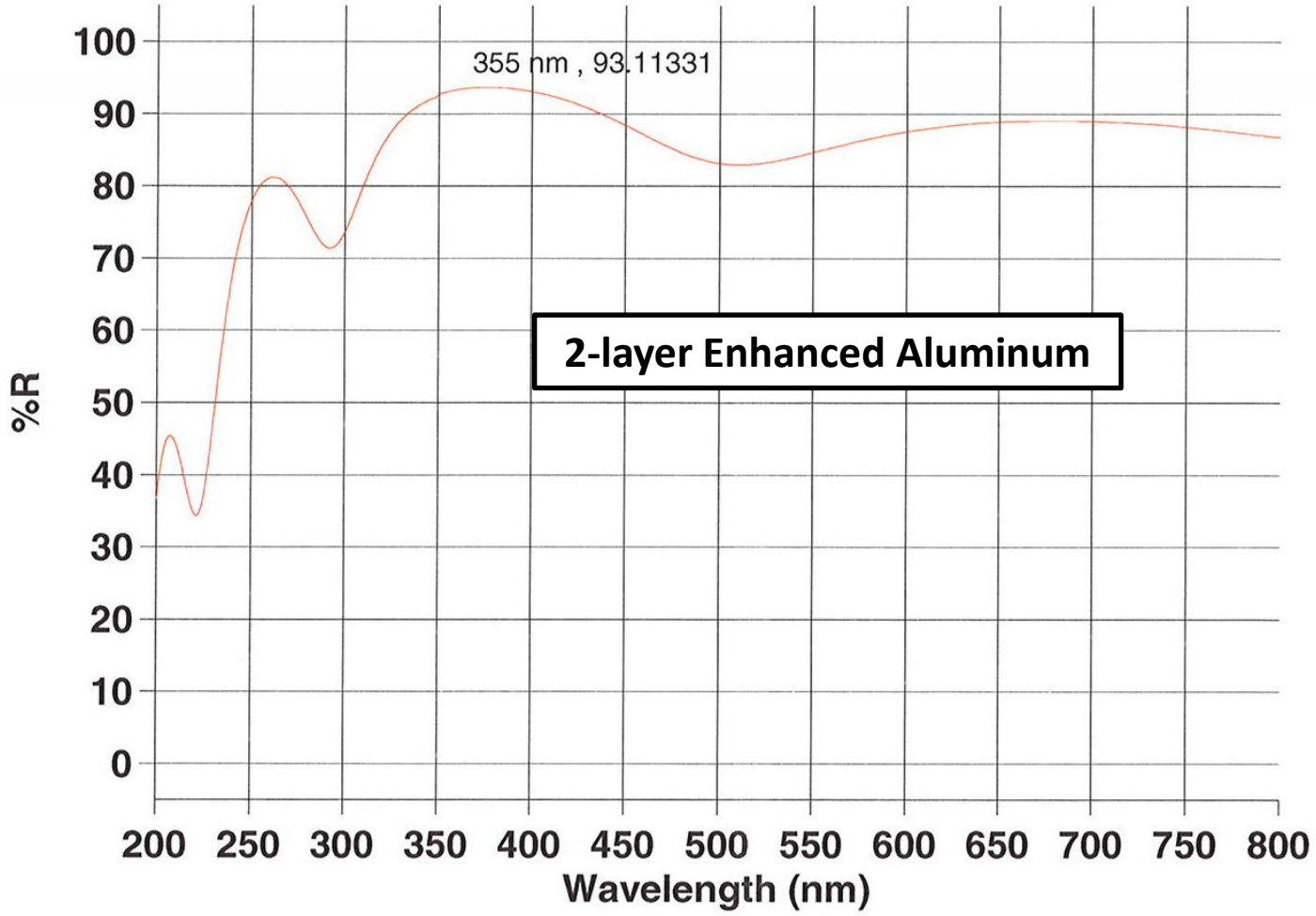
Laser Damage Testing Setup

- We damage tested at both 1060nm and 355nm wavelengths.
  - 2-Layer Enhanced Aluminum for 355nm
  - 4-Layer Enhanced Silver for 1060nm
- We tested both nitrocellulose and polyimide membranes.

Tale of Failed Coatings

- Unfortunately, there was a mistake with the coating run and the polyimide samples needed to be stripped, cleaned, and re-processed.
- Despite the fragile nature of the membranes, the polyimide material was extremely robust.
  - No membranes were ruptured during the strip
- This left many of the samples damaged before the second coating was applied.
- We had some samples that we felt were good enough to move forward, but we believe that we could do better with a new batch of membranes.

355nm Coating Reflectivity
2-Layer Enhanced Aluminum



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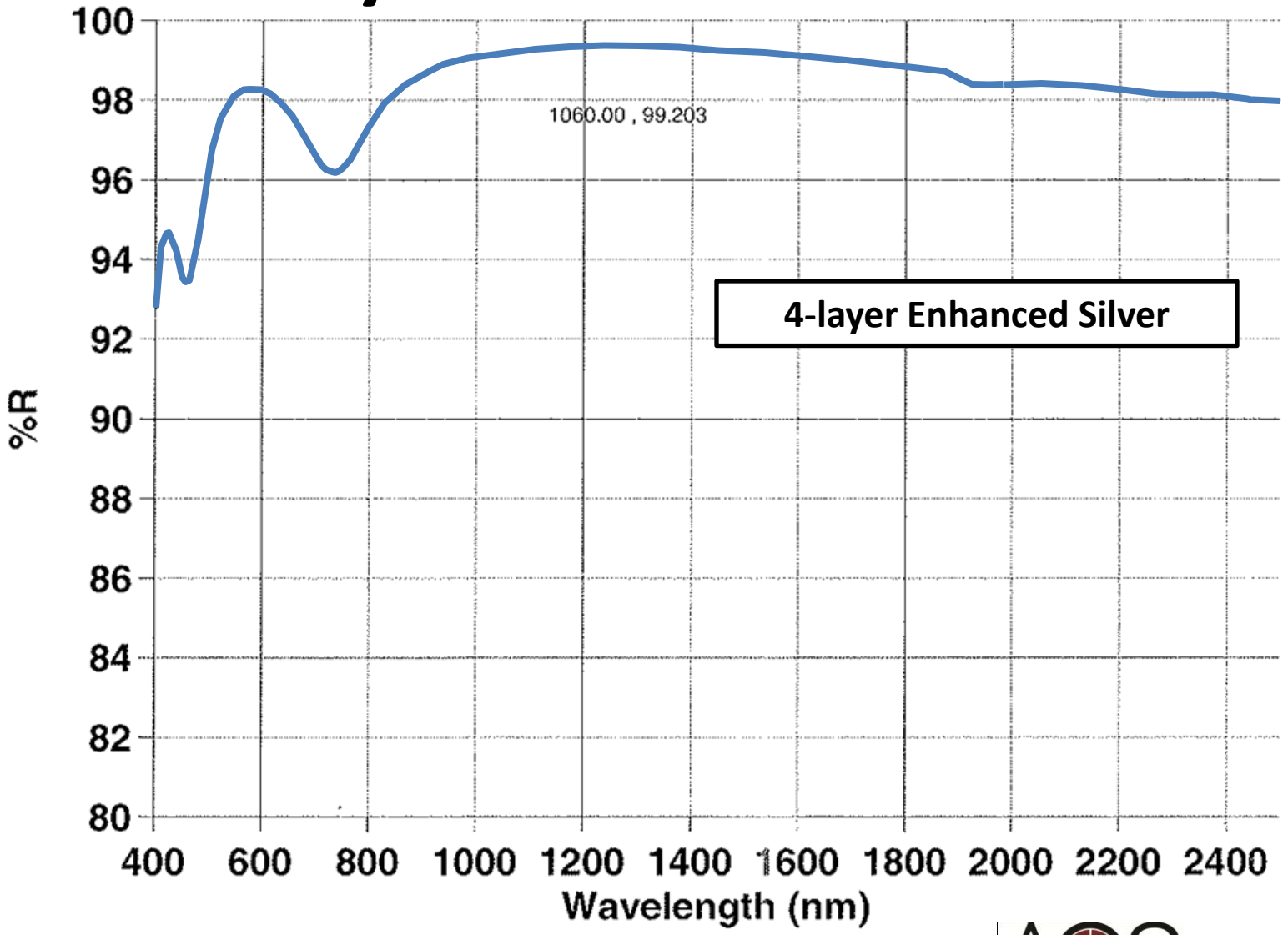
1060nm Coating Reflectivity
4-Layer Enhanced Silver



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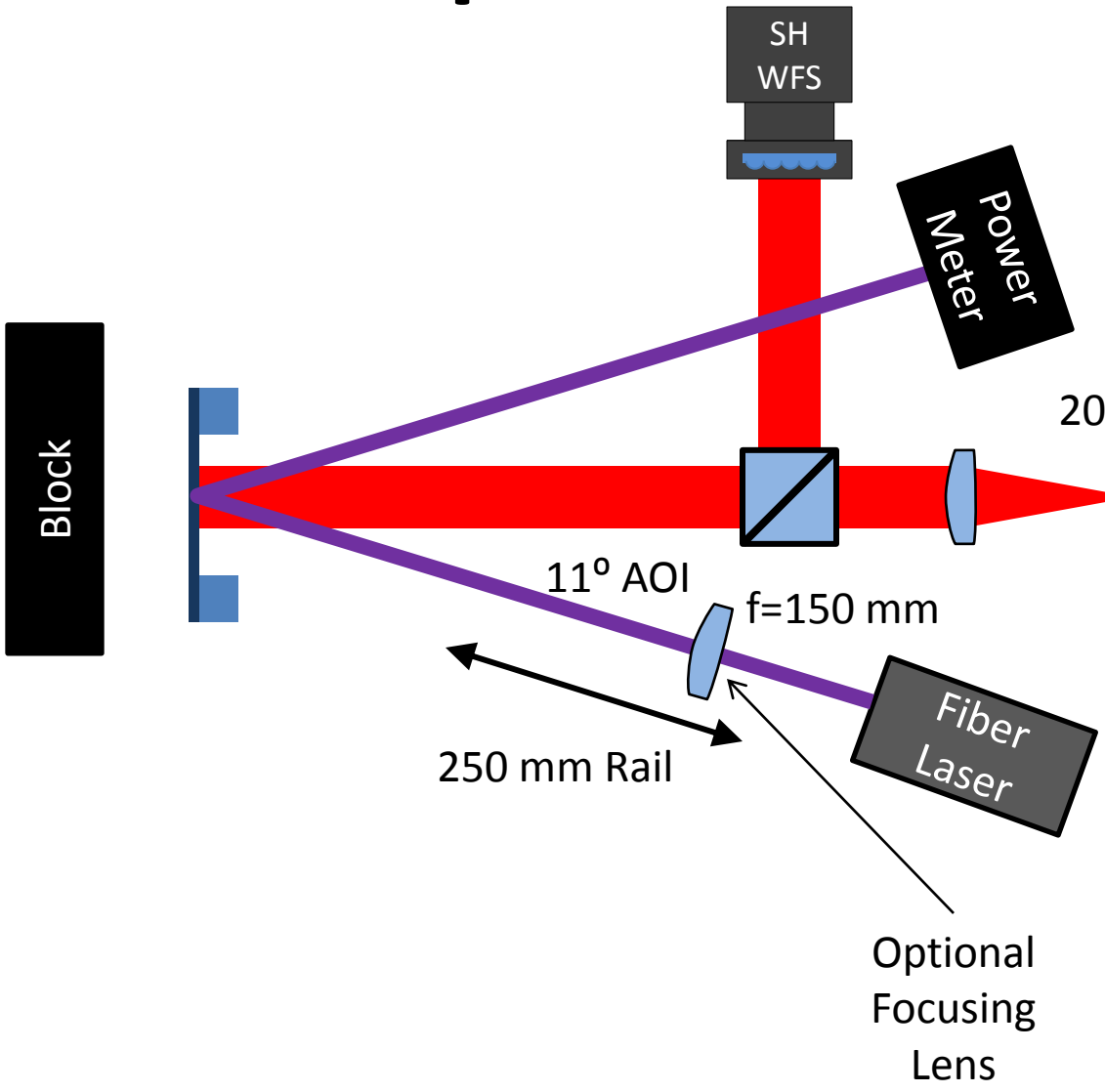
LASER POWER HANDLING EVALUATION

Experimental Setup



1060 nm IPG Q-Switched Fiber Laser: Set to 20 kHz repetition rate with ~10 ns pulses means a ratio of peak to average power of about 5000x.

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Laser Damage Testing: Beam Sizes

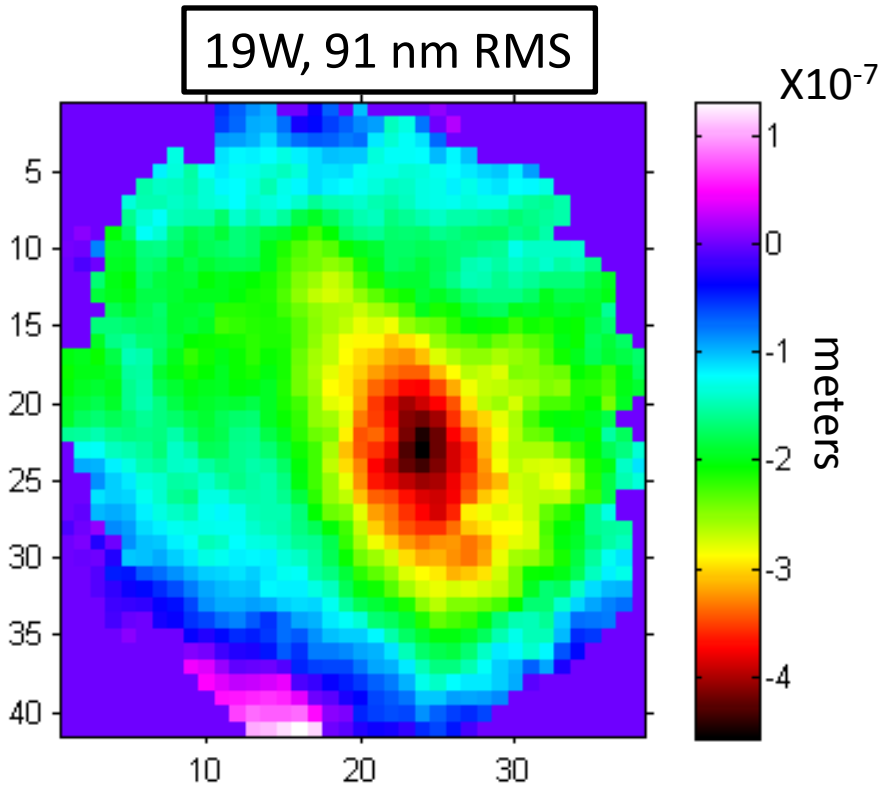
- Started with a 7-mm diameter nominally Gaussian beam
- When focusing, we placed the sample 45 mm from focus of 150-mm focal length lens
  - Approximately 2.1 mm diameter beam on the membrane
  - Beam area was .035 cm^2

1060nm Samples

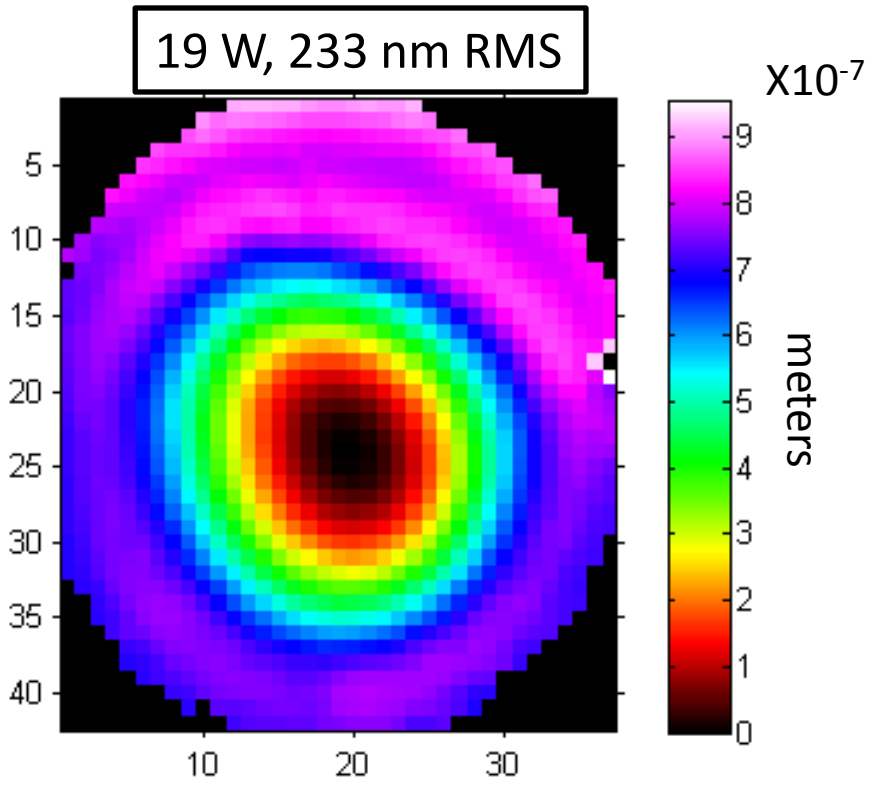
- Sample 5: Nitrocellulose Membrane with Enhanced Silver
- Sample 7: Polyimide Membrane with Enhanced Silver Coating

Maximum Thermally-Induced Wavefront Distortion

Polyimide



Nitrocellulose



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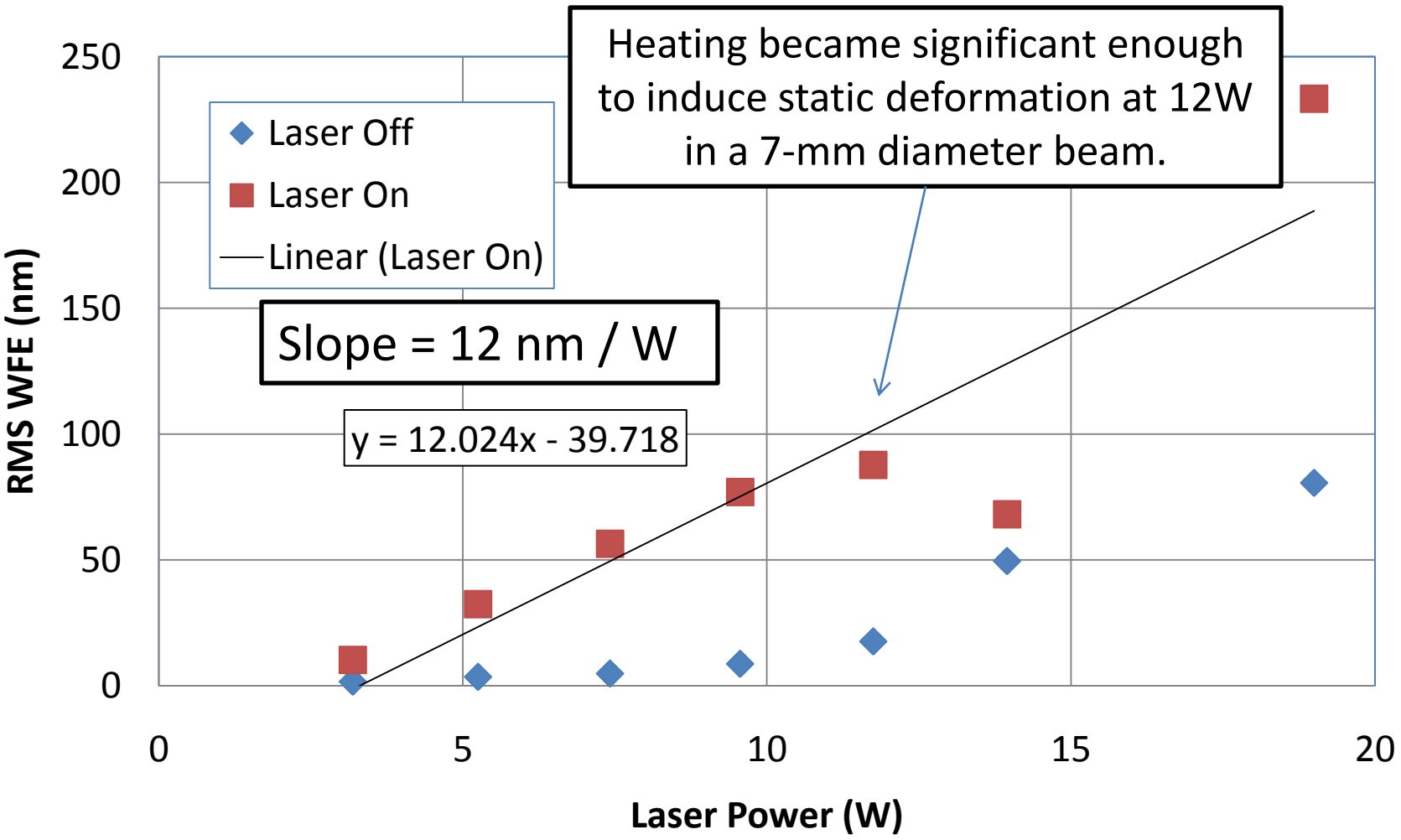
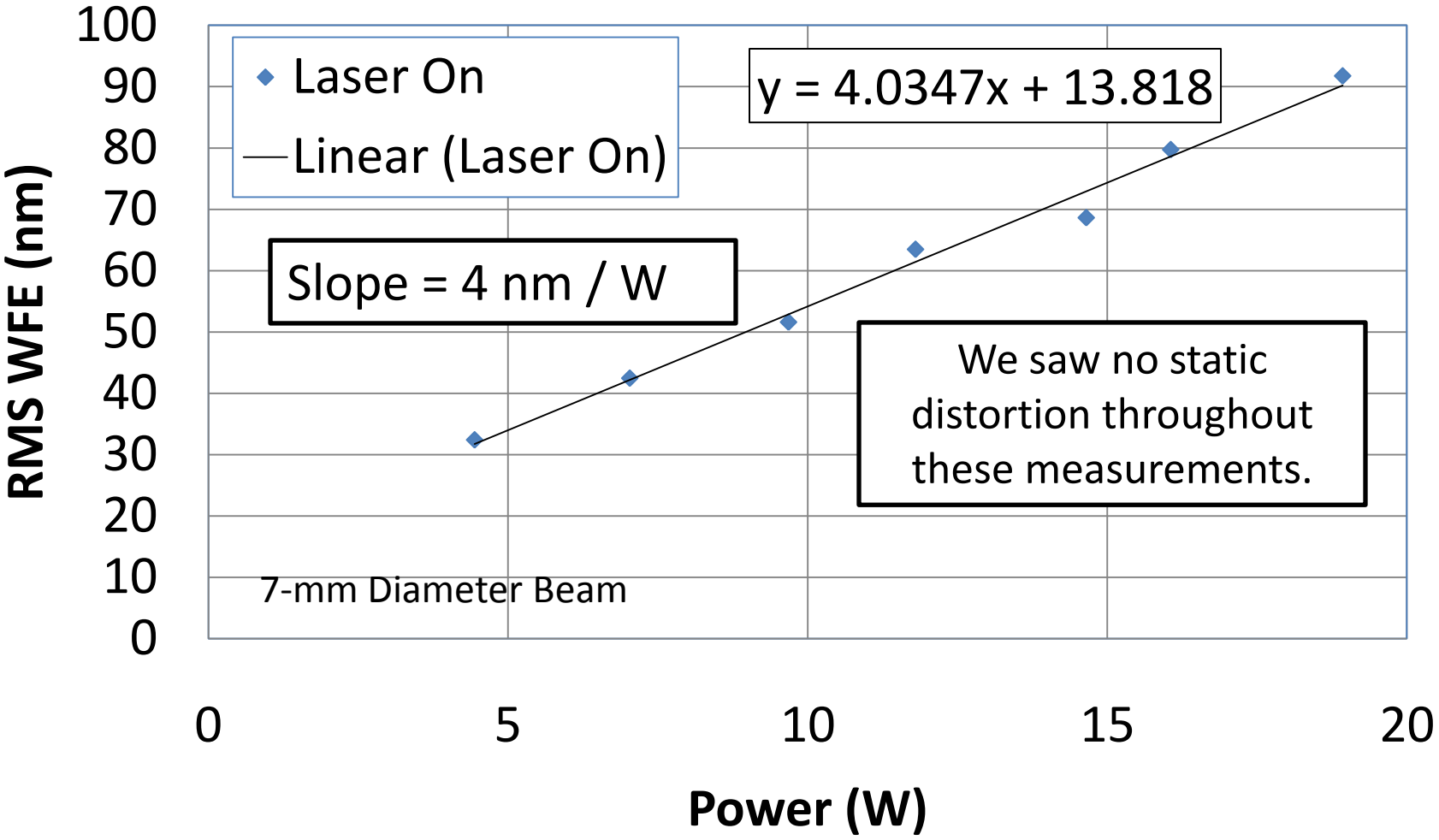
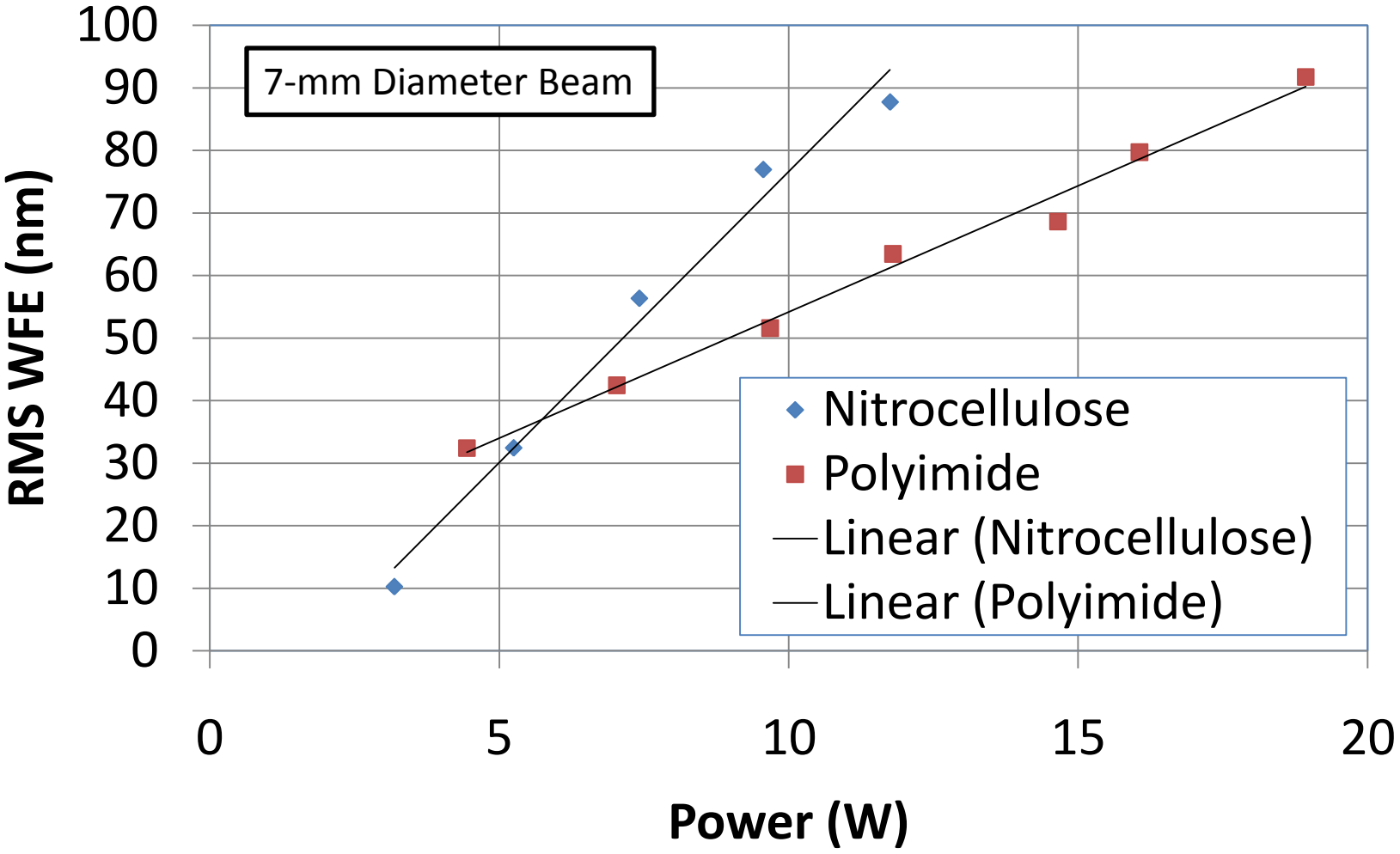
Nitrocellulose 1060nm Sample



Polyimide 1060nm Sample



Comparison of NC to Polyimide



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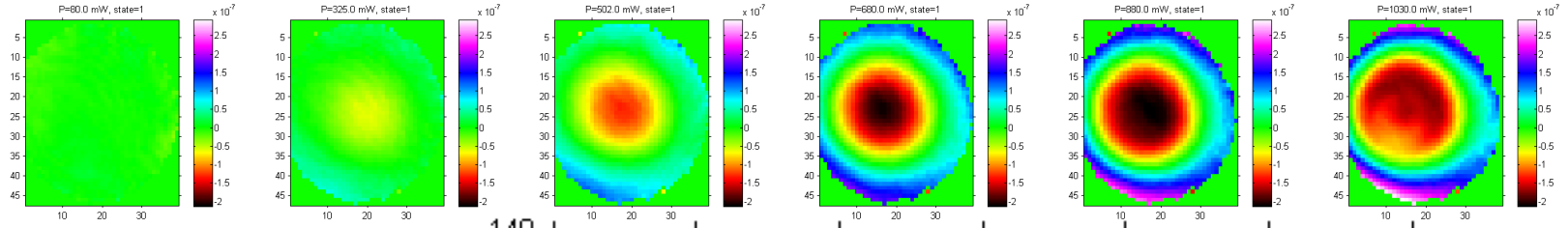
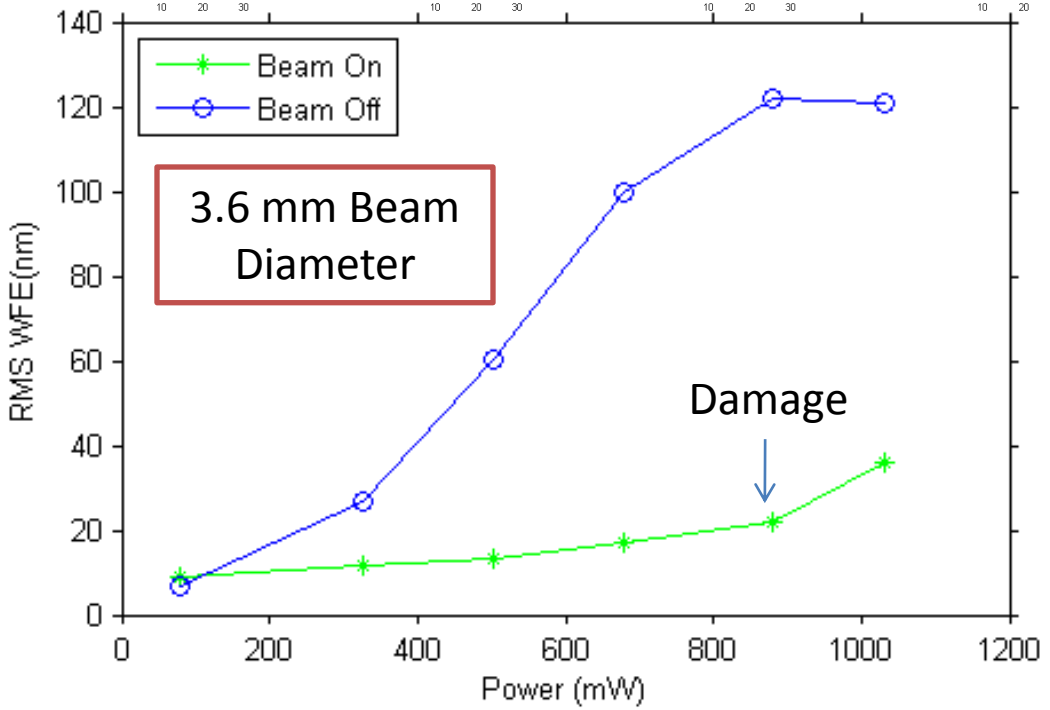
355-nm Testing

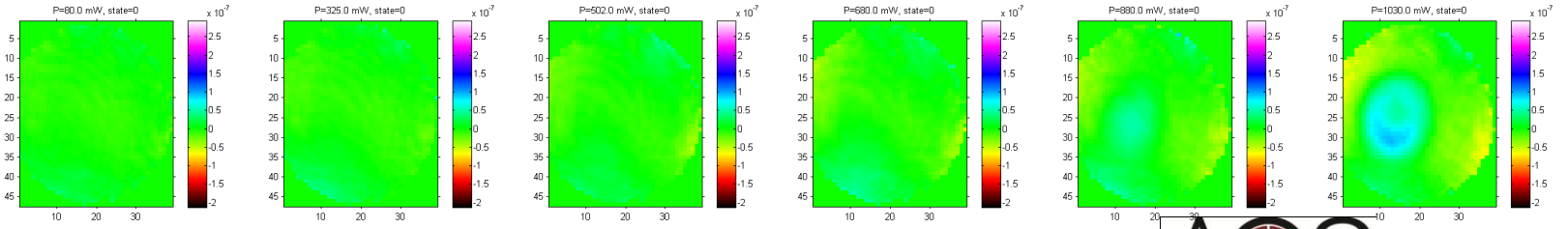
Wavefronts Laser On



Estimated Damage Threshold at 8.84 W/cm^2



Wavefronts Laser Off



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Damage and Distortion Thresholds

Membrane Material	Wave-length (nm)	Average Static Deformation Irradiance (W/cm^2)	Average Laser Damage Threshold (W/cm2)
Nitrocellulose	1060	31	140 ($700\ kW/cm^2$ peak power)
Polyimide	1060	Not Measured	338 ($1.7\ MW/cm^2$ peak power)
Polyimide	355	8.8	Not Measured

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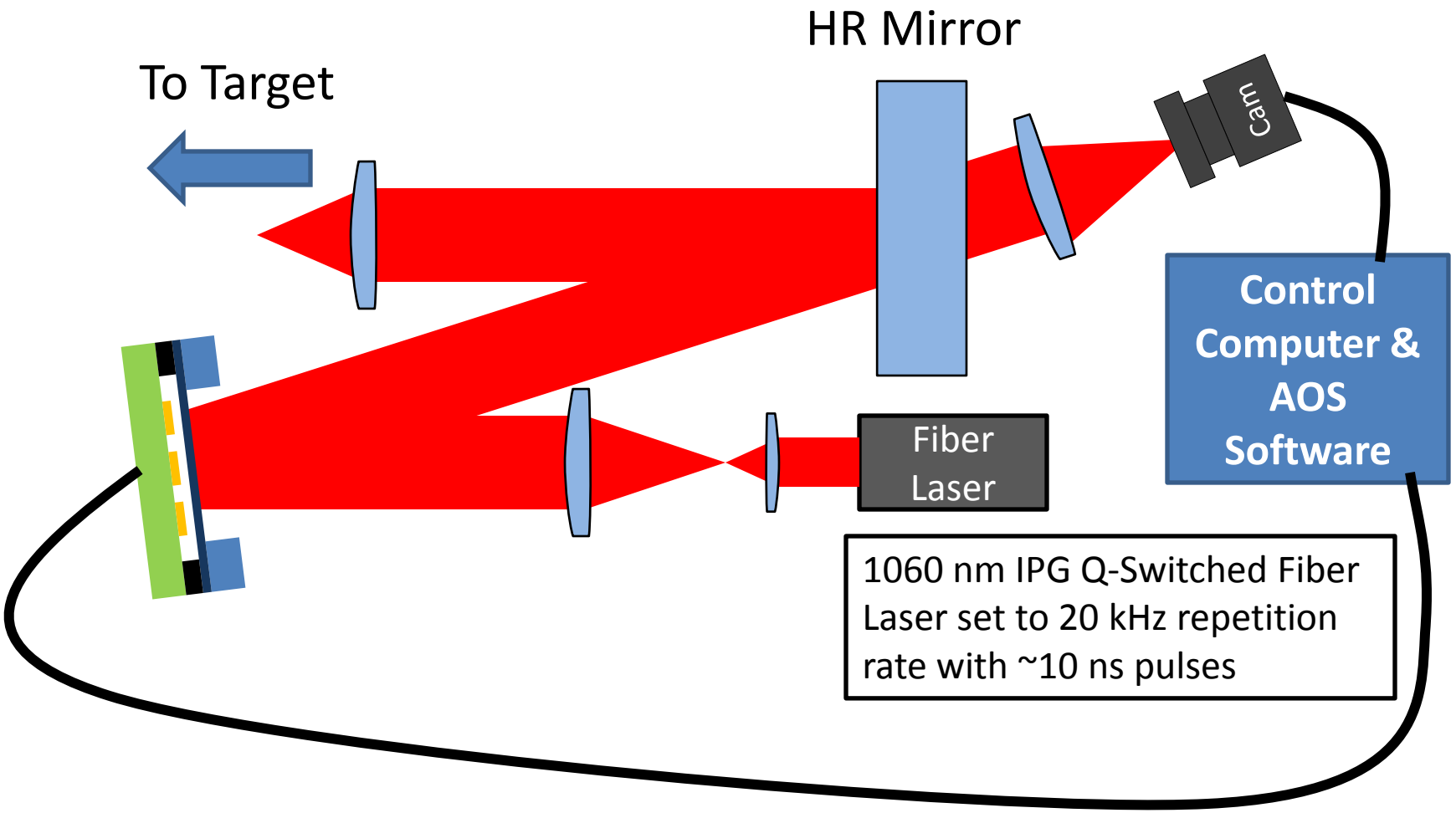
RECENT BEAM SHAPING EXPERIMENTS

Beam Shaping Results from Fiber Laser Experiments

- Leveraged the AOS software for beam shaping.
  - Used a searching algorithm with RMS intensity difference as metric for feedback.
  - In some cases, used grouping of actuators to minimize the search space.
- Used the Q-switched 1060 nm fiber laser for the beam shaping experimentation.

Beam Shaping Optical Setup



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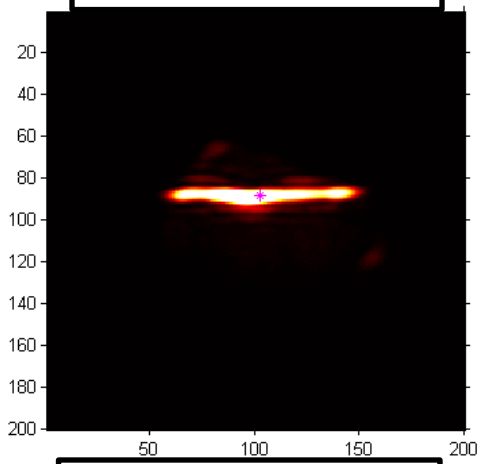
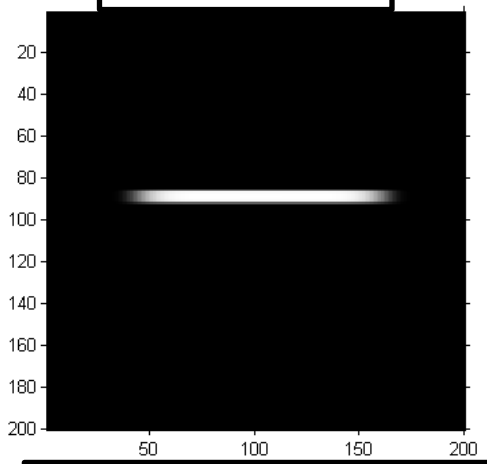
Horizontal Line Focus

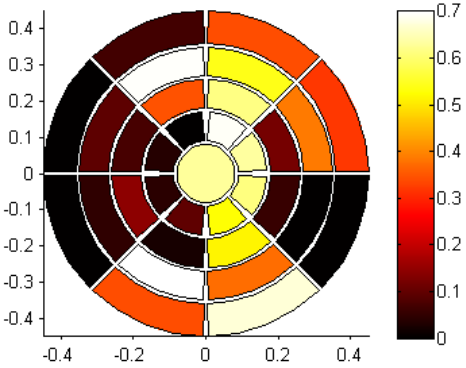
Measured Shape



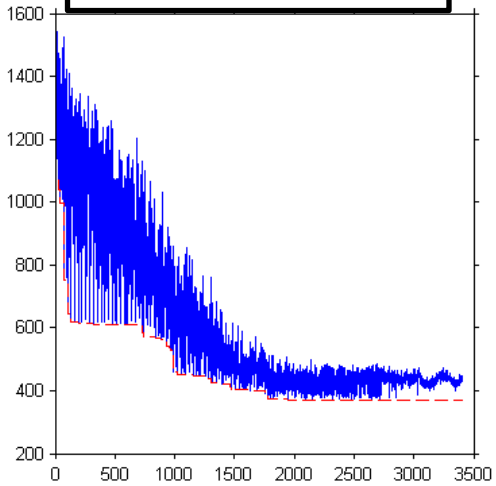
Target Shape



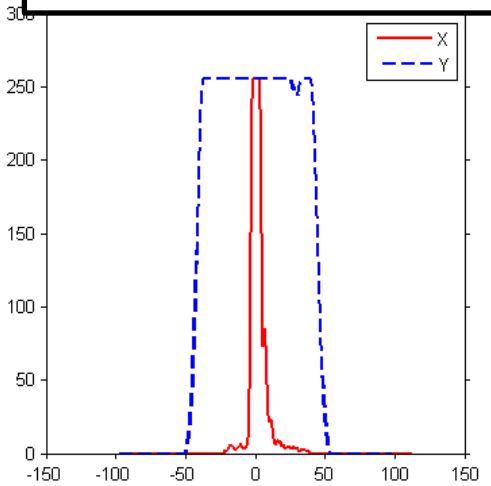
DM Commands



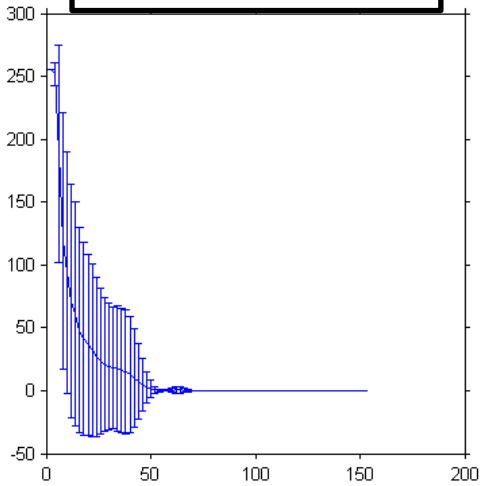
Error vs. Iteration



X and Y Cross-Sections



Power vs. Radius



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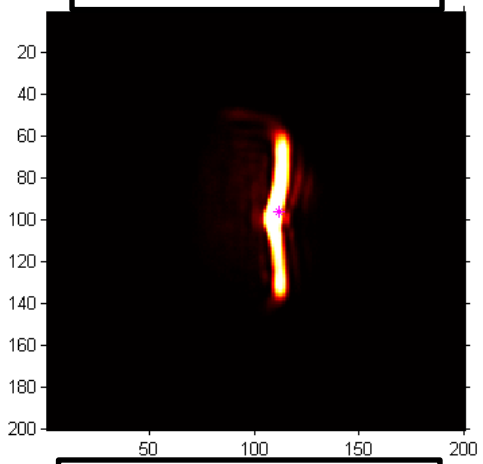
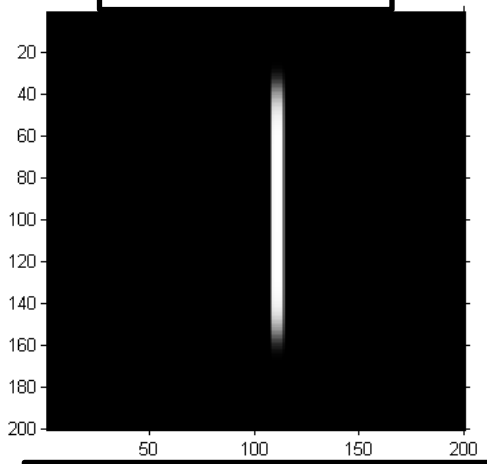
Vertical Line Focus Creation

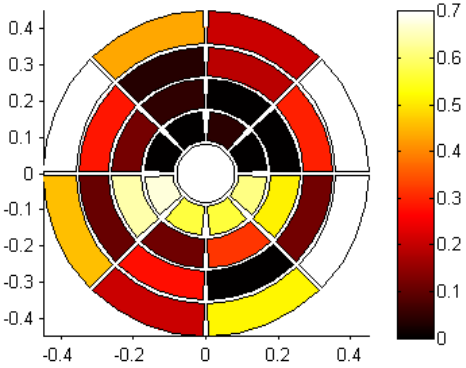
Measured Shape



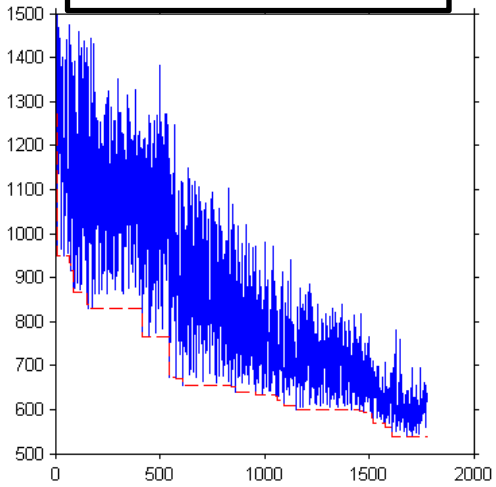
Target Shape



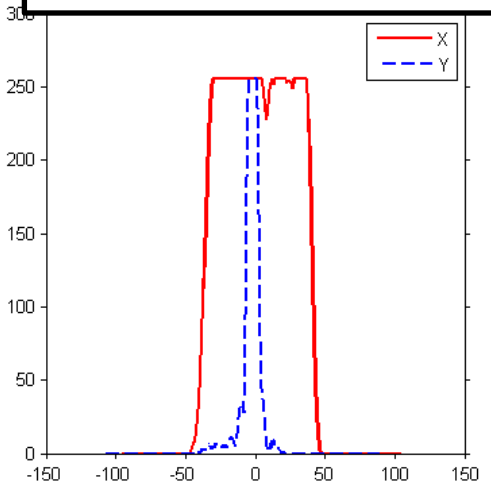
DM Commands



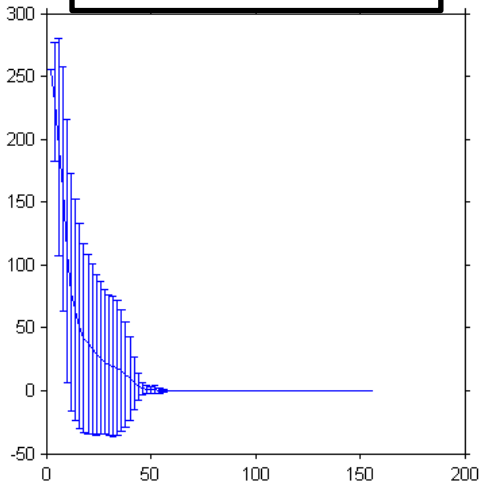
Error vs. Iteration



X and Y Cross-Sections



Power vs. Radius



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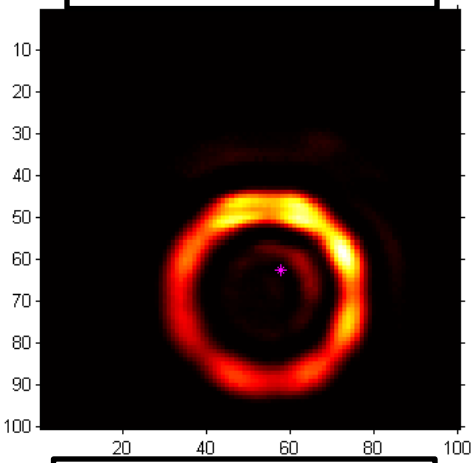
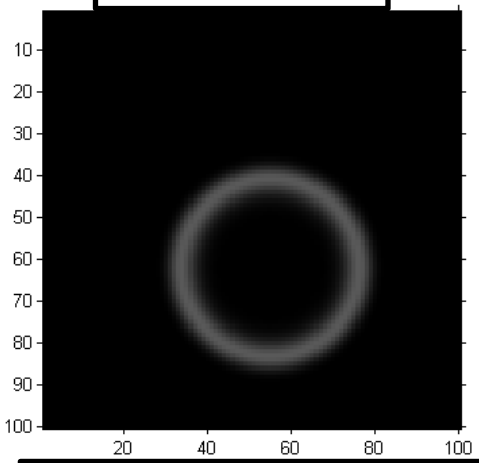
ACTIVE OPTICAL SYSTEMS

Annulus Creation Results

Measured Shape



Target Shape



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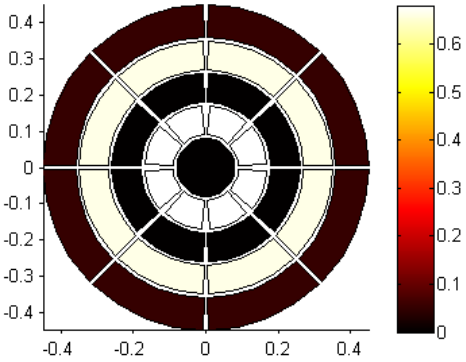
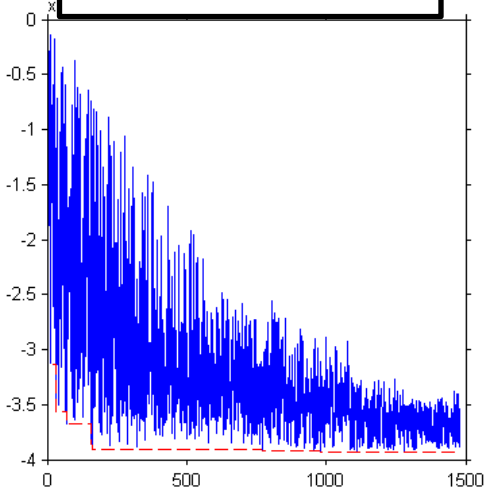
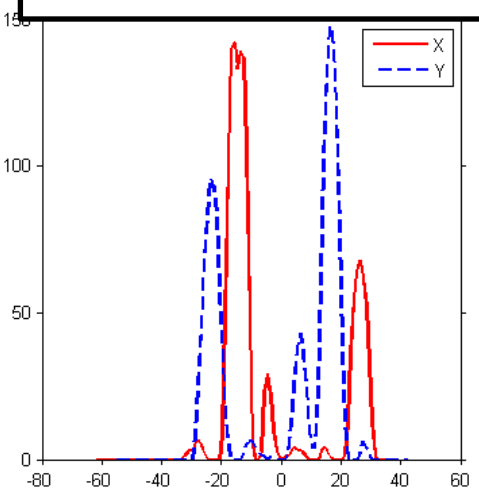


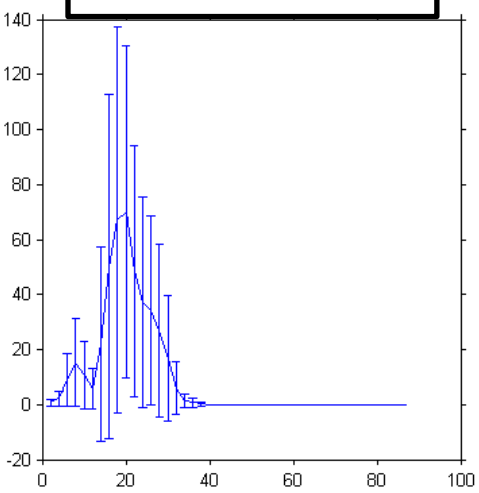
Error vs. Iteration



X and Y Cross-Sections



Power vs. Radius



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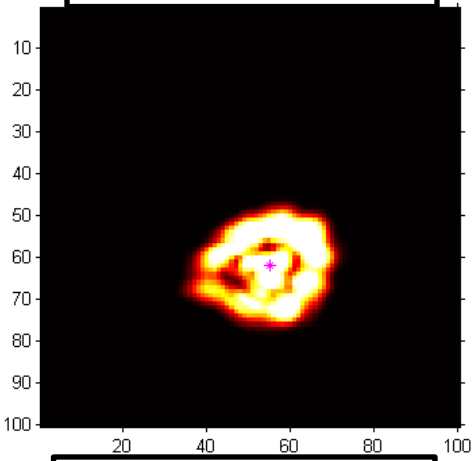
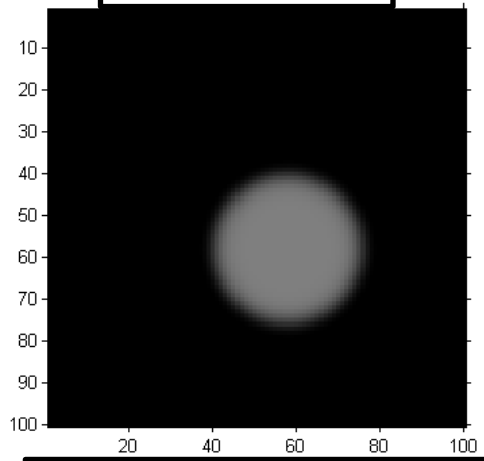
ACTIVE OPTICAL SYSTEMS

Small Top-Hat Creation Results

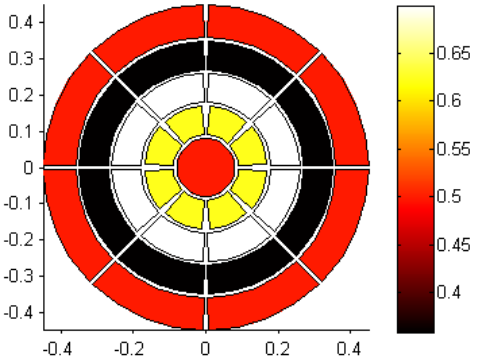
Measured Shape



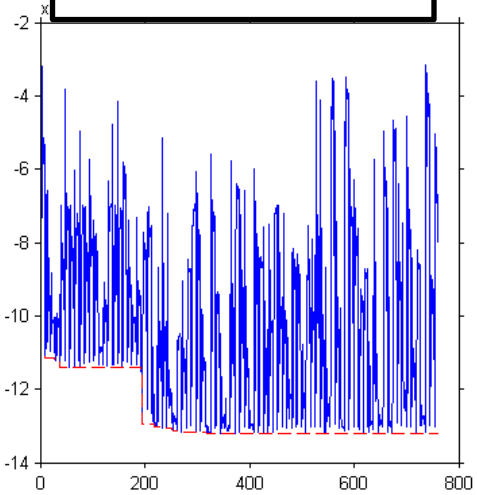
Target Shape



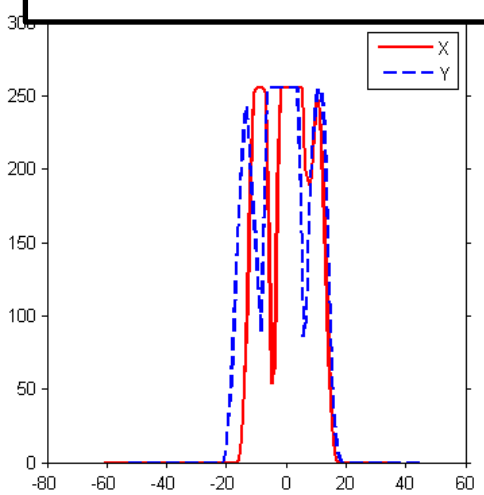
DM Commands



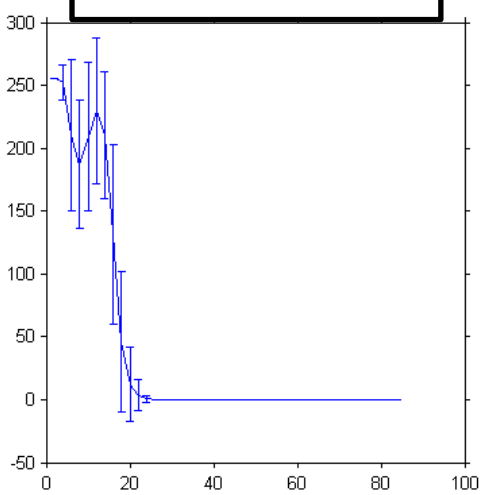
Error vs. Iteration



X and Y Cross-Sections



Power vs. Radius



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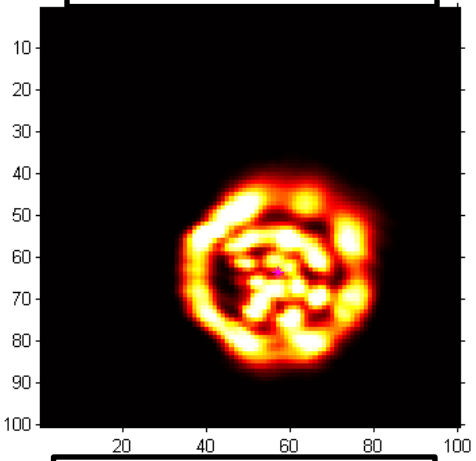
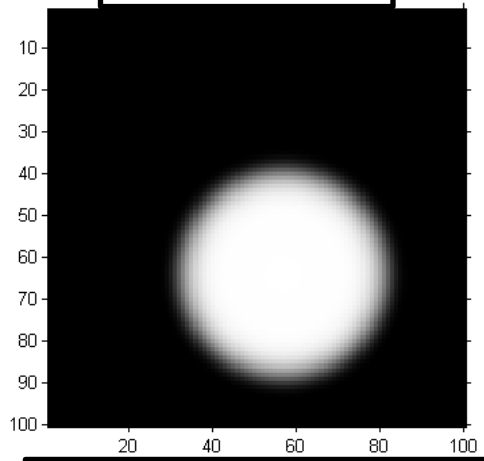
ACTIVE OPTICAL SYSTEMS

Large Top-Hat Creation Results

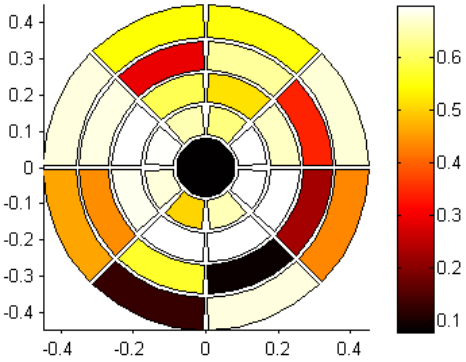
Measured Shape



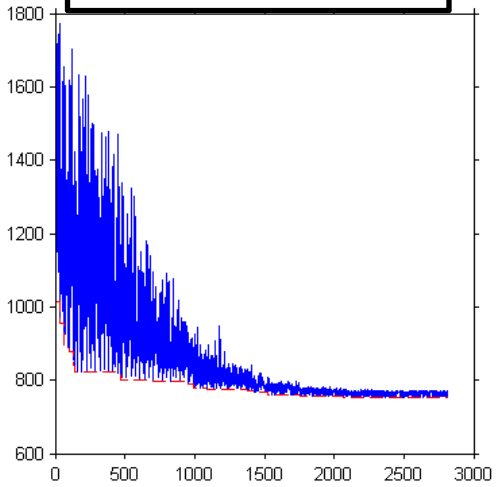
Target Shape



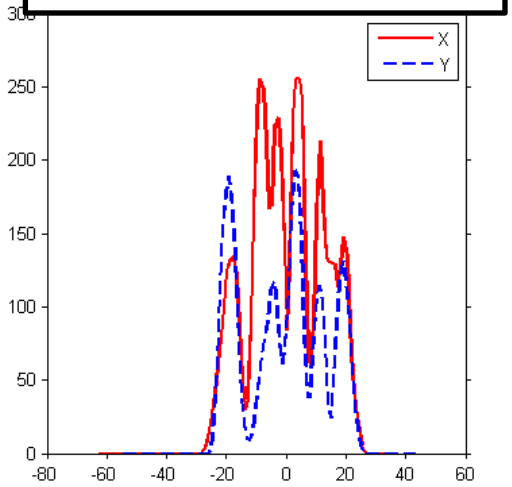
DM Commands



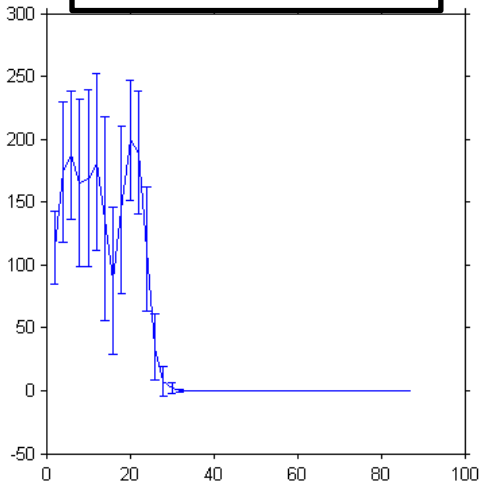
Error vs. Iteration



X and Y Cross-Sections



Power vs. Radius



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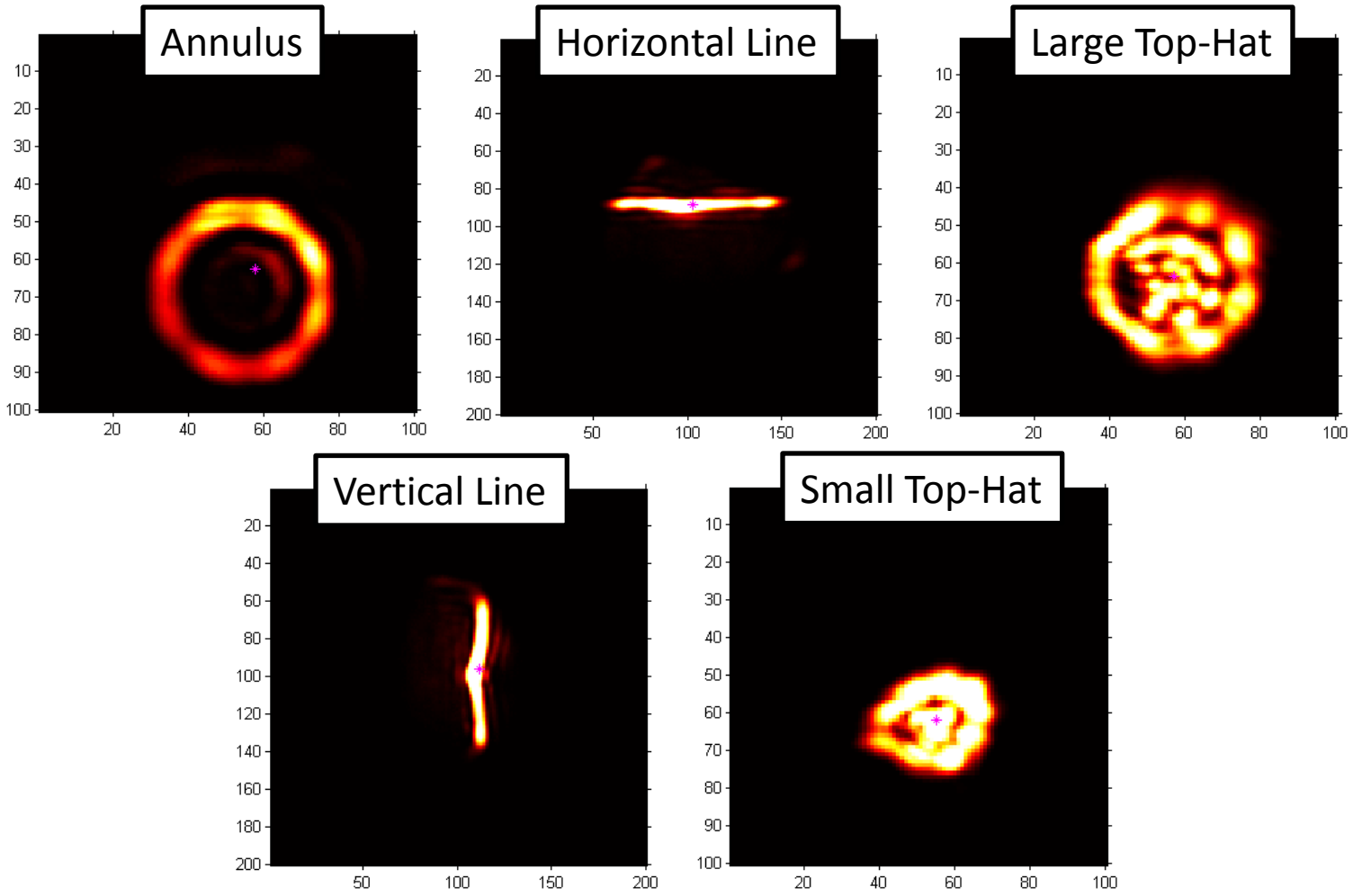
ACTIVE OPTICAL SYSTEMS

Summary of Shapes



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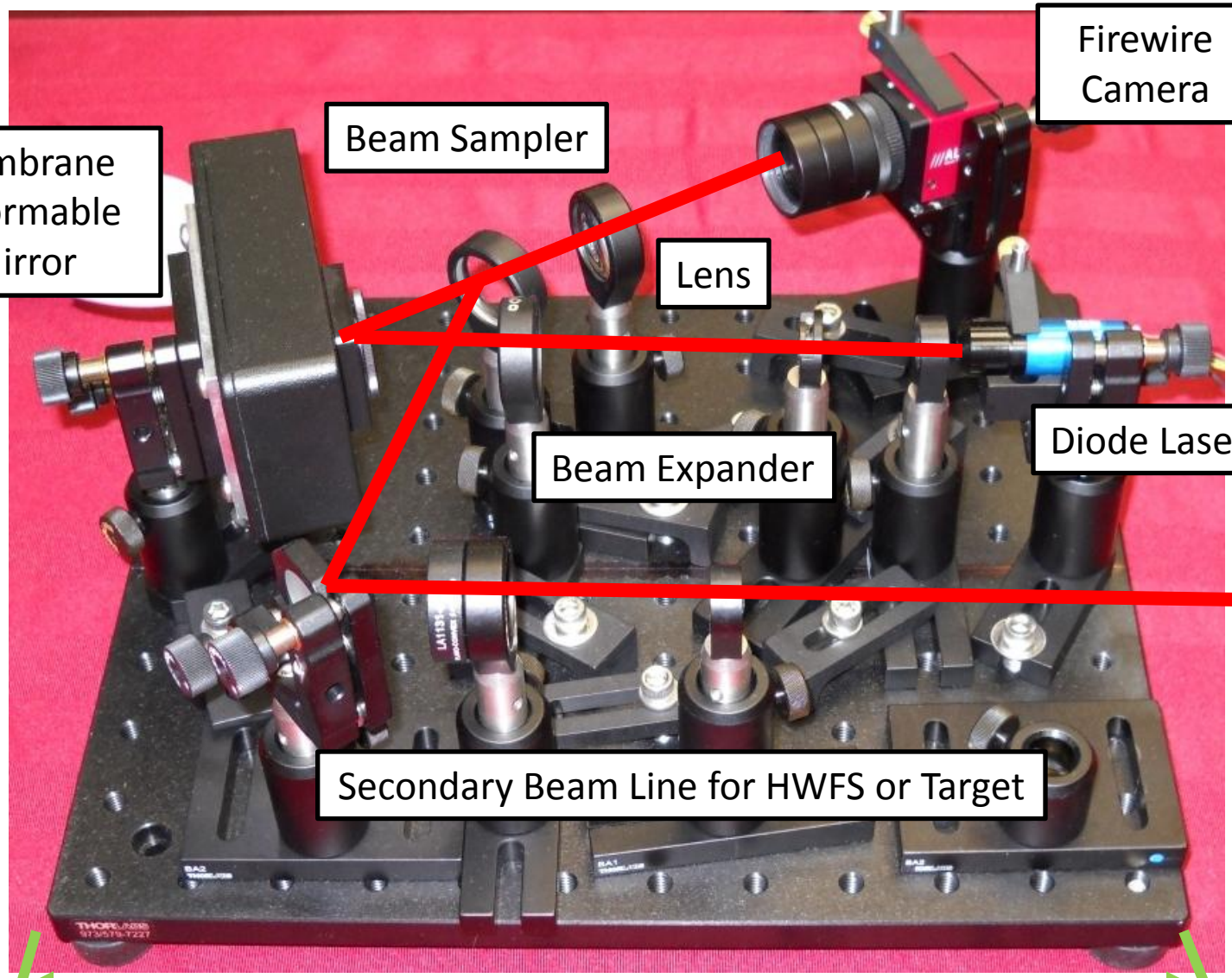
Beam Shaping Conclusions

- Alignment of the DM to the beam is fairly important, but can be compensated to a certain degree by the system.
  - Close-packed actuator patterns may make that less critical in the future.
- We were able to get fairly good results for a variety of different patterns.

COMPACT BEAM SHAPING SYSTEM

Beam Shaping Optical Configuration



CONCLUSIONS AND FUTURE WORK

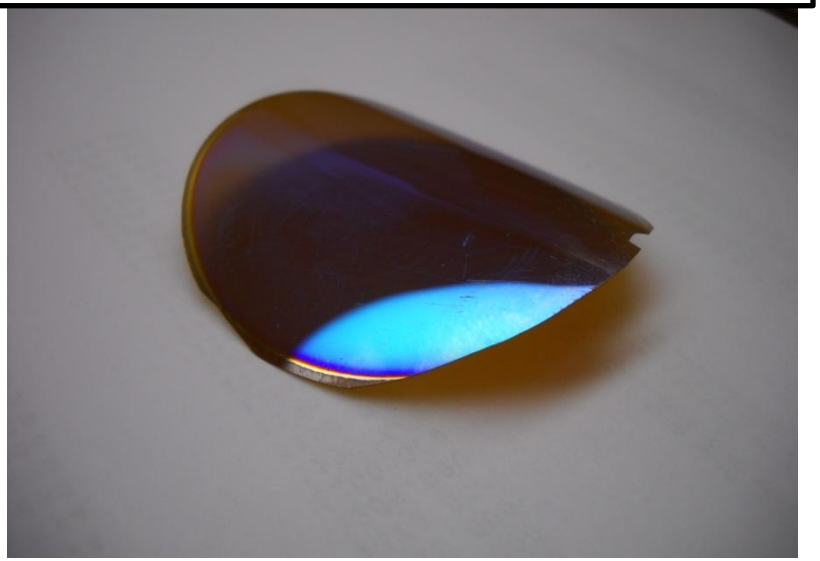
Conclusions

- In this paper we have introduced polyimide deformable mirrors and explored the limits of this technology by examining
  - Effect of Humidity on Tension/Resonance
  - Q-Switched Laser Damage Threshold
  - Fracture/Ultimate Deformation
- We have also demonstrated a compact AO and Beam Shaping system leveraging these devices.

Future Work

- Dedicated Further Miniaturized System for Beam Shaping
- Improved Dielectric Coatings
- Commercial application of this technology

Demonstration of a Polyimide Sheet with 31-Layer Dielectric Coating



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Questions?

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