space structures laboratory

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California Insititute of Technology

Thin, Lightweight Deformable Mirrors for a Reconfigurable Space Telescope Aperture

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SPIE Mirror Technology SBIR/STTR Workshop

Talk Outline

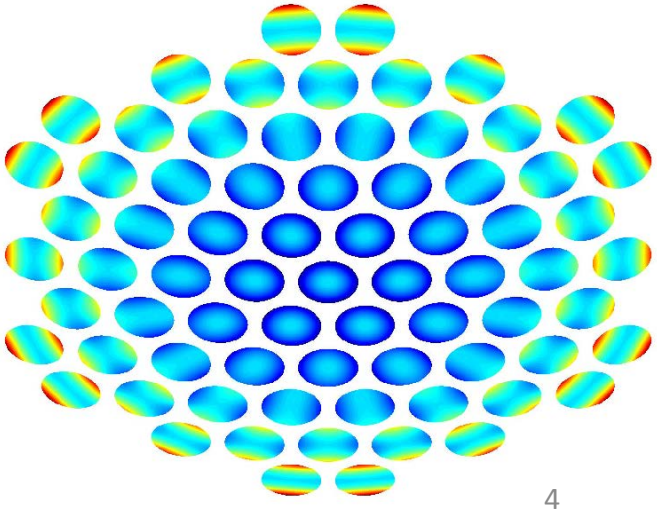
I. Introduction & Background
II. Mirror Design
III. Fabrication
IV. Initial Testing
V. Conclusion

I. Introduction & Background

Future Large Space Telescopes

- How to build aperture > 10 meters?
  - Segmented primary mirror
  - Many segments
  - Multiple launches
  - On-orbit autonomous assembly

- Mirror segments
  - Lightweight
  - Identical (nominally spherical)
    - Lower cost
    - Redundancy
    - Ease of manufacture and test
    - BUT: Curvature errors across array
  - Deformable capability



Demonstration of Key Technologies

- Collaboration between Caltech, Univ. of Surrey, JPL
- Small telescope mission
  - Lightweight adaptive mirrors
    - Each 10 cm diameter
    - Mounted on Cubesats (“Mirrorsats”)
    - Lightweight and deformable
  - Prime focus design
    - Deployable detector package (operating in VISNIR) with WFS
  - Autonomous assembly and docking
    - Segments detach, reconfigure and reattach

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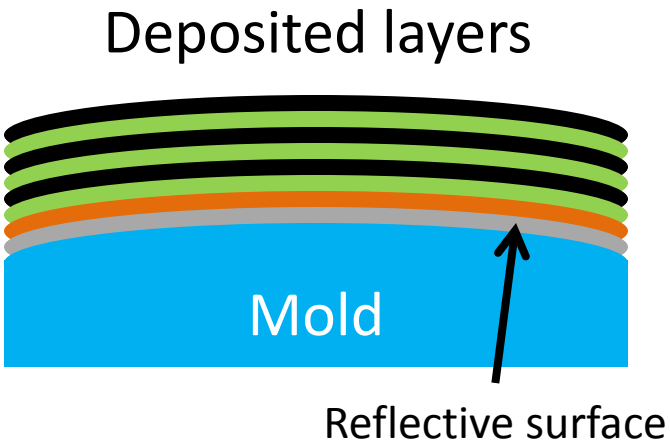
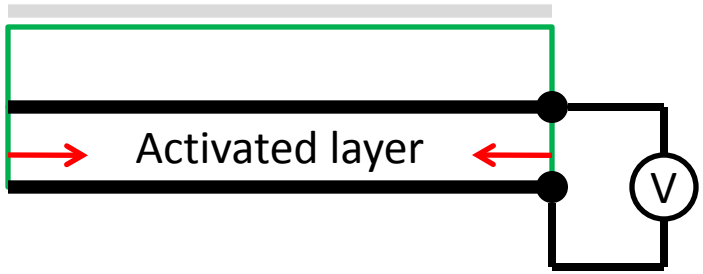
II. Mirror Design

Basic Mirror Concept

- Thin shell laminate
  - Built up on polished mold
    - Replication
  - Lightweight, stiff substrate
  - Active materials
    - Piezoceramics (e.g. PZT)
    - Electrostrictives (e.g. PMN-PT)
    - Electro-active polymers (e.g. PVDF)

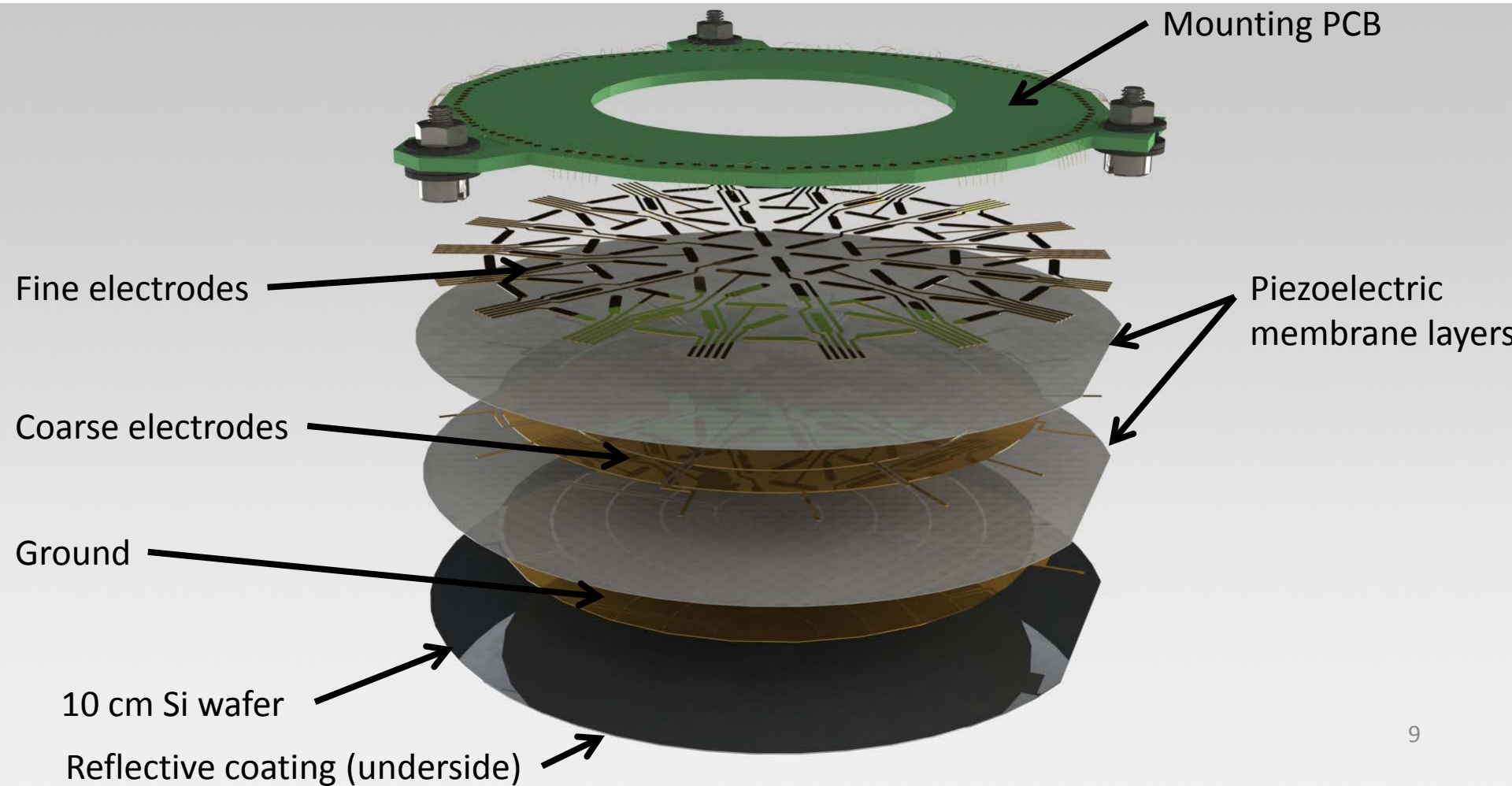


- Surface parallel actuation
  - In-plane strains create mirror curvature
  - Thin, low areal density



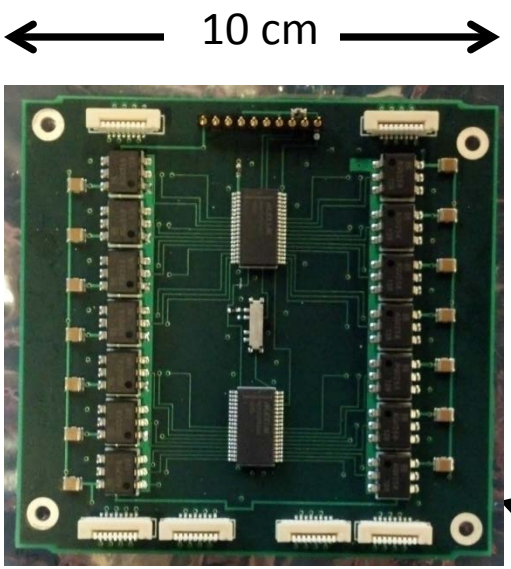
Mirror Design

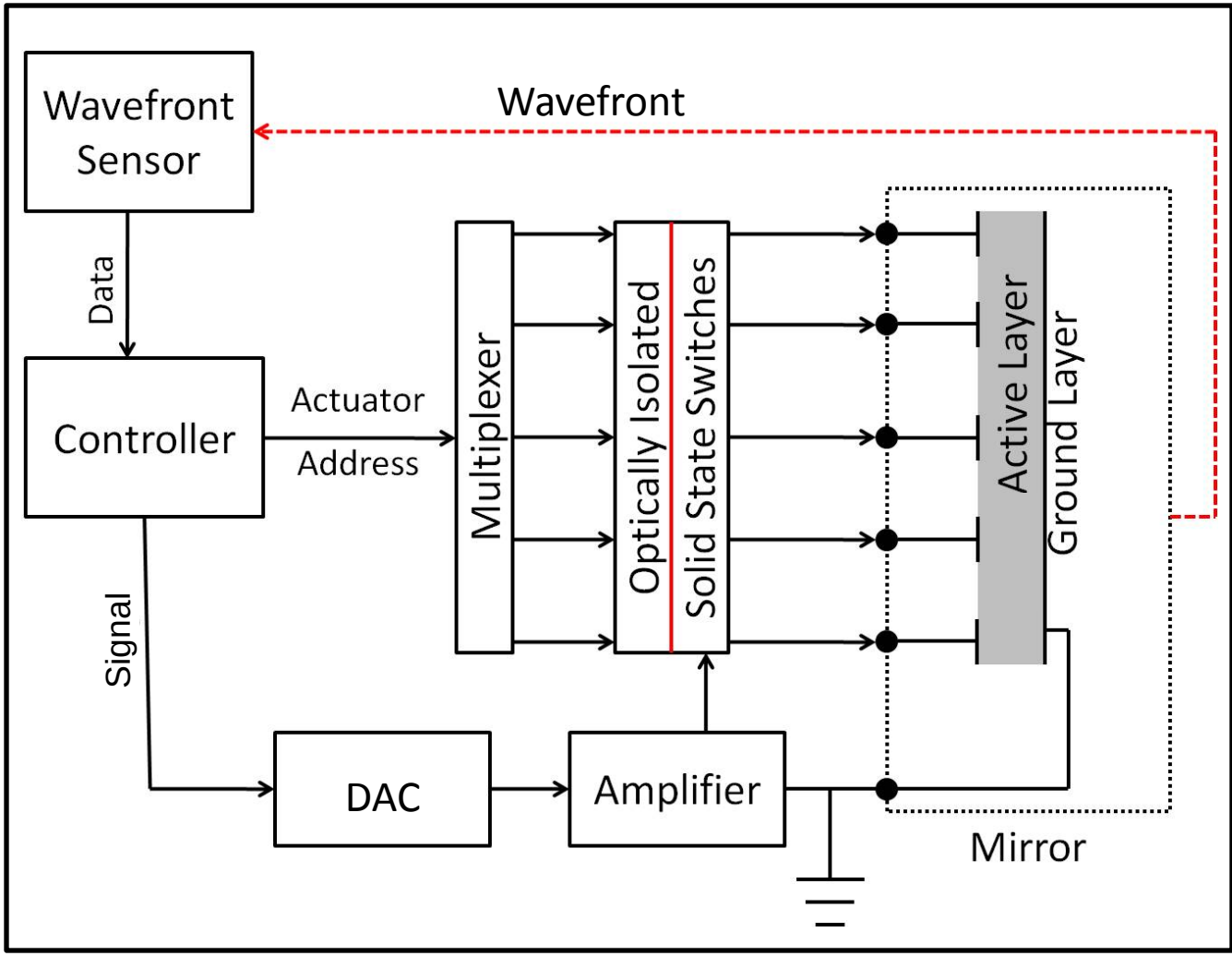
- Alternating layers of electrodes and active material
- 90 (fine pattern) + 16 (coarse pattern) channels
- Mirror < 5 grams (0.6 kg/m^2)



Mirror Control Architecture

- Single high voltage signal multiplexed into N channels
- Trades bandwidth for mass, power, volume





Multiplexer Prototype (42 chnls, +/- 500V)

Mirror Control Architecture

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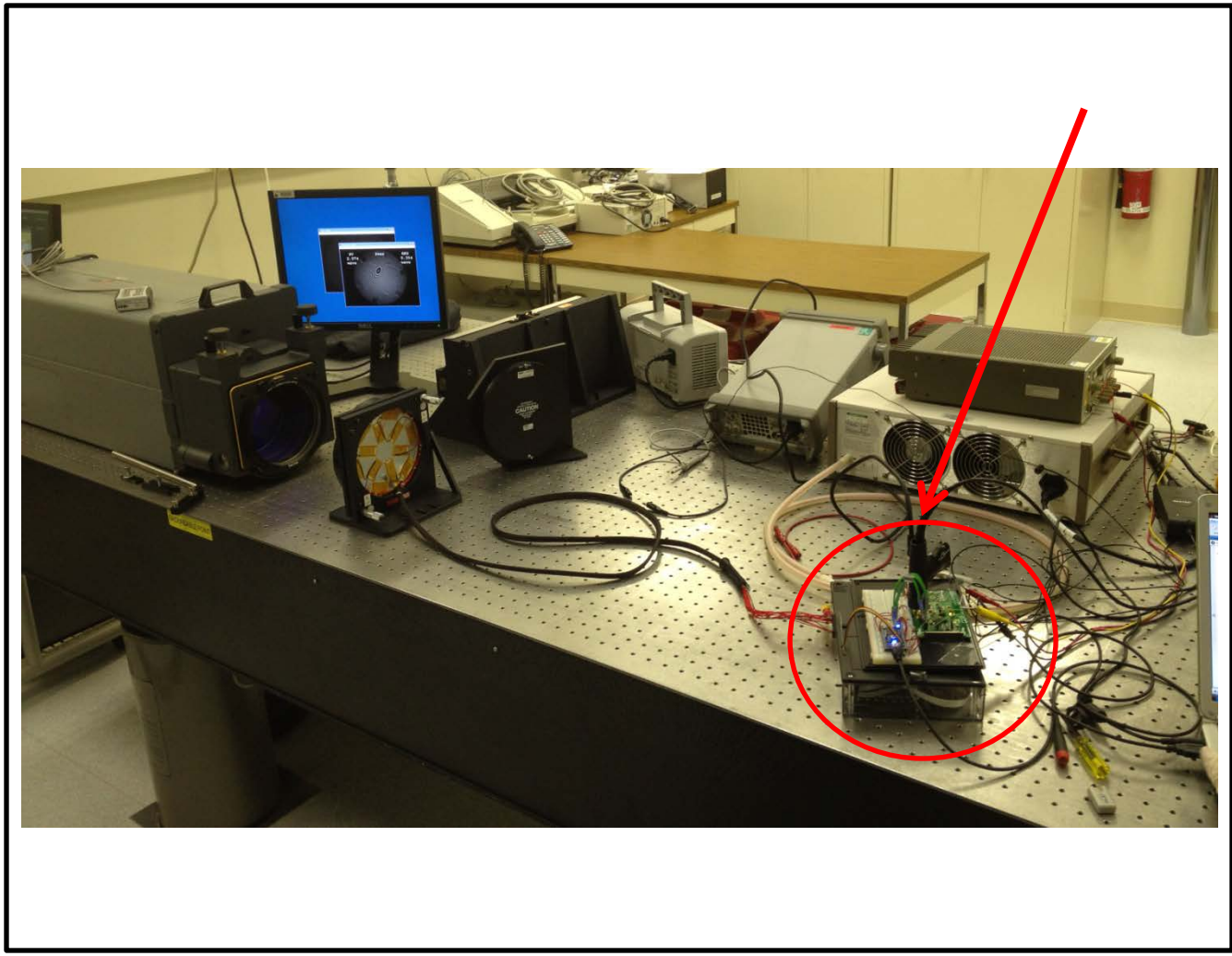
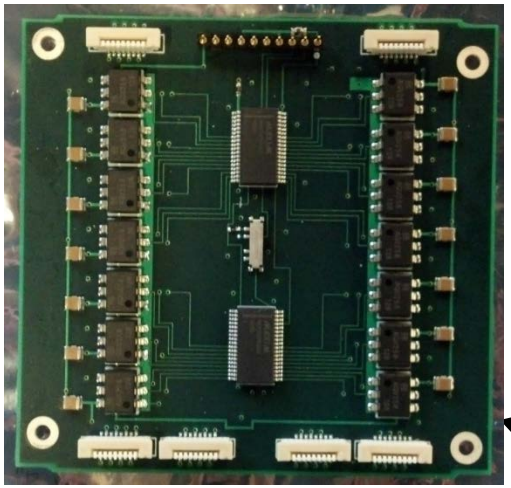


10 cm



Multiplexer Prototype (42 chnls, +/- 500V)

Thermal Control

- Mirror temperature is biased cold
  - Pointed towards cold background
  - Isolated thermally from S/C
- Monitor temperature
  - Using thermocouple, or
  - By measuring film dielectric constant
- Superimpose AC RF signal on top of DC shape control signal
  - Polymer would absorb the RF electrical energy as heat (capacitors look like shorts at high frequency)
  - ~100 MHz, ~0.1 Watts per mirror
  - Piezoelectric response negligible at high frequency
  - Modulate AC signal as required for temperature control

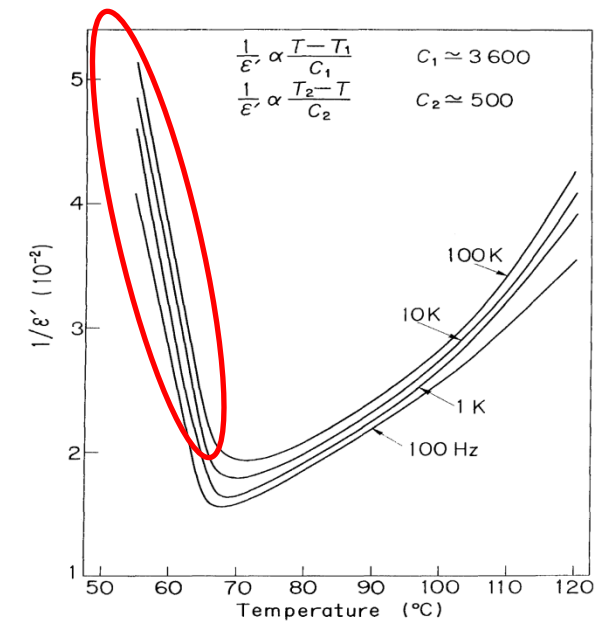


Fig. 2. Plot of reciprocal dielectric constant $1/\varepsilon'$ against temperature. C_0 and C_2 indicate the Curie constants above and below the transition temperature.

Furukawa et al, 1980

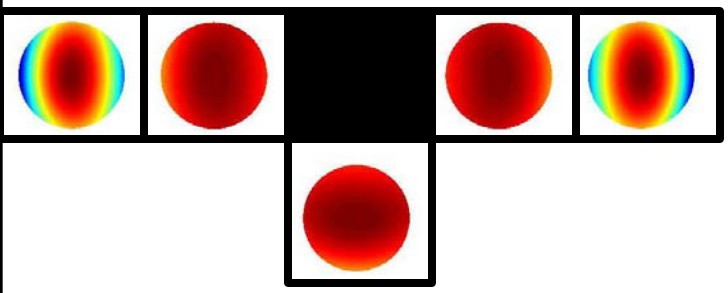
Ferroelectric Behavior in the Copolymer of Vinylidenefluouride and Trifluouroethylene

(55/45 VDF/TrFE)

Predicted Mission Performance

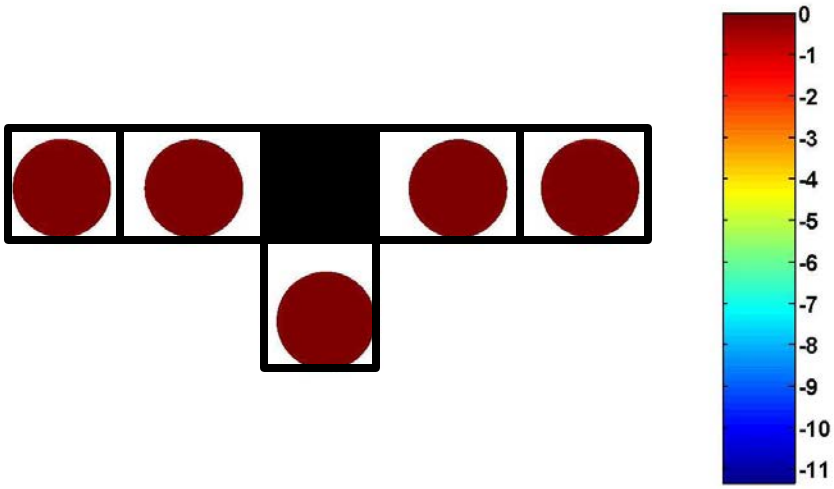
- Errors across aperture
  - Due to common shape (spherical)
- 1.2m FL hyperboloid (R-C primary) desired
- Scale is in 633 nm reference wavelengths

Initial Error



RMS = 6.1 waves

Corrected Error

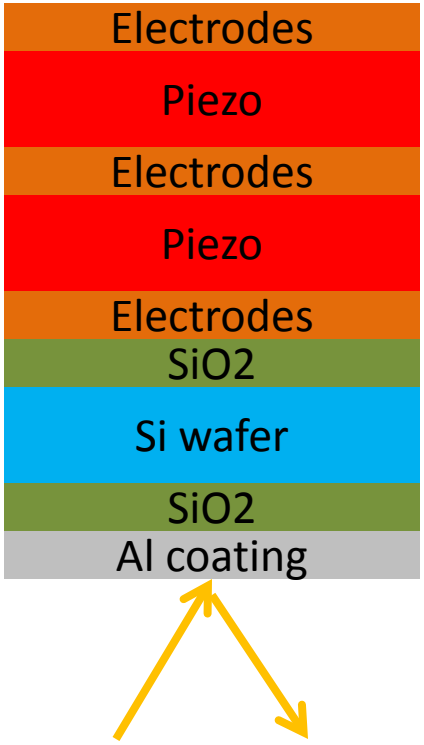


RMS = 0.17 waves

III. Mirror Fabrication

General Fabrication Process

1. Double side polished Si wafers
2. Grow high stress thermal oxide coatings
3. Add layers of active materials and electrodes
   - Active material used:
     - P(VDF-TrFE) electroactive polymer
   - Electrode materials
     - Au or Al
4. Pole active material layer(s)
5. Etch back oxide to achieve nominal curvature
6. Add reflective coating

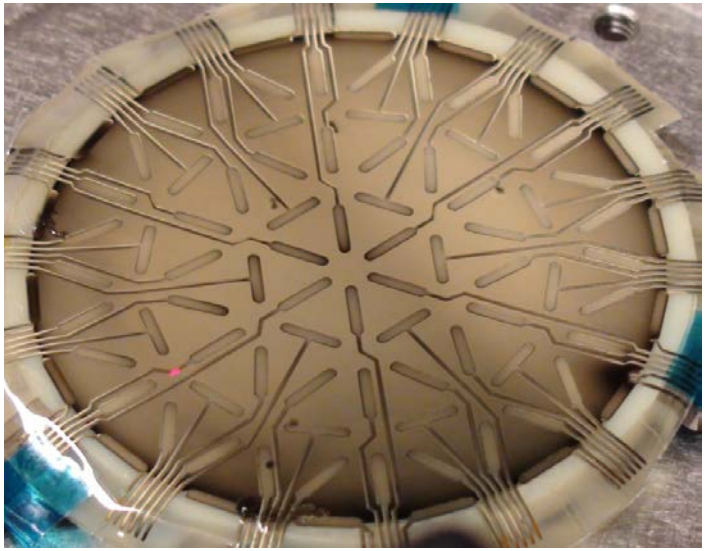


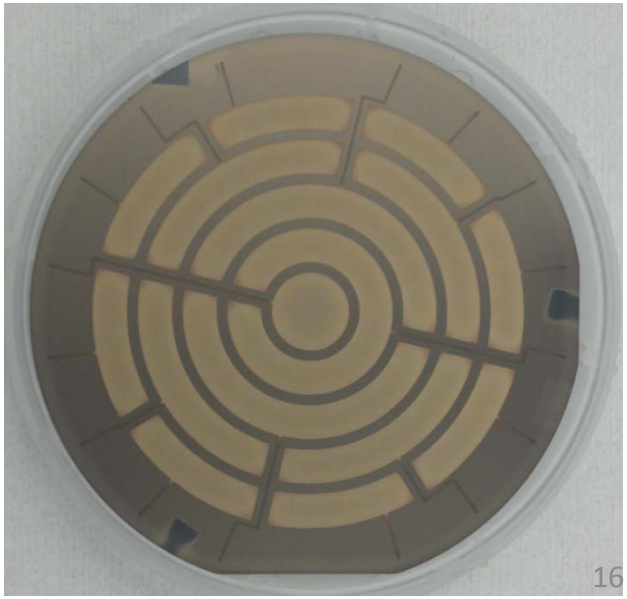
Peeled Polymer Laminate

On Wafer

Front

Back

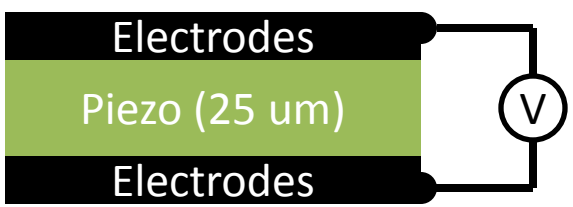


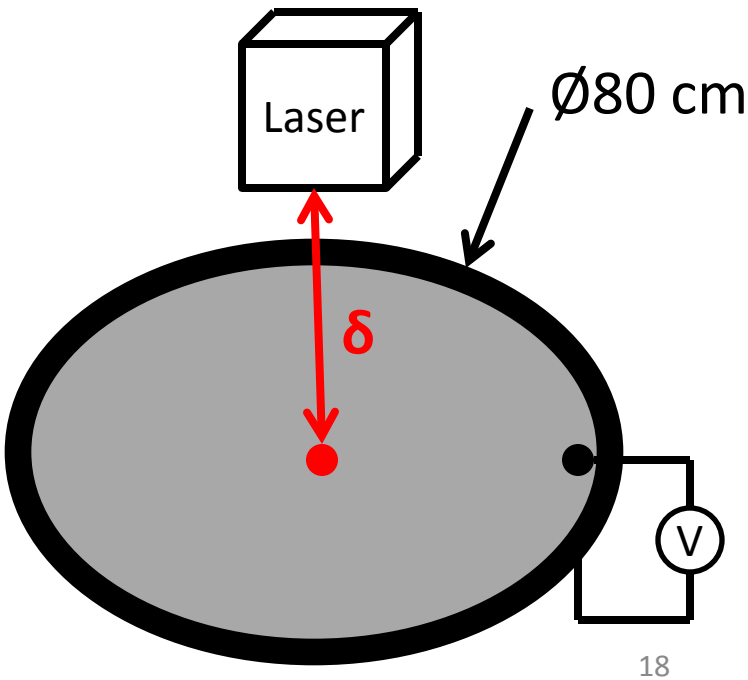


IV. Mirror Testing

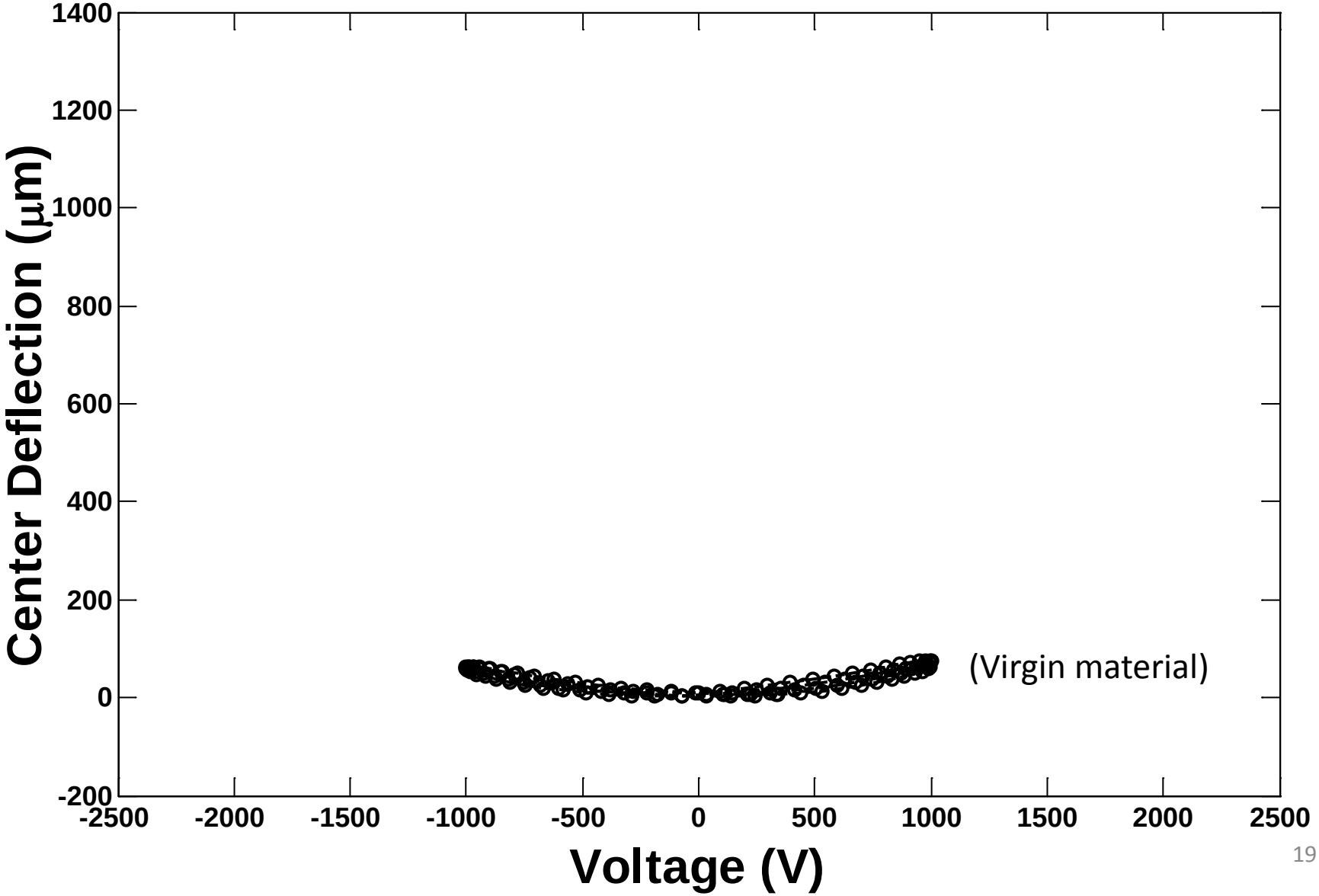
Freestanding Film

- Two continuous (blanket) electrodes
- Bonded to simple ring around edge
- Measurement
  - Deflection of center point

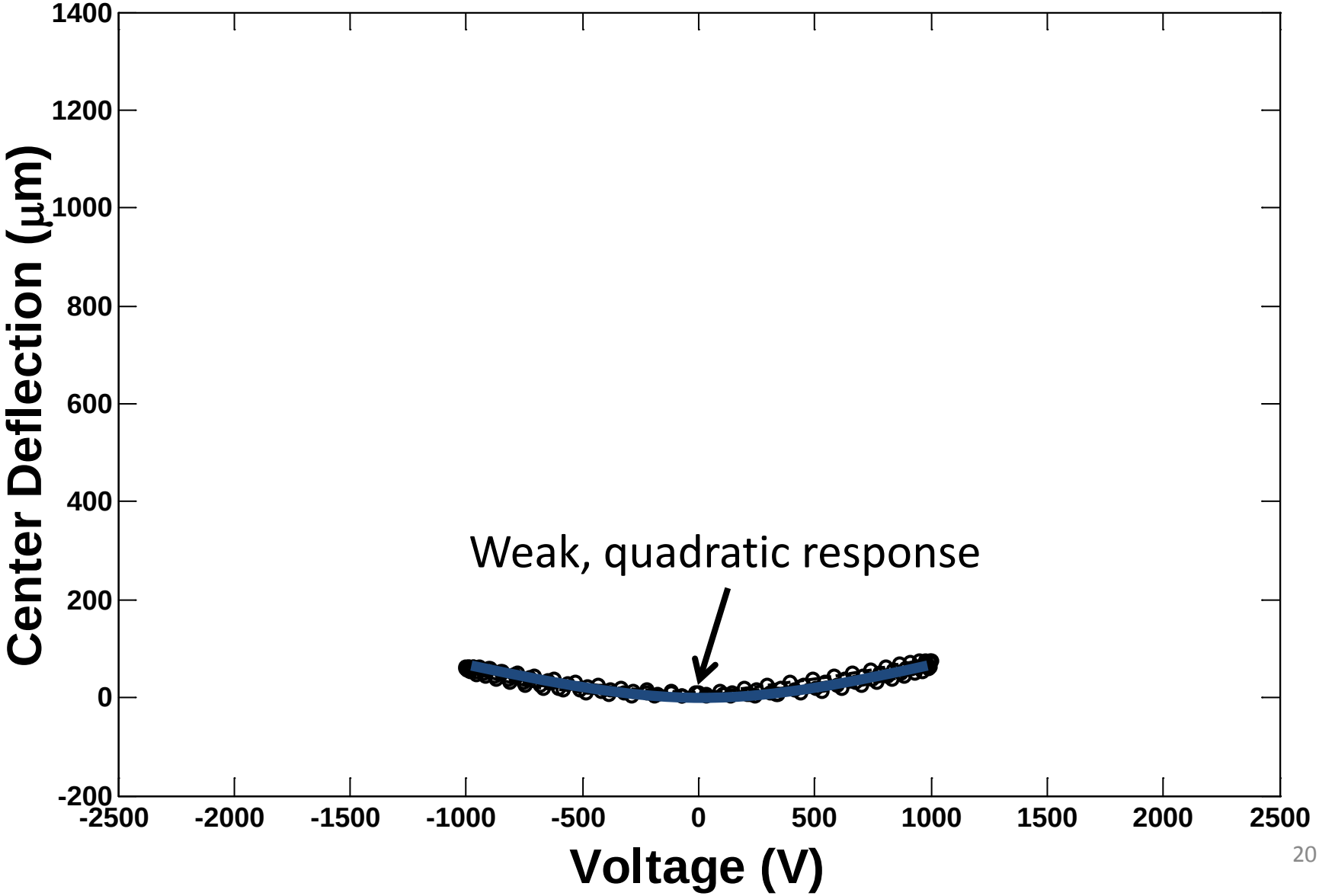




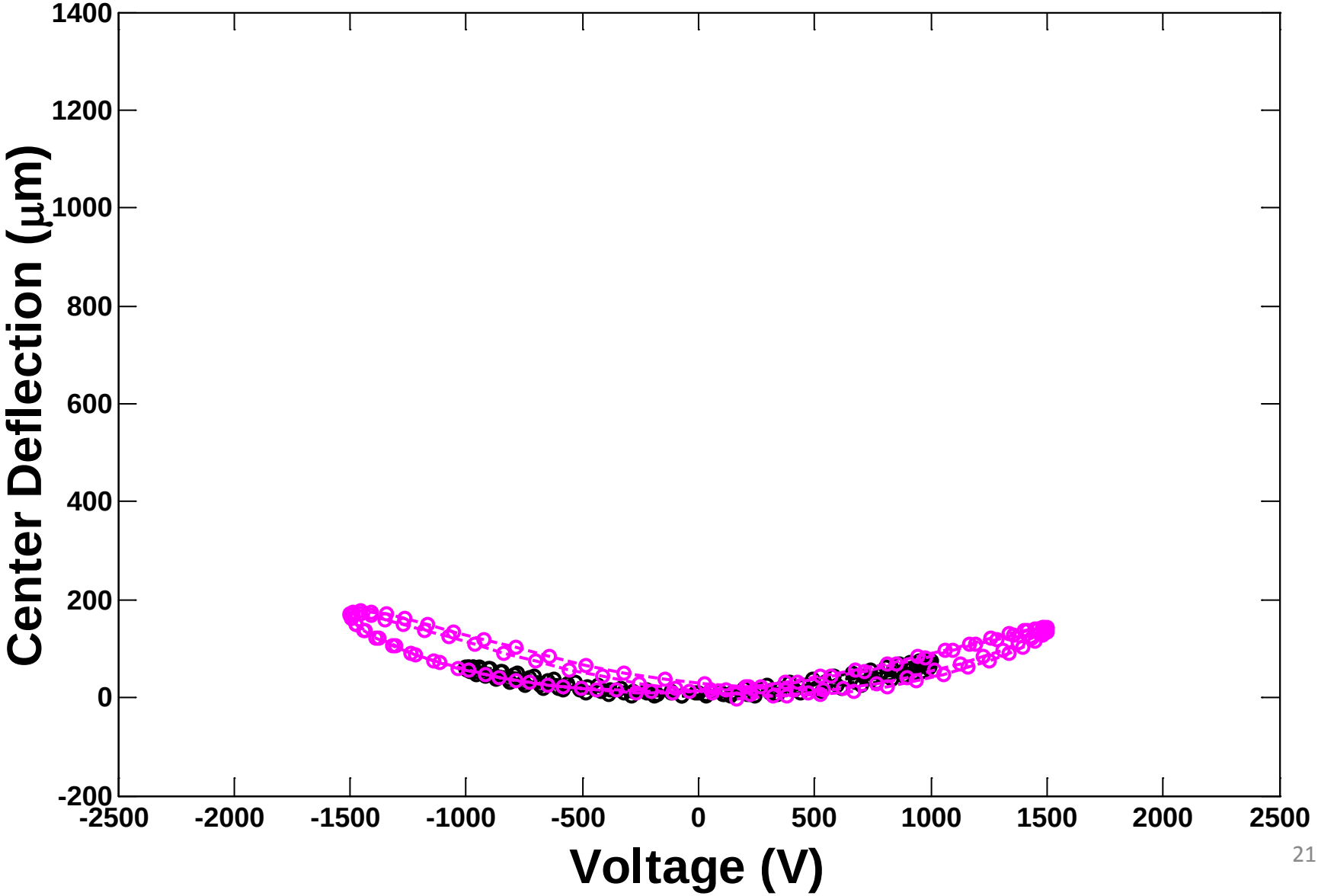
Initial Response, 1000V cycle



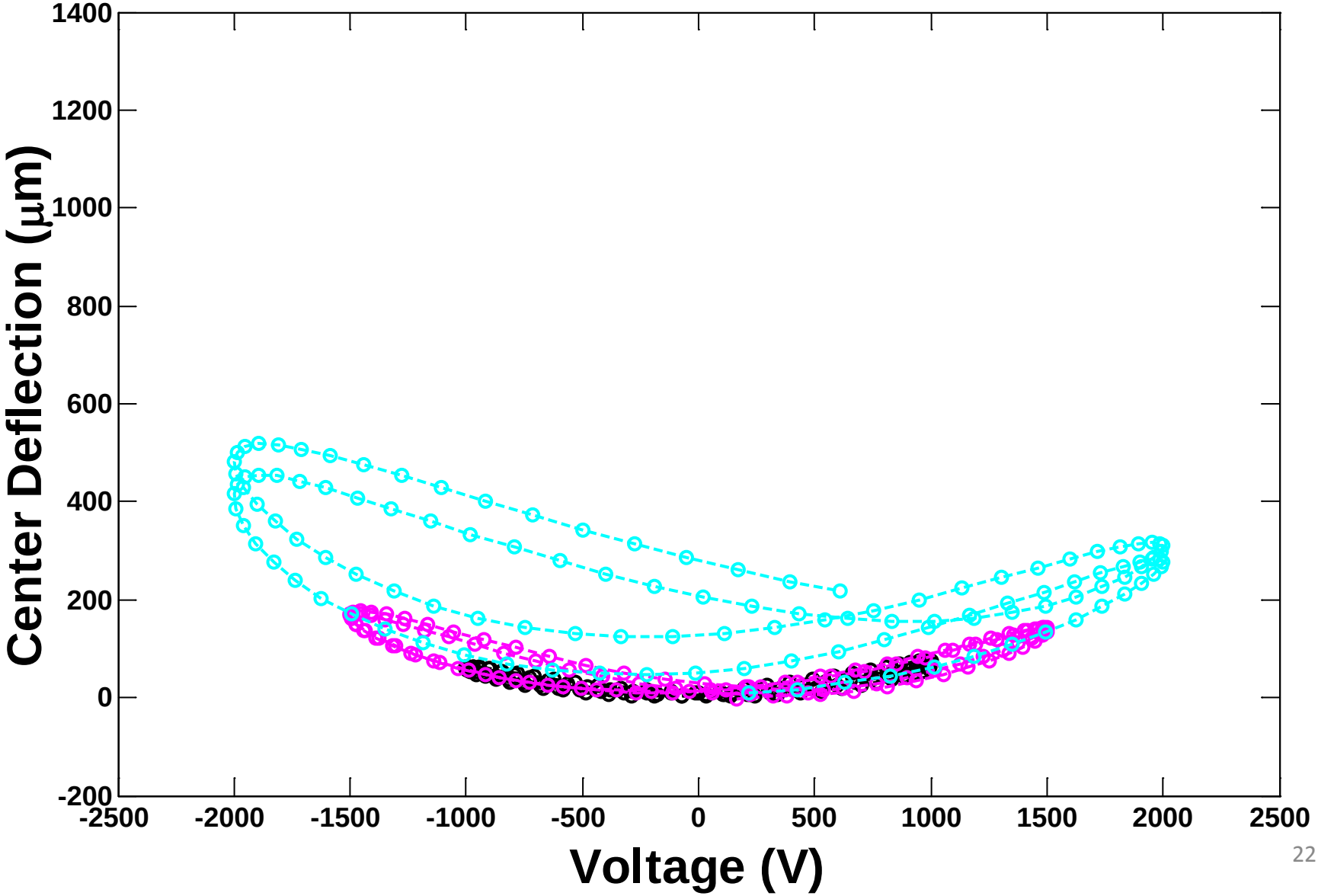
Initial Response, 1000V cycle



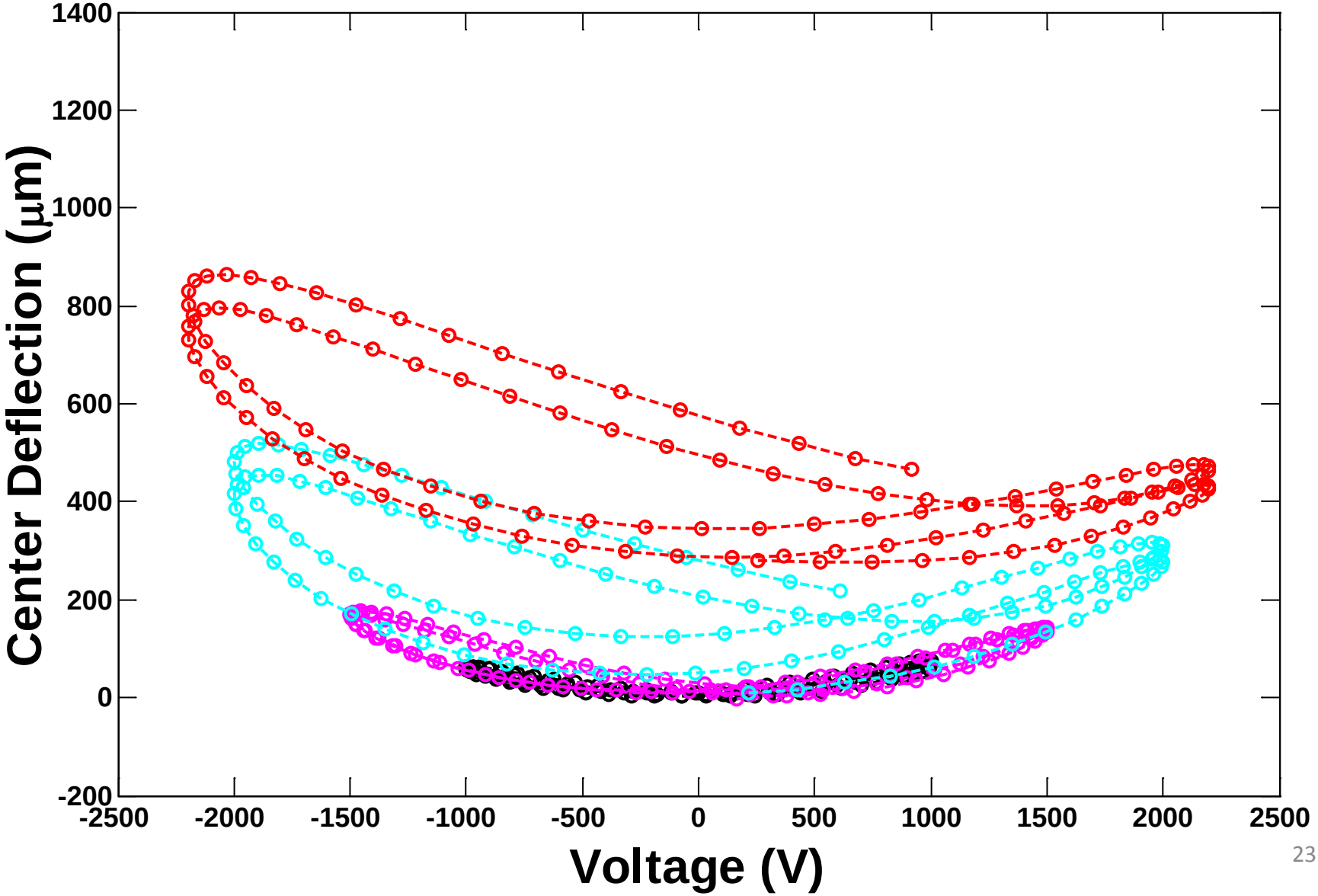
Cycled at 1500V



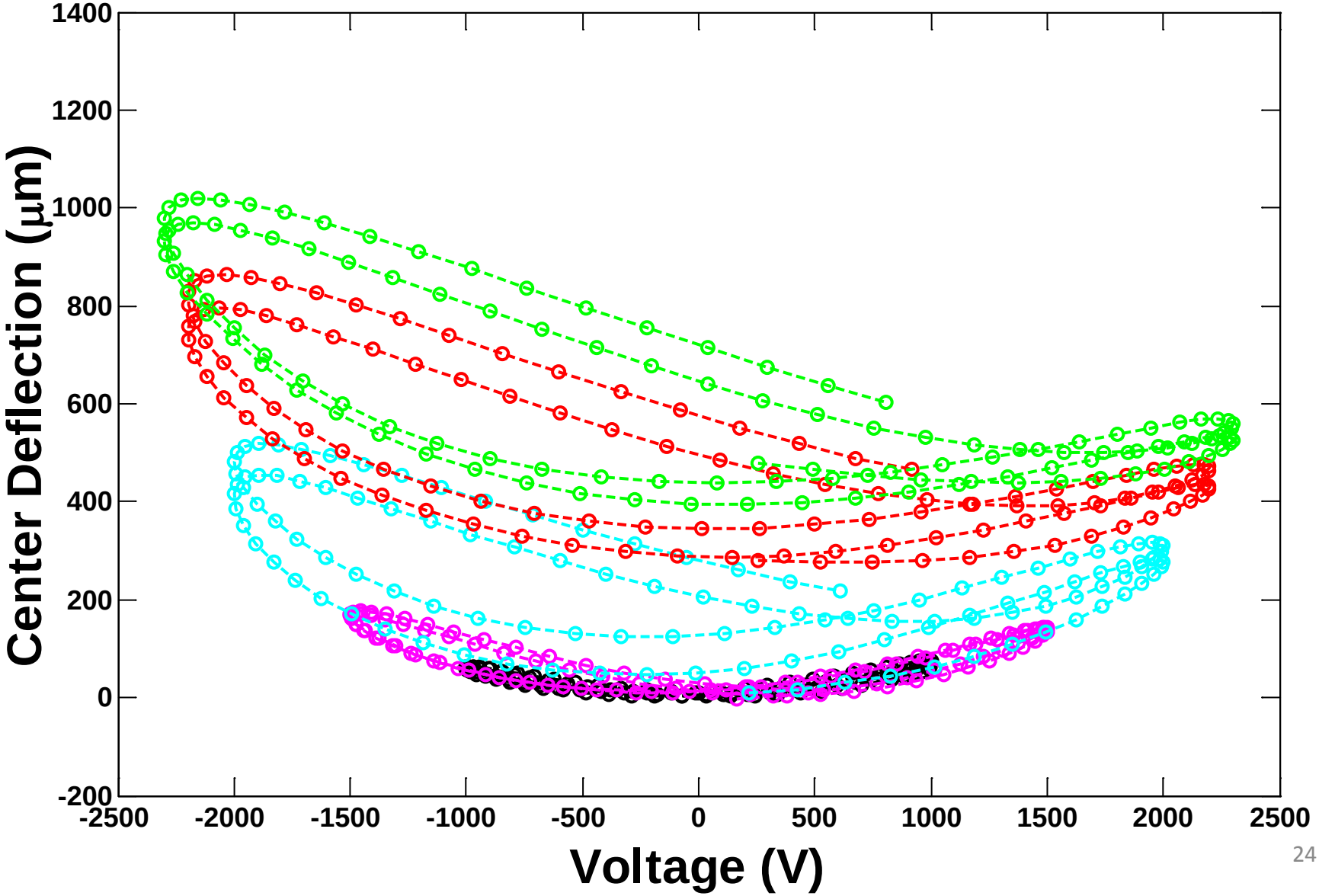
Cycled at 2000V



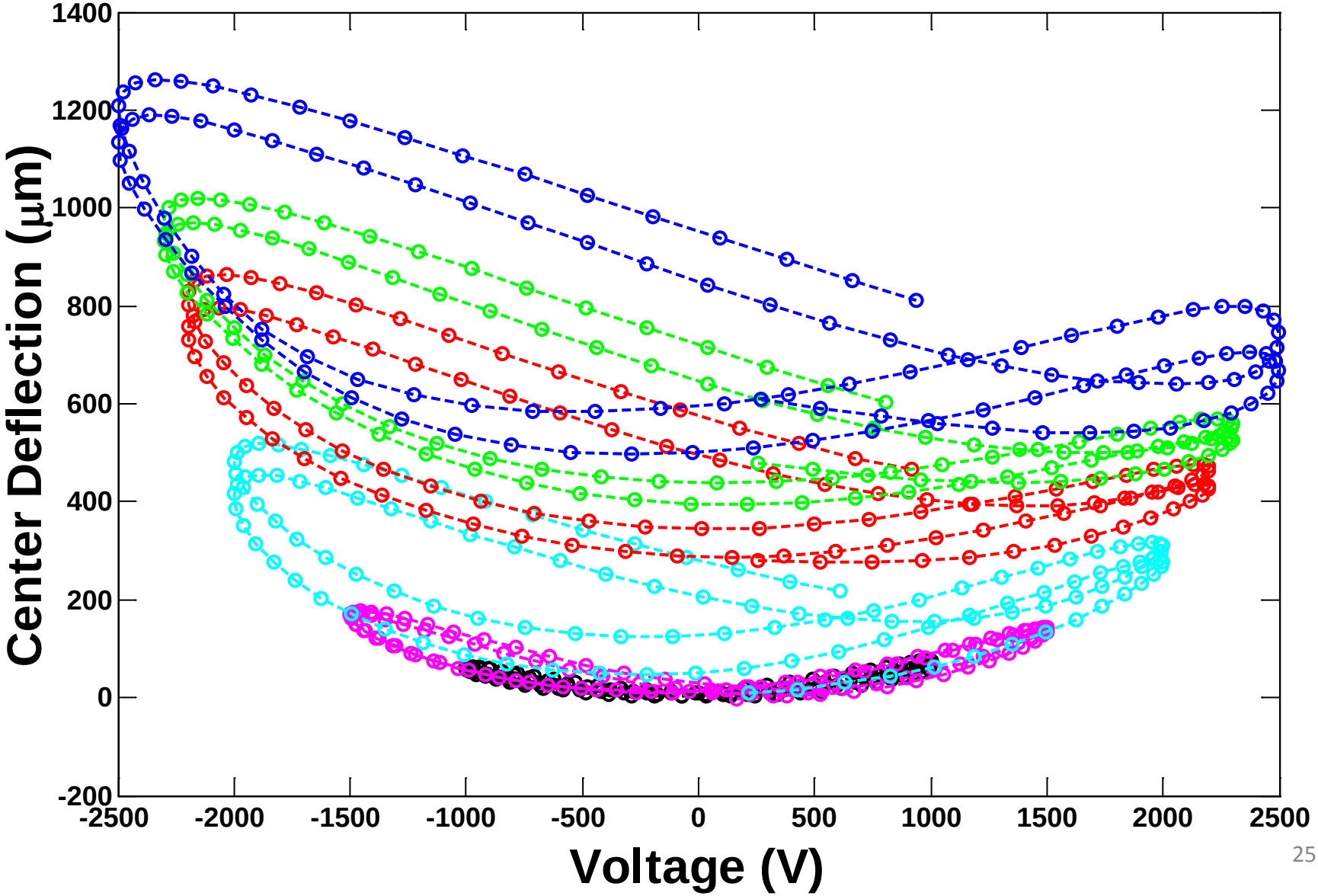
Cycled at 2200V



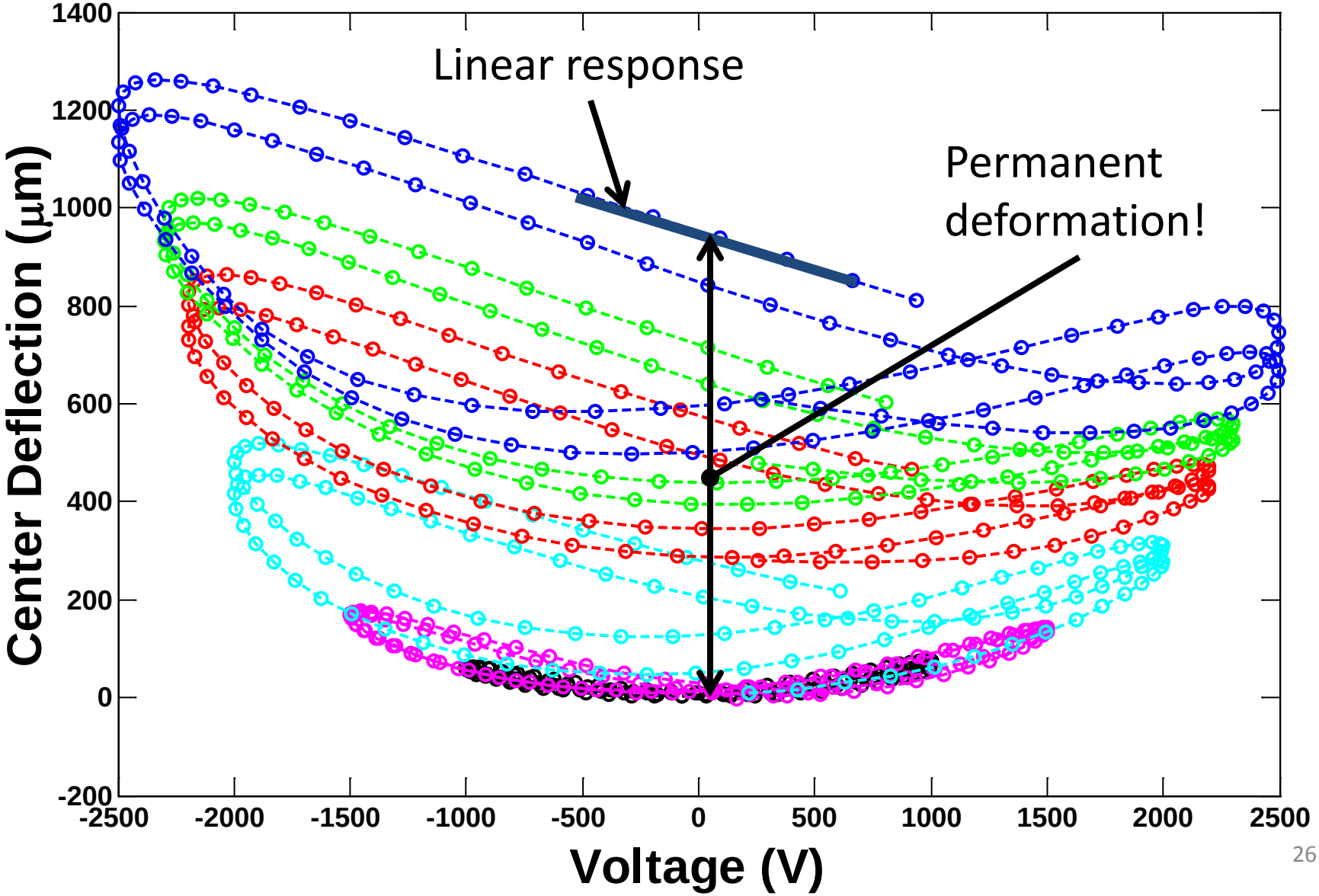
Cycled at 2300V



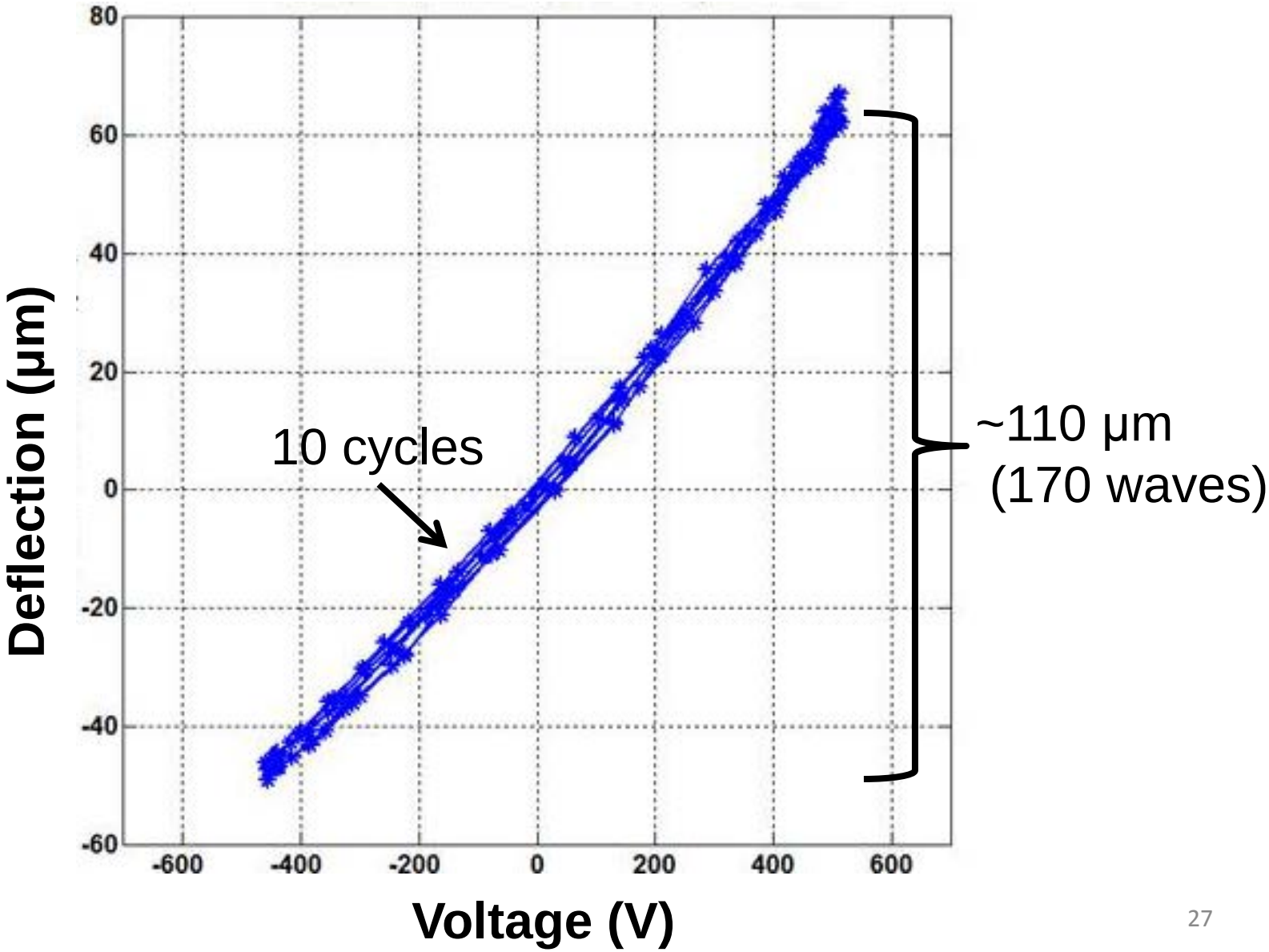
Cycled at 2500V



Cycled at 2500V

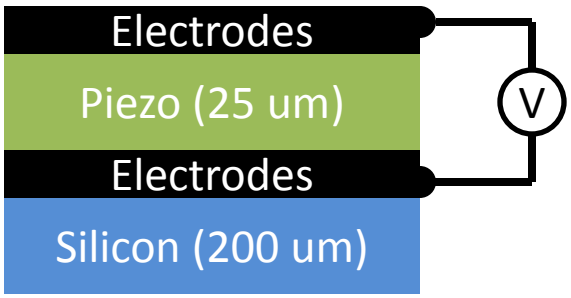


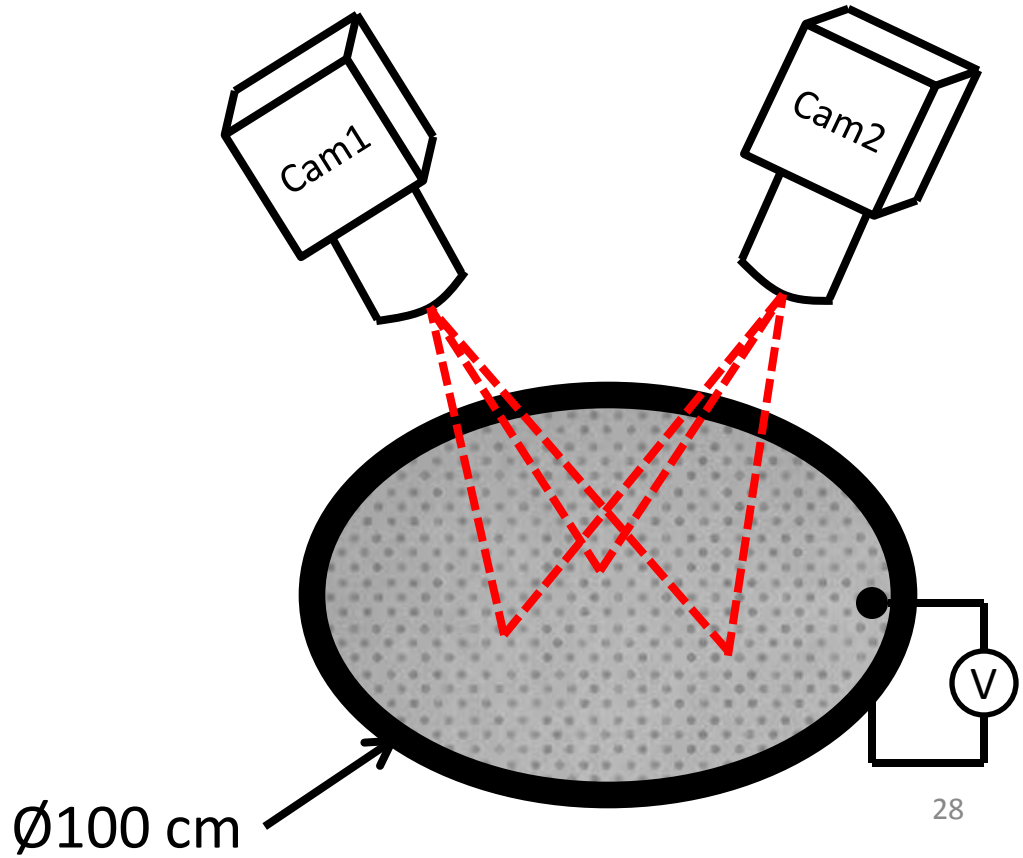
Operating Response



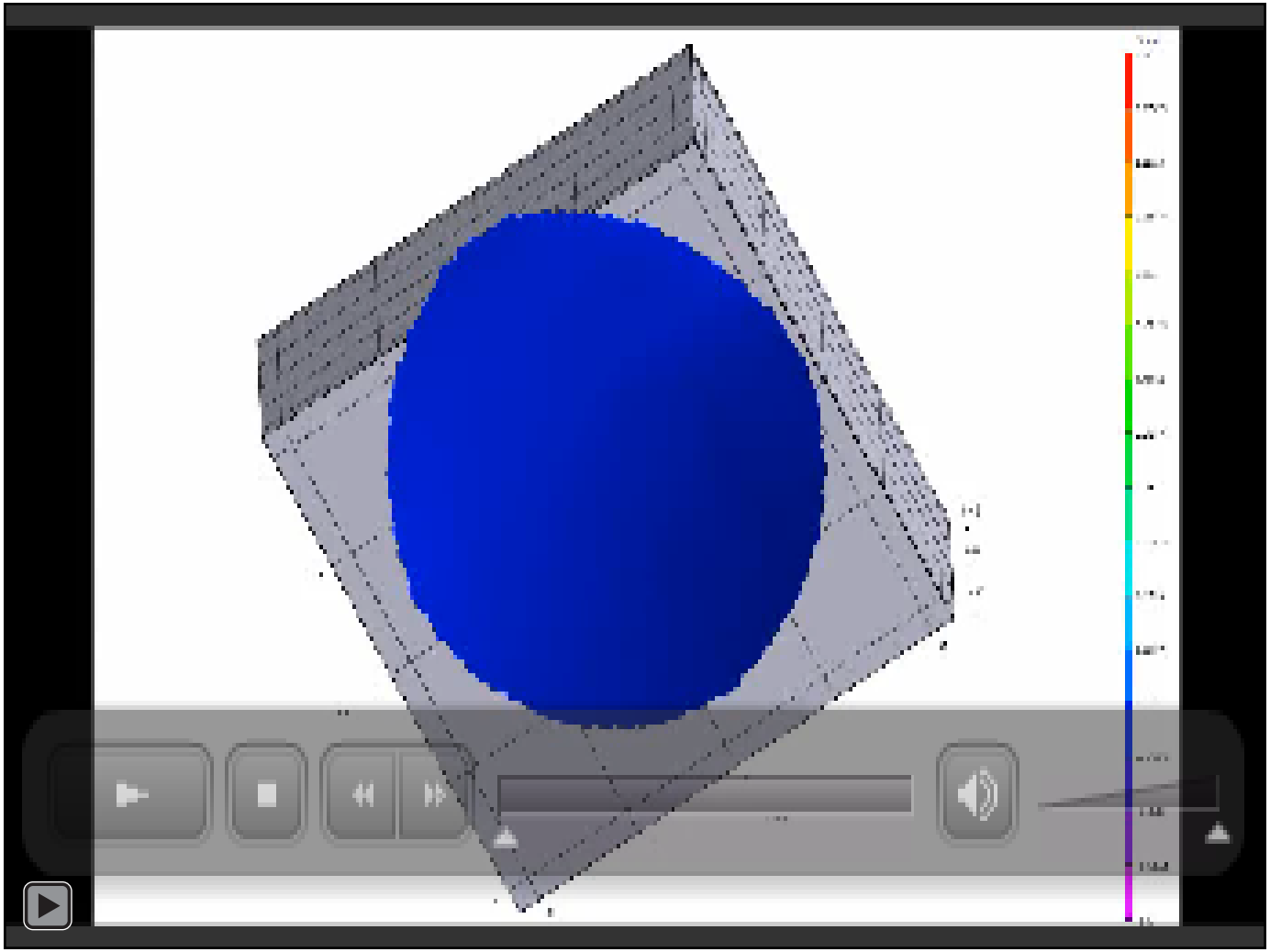
Film on Wafer

- Attached to 200 micron thick wafer
- 3D Digital Image Correlation (DIC)



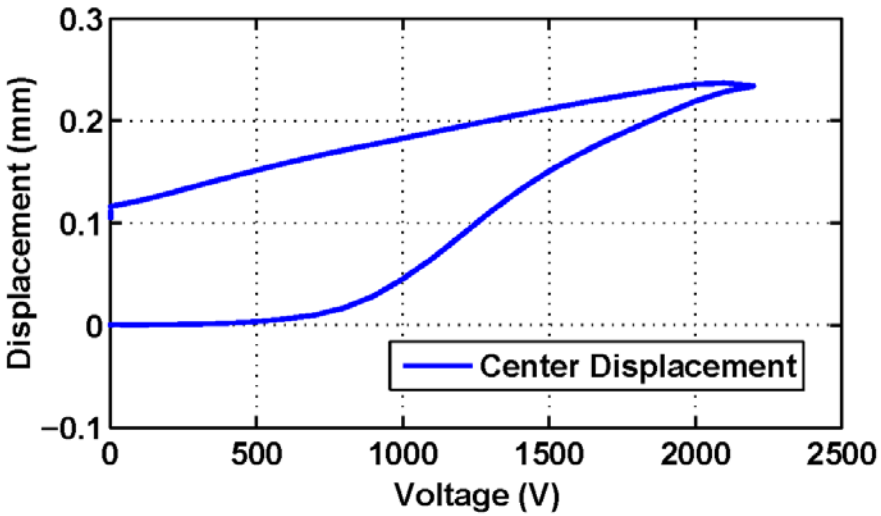


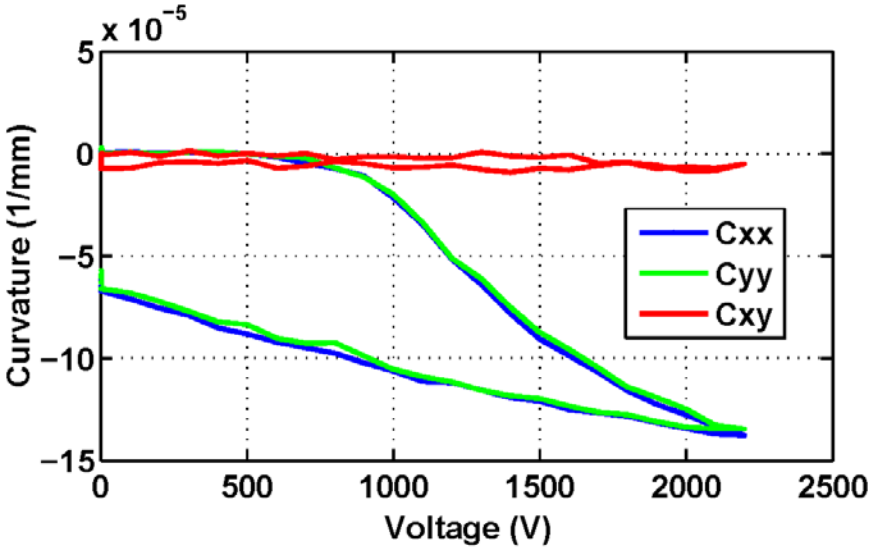
Poling Process (On Wafer)

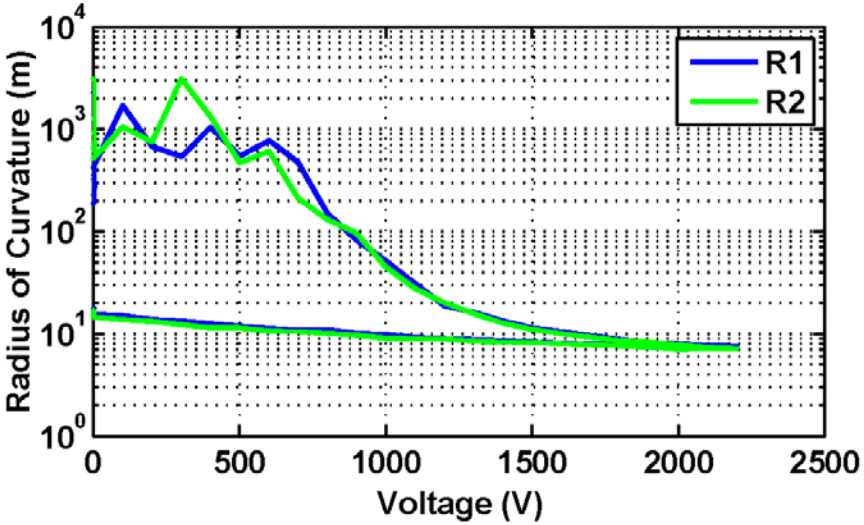


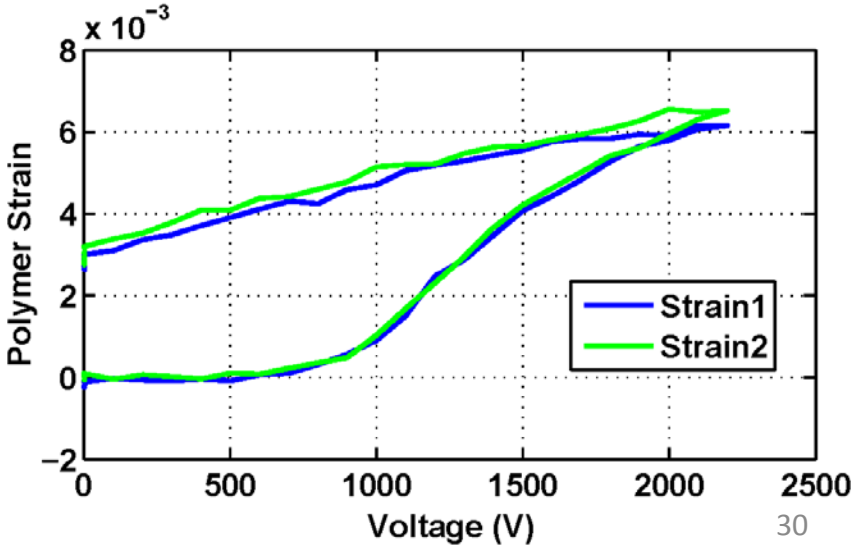
DIC Measurement Data

Poling Data

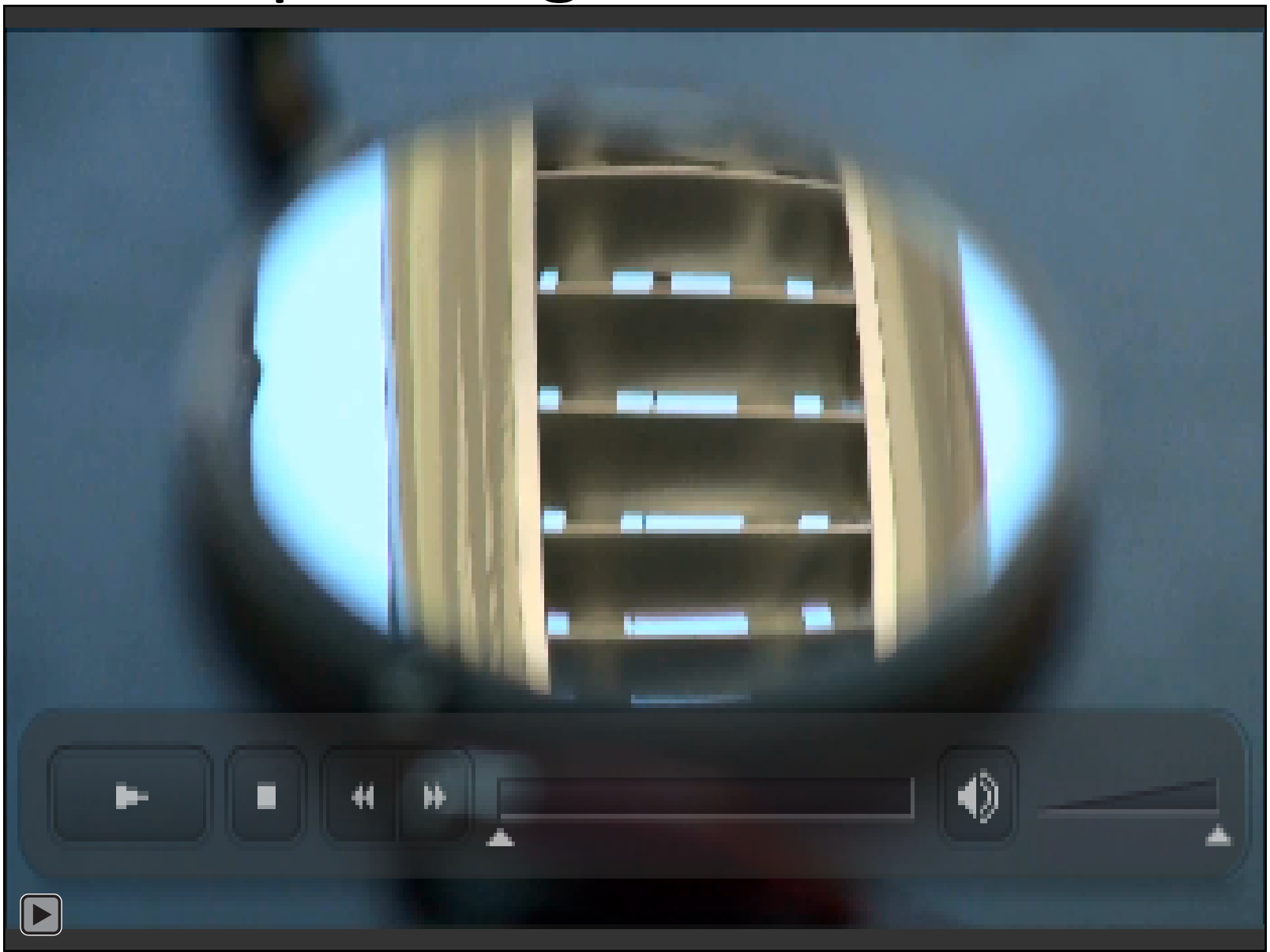

Displacement (mm)
Voltage (V)
Center Displacement


x 10^-5
Curvature (1/mm)
Voltage (V)
Cxx
Cyy
Cxy

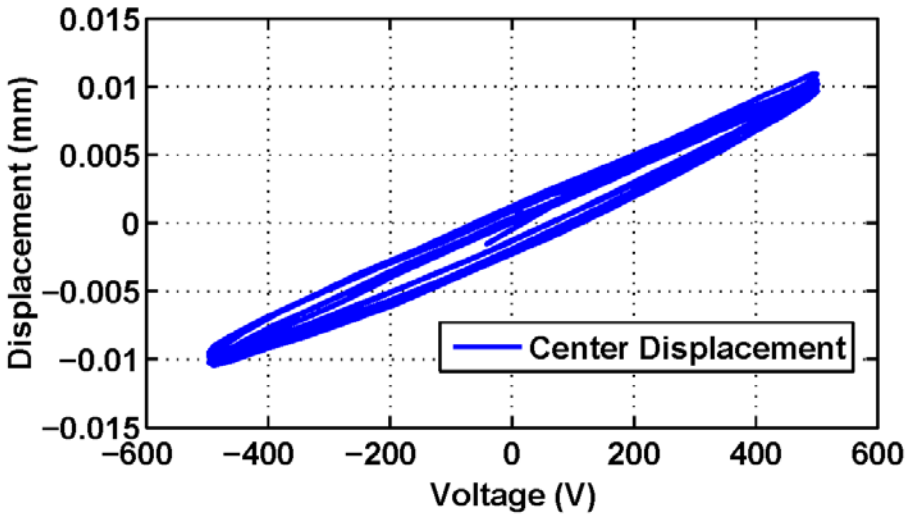

Radius of Curvature (m)
Voltage (V)
R1
R2

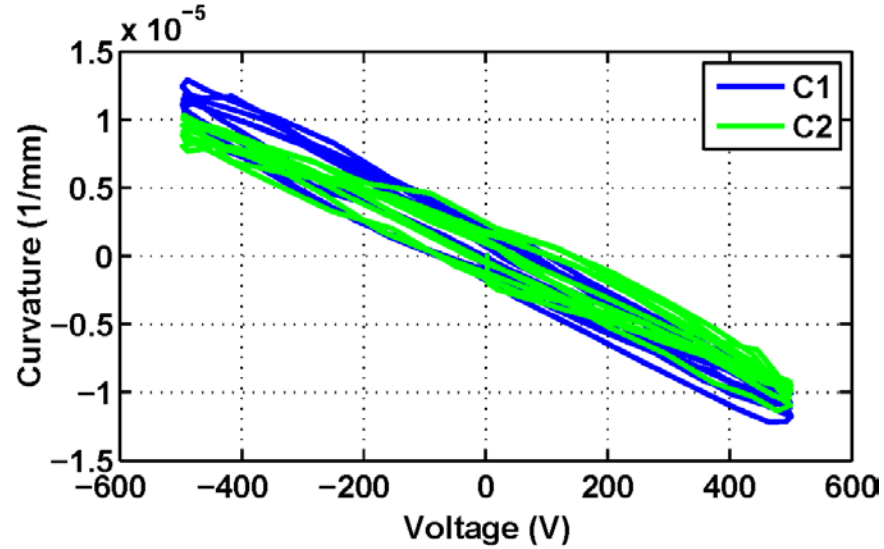

x 10^-3
Polymer Strain
Voltage (V)
Strain1
Strain2

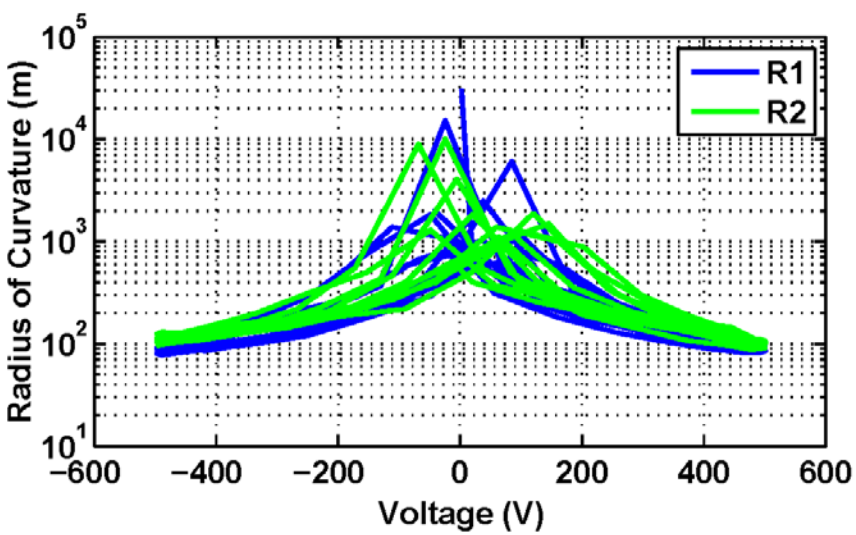
Operating Mirror Video

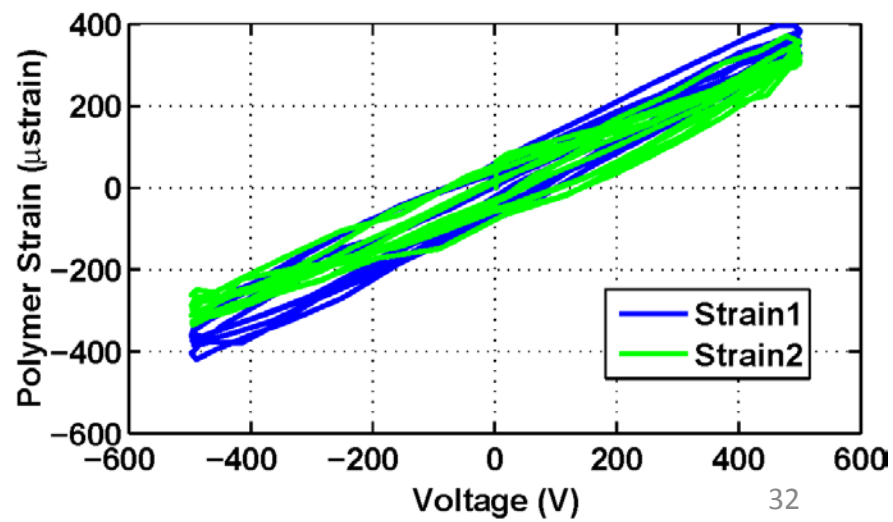


Operating Data





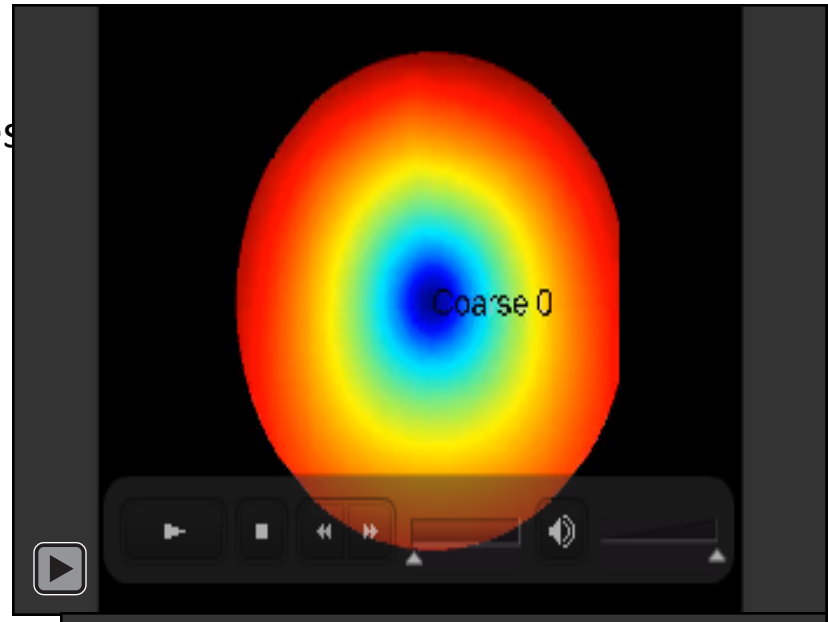




V. Conclusion

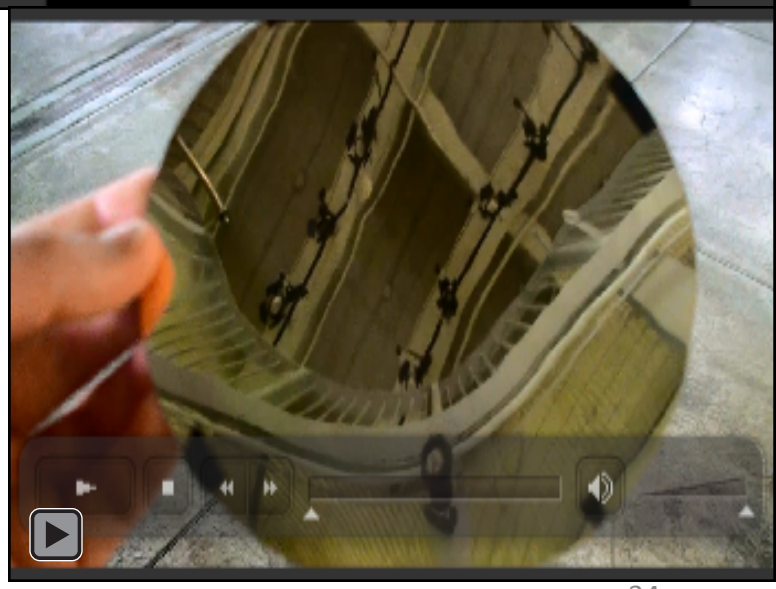
Conclusion

- So far successfully:
  - Replicated surface finish from polished wafers
  - Produced basic thin deformable mirror samples
  - Processed single actuator samples
  - Demonstrated ample mirror response
    - 20 µm on 200 µm wafer
    - Model: ~100 µm on 100 µm
- Still to come, more testing:
  - Influence function measurements
  - Multi-channel closed loop control



What about large apertures?

- Concept still valid, but…
- Silicon wafers constrained to 12” diameters
- Other thin, lightweight yet stiff substrates
  - Carbon fiber? How to achieve lasting polished surface with acceptable roughness? TBD…



Courtesy of John Steeves (Caltech)

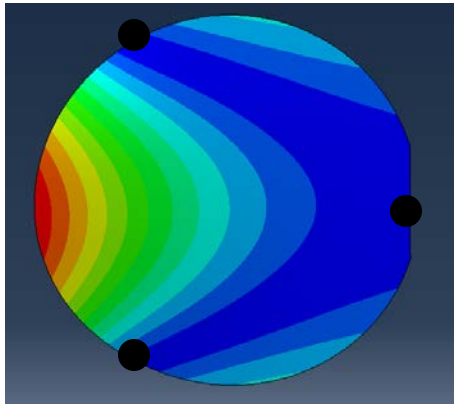
Acknowledgements

- Funding
  - Keck Institute for Space Studies (KISS)
- Collaborators
  - Advisor, Prof. Sergio Pellegrino
  - Dr. Breckinridge, John Steeves, Prof. Daraio, Dr. Yamamoto, and Terry Gdoutos, Ae105 students (Caltech)
  - Harish Manohara, Risaku Toda, Victor White, Andrew Shapiro (JPL)
- Cleanroom fabrication facilities
  - Kavli Nanoscience Institute (Caltech)
  - Microdevices Lab (JPL)

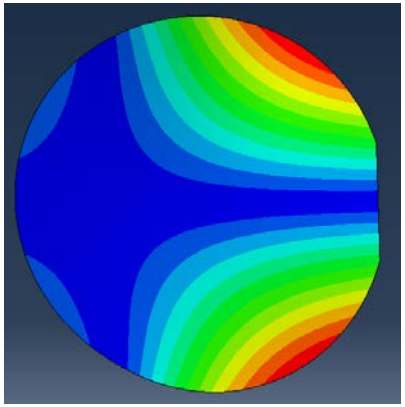
Thank you!
kdpatter@caltech.edu

- backup

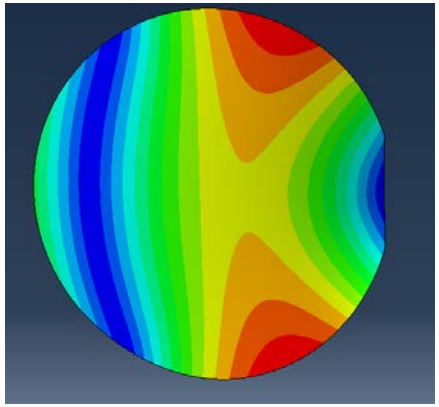
Dynamic Modes (Model)



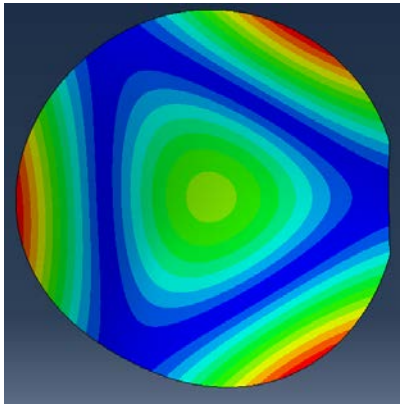
50 Hz



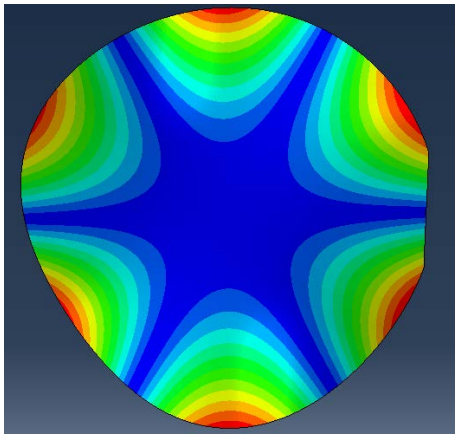
51 Hz



53 Hz



140 Hz

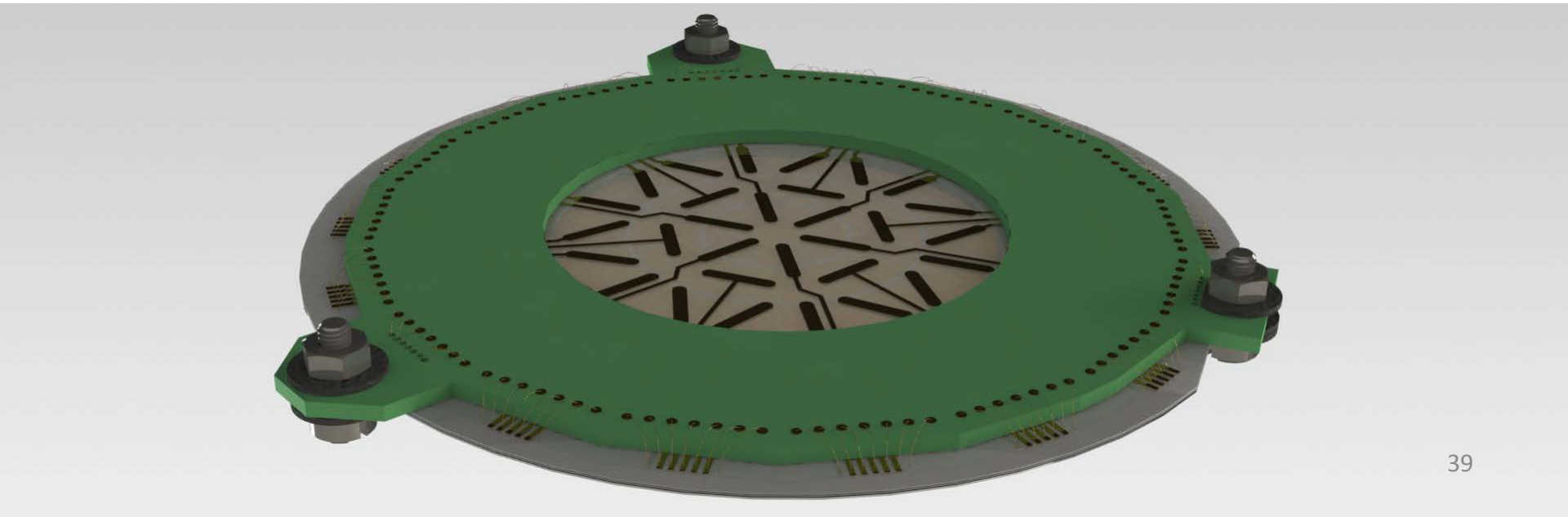


179 Hz

- Stiff Si established mode frequencies
- Polymer provides significant damping
  - Especially if shunted (via passively or actively tuned LRC circuit)

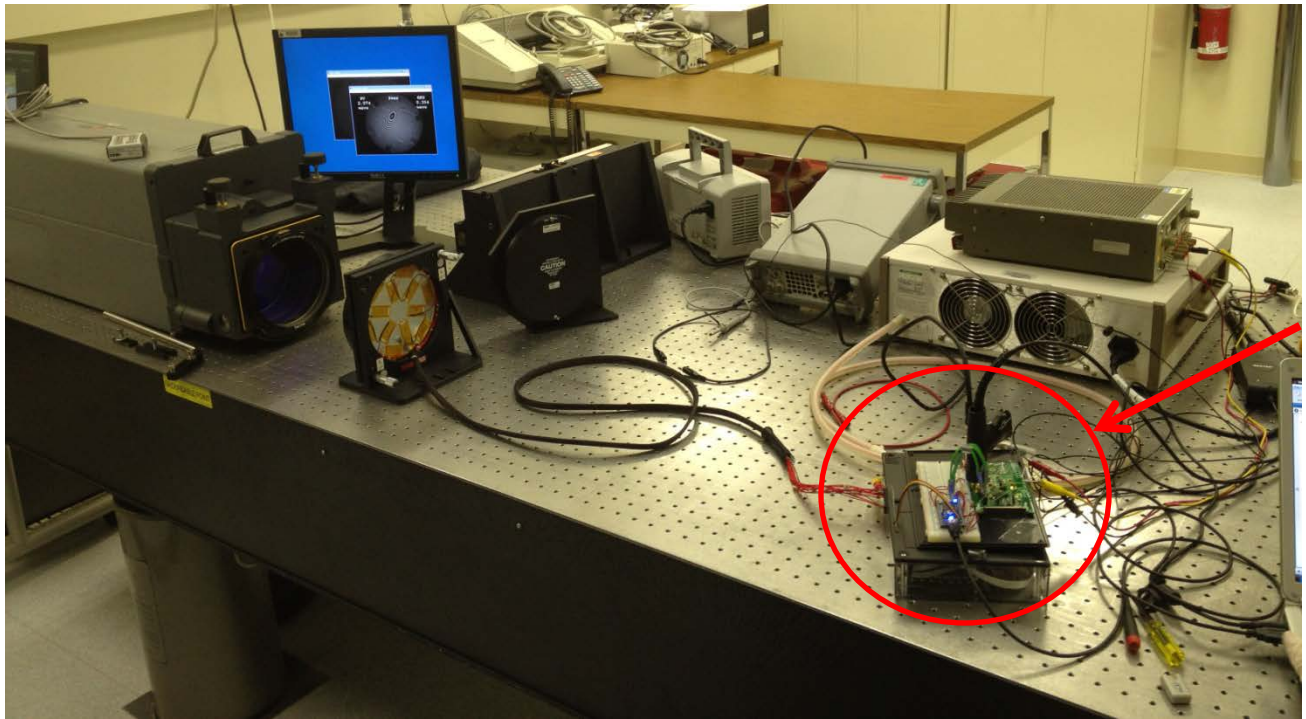
Mirror Design

- Mass
  - Mirror < 5 grams (0.6 kg/m^2)
  - Controller boards mass ~250 grams total
  - Plus additional mass
    - 3DOF Gimbal mount
    - Shutter and casing
    - Hardware
    - Cabling
  - Expected total mass



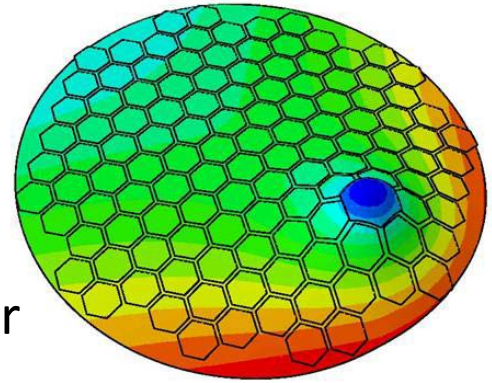
Testing

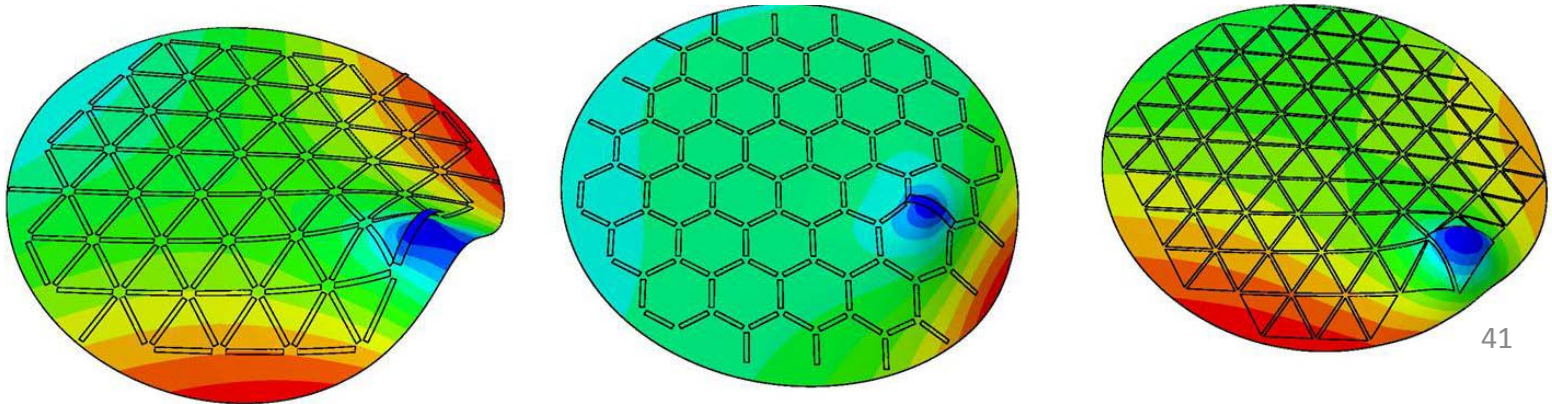
- Tested electronics on 6” mirrors in front of Zygo interferometer
  - Successfully demonstrated multiple channel control on 6” Si and glass mirrors with 12 channels up to +/- 400 V
  - Stable fringes



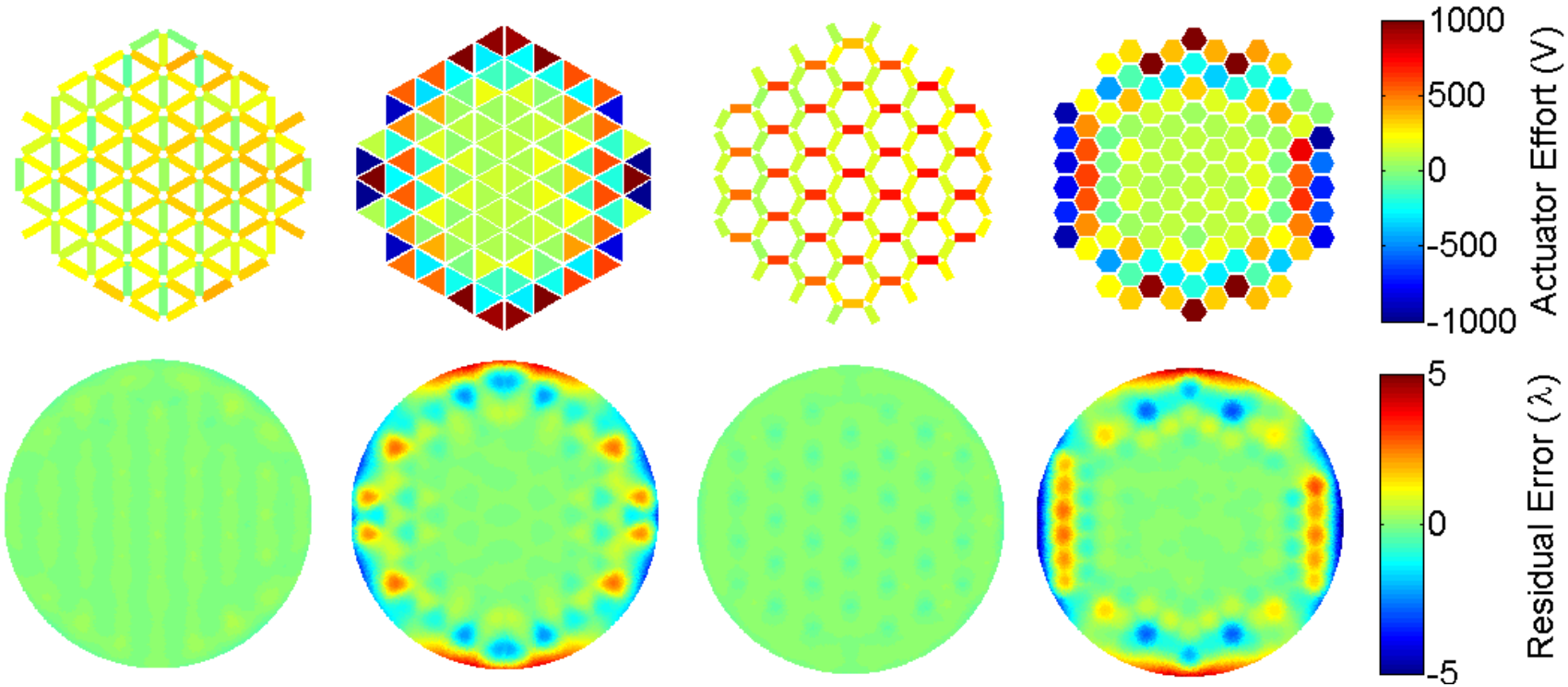
Previous Studies

- Design requirements
  - Broad family of deformation modes
  - Low residual error
- Solution: divide electrodes into patterns
  - Individually addressable
  - Found lattice of narrow electrodes better than filled tesselation
- Even better: multiple overlying patterns
  - Combine a fine pattern with a coarse pattern for bulk curvature changes

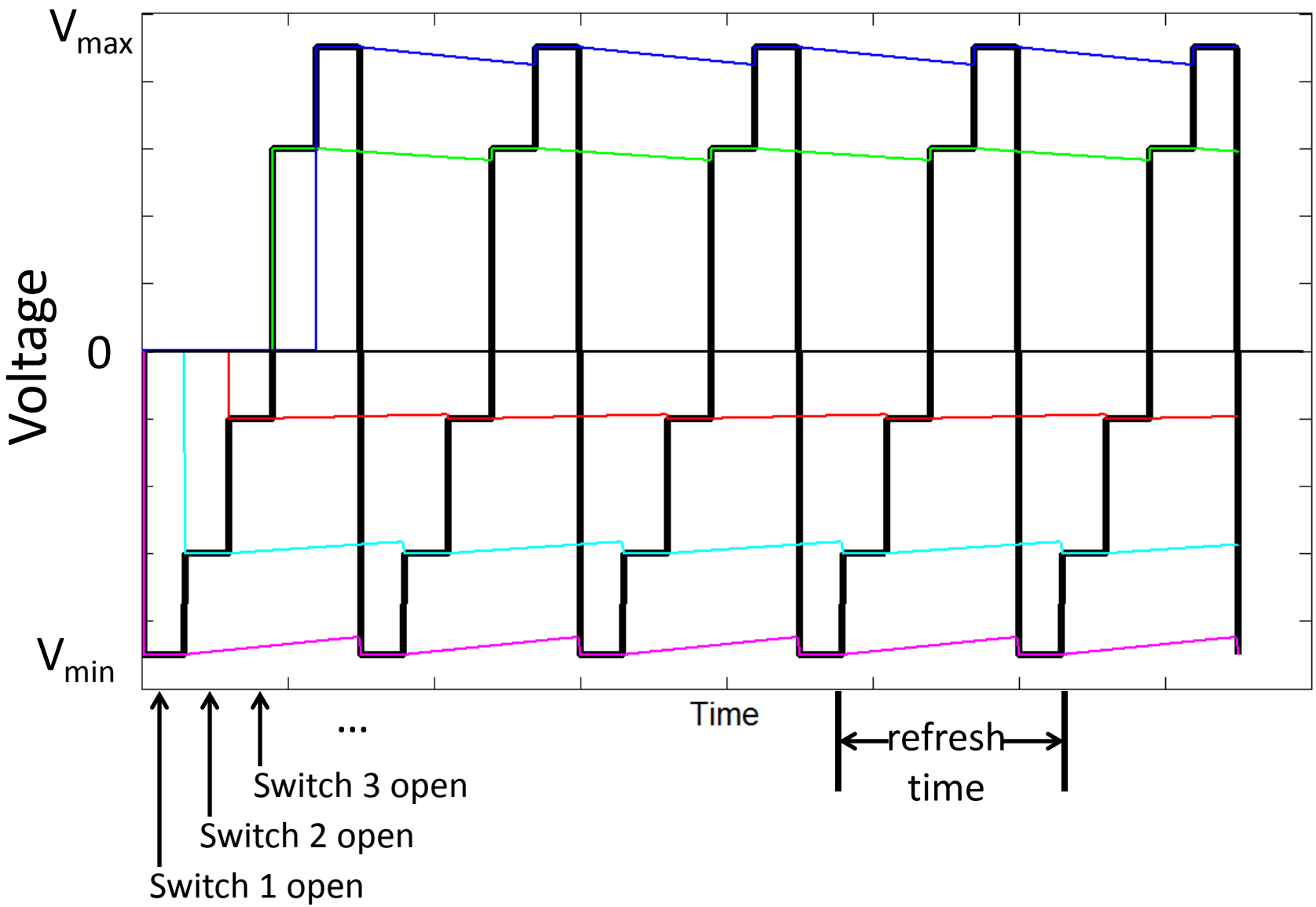




Patch vs. Bar Comparison



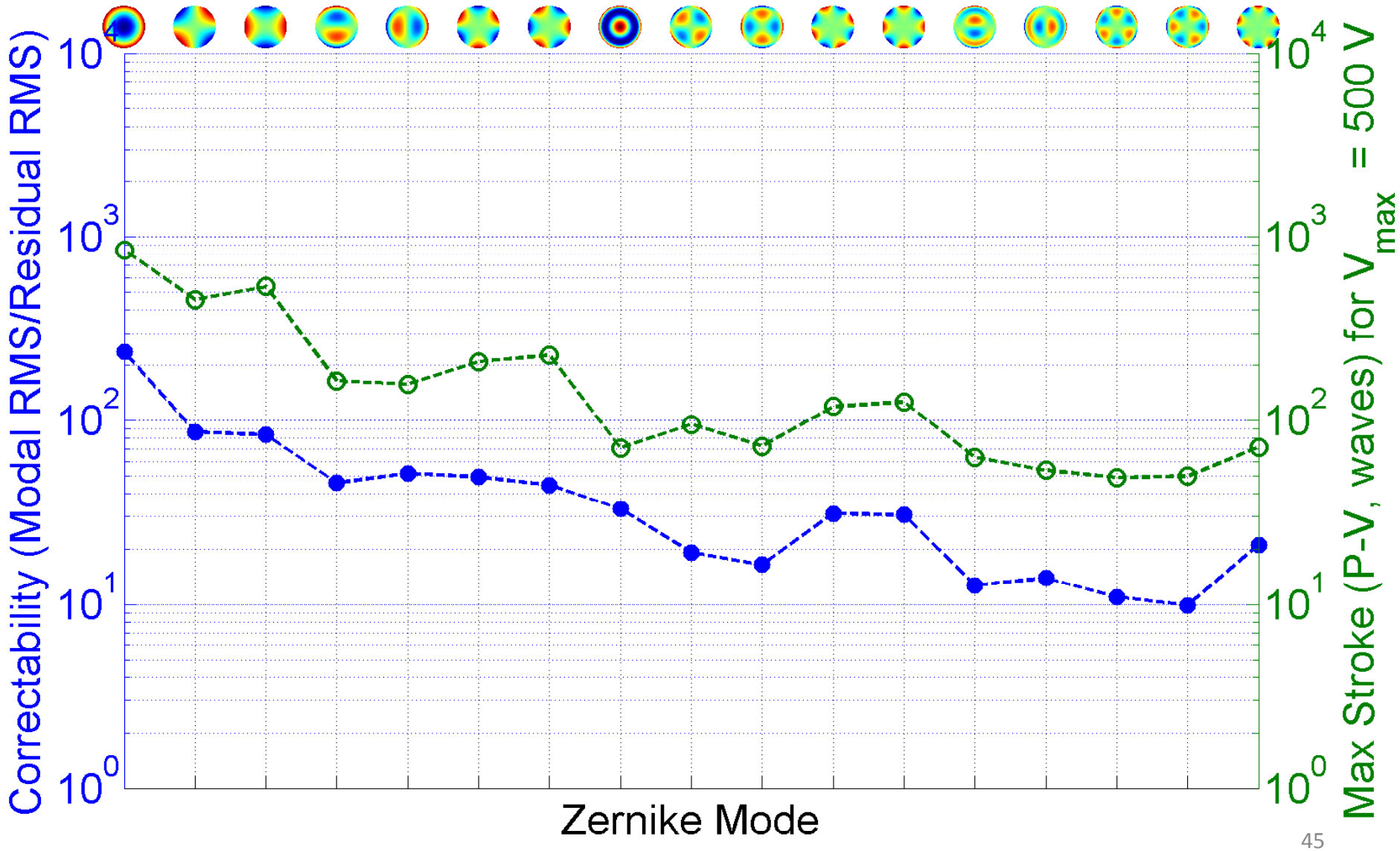
Multiplexing Concept



Process Development

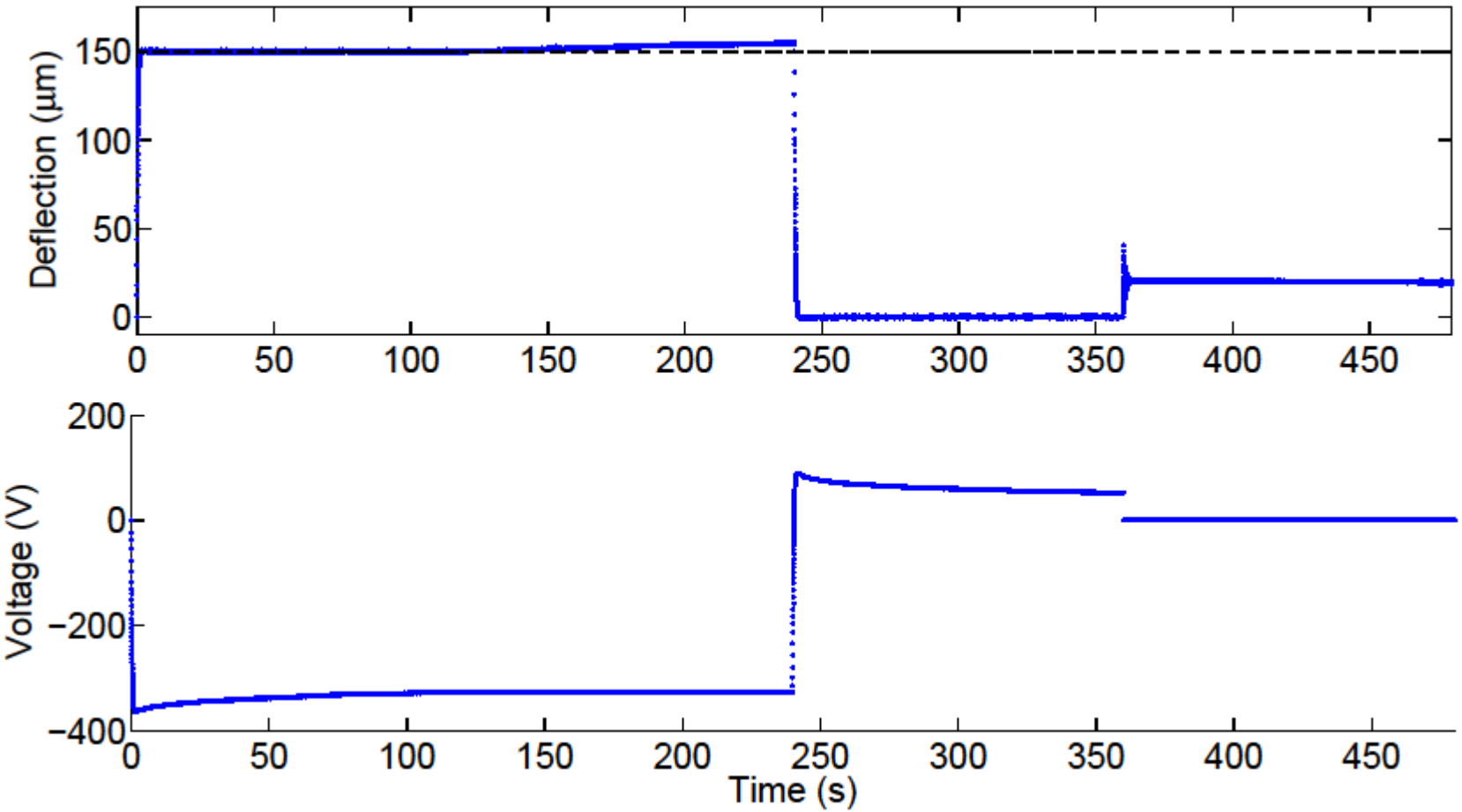
- Mirrors require high dielectric strength
  - Large voltages (1000's of Volts) applied during poling
- Need uniform layer thicknesses
- Much trial and error to improve quality
  - Interlayer adhesion
  - Polymer thermal damage
  - Metal thermal stress cracking
  - Voids, bubbles, defects, contaminants

Predicted General Performance (Free Film)



PVDF Behavior

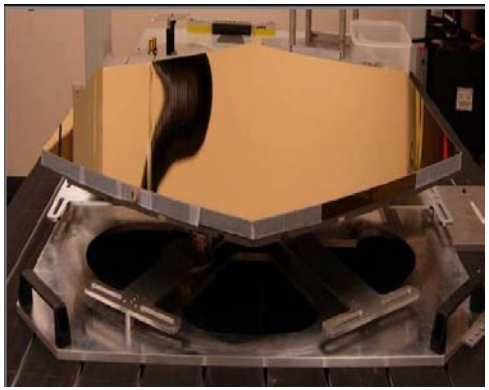
- Viscoelastic relaxation under voltage



- Low leakage current, can hold charge on the order of minutes

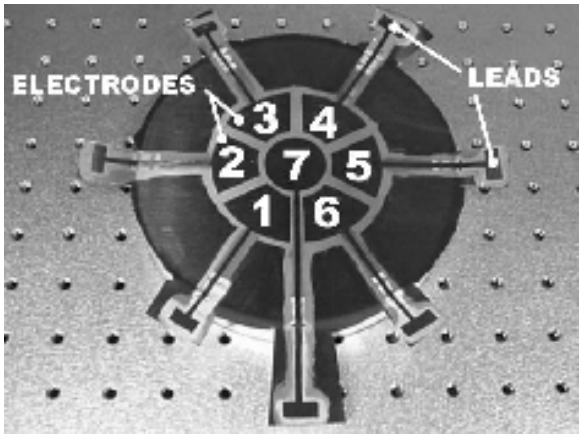
Related Work

Xinetics/JPL/LLNL
(Ealey, Hickey, Barbee, Redding)



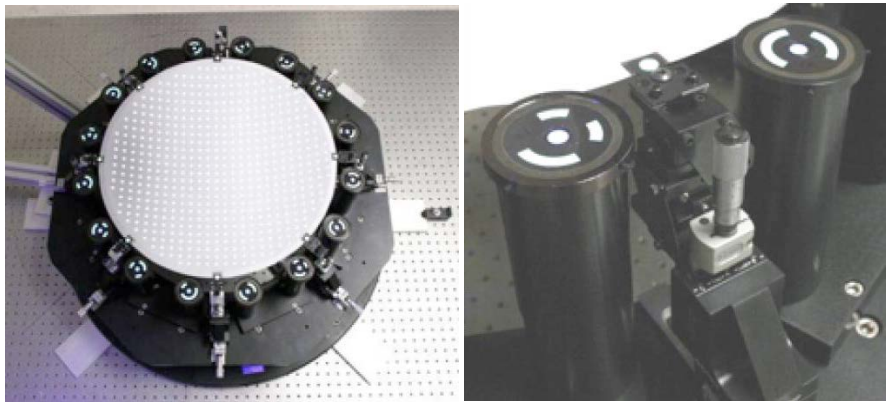
Thin facesheet, SiC backing structure with embedded ceramic actuators

Air Force (Sobers, Agnes, Mollenhauer)



Tensioned PVDF mirror with bonded electrodes

Mevicon (Lindler, Flint)



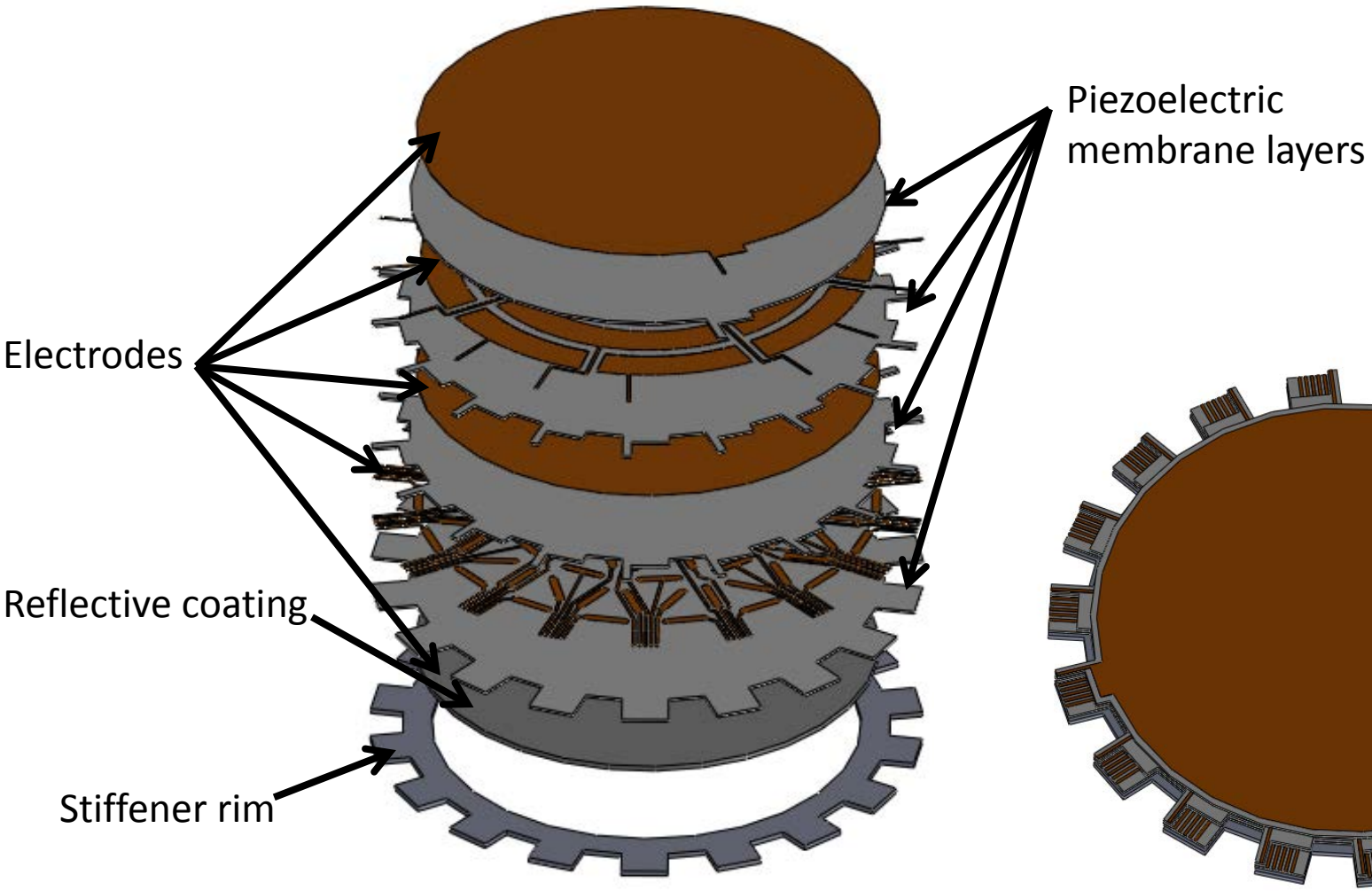
Edge actuation

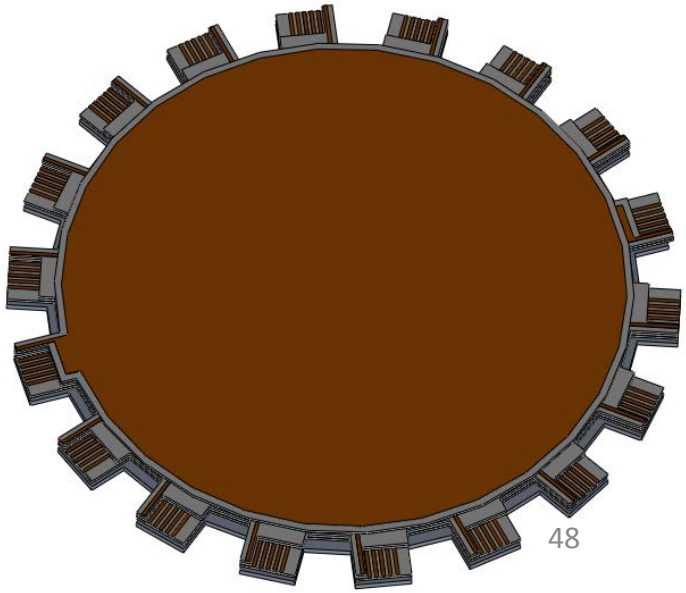
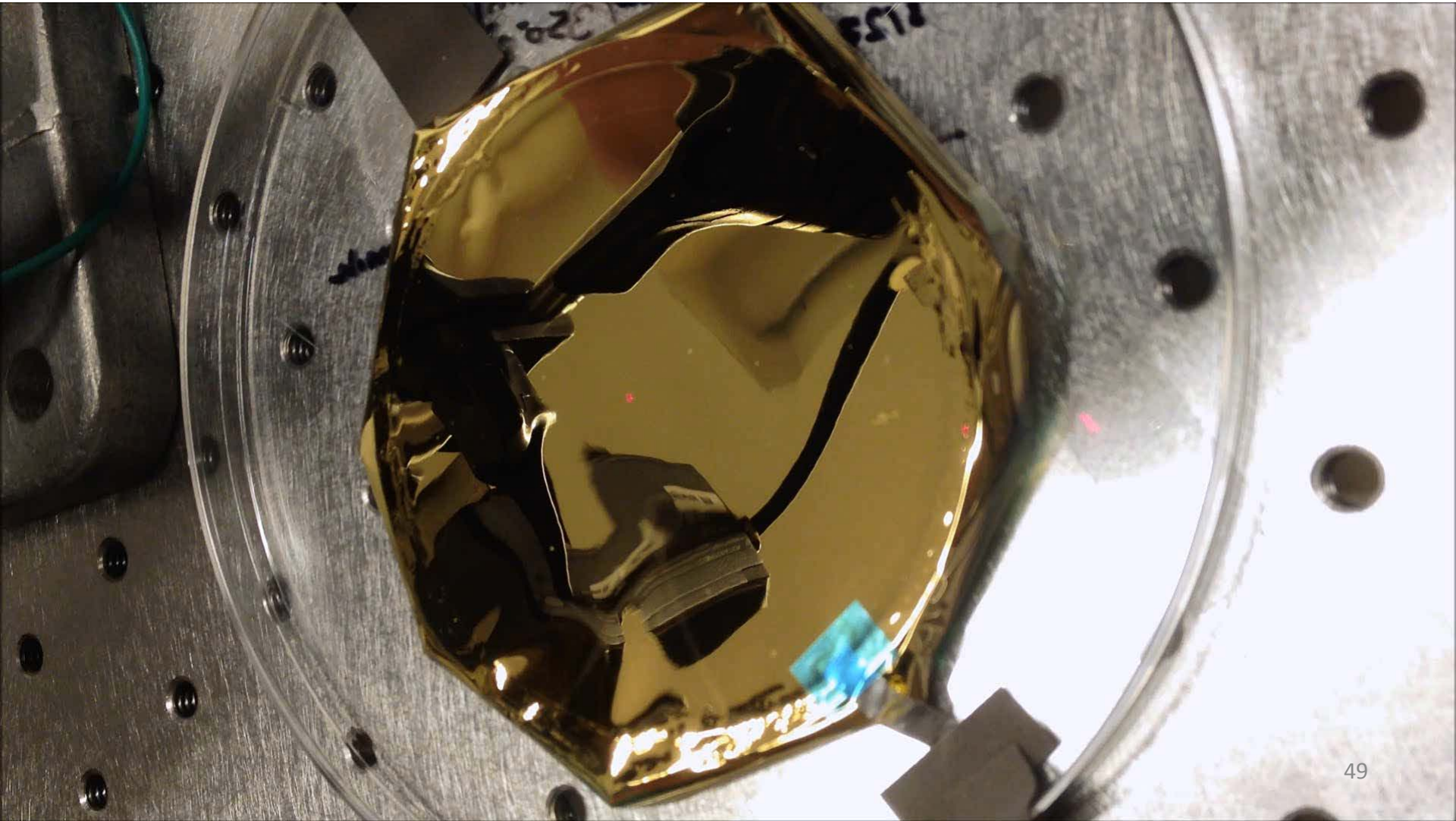
Mantech/JPL (Pearson, Moore, Fang)

Self-tensioning PVDF film

Mirror Design

- Alternating layers of electrodes and active material
- 90 (fine pattern) + 16 (coarse pattern) channels





Poling Process Video (Freestanding Film)