MEMS Deformable Mirror Technology for Exoplanet Imaging Instrumentation

Exoplanet Imaging and Characterization: Coherent Differential Imaging and Signal Detection Statistics - Part 2
December 5 - 8, 2016
California Institute of Technology - Pasadena, CA 91125

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Outline

- BMC DM Technology
- Mirror technology programs
- Space qualification programs
- DMs in telescopes
  - Ground
  - Space
- Next steps for scaling DM actuator count

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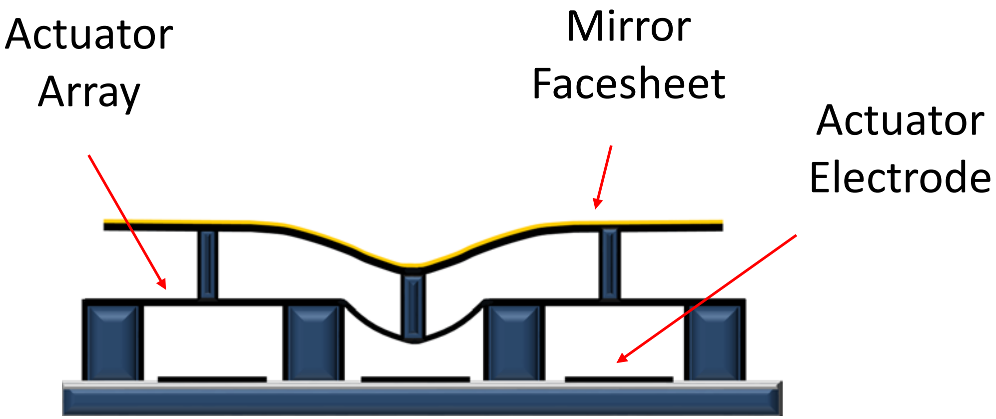
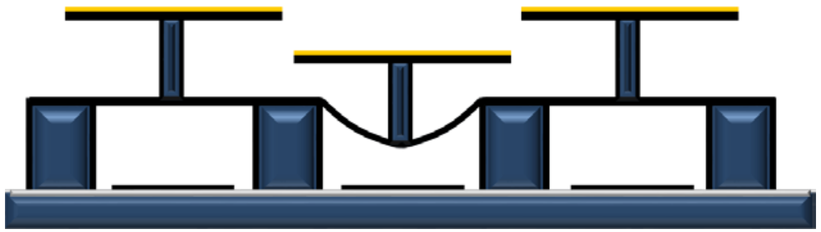
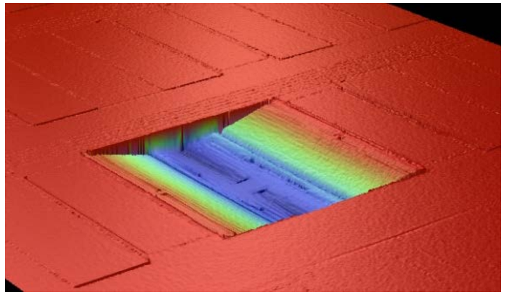
MEMS DM Architecture



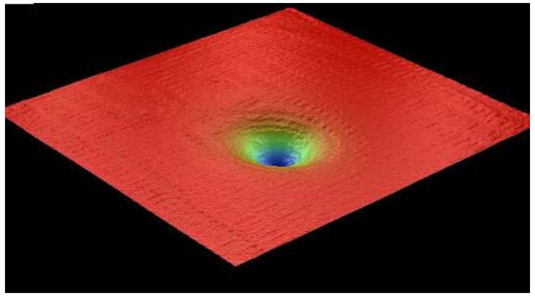
Continuous mirror
(smooth phase control)



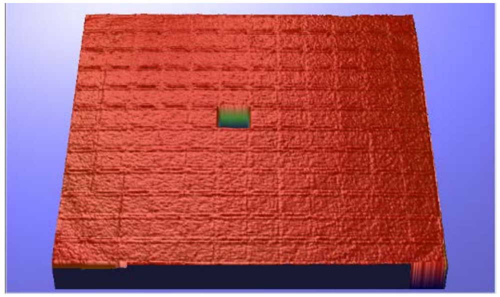
Segmented mirror
(uncoupled control)



Deflected Actuator



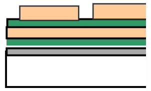
Deformed Mirror Membrane



Deformed Segmented Mirror

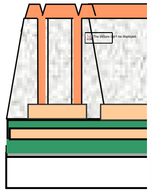
MEMS DM Fabrication

(deposit, pattern, etch, repeat)

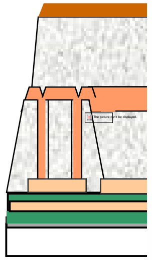


El

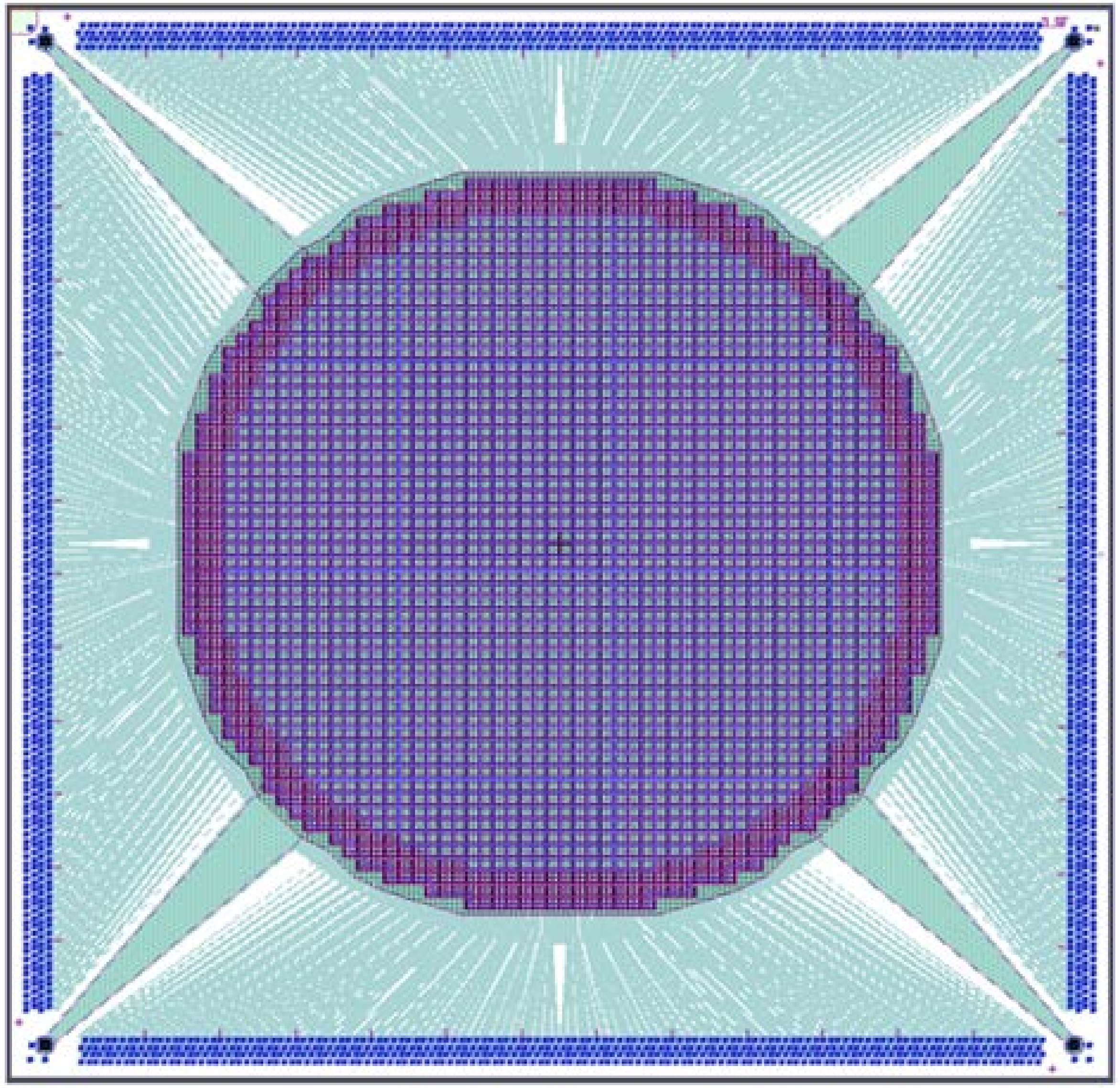
polysilicon (co

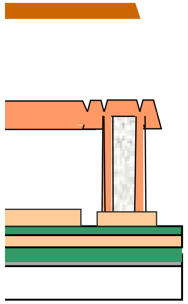


oxide (sacrific



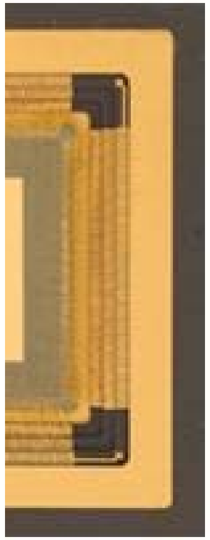
oxide (s





es in HF, and

oating

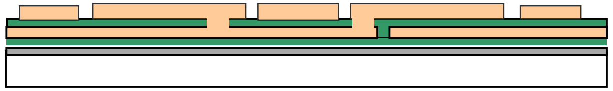


package and

wirebond

MEMS DM Fabrication

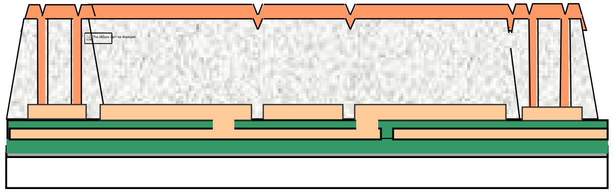
(deposit, pattern, etch, repeat)



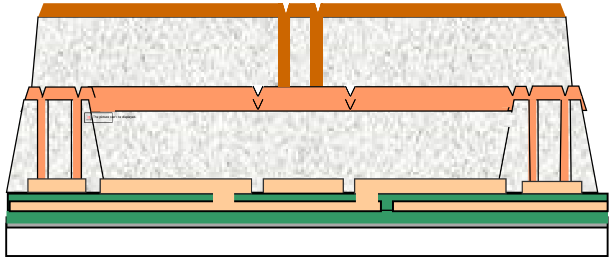
Electrodes & wire traces:
polysilicon (conductor) & silicon nitride (insulator)

Ground 8µm

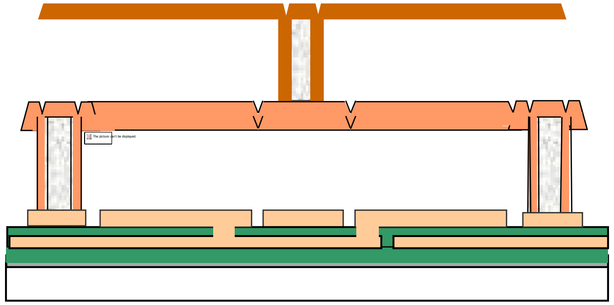
Space 5µm



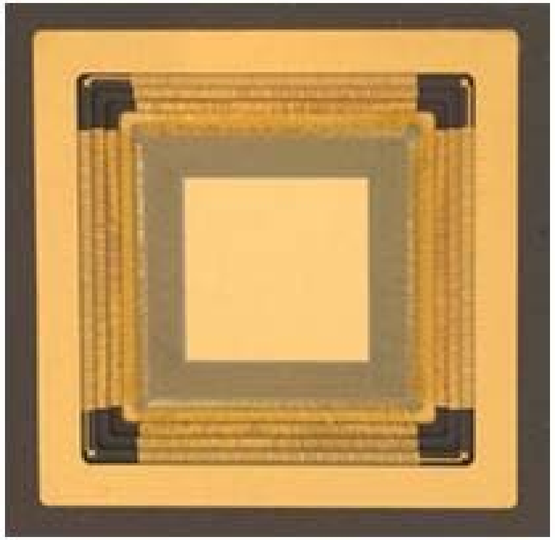
Actuator array:
oxide (sacrificial spacer) and polysilicon (actuator structure)



Mirror membrane:
oxide (spacer) and polysilicon (mirror)



MEMS DM:
Etch away sacrificial oxides in HF, and deposit reflective coating



Attach die to a ceramic package and wirebond

BMC Mirror Family

Small Cartesian Arrays

- Square arrays from 32 to 140 actuators
- Strokes: 1.5µm, 3.5µm or 5.5µm

Medium Cartesian Arrays

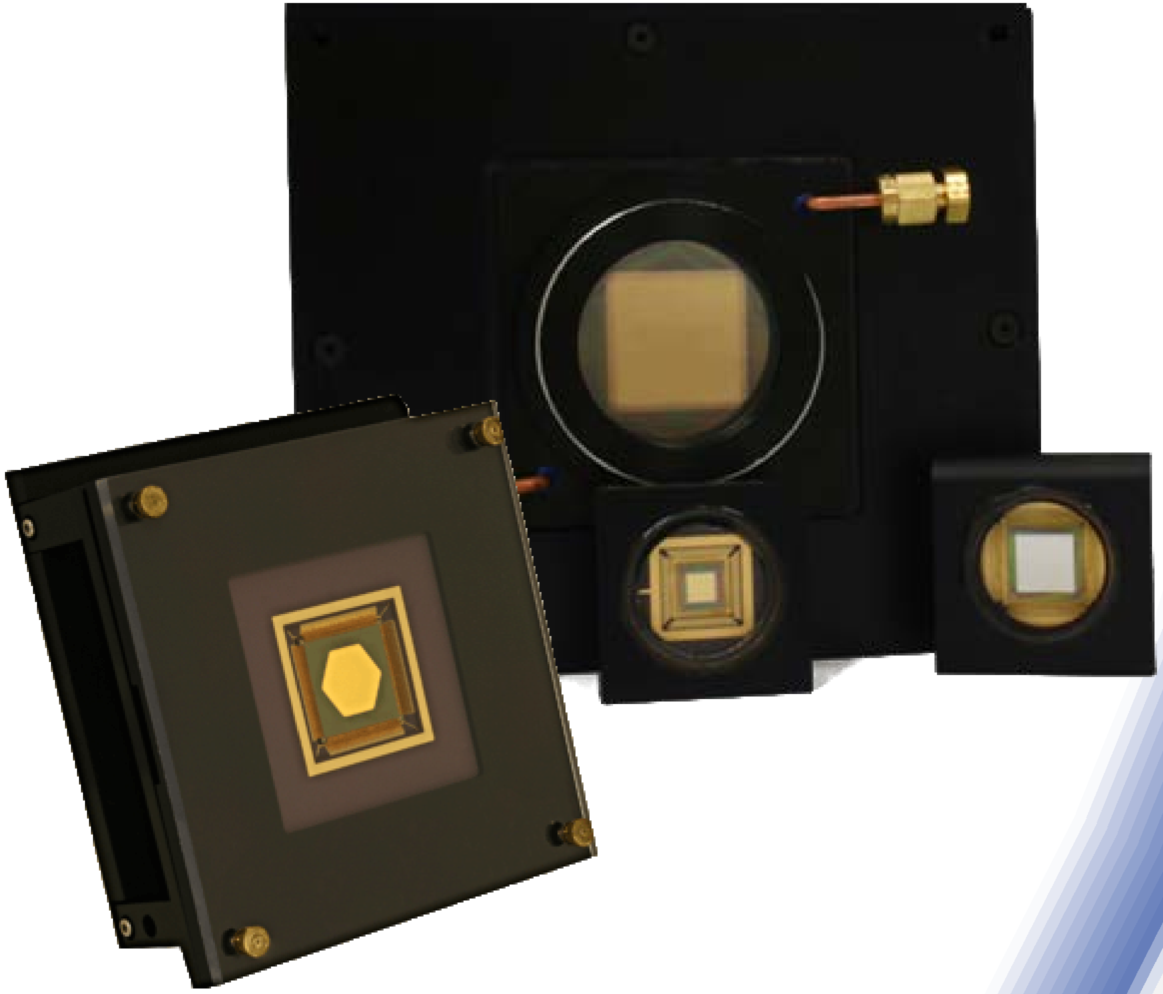
- Square and circular arrays from 492 to 1020
- 1.5µm & 3.5µm stroke

Large Cartesian Arrays

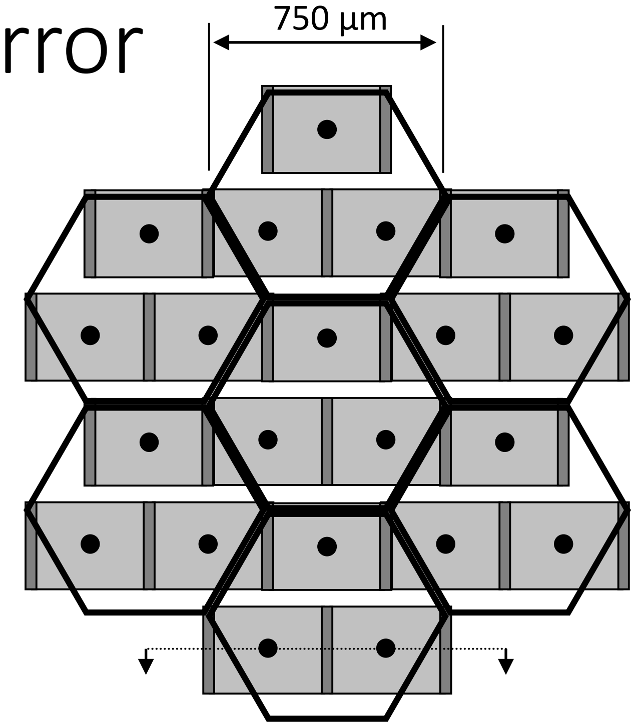
- Square and circular arrays from 2040 to 4092
- 1.5µm and 3.5µm stroke

Hex Tip-Tilt-Piston

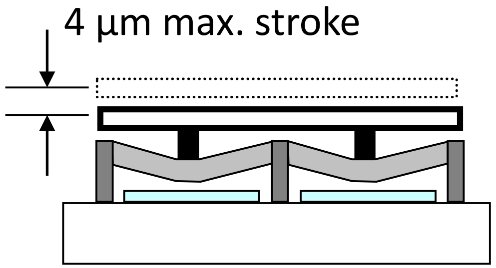
- 37, 331- and 1021-Segment Devices

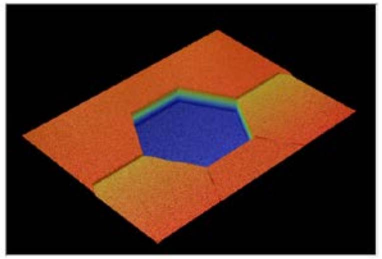


Hex Tip-Tilt-Piston Deformable Mirror

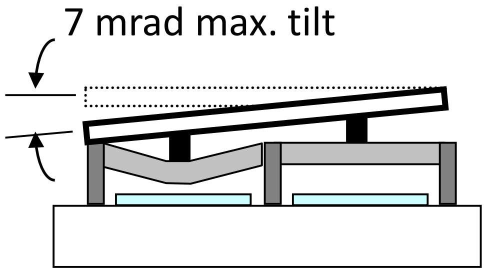


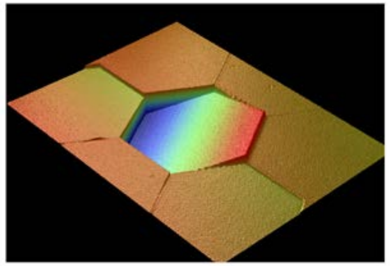
- Up to 3063 actuators
- Independent hexagonal segments
  - 3 actuators per segment





- 4 µm max. stroke
- 7 mrad max. tilt angle





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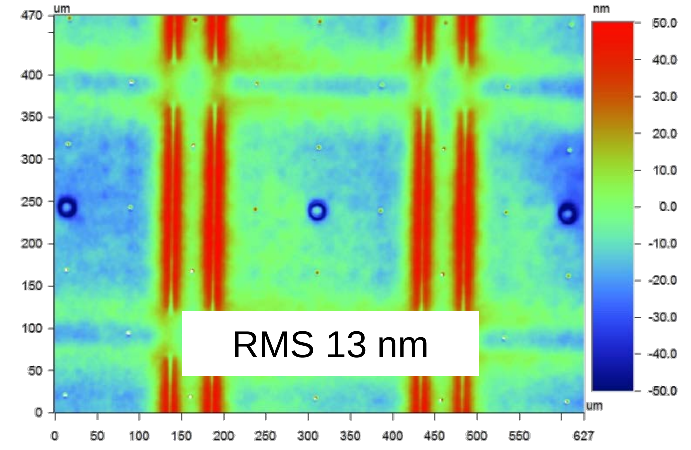
Funded Technology Research

Over the past years BMC has received funding for the improvement of MEMS DM for space applications

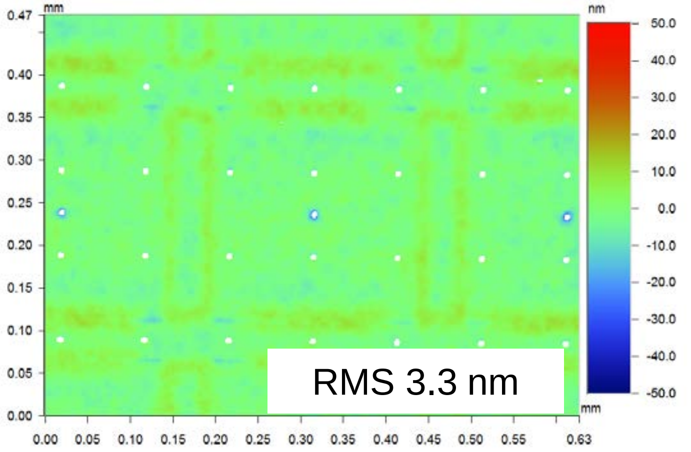
- Topography
- Yield
- Reliability
- Reduced operating voltage
- Hex TTP development

Topography Improvements

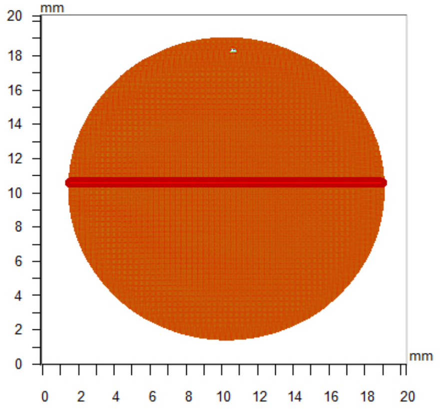
Heritage Process

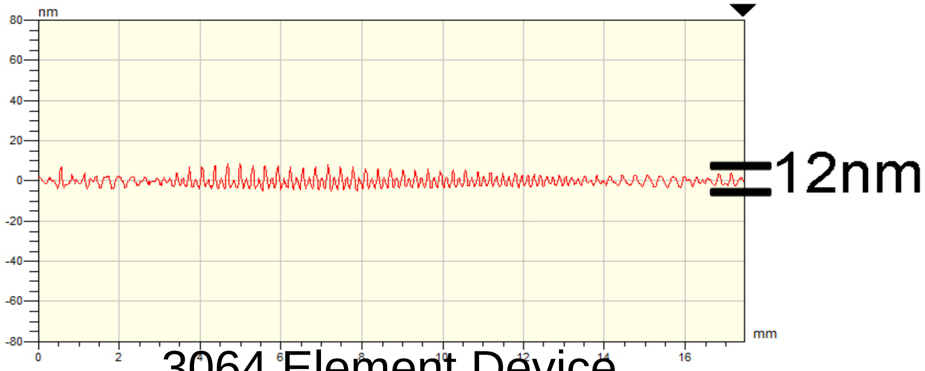


Modified Process

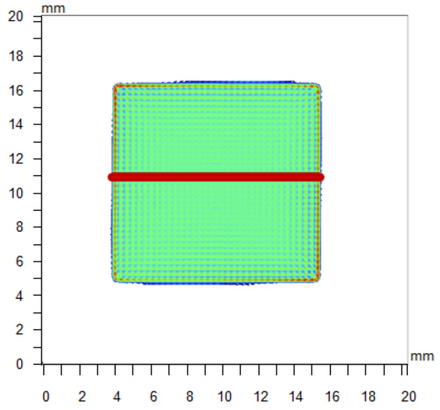


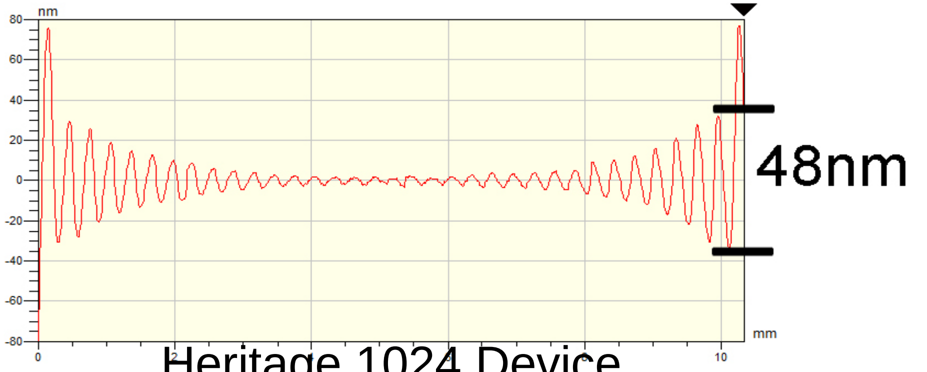
Scalloping across mirror compared to heritage devices





3064 Element Device

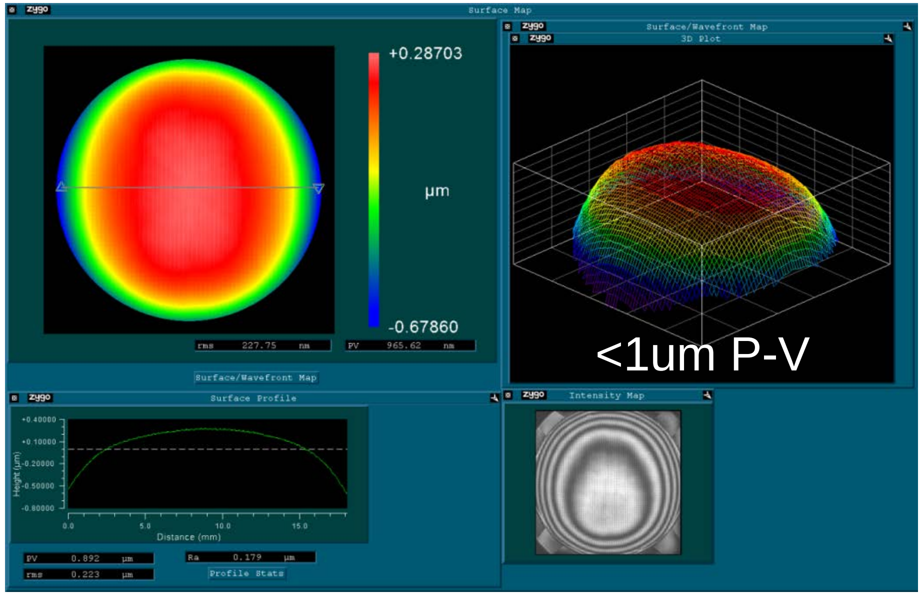




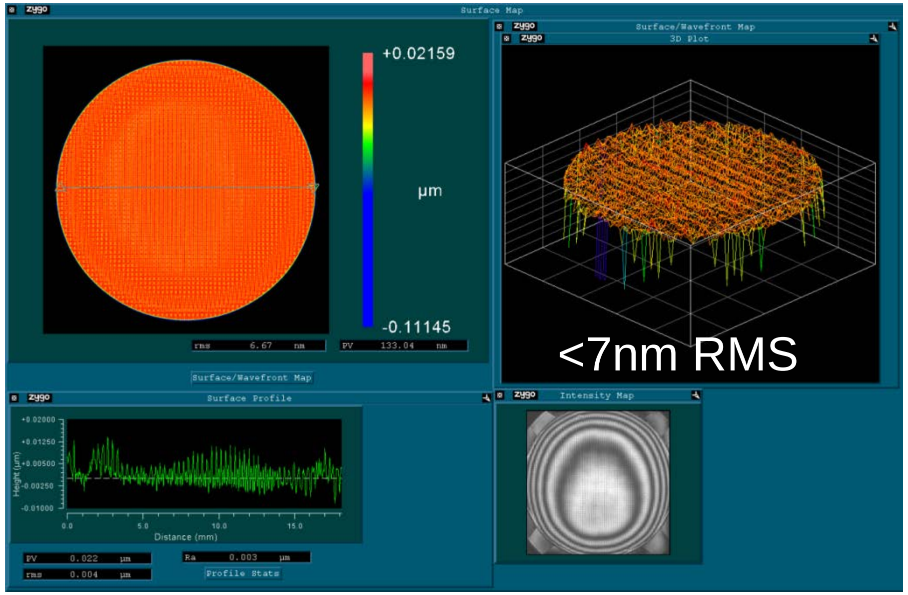
Heritage 1024 Device

Note 3064 aperture is 17mm while heritage is 10mm

Topography Improvements

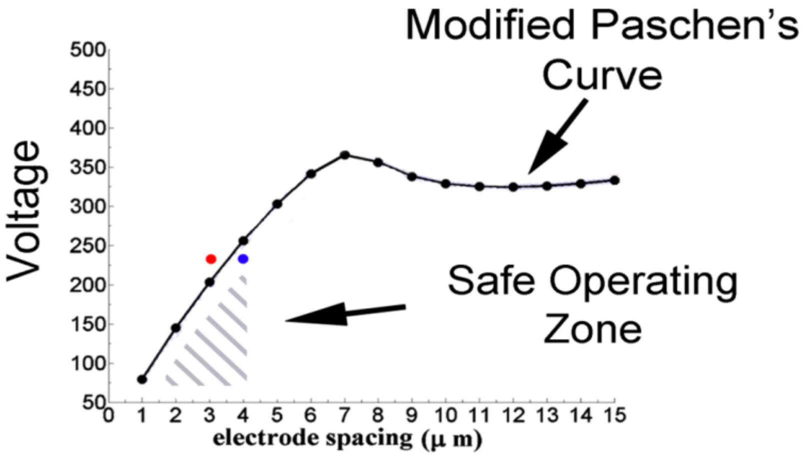


Unpowered Surface



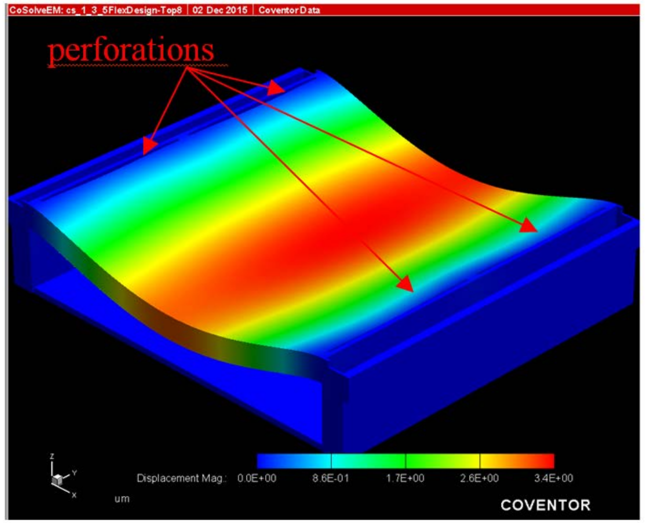
With low order filtered
(control bandwidth)

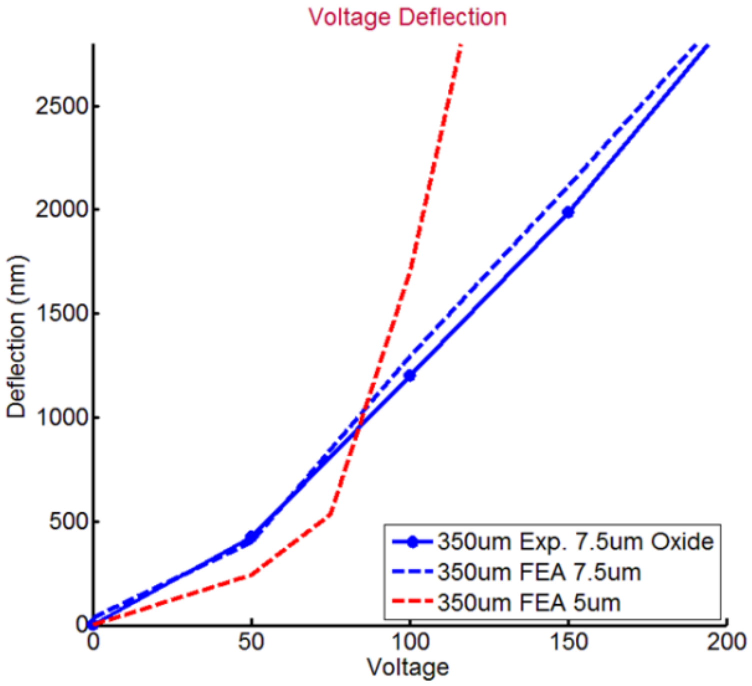
Reduction in Operating Voltage (Ongoing)



Reduced Operating Voltage

- Lower power usage
- Easier electronics
- Safer operation

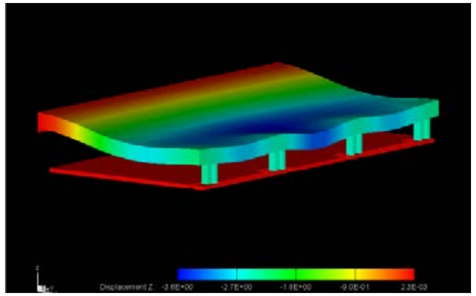


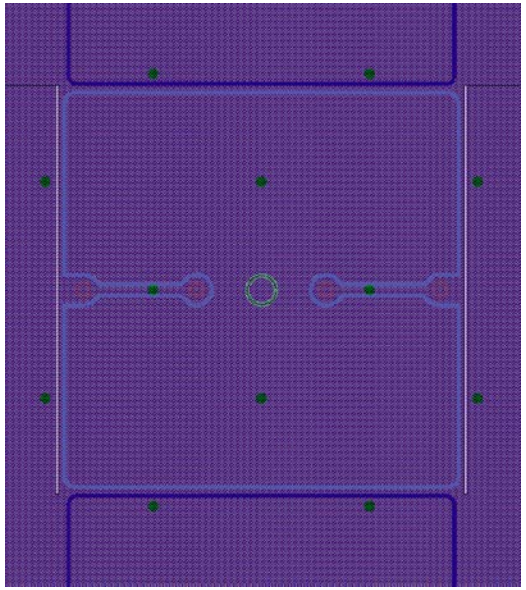


Modified design allows full actuation at lower voltage

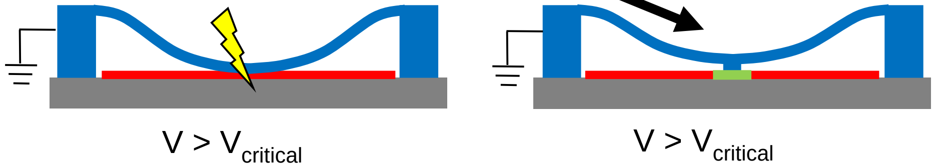
Enhanced Reliability Concept

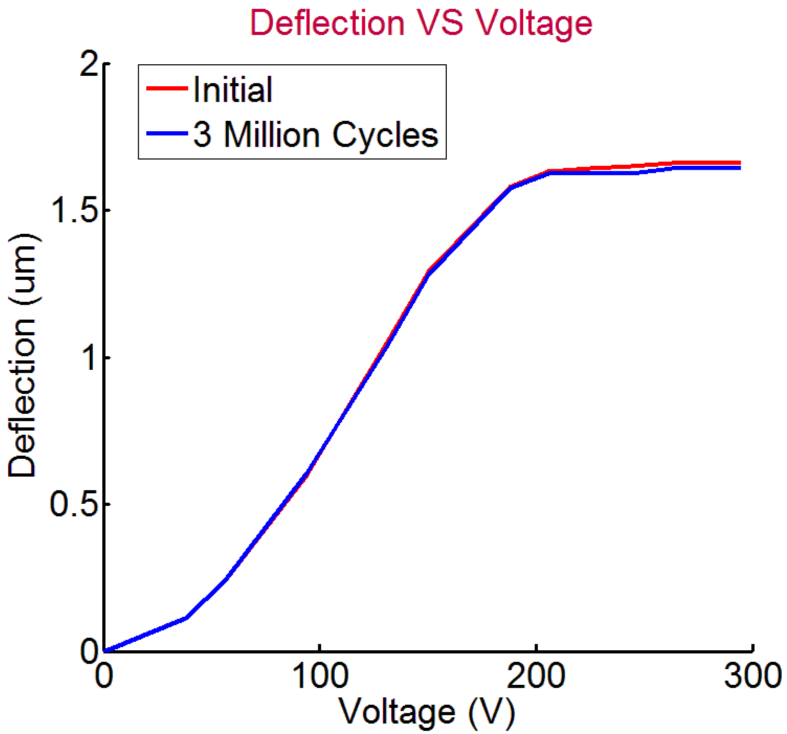
"Hard Stops"





Enhanced Reliability Actuator Design





Deflection versus voltage. Initial, after cycling 3 million times above critical voltage (295V).

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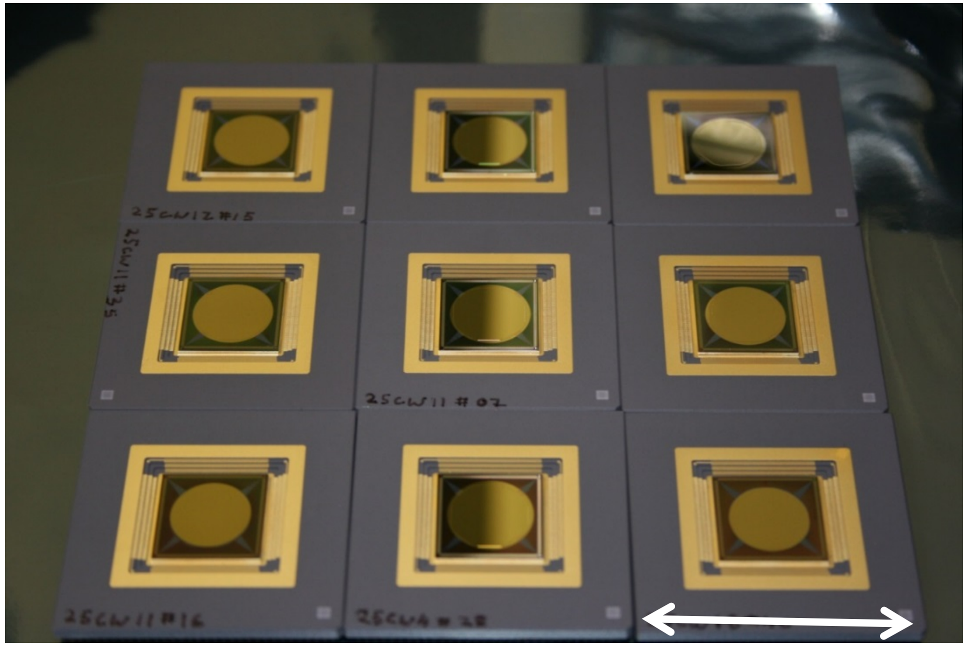
TDEM Program

Ongoing Contract#: NNH12CQ27C
TDEM/ROSES
MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection

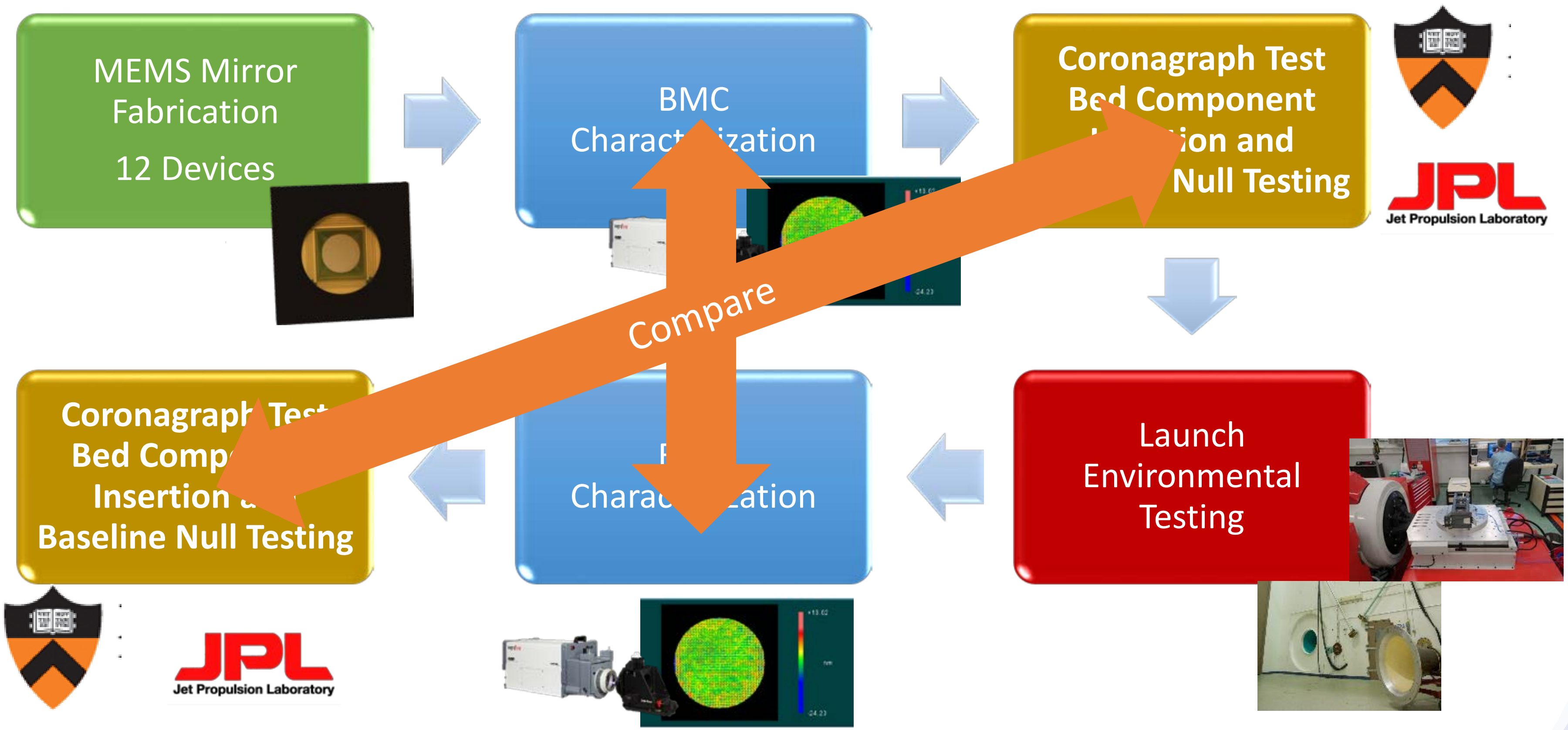
Objective: Demonstrate survivability of the BMC MEMS Deformable Mirror after exposure to dynamic mechanical environments close to those expected in space based coronagraph launch.

9 Mirrors ready for testing



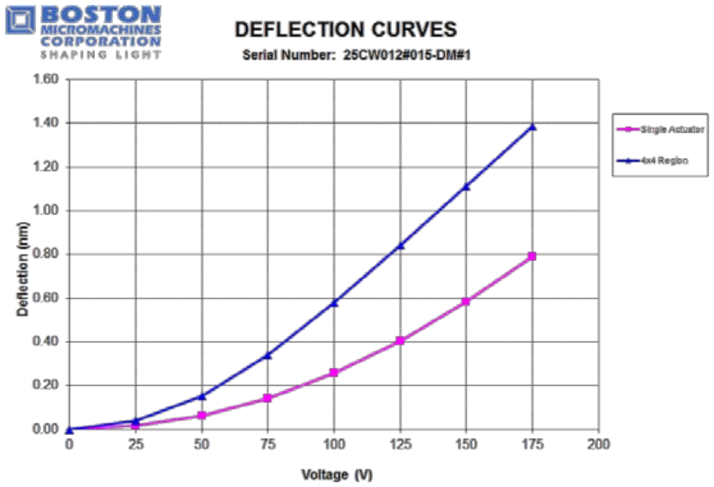
5cm

Project Flow

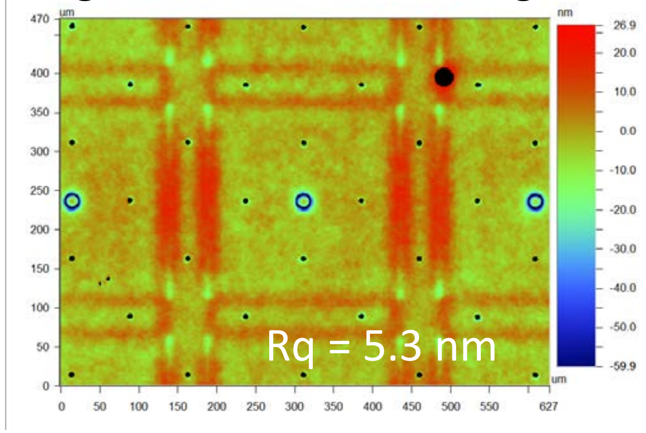


12 DMs Fabricated and Characterized

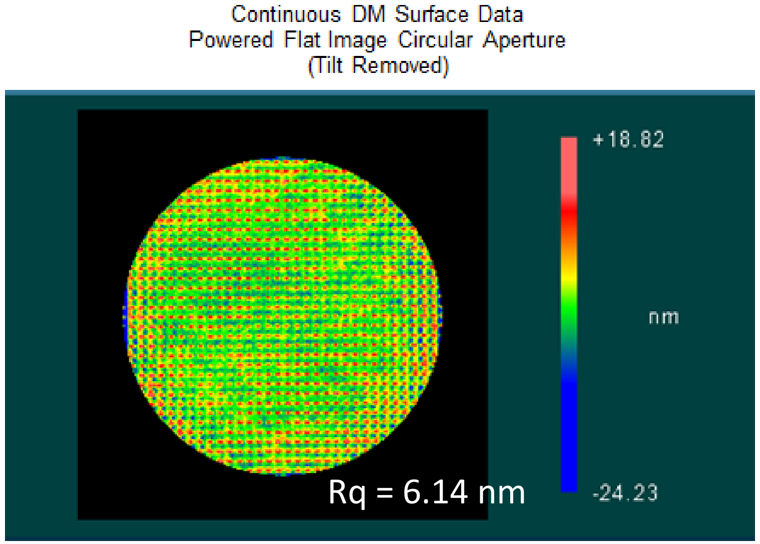
Voltage v. Deflection



Single Actuator Surface Figure

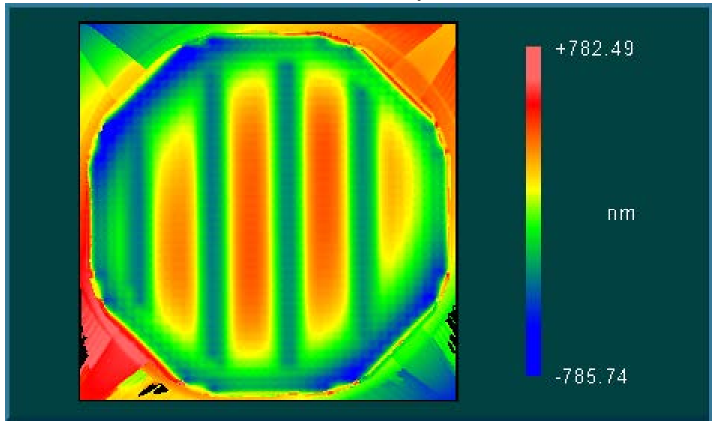


Active Flattening of DM Surface



Sinusoid Shape

4 Period, 400nm Amplitude



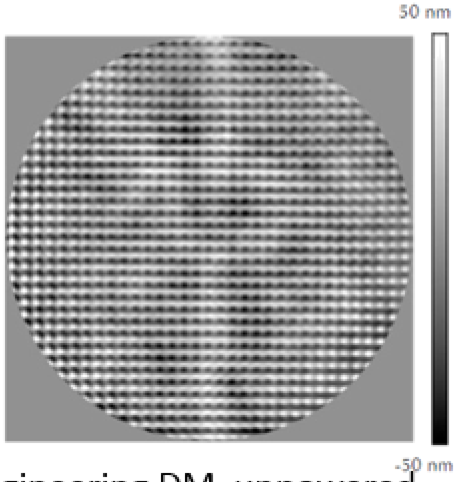
Delivered to JPL (2) and Princeton (2)

Vacuum Surface Gauge (VSG) Measurements

Two 952 a
separatel

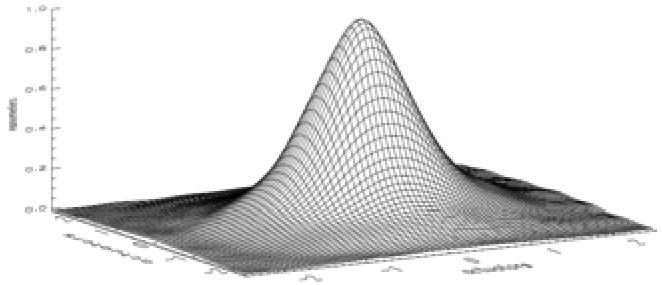
- Surface fi
- Surface fi
- Actuator
  up/down
  condition
- Drift in su
  period
- Repeatab
  for 10 repeats

Initial Testing Results



BMC Engineering DM, unpowered –

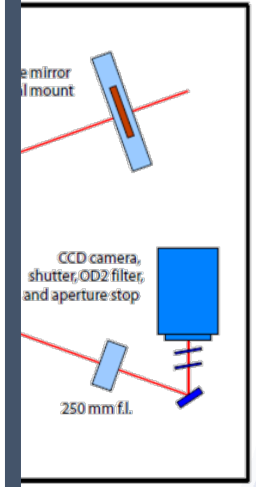
- Zernike fit to the central actuators to the diameter = 34 actuators
- 37 zernikes removed
- Residual high order surface beyond z37 = 18nm rms = 130 PV



Influence Function Measurements, BMC DM1

- Average of 20 individual pokes, 42 volt pokes over 50 volt bias

John Trauger, Frank Greer
9/30/2016



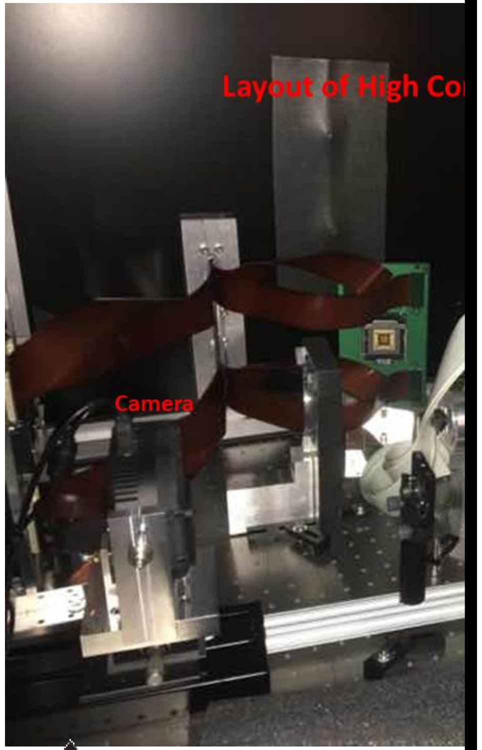
s. Beam height = 4.405 inches.

mounted in
r
HeNe laser
ezo-driven

- Deformable mirror under test is on a gimbal mount with a temperature controlled stage

High Con

K



Recent Lab Results

- Stroke minimization controller
- Two BMC DMs with 952 actuators on each
- Achieved 3 x 10^{-7} contrast within 30 iterations 5.5-10.5 λ/D

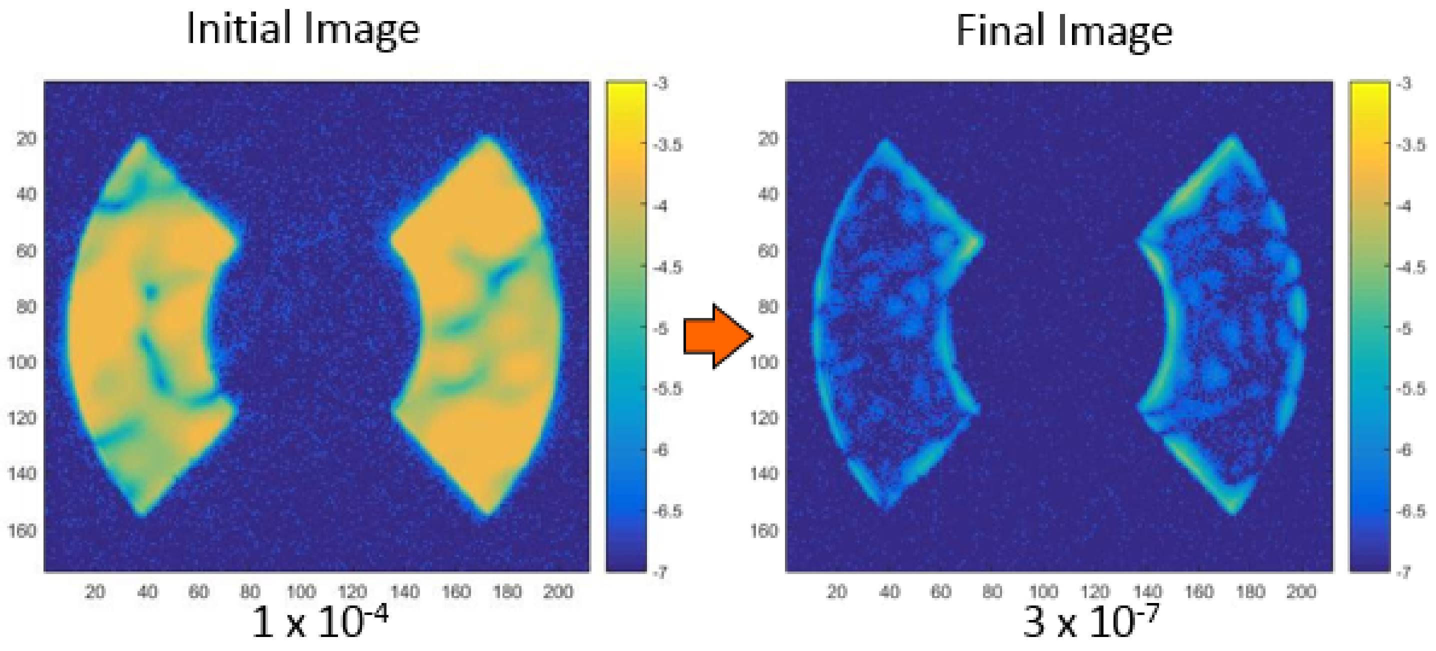
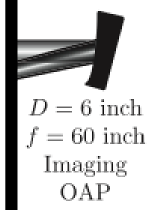


Image Credit:
Groff & Kasdin 2013



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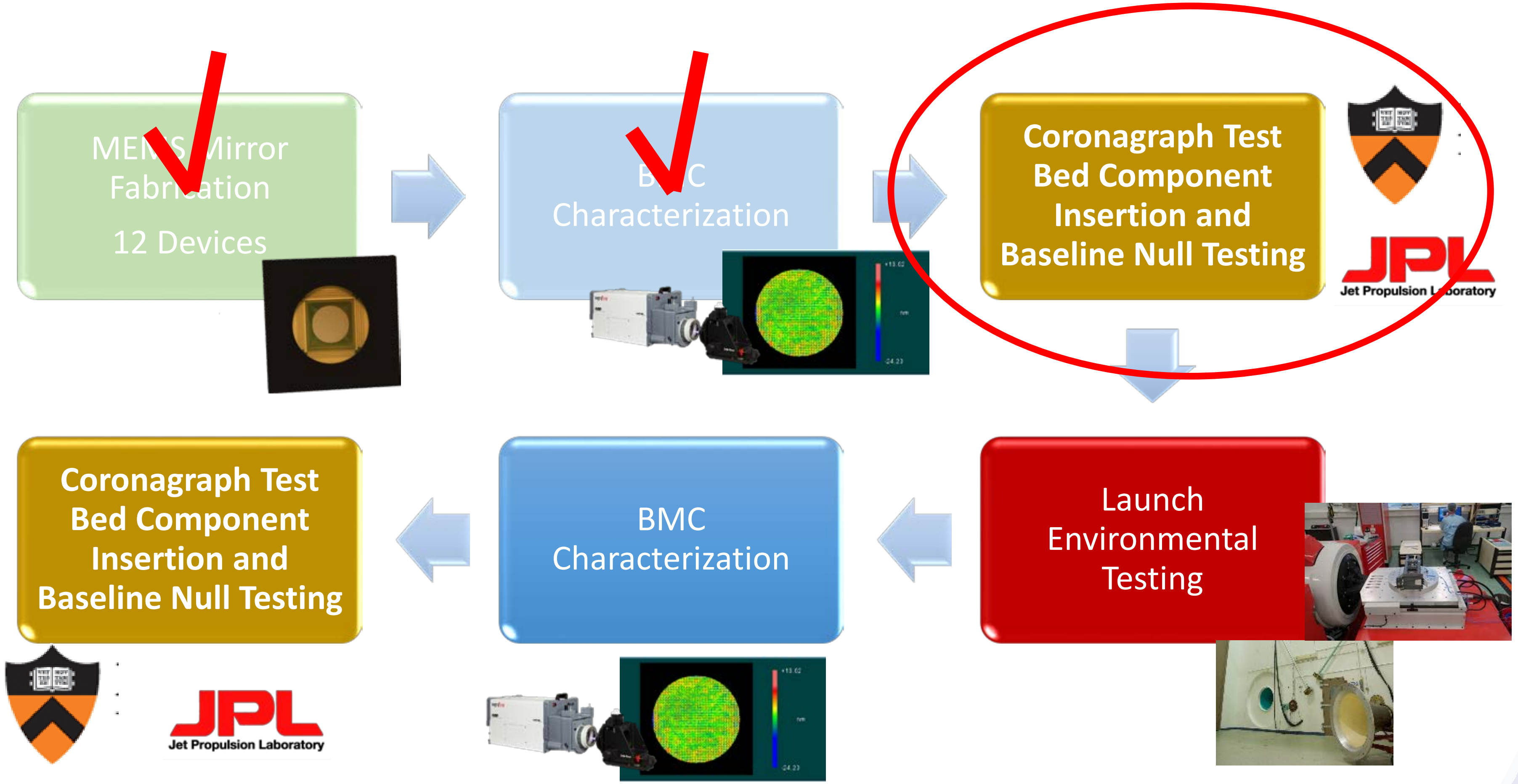
Project Flow



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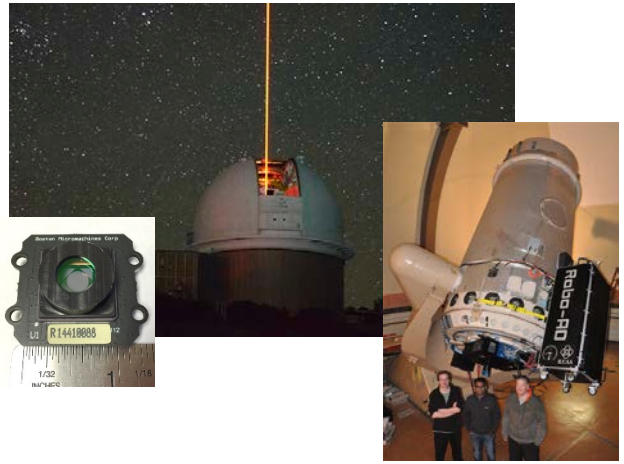
On-Sky Instruments using BMC Mirrors

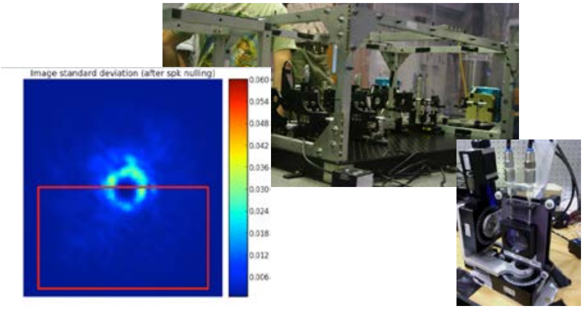
ROBO-AO

- Multi-DM Installed Palomar 2011/ Moved to Kitt Peak 2015



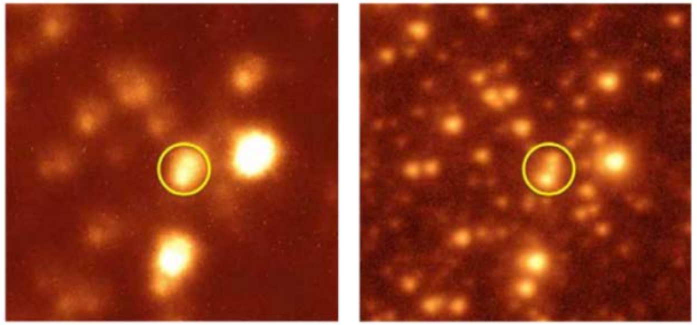
SCExAO, Subaru telescope

- 2040 installed 2013

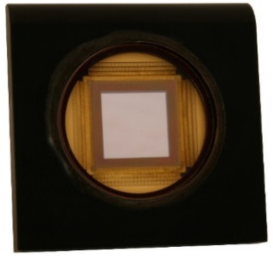


Shane-AO, Lick Observatory

- Kilo-DM installed 2013
- Visible Light Laser Guidestar Experiments



Shane AO off Shane AO on

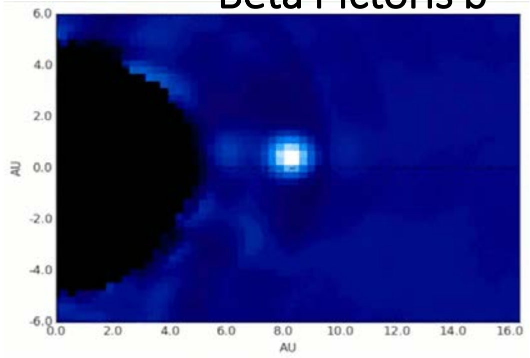


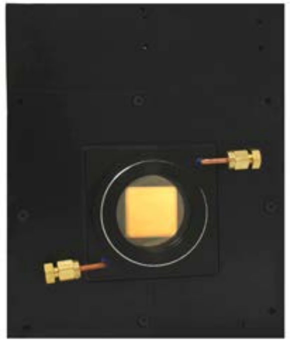
Portion of the M92 globular cluster taken in H band.

Gemini Planet Imager, Gemini South

- 4092 installed 2013

Beta Pictoris b

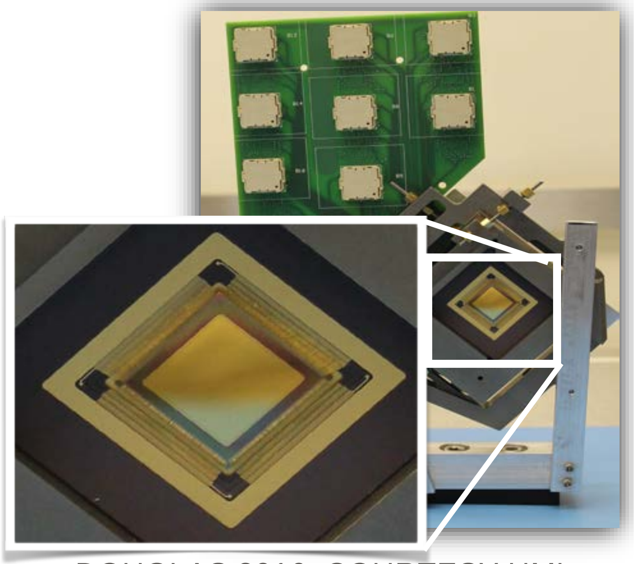




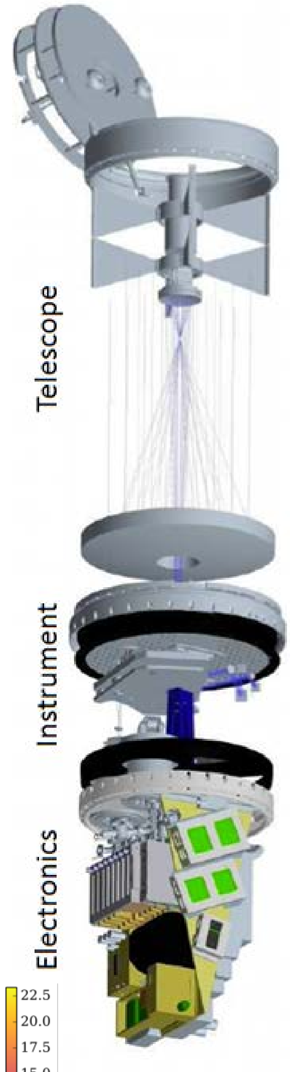
THE PICTURE(-B) SOUNDING ROCKET

PI: Supriya Chakrabarti, UMASS Lowell
November 2015

- Reflected light from Exoplanets
- Scattered Light from Exozodi
- Visible Light Coronagraphy (in space)
- Active wavefront control

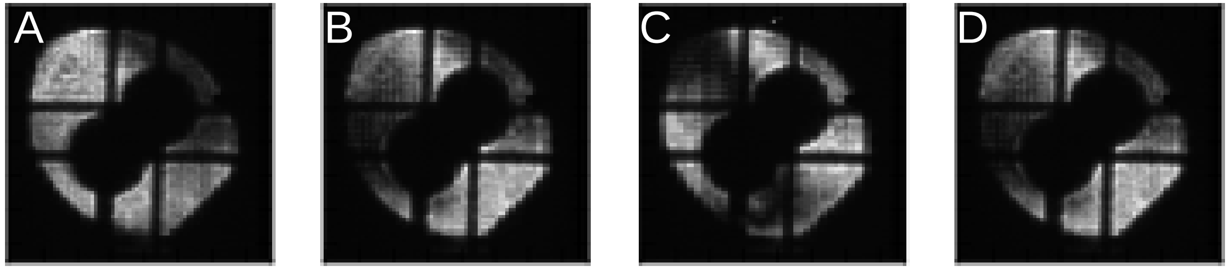


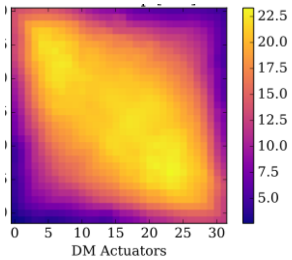
DOUGLAS 2016, COURTESY UML



The DM was powered in flight.
Deformable mirror “flat” map applied in flight to remove curvature:

Flat ***Flight*** Wavefront Sensor Measurements of Pupil Plane Fringes:





DOUGLAS 2016

Cubesat: Deformable Mirror Demonstration Mission (DeMi)

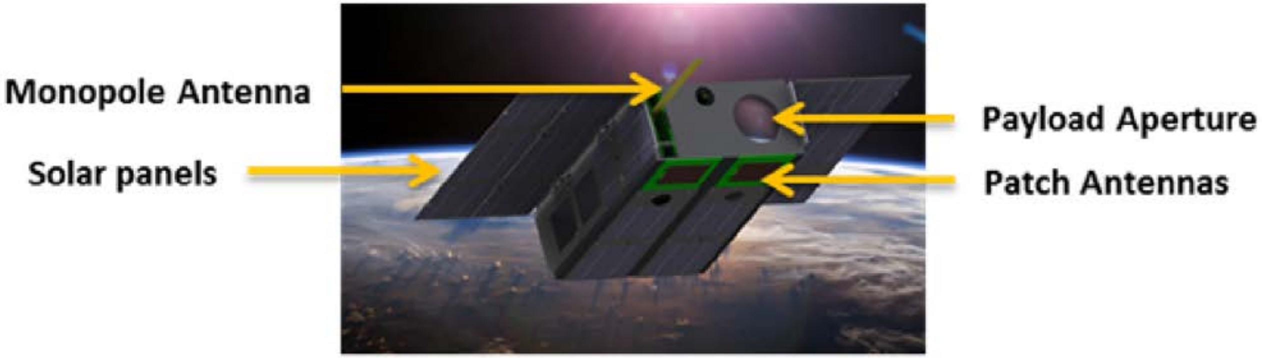
PI: John Merk, Aurora Flight Systems, Keri Kahoy, MIT

- Validate and demonstrate the capabilities of high actuator count MEMS deformable mirrors for high contrast astronomical imaging.
- Characterize MEMS deformable mirror operation using both a Shack Hartmann wavefront sensor as well as sensorless wavefront control.

Aurora FLIGHT SCIENCES

MIT STAR Lab

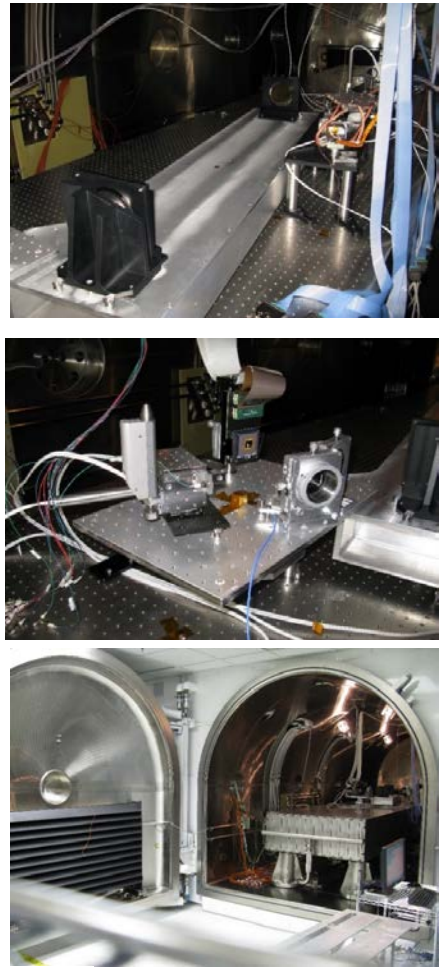
Space Telecommunications, Astronomy, and Radiation Lab



Proposed mission configuration

EXoplanetary Circumstellar Environments and Disk Explorer (EXCEDE)

Final Broadband Milestone Results



Lockheed Martin Vacuum Chamber

λ_0 = 650nm, Bandwidth = 10%

- Test A

  Time interval: 67 min

  1.2– 2.0 λ_0/D: 1.35×10^{-5}

  2.0–11.0 λ_0/D: 2.82×10^{-7}

- Test B

  Time interval: 816 mins

  1.2– 2.0 λ_0/D: 1.29×10^{-5}

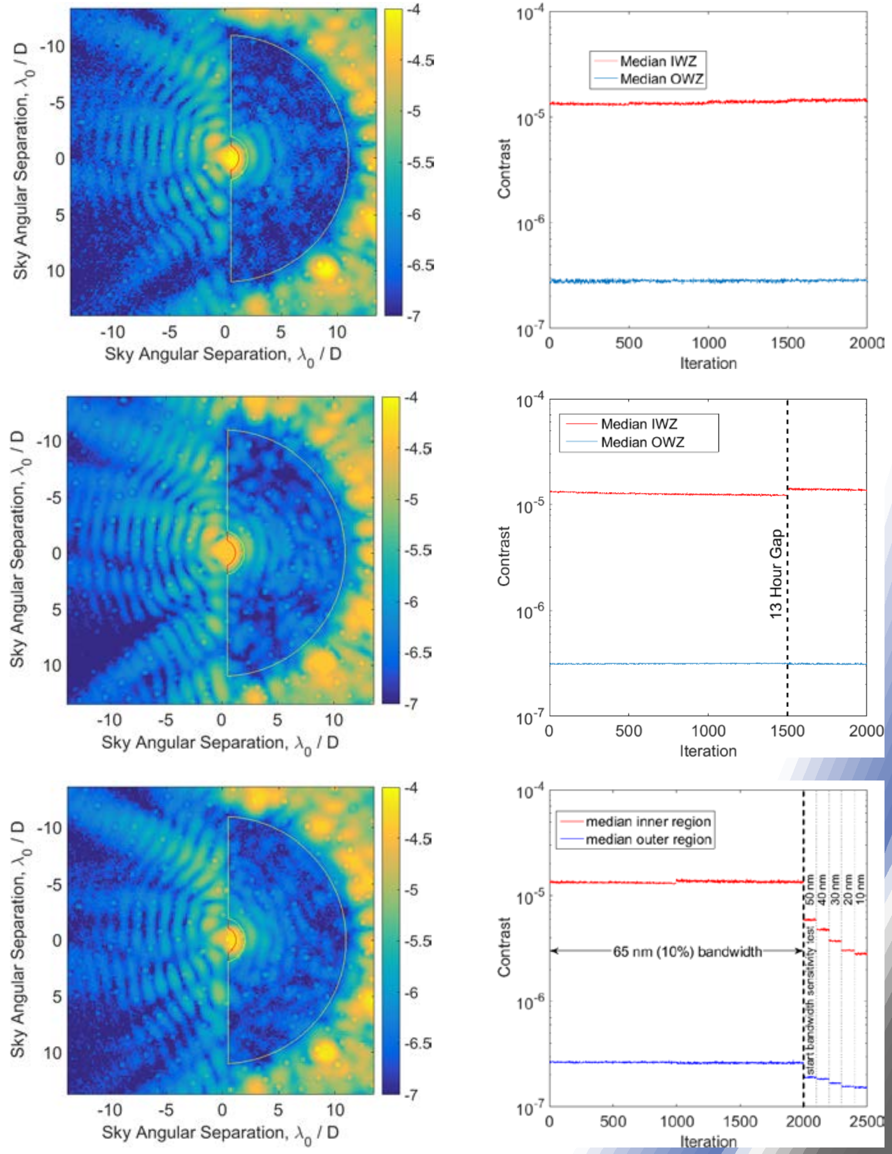
  2.0–11.0 λ_0/D: 3.14×10^{-7}

- Test C

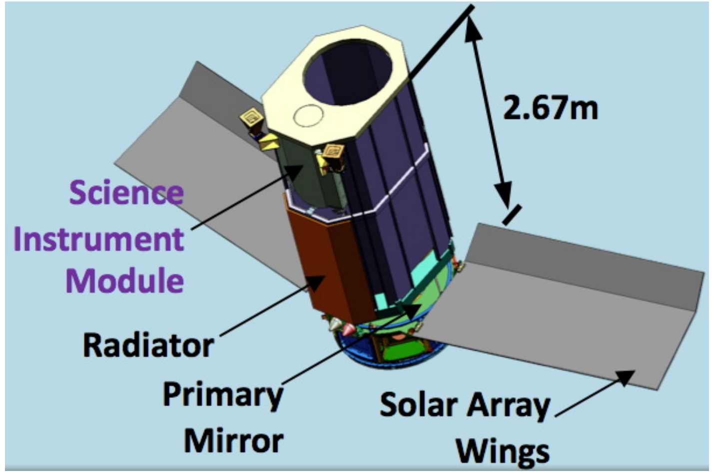
  Time interval: 61 mins

  1.2– 2.0 λ_0/D: 1.33×10^{-5}

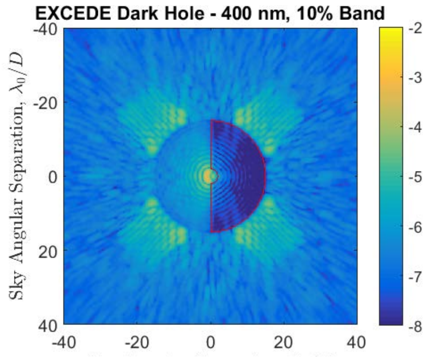
  2.0–11.0 λ_0/D: 2.63×10^{-7}



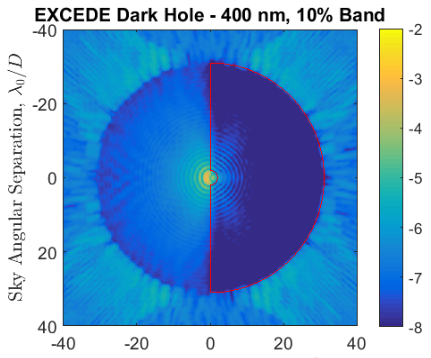
EXCEDE Proposing for the 2016 MidEX AO



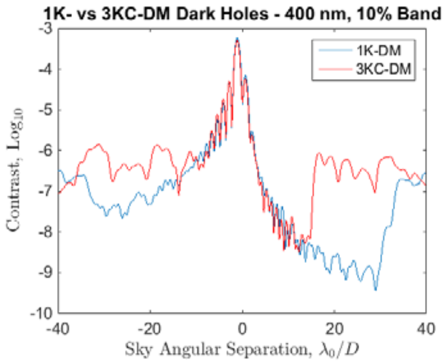
- Technical specs:
  - 0.7m primary, TMA unobstructed optical telescope
  - PIAA Coronagraph
- Mission overview
  - Survey of ~ 350 nearby exoplanetary systems
- Science Capabilities
  - Circumstellar debris systems including the habitable zone
  - Gas giants (if sufficiently bright)

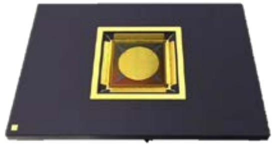


1K Boston MEMS DM
Outer Working Angle – 15 L/D



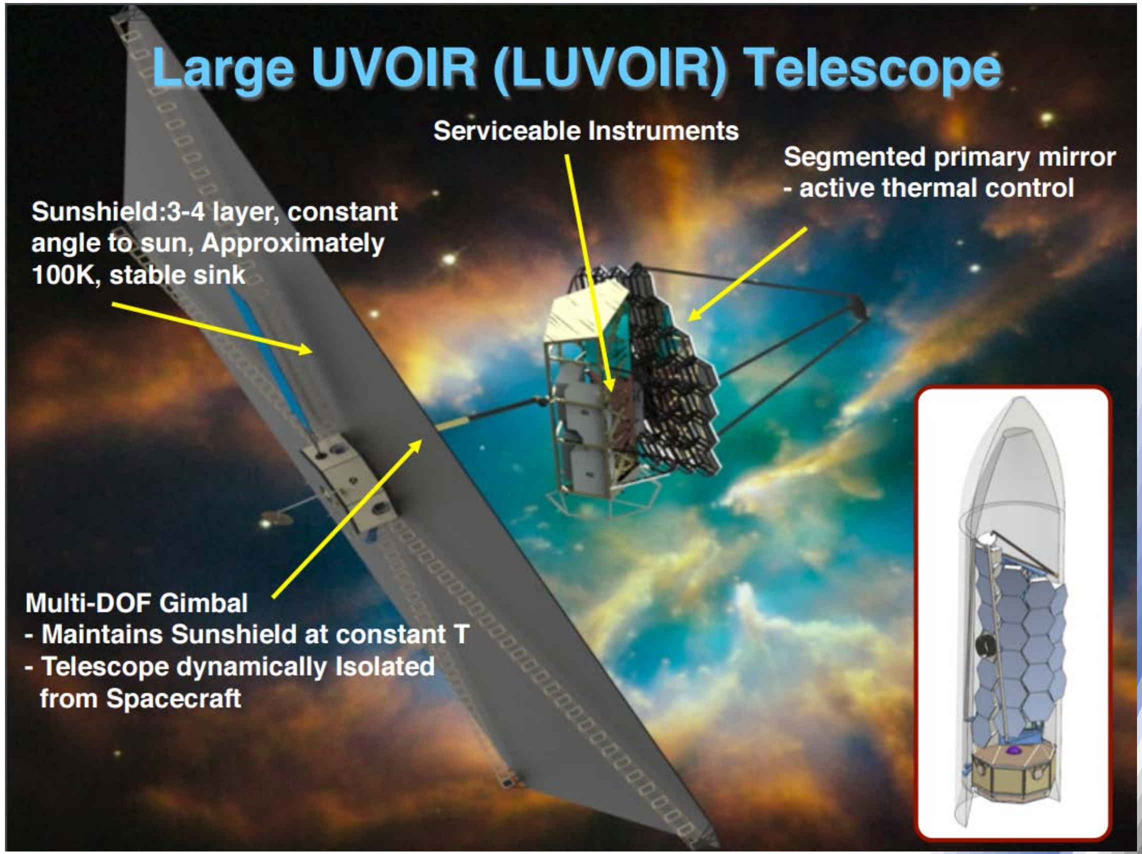
3K-C Boston MEMS DM
Outer Working Angle – 31 L/D





Large UV/Optical/Infrared Surveyor

- Deformable mirror needs
  - 10k+ actuators
  - Space qualified
  - TRL 6
  - …
- Instrument Components subgroup of the Technical Working Group
- Targeted Performance
- Demonstrated Performance
- Technology Readiness Levels



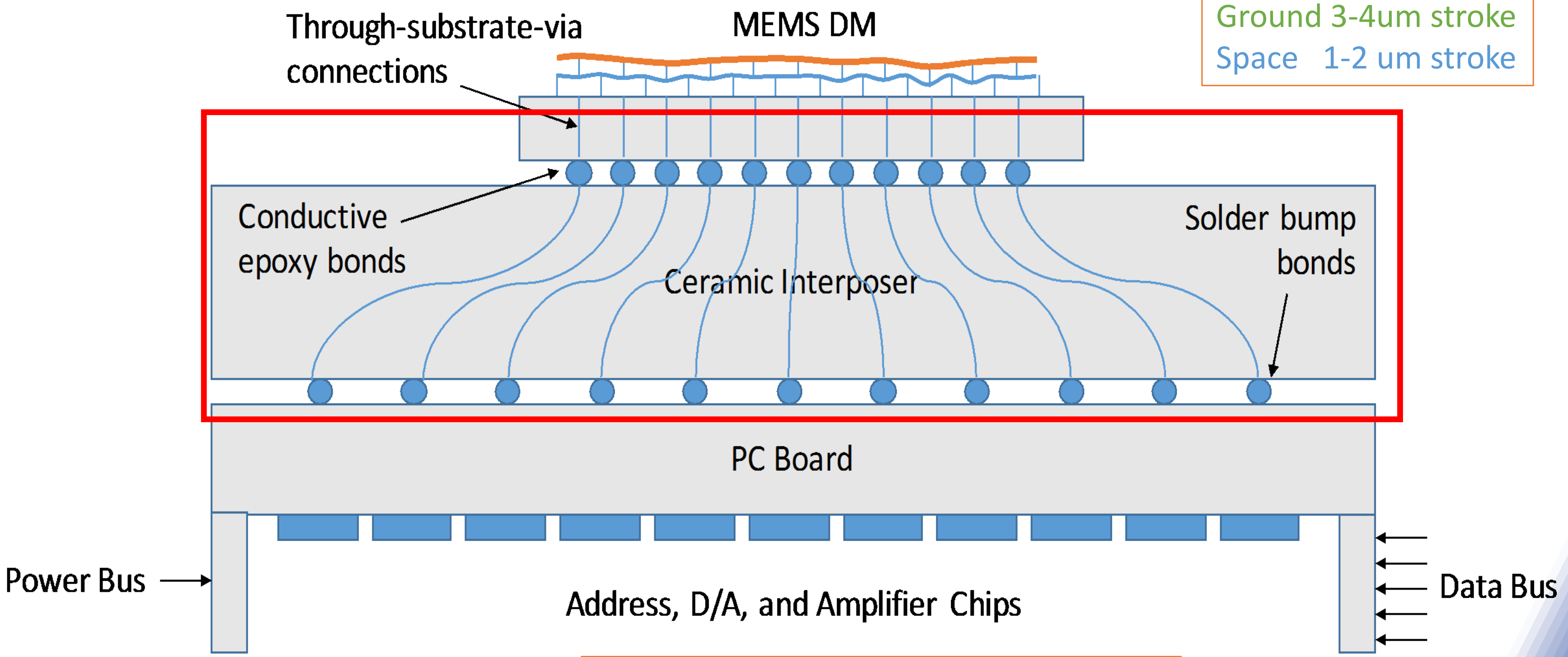
Outline

- BMC DM Technology
- Mirror technology programs
- Space qualification programs
- DMs in telescopes
  - Ground
  - Space
- Next steps for scaling DM actuator count

Need for Even Higher Actuator Count DM (10k +)

- For many next generation instruments, more actuators are needed
- Limited by electrical interconnects
  - Wirebond for each actuator
  - Span of active optical surface scales with N
  - Span of the chip scales with N^2
  - Limits number of die on a wafer
  - Increases the likely hood of a single point defect causing short/failure

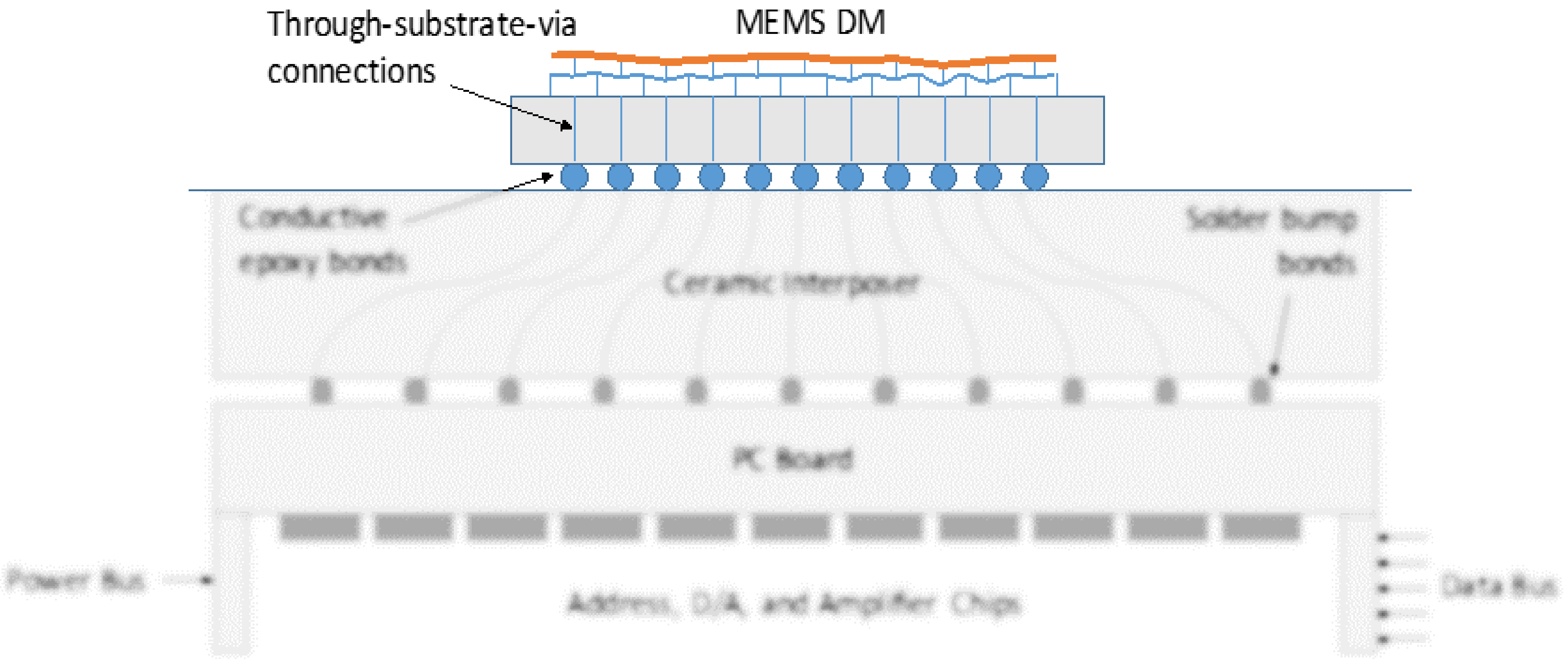
Proposed Architecture (Concept)



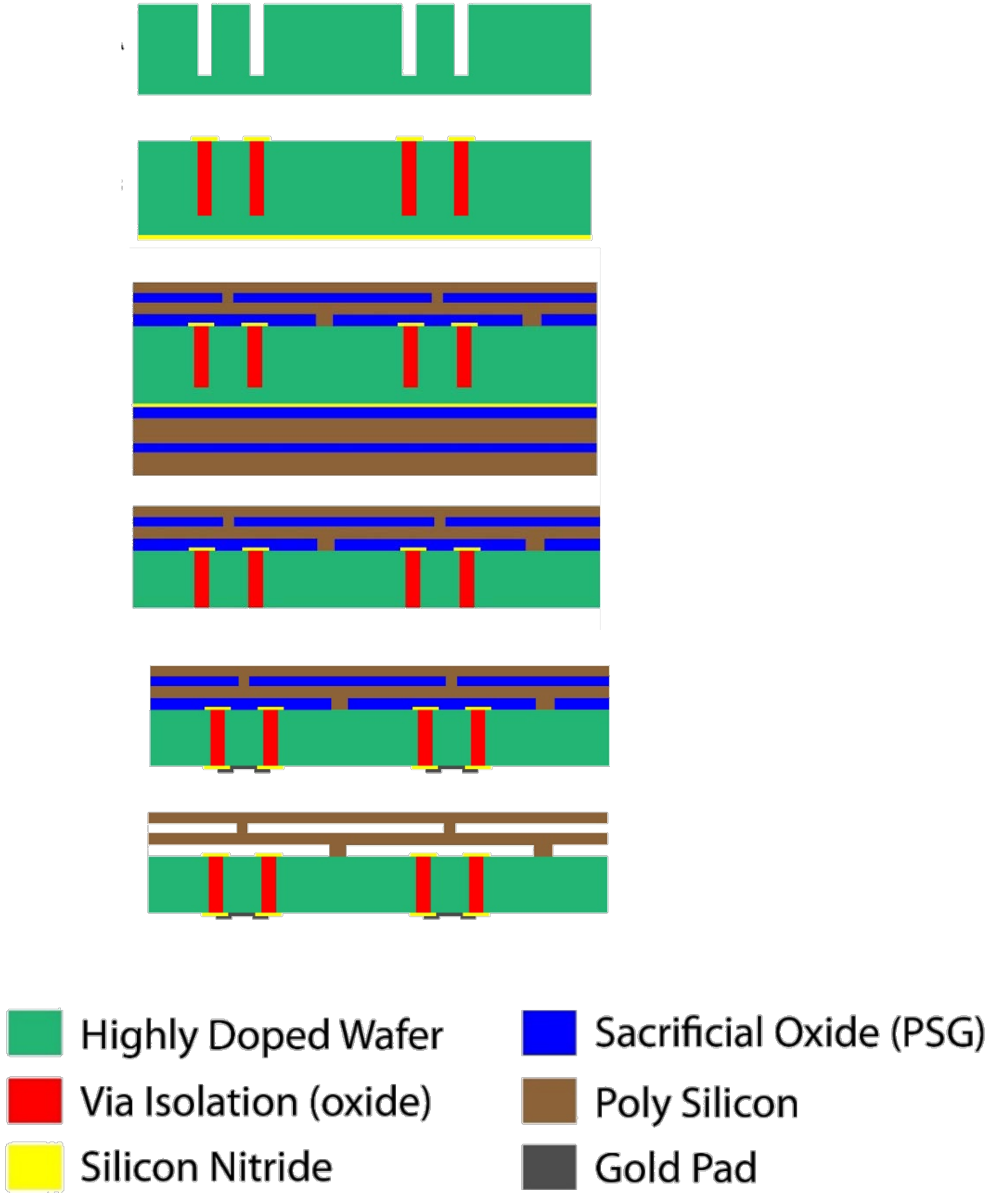
Ground 3-4um stroke
Space 1-2 um stroke

Ground 10kHz, 12-14 bit
Space 100 Hz, 16+ bit, SWAP important

Proposed Architecture (Concept)



Through-Wafer-Via DM Fabrication Prototype



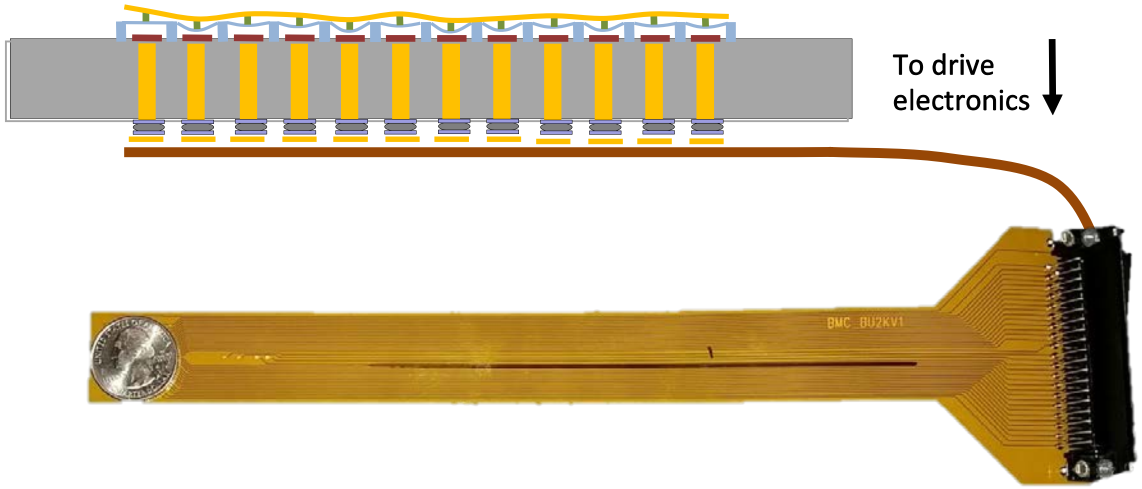
New process (and new foundry for manufacturing) relies on BMC heritage actuator and mirror design, but eliminates wire bonds and instead uses through-wafer-via (TWV) technology

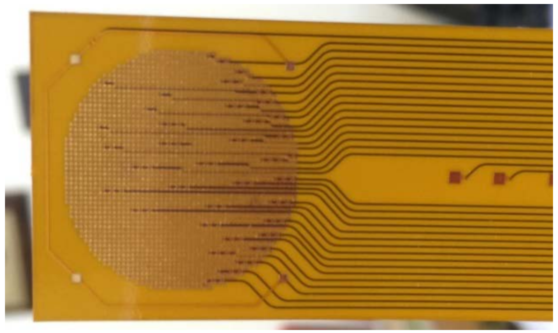
TWV is single crystal silicon: exceptionally low defect level allows major increase in device yield and reliability

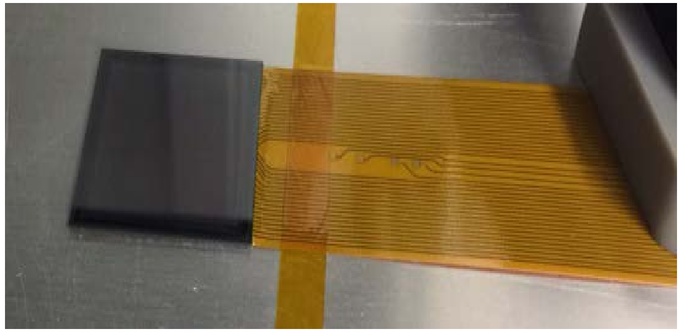
Manufacturing challenge is shifted to packaging of TWV devices

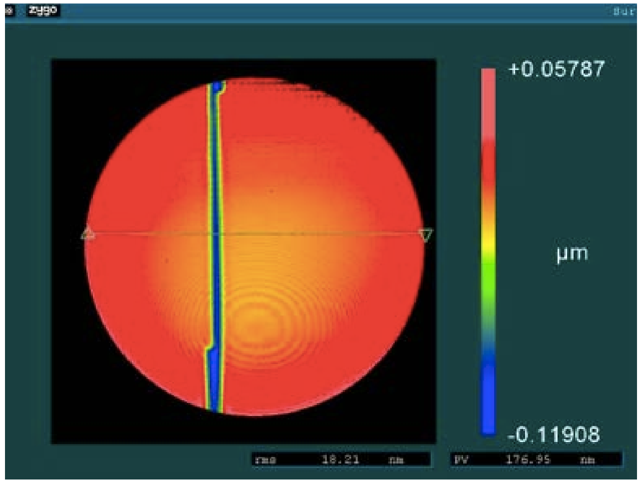
In prototype project, 140 actuator, 500 actuator, and 2000 actuator devices were fabricated and tested

Flex cable packaging of 2000 actuator TWV devices







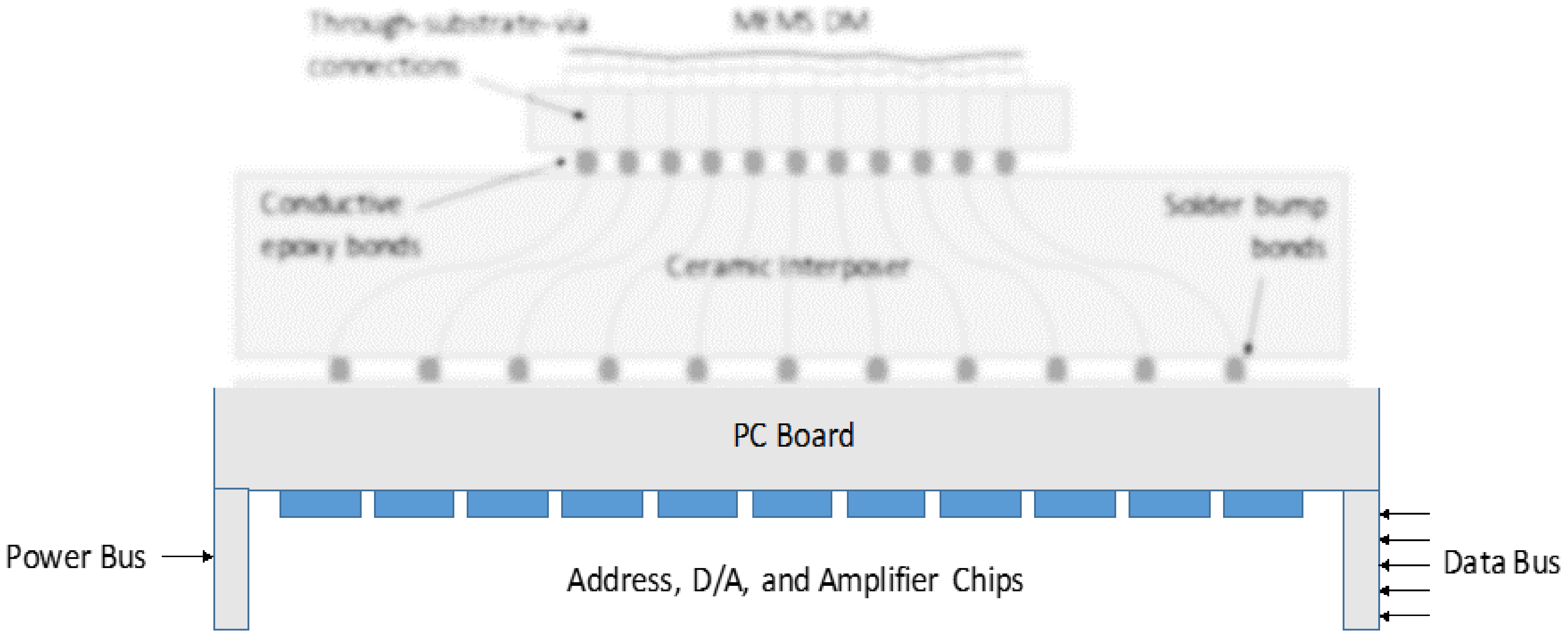


Polymer bump bonds

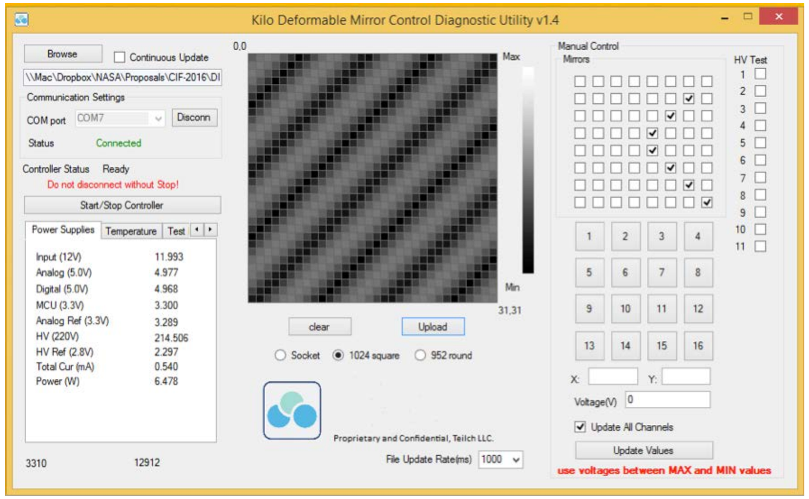
Chip and cable curvature over large area device diminished bond yield (~70%)

Testing of well-bonded sections yielded reliable actuation performance

Proposed Architecture (Concept)



Electronics Design



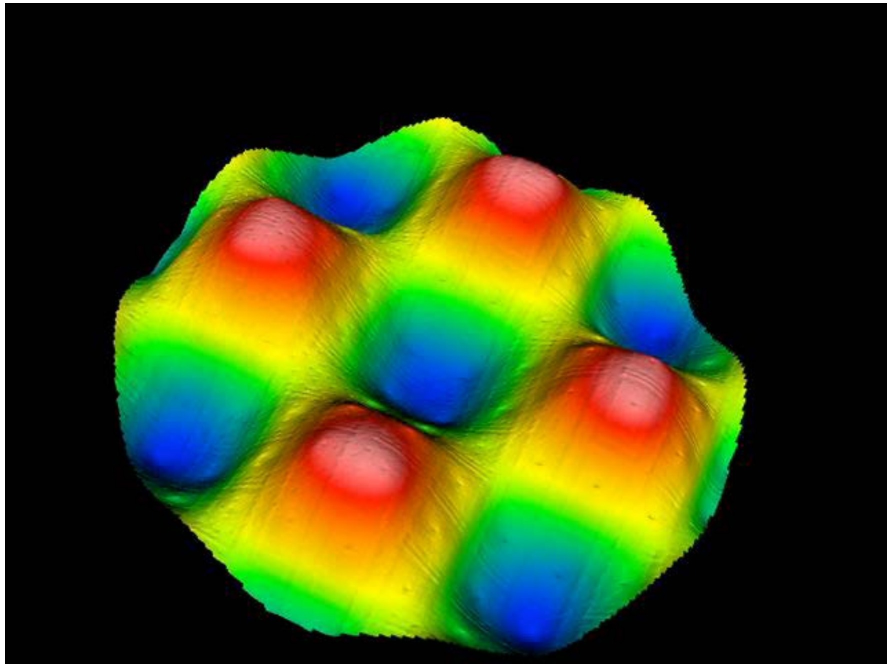
- The controller has a volume of 90mm (w) x 90mm (l) x 54.6mm (h), w/o mirror and socket.
- It only requires a 12V power supply and consumes 6W.
- USB interface for data
- 0-215V, 16 bits
- Scalable technology for greater channel count

Conclusion

- MEMS DM have been proven in astronomical instrumentation
- Continued technology development is ongoing
- Poised for next generation instruments, but development needs to occur.

Thank You

Questions?



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