**Low voltage deformable mirror system driven by MEMS-based Lorentz actuator arrays**

Park, Byoungyoul; Bergren, Adam Johan; Belov, Miroslav; Burley, Greg; Shafai, Cyrus



https://doi.org/10.4224/40002661

# Low Voltage Deformable Mirror System Driven by MEMS-Based Lorentz Actuator Arrays

April 22, 2021

By: Byoungyoul Park[1], Adam Johan Bergren[1], Miroslav Belov[1], Greg Burley[2], and Cyrus Shafai[3]

1. NRC-Nanotechnology Research Centre, 11421 Saskatchewan Drive, Edmonton, AB T6G 2M9 Canada
2. NRC-Herzberg Astronomy & Astrophysics Research Centre , 5071 W. Saanich Rd., Victoria, BC, V9E 2E7, Canada
3. Dept. Of Elec. and Comp. Eng. University of Manitoba, Winnipeg, MB, R3T 5V6, Canada

# Content

1. **Introduction:** TMT Telescope / Adaptive Optics (AO)
2. **Deformable Mirror (DM):** Overall Design
3. **Simulation:** Issues/solutions
    - Structure Simplification
    - Mesh Optimization
    - Independent Simulation
4. **Results:** STEP 1, STEP 2, Heat Concern, STEP 3 and Mirror Deformation

# 1. Introduction: TMT Telescope

$1.4B worldwide project to build the **T**hirty **M**eter **T**elescope (TMT) collaborating with Canada, U.S., China, India and Japan.

- ✓ Location; Mauna Kea in Hawaii
- ✓ Operating wavelength range: UV to mid-infrared
- ✓ 9 times the light collecting area of the current largest telescope (the 10-meter Keck Telescopes)

✓More than **12 times** higher resolution than Hubble Space Telescope **with AO (Adaptive Optics) Technology**.

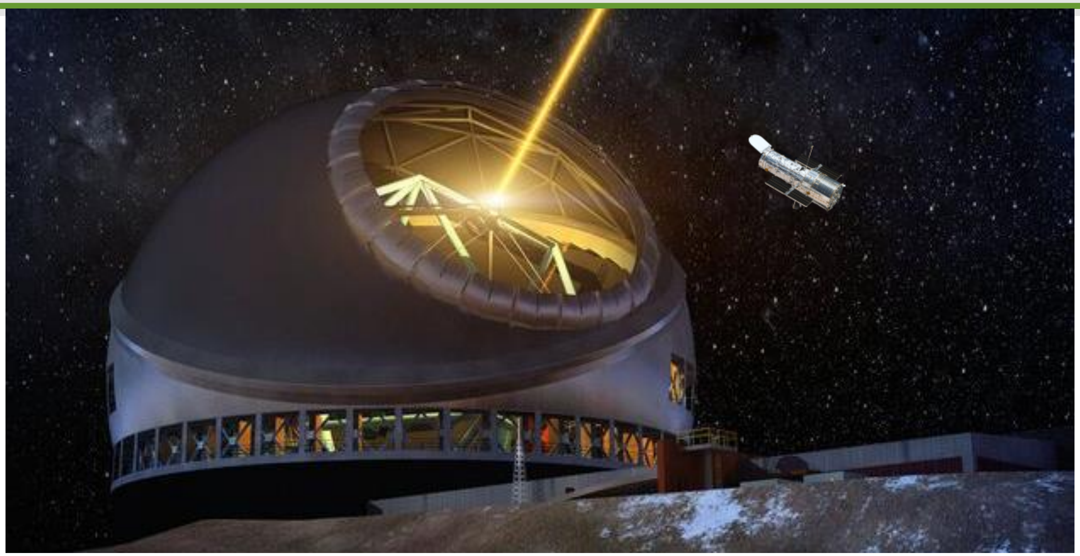


*Figure.* An artist concept of the Thirty Meter Telescope at night. Adapted from " Native Hawaiians Arrested During Protests Over Massive Telescope," by Chris D'Angelo, Huffpost US, 2019, retrieved from https://www.huffingtonpost.ca/entry/hawaii-protests-thirty-meter-telescope-2019_n_5d2f76bee4b020cd993e0a54. Courtesy TMT International Observatory.

## ❖ MEMS DM specification and achievement … T AO

| Items | Specification | Achievement |
|---|---|---|
| Dimension | 63 × 63 or 76 × … | …emonstrated 5 × 5 deformable mirror |
| Actuator Pitch | ~ 2 mm… | |
| Mirror Stroke | 10 µm… | …t < 1V (single actuator) |
| Actuation Speed | > 800 … | |
| Mirror Surface Roughness | < 30 n… | |
| Inter-Actuator Coupling | 10 - 30% | …0 % by adjusting the spring constant of actuator |

Figure: Hubble space telescope (primary mirror diameter is 2.4 meters)

**Scaling up to 20 × 20 actuator array DM**

# 1. Introduction: Adaptive Optics (AO)

- ✓ Horace. W. Babcock (1953); the first conceptual AO system, US.
- ✓ The first operational AO system; Haleakala Observatory in Maui, Hawaii (1980’s), US.

### ❖ Working Principle

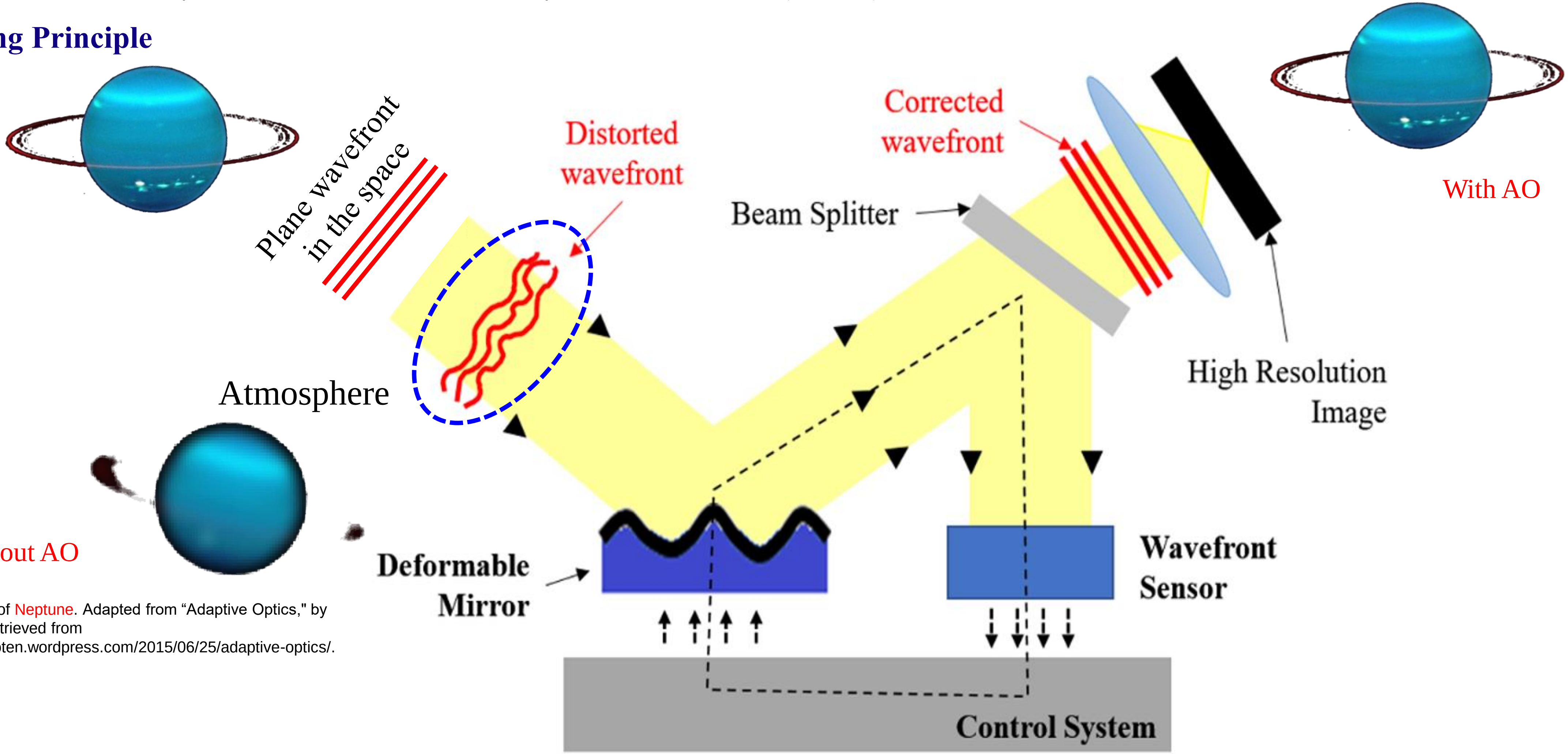



*Figure.* Keck image of Neptune. Adapted from “Adaptive Optics," by MAAIKEVK, 2015, retrieved from https://maaikevankooten.wordpress.com/2015/06/25/adaptive-optics/.

# 2. Deformable Mirror: Design

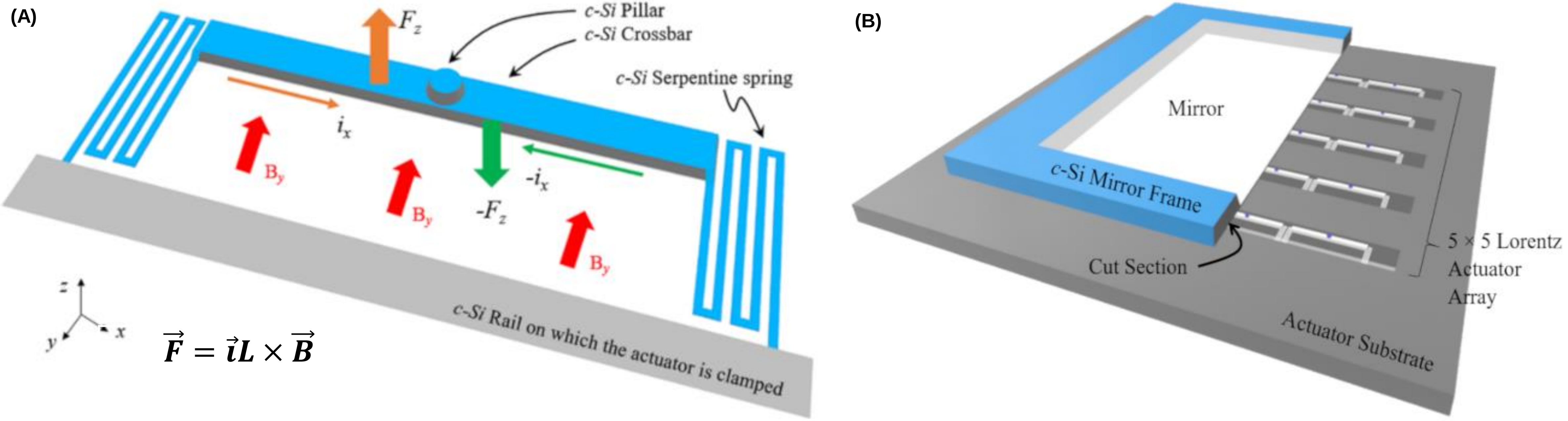
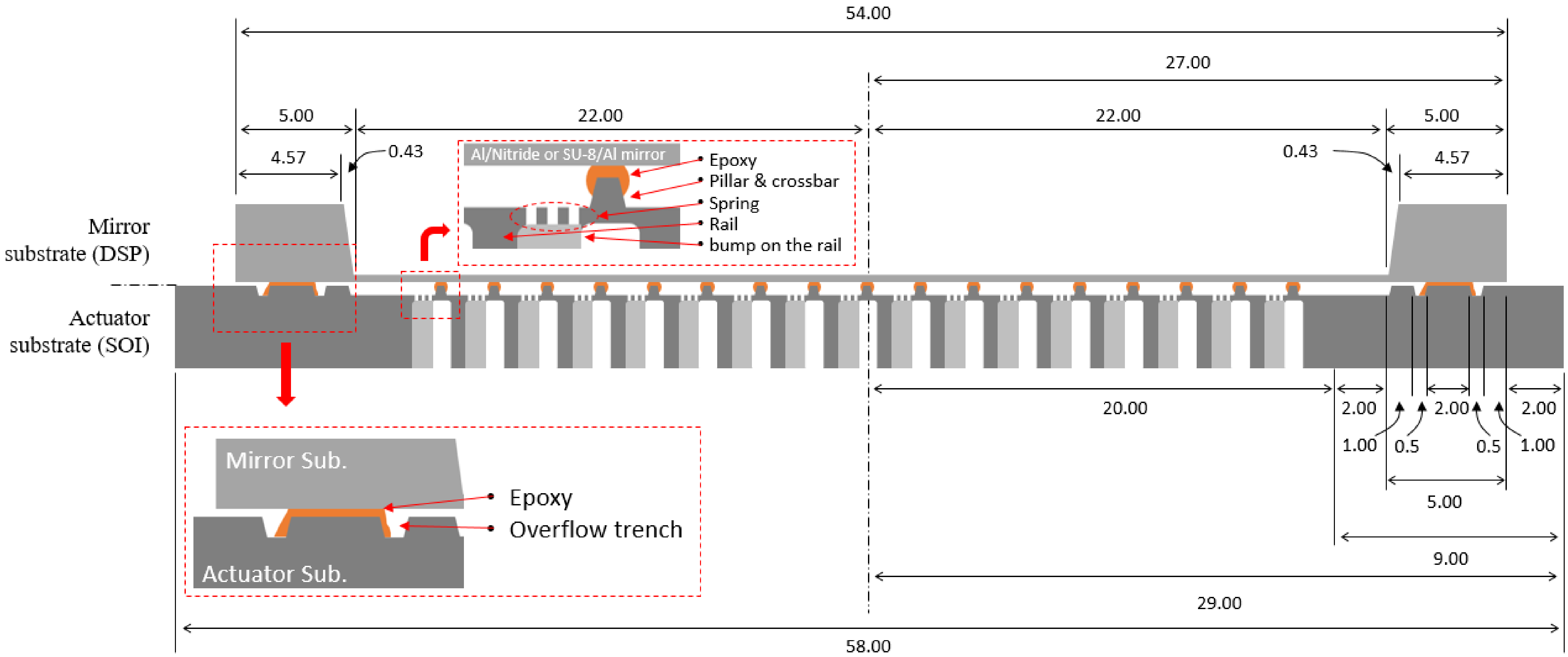



Figure. Illustration of a Lorentz force actuator showing the working principle (A), and a 5 × 5 array of Lorentz actuators with mirror attached (B)

# 2. Deformable Mirror: cross-section view



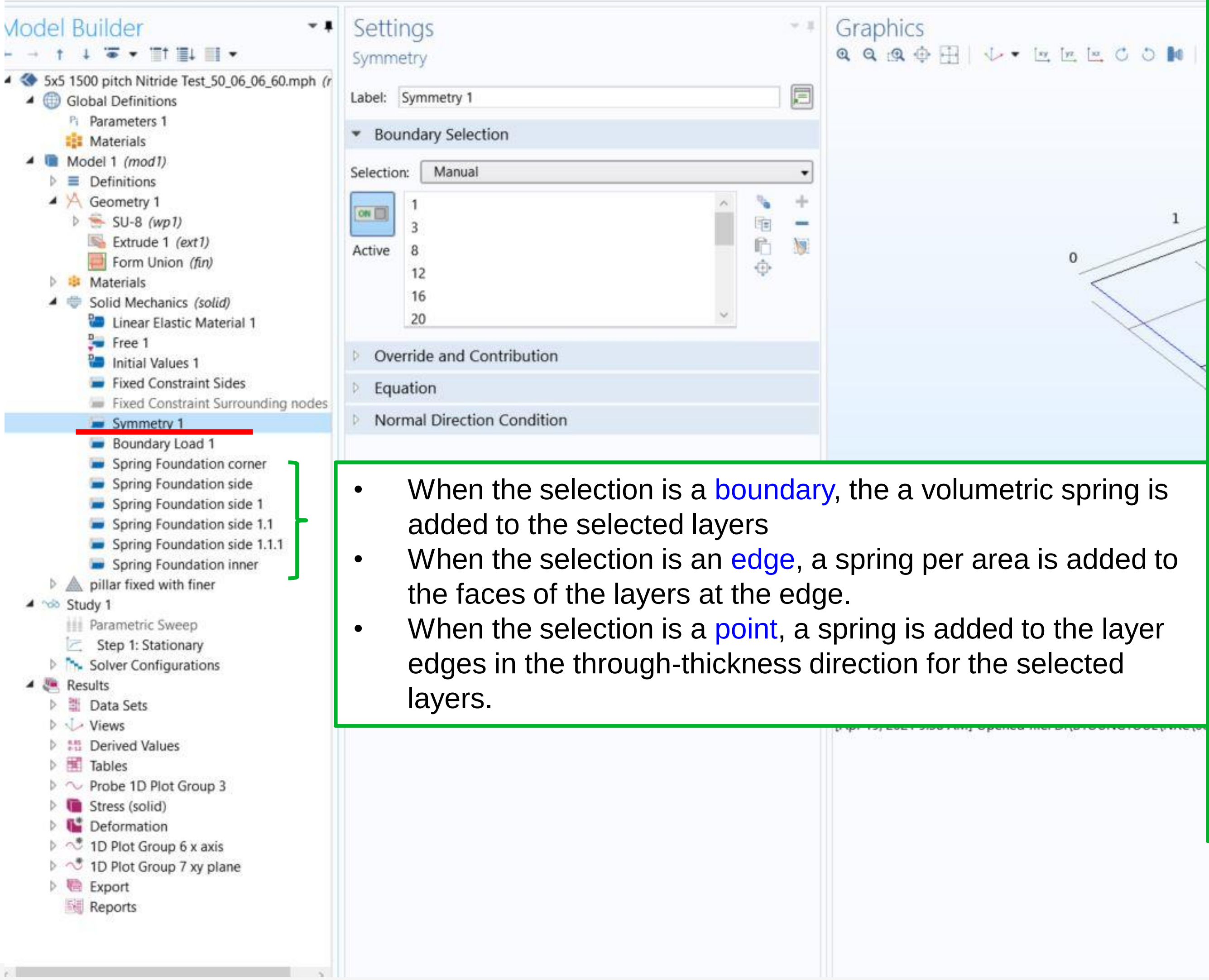

System can be represented by **thin membrane mirror with an array of spring attached**

# 3. Simulation: Issues/solutions

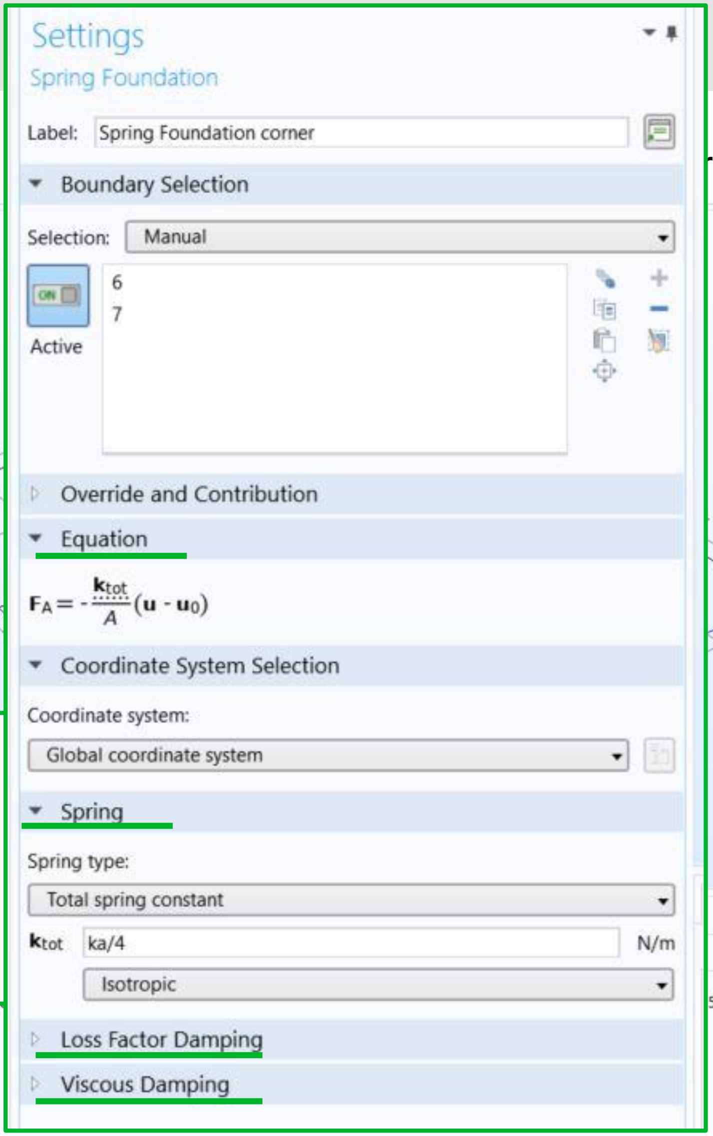
| Causes of the convergence Issues | Solutions |
|---|---|
| High aspect ratio: Too many mesh based on smallest dimension of the structure. (i.e. Tm = 1 µm and Wm = $2 \times 10^3$ µm) | • Mesh optimization[2]<br>• Symmetry[1] |
| Complex structure: over 1000s array of actuator coupled with mirror membrane | • Limit the number of actuators (5 x 5)[1]<br>• Applied spring foundations[1] to simulate and predict the spring constant of mirror and actuators<br>• Symmetry |
| Complex mixed Multiphysics system | • Independent simulation[3] of each physical quantities and determine optimal design area using design map. |

# 3. Simulation: Issues/solutions

## 1. Structure simplification: membrane with springs

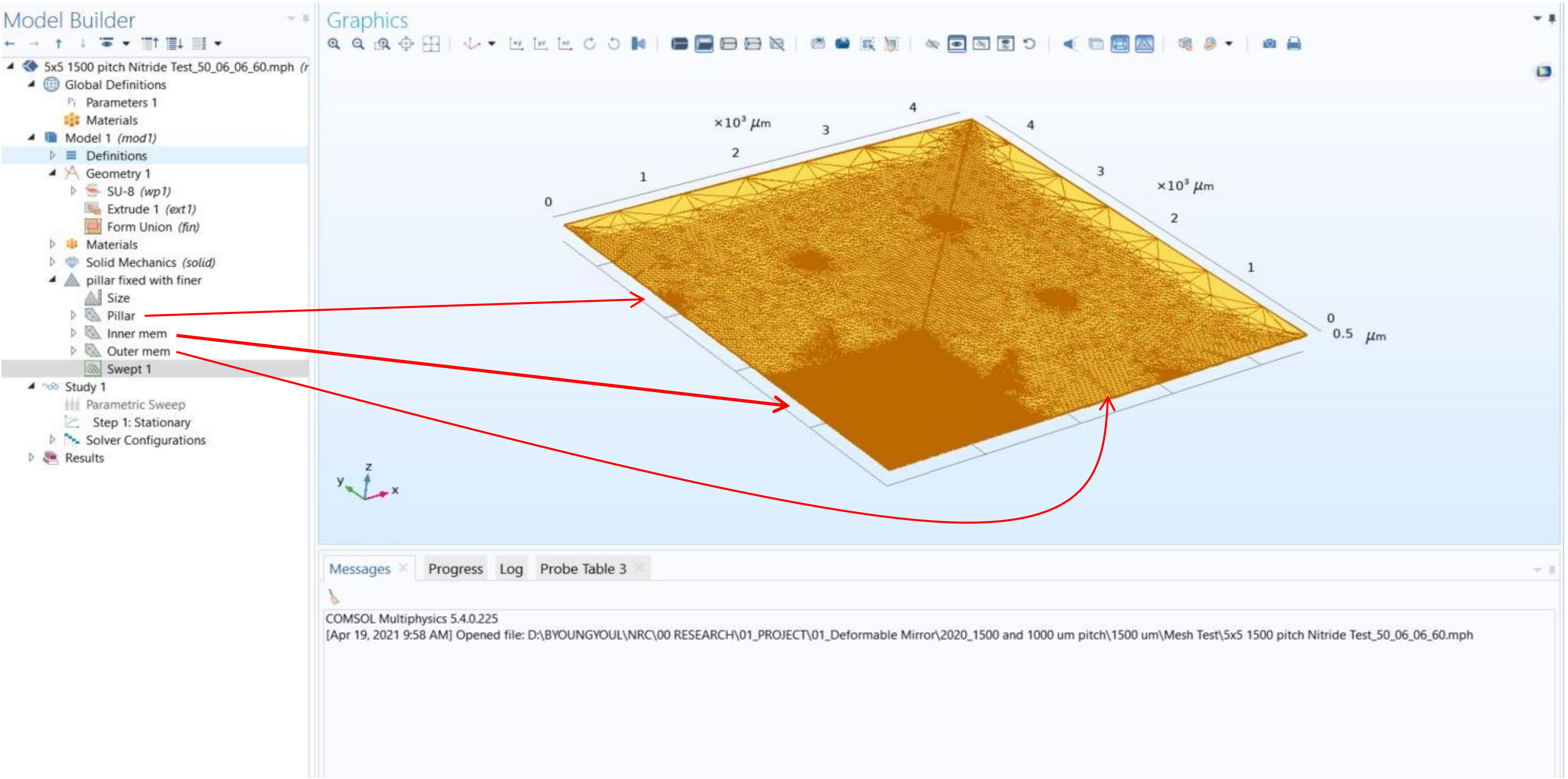



- When the selection is a boundary, the a volumetric spring is added to the selected layers
- When the selection is an edge, a spring per area is added to the faces of the layers at the edge.
- When the selection is a point, a spring is added to the layer edges in the through-thickness direction for the selected layers.



# 3. Simulation: Issues/solutions

## 2. Mesh Optimization

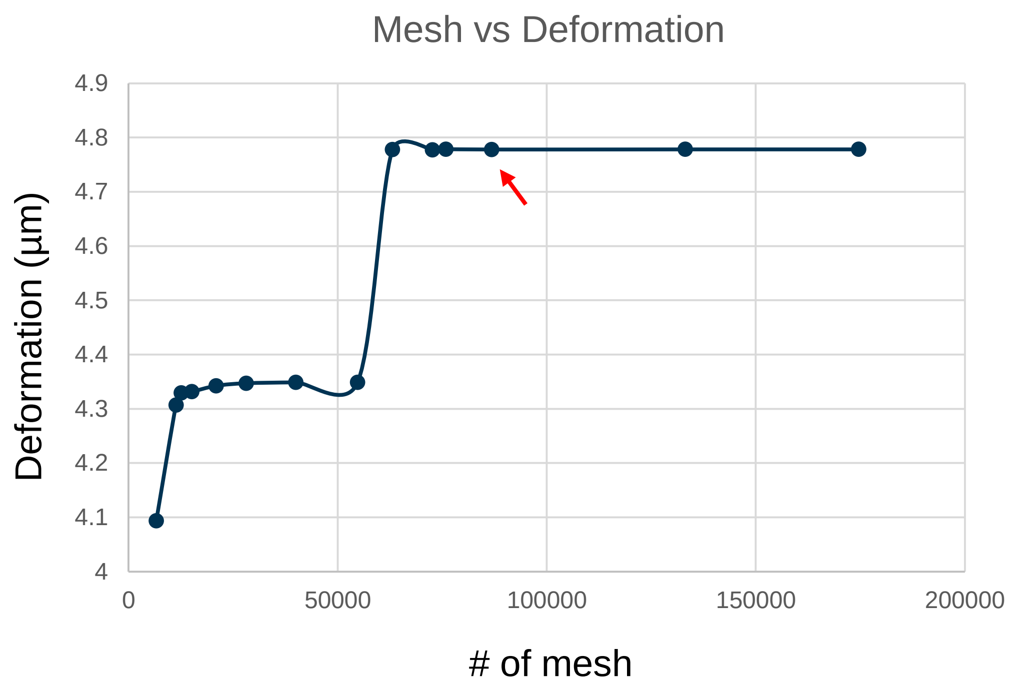


# 3. Simulation: Issues/solutions

## 2. Mesh Optimization

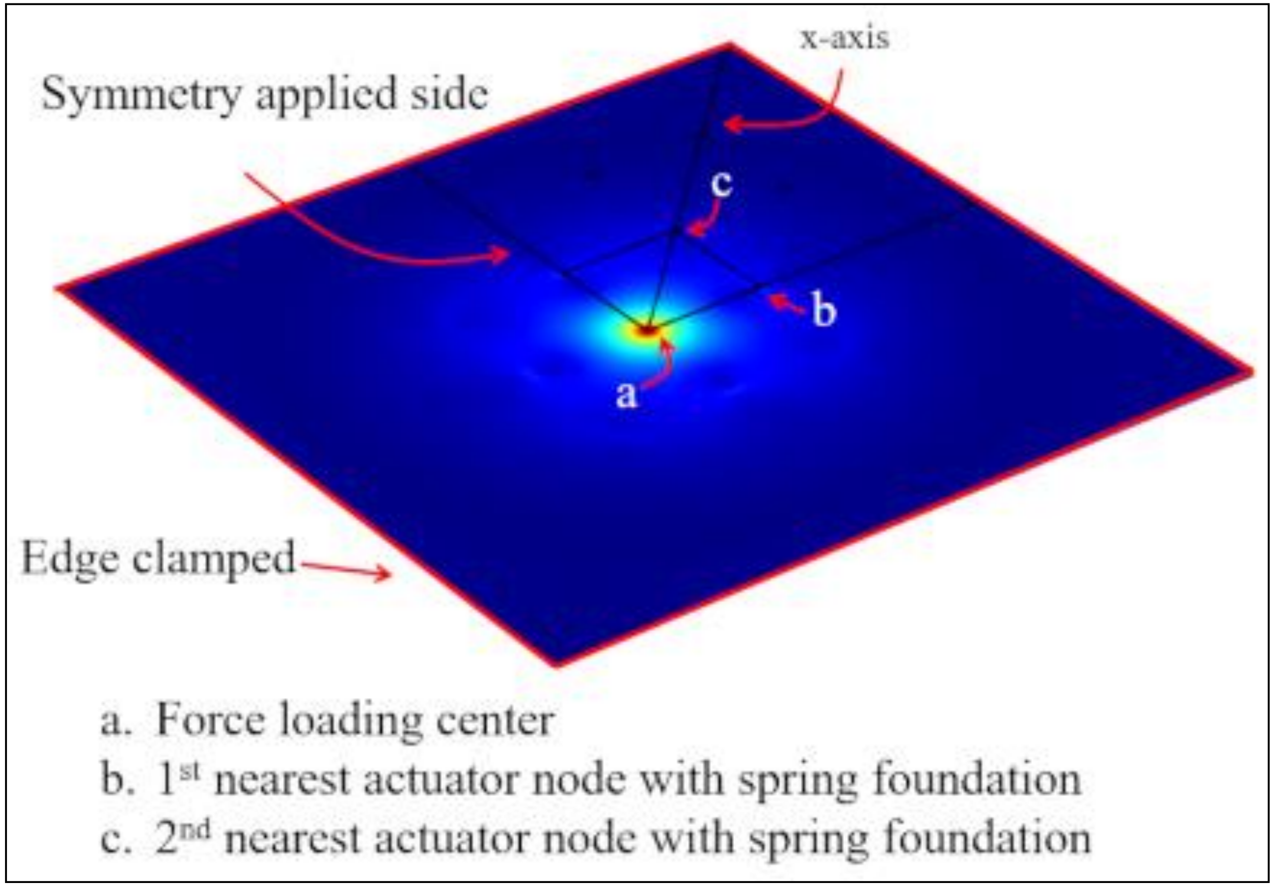
Max. Element size

| overall | Pillar | Inner Mem | Outer Mem | Distribution | # of Domain | Time (sec) | Deformation |
|---|---|---|---|---|---|---|---|
| 90 | 90 | 90 | 90 | 7 | 6622 | 34 | 4.0937 |
| 50 | 90 | 90 | 90 | 7 | 11331 | 49 | 4.3069 |
| 50 | 30 | 40 | 90 | 7 | 12584 | 52 | 4.3292 |
| ••• | ••• | ••• | ••• | ••• | ••• | ••• | ••• |
| 50 | 10 | 10 | 60 | 7 | 72710 | 245 | 4.7772 |
| 30 | 10 | 10 | 50 | 7 | 75888 | 252 | 4.7785 |
| **50** | **9** | **9** | **60** | **7** | **86840** | **300** | **4.7779** |
| 50 | 7 | 7 | 60 | 7 | 133170 | 583 | 4.7781 |
| 50 | 6 | 6 | 60 | 7 | 174598 | 2187 | 4.7781 |



# 3. Simulation: Issues/solutions

## 3. Independent simulation: Simulation Strategy



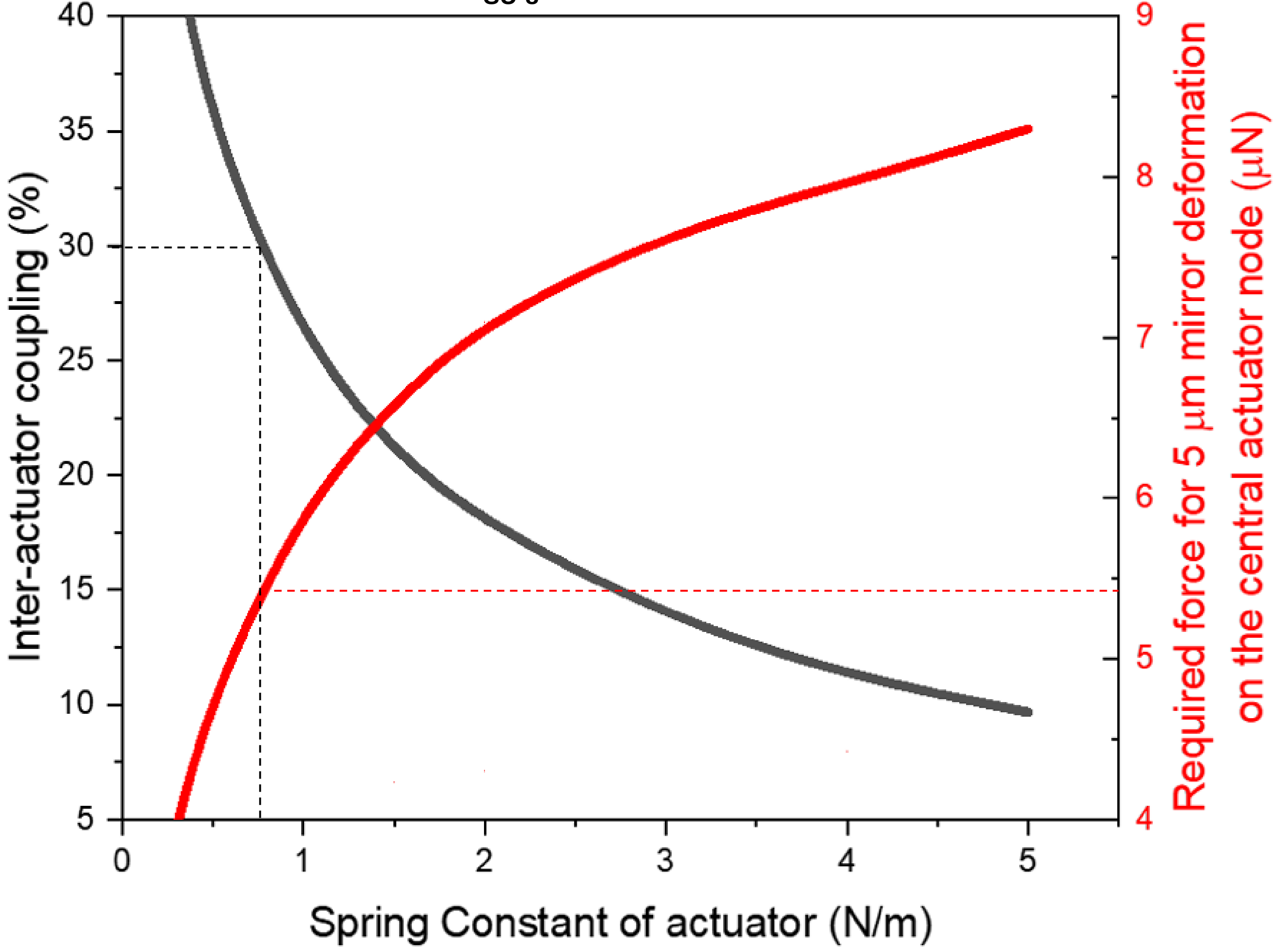

STEP 1: Simulation on inter-actuator coupling and corresponding actuator spring constant with 5 x 5 actuator array (spring foundation)
➔ Find fundamental design rule

STEP 2: Simulating the mechanical properties of the Lorentz actuator using various dimensional parameters (Length, thickness, width…etc).

STEP 3: Incorporate and analysis of simulation results with design map

## Design rule

**SU-8 membrane face-sheet (mirror)**
**Structure: (0.25)Al/(4)SU-8/(0.25)Al**
**$E_{SU\text{-}8}$: ~ 2GPa**




**Variables:**

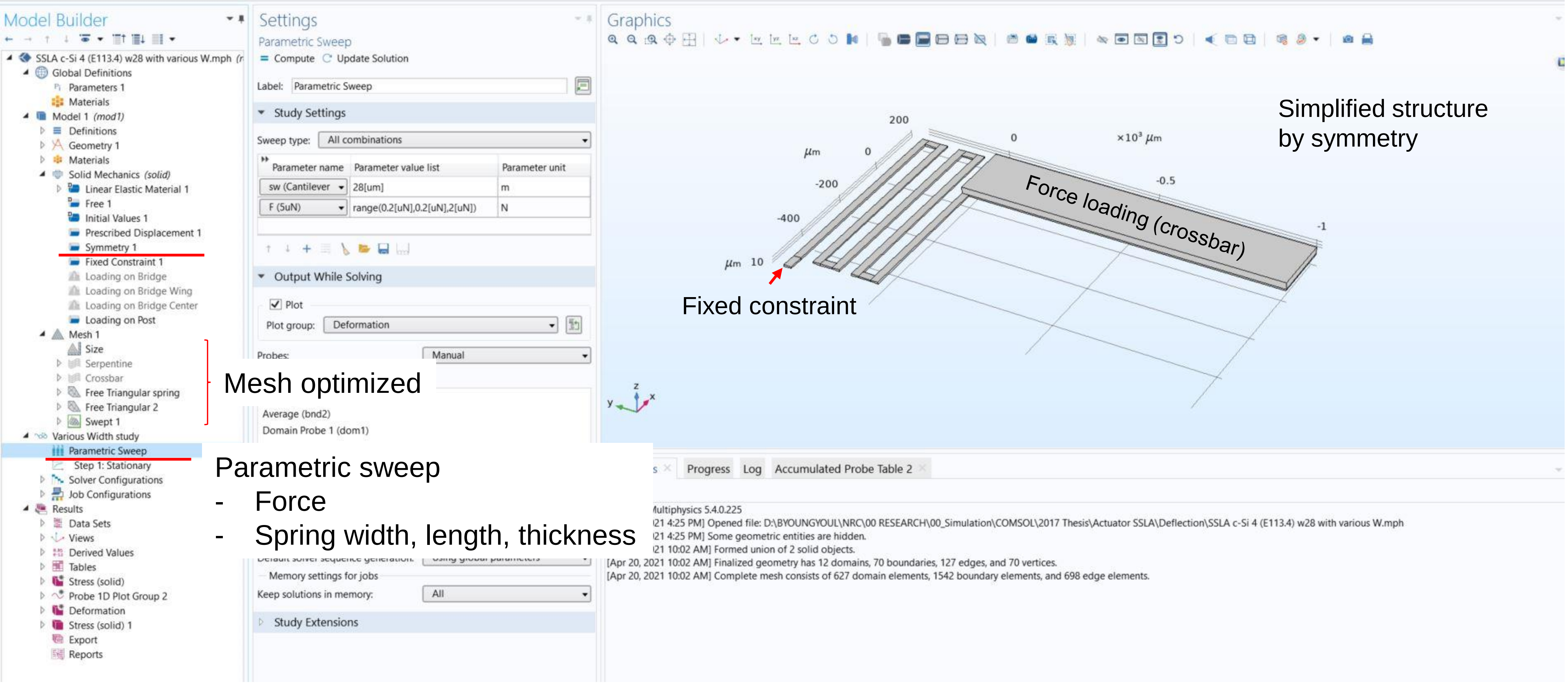
- Spring constant of actuators
- Applied force on the central actuator pillar (a)

**Example: 30% coupling DM**

- Actuator Spring constant required: **0.7 N/m**
- Force for 5 μm deformation: **5.5 μN**

# 4. Results: STEP 2

## Lorentz Actuator



# 4. Results: STEP 2

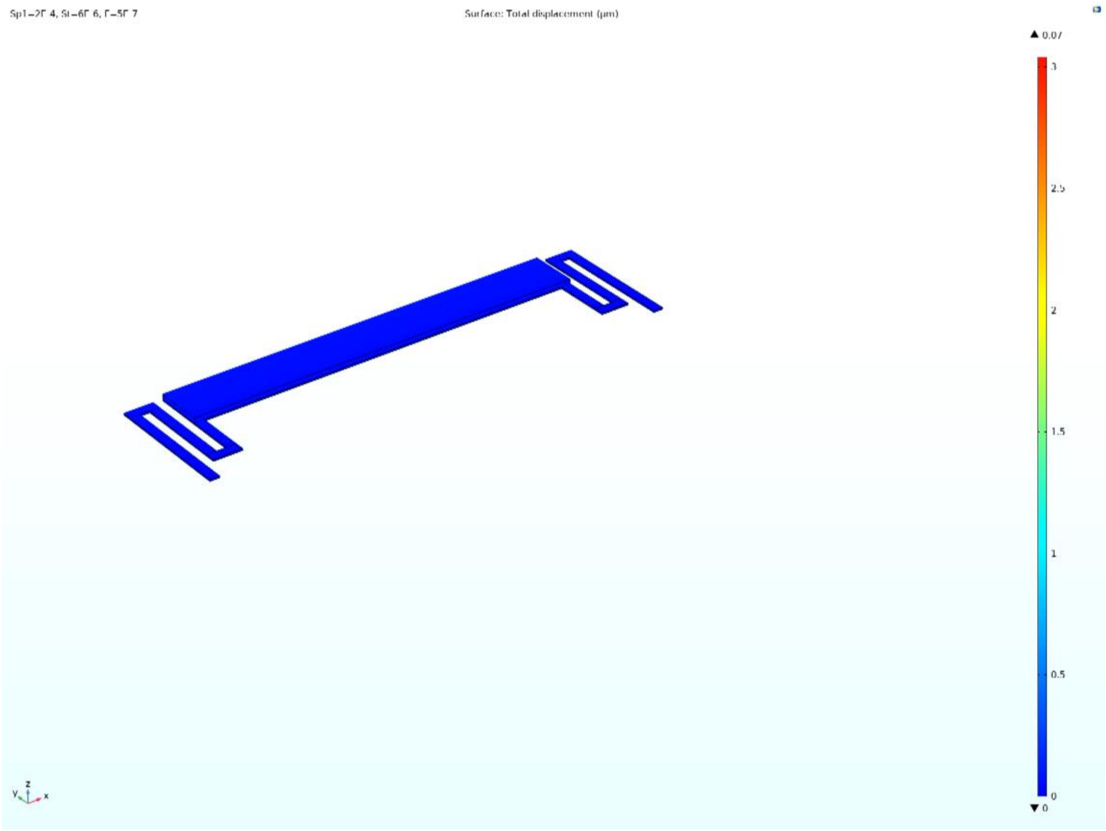
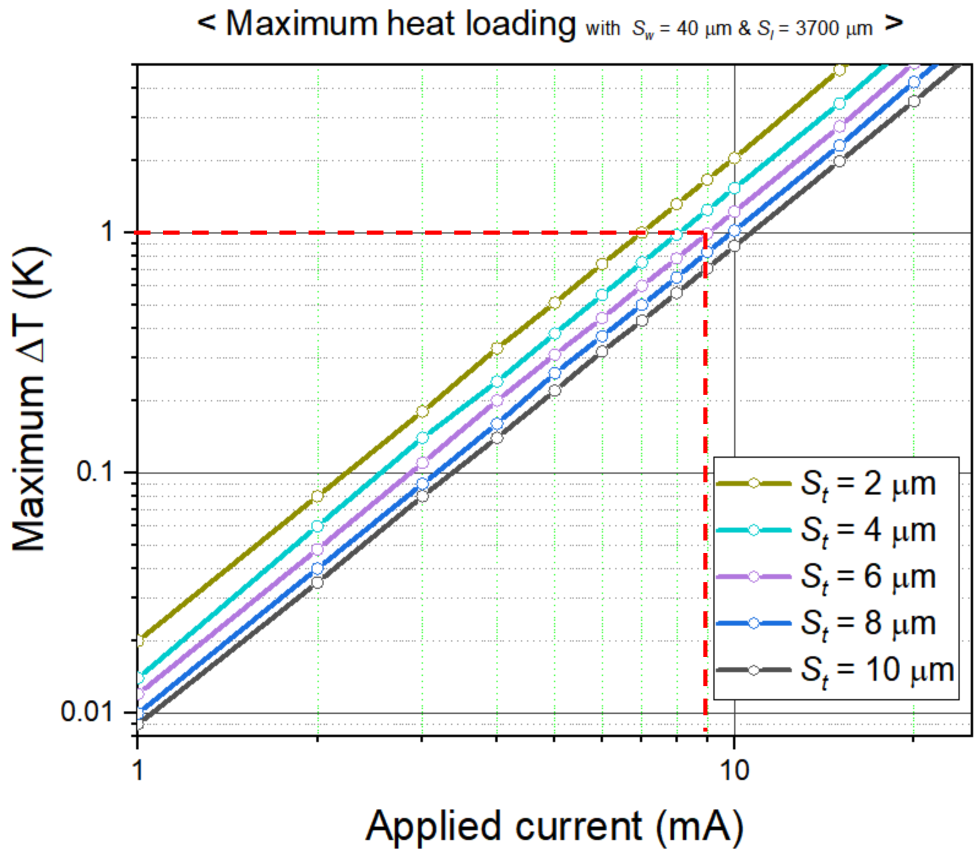


Figure: Actuator deflection with various length of serpentine spring (force is fixed)

# 4. Results: Heat concern




**Target: < 1K**
**For Telescope application**

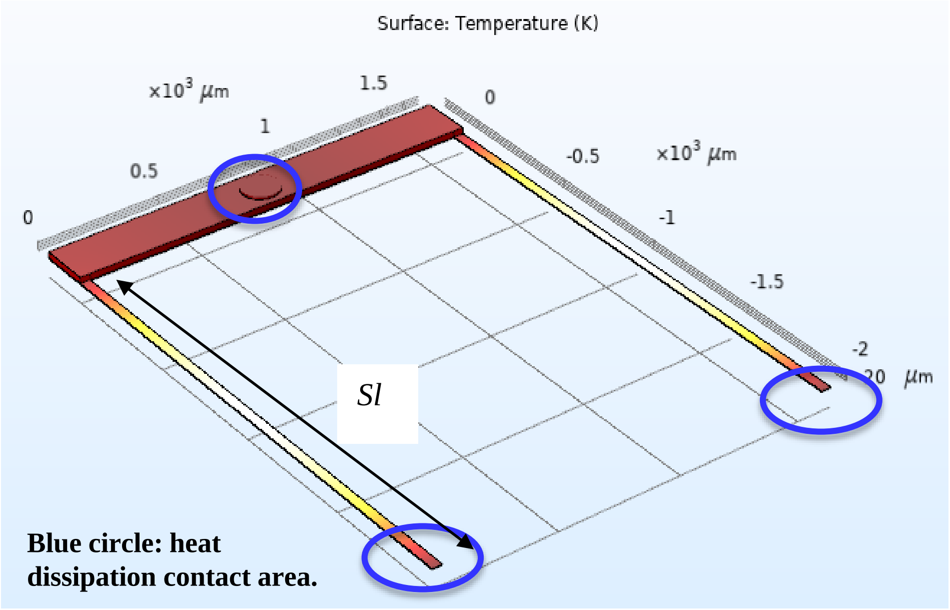



Figure: Simplified design with heat dissipation

If, B ~ 0.3 *Tesla* (worst case), required force for ± 5 µm deformation of the nitride mirror is ~ ± 4.5 µN (with 17 % coupling)

→ Required current ~ 9 mA (total current for 20 × 20 actuator = 3.6 A)

→ Spring thickness should be **6 µm** to have proper spring constant (0.5 N/m) and better heat dissipation)

# 4. Results: STEP 3 (actuator design map)

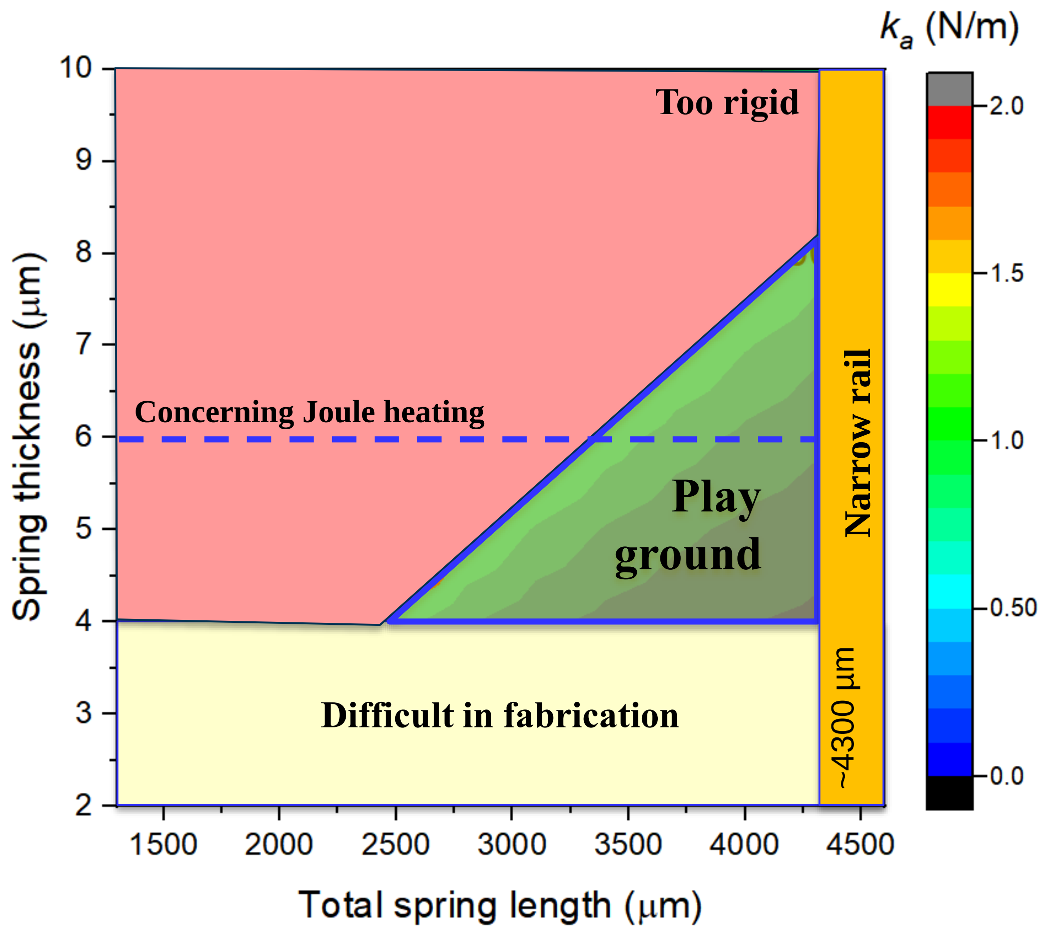


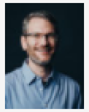

Figure. Design map to determine the optimized spring dimension of the actuator.

| Total spring length (μm) | Rail width (μm) | Remarks |
|---|---|---|
| 4600 | 260 | Too narrow Rail |
| 4300 | 360 | |
| 4000 | 460 | Design area |
| 3700 | 560 | |
| 3400 | 660 | |
| 3100 | 760 | Too **rigid** by concerning the length and thickness of the spring |
| 2800 | 860 | |
| 2500 | 960 | |
| 2200 | 1060 | |
| 1900 | 1160 | |
| 1600 | 1260 | |
| 1300 | 1360 | |

# Detection and Automation Team

Nanotechnology Research Centre, Detection and Automation Team
https://nrc.canada.ca/en/research-development/products-services/technical-advisory-services/expertise-detection-automation

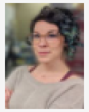
**Adam Bergren**
**Team Lead**



- Analytical chemistry
- Nanoelectronics
- Optoelectronics

**Email**: Adam.Bergren@nrc-cnrc.gc.ca
**Telephone**: 780-641-1762

**Carissa Ouellette**

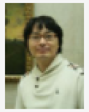


- Electronics
- Software
- Prototyping
- Engineering

**Miro Belov**

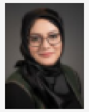
- Electronics
- Optics
- Fabrication and prototyping

**Byoungyoul Park**



- MEMS and adaptive optics
- MEMS actuators and magnetic field sensors
- Microfabrication
- 3D-printed electronics

**Narges Shaabani**



- Microfluidics
- Electrochemistry

**Mehdi Nosrati**

- Microwave and millimeter-wave engineering
- Design and fabrication of sensors

**Rajesh Pillai**

- Analytical chemistry
- Electrochemistry
- Surface modifications
- Organic electronics

**Bryan Szeto**

- Electronic measurement (DAQ)
- Data acquisition and processing
- Micro/nano-fabrication
- Vacuum systems

**Abebaw Jemere**

- Microfluidics
- Sensors development
- Electrochemical, mass and fluorescent-based detections

**Wayne Hiebert**

- Optomechanics
- Devices

**Michael Bergen**

- Programming
- Automation
- Machine learning

**Nikola Pekas**

- Microfabrication
- Microfluidics
- Sensors and actuators
- Optical microscopy
- Magnetics and electronics

**Wide Research Spectrum**

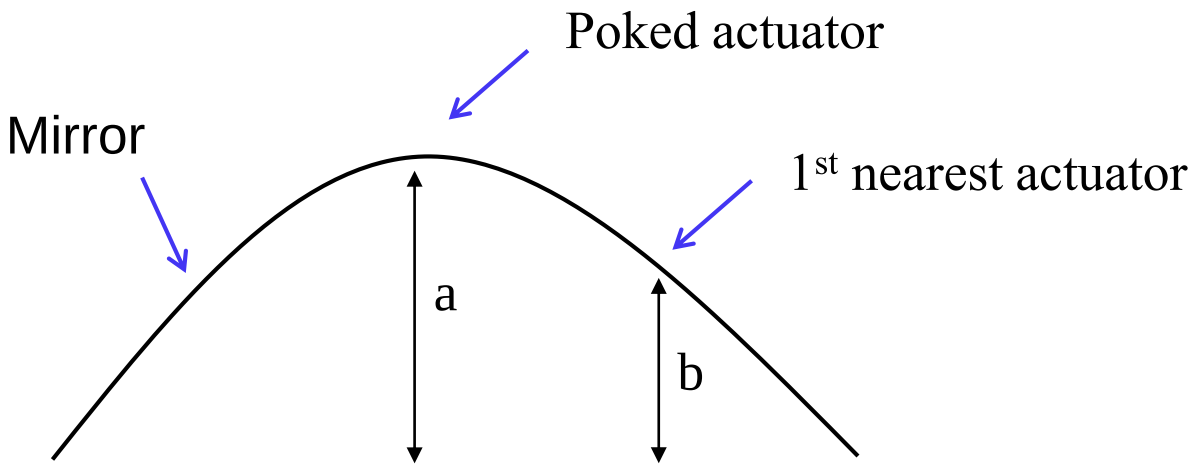
- Analytical Chemistry
- Electrochemistry
- Organic Electronics
- Microfluidic
- Nanoelectronics
- Optoelectronics,
- Optomechanics
- Microfabrication
- Sensors and Actuators
- 3D printed electronics

# THANK YOU

Byoungyoul Park • AsRO
Byoungyoul.Park@nrc-cnrc.gc.ca

# Inter-actuator Coupling

Inter-actuator coupling: The ratio of the displacement of the DM surface at the poked actuator to that obtained at its neighboring actuator.




- Crosstalk (inter actuator coupling, %) = b/a × 100

# Equations for design

- Lorentz force: $\vec{F} = \vec{B} \times i\vec{L}$
- Resonance Frequency: $f = \frac{1}{2\pi}\sqrt{\frac{k_{eq}}{m_{eq}}}$
- Cantilever displacement: $d_z = \left(\frac{F_z l_c^3}{3EI}\right)$

  Moment of inertia

  $I = \frac{w_c t_c^3}{12}$

- Joule heating: $P \approx I^2 R$ $\quad P = kA\frac{\Delta T}{L}$ $\quad \Delta T = \rho I^2 \frac{l^2}{kA^2}$

  Electrical Power

  Heat conduction from Fourier's law

# 4. Results: Mirror Deformation

**Correlation between the Lorentz force and current**

- Magnetic flux: 0.3, 0.5, and 0.7 *Tesla*
- Crossbar length: 1.9 mm → ***1.64 mm***

$$\vec{F} = \vec{I} \cdot l \times \vec{B}$$

The stronger the external magnetic

flux, the lower the;

- **Power consumption**
- **Heat**

Required current within different B field with 4.5 μN for SU-8 mirror (5 μm deformation)

- **0.3T → 9 mA**
- 0.5T → 5.5 mA
- 0.7T → 4 mA

< I-F curve with 1640 μm crossbar >

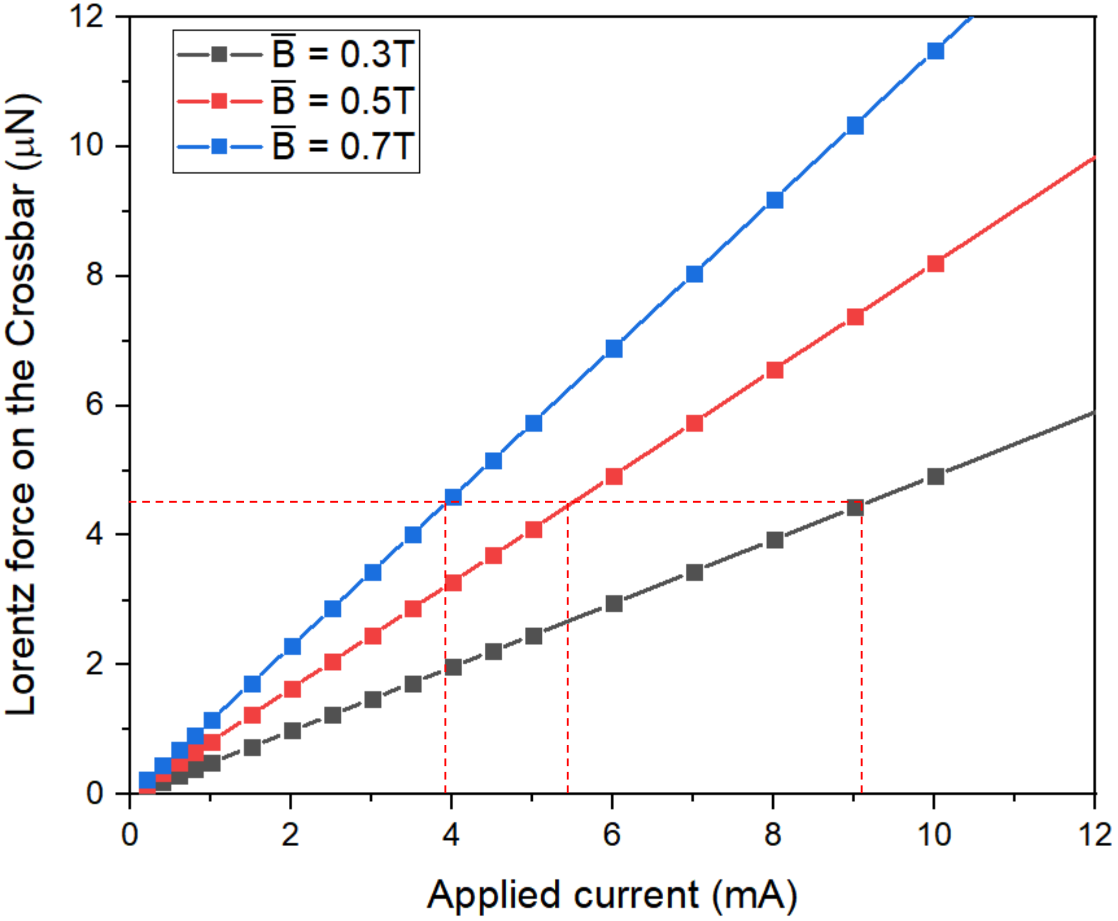
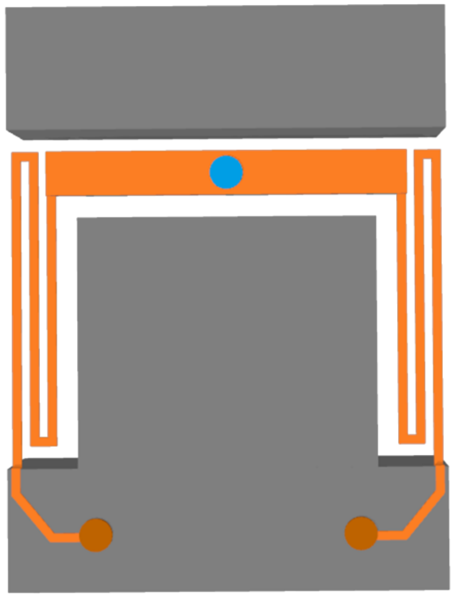
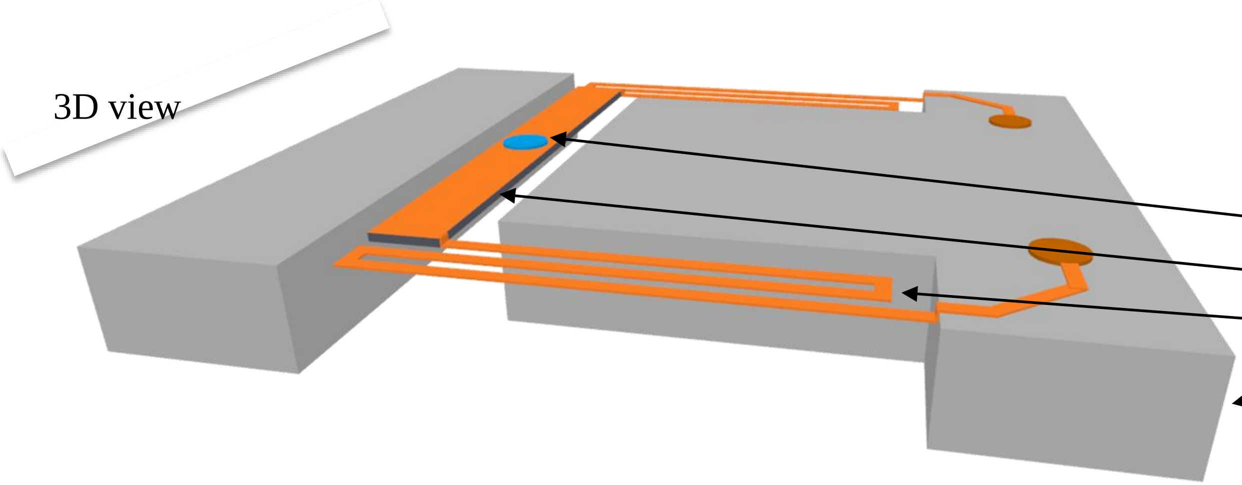



Figure: operation current in different magnetic field computed by $\vec{F} = \vec{i}L \times \vec{B}$

# 5. Actuator Design

Front side view






**Thickness**

- Pillar: 15 µm
- Crossbar: 25 µm
- Spring: 6 µm
- Handle layer: 300 µm