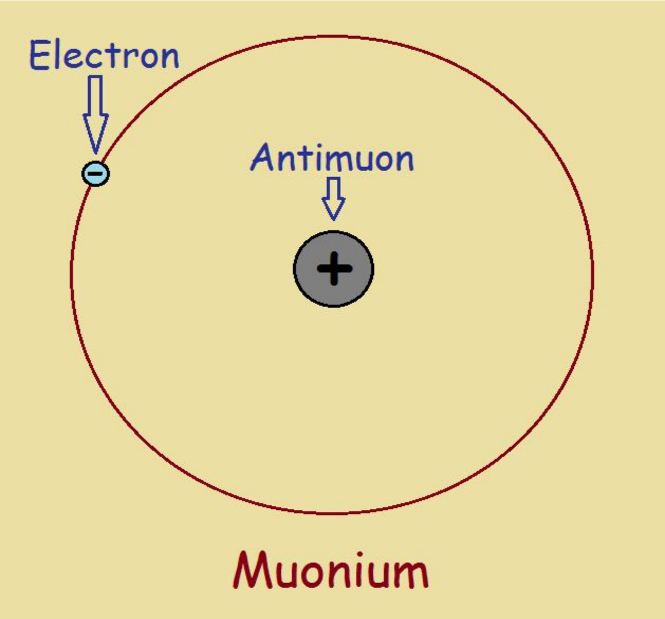
# IPRO 497 - 204: Antimatter Gravity Interferometer

FINAL PRESENTATION

NOVEMBER 21, 2019

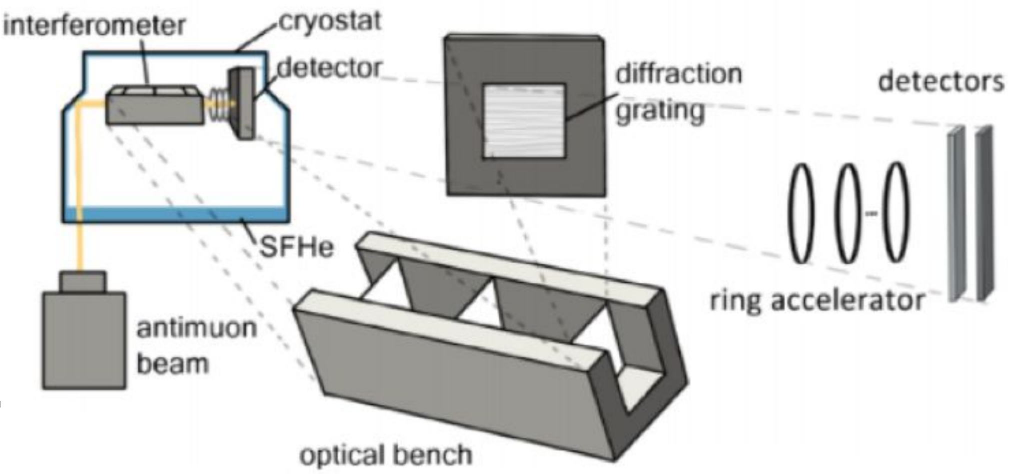
# Introduction

- Gravitational acceleration of antimatter - not directly measured
- Goal: measure gravity of muonium through interferometer
- Solve problems about dark energy & dark matter



# Process

1. Antimuon beam enters cryostat
2. Some antimuons converted to muonium in SFHe
3. Beam reflected into the interferometer
4. Beam diffracted by gratings
5. Pattern sampled by detector

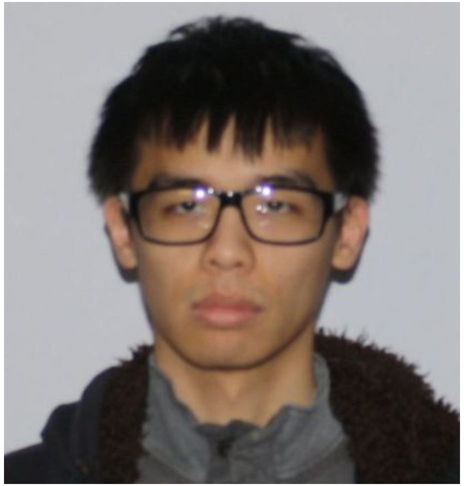


# The Team

Optical Simulation Team

Henry Post - ITM ‘19

Michael Elnajami - CS ‘20



Andy Fung - CS ‘21

# The Team

Mechanical Team - Flex Hinges & Nanogratings

Matt Dubiel - MMAE ‘20

Seth Graham - MMAE ‘21

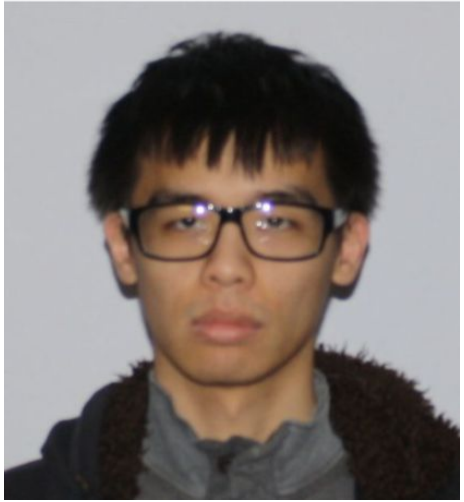
Pranoy Roy - PSYCH, MMAE ‘20

# The Team

X-Ray Calibration

Public Outreach

Brack Turner - CS ‘21



Andy Fung - CS ‘21

Pranoy Roy - PSYCH, MMAE ‘20

# Optical Simulation

# Background

- We are using 2D optics simulation code from previous team
- Code estimates what an interference pattern may look like
  - Simulate propagation of waves through one-dimensional gratings
  - Code uses the Huygens-Fresnel principle to perform the calculations to generate a diffraction pattern

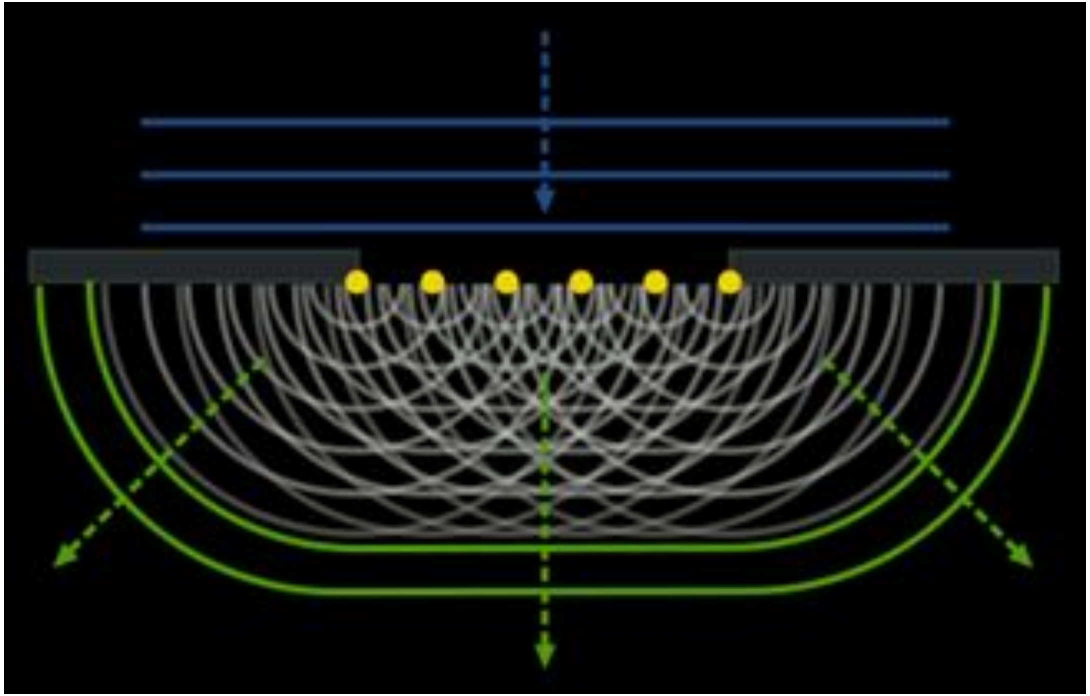
# Huygens-Fresnel Principle



- Reasons for using Huygens-Fresnel principle:
  - Employs a brute force calculation that is viable due to available computing power
    - Can handle arbitrary geometries
      - Allows for non-trivial variations in diffraction like effect of gravity or defects within the grating

# Huygens-Fresnel Principle





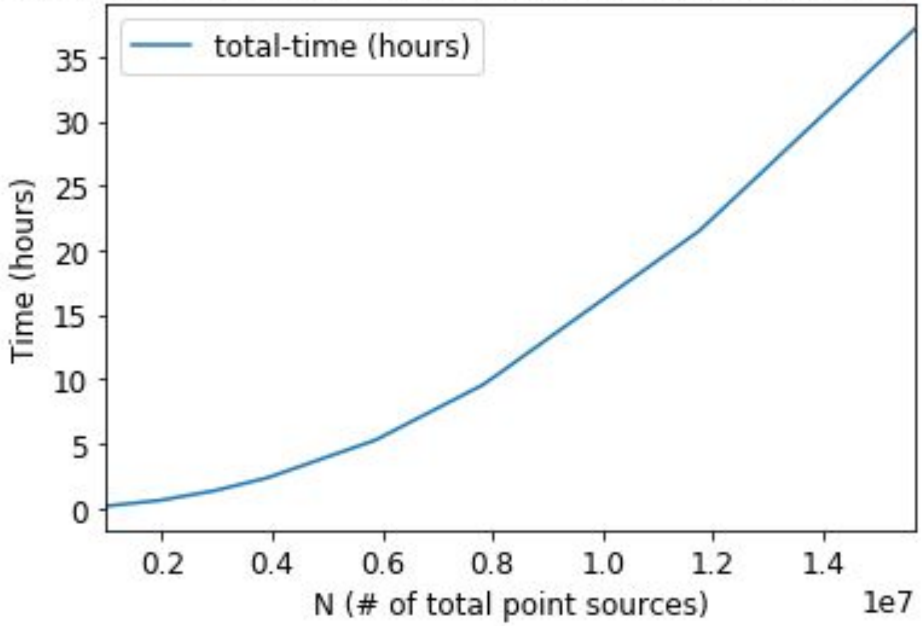
# Initial Goals

- Decrease runtime of simulation
  - Parallelize more parts of algorithm
  - Identify sub-algorithms that take the longest time
  - Attempt to correct those algorithms
- Allow gratings to be procedurally generated/pseudo-random
- Make simulation 3-dimensional

# Analyzing Runtime

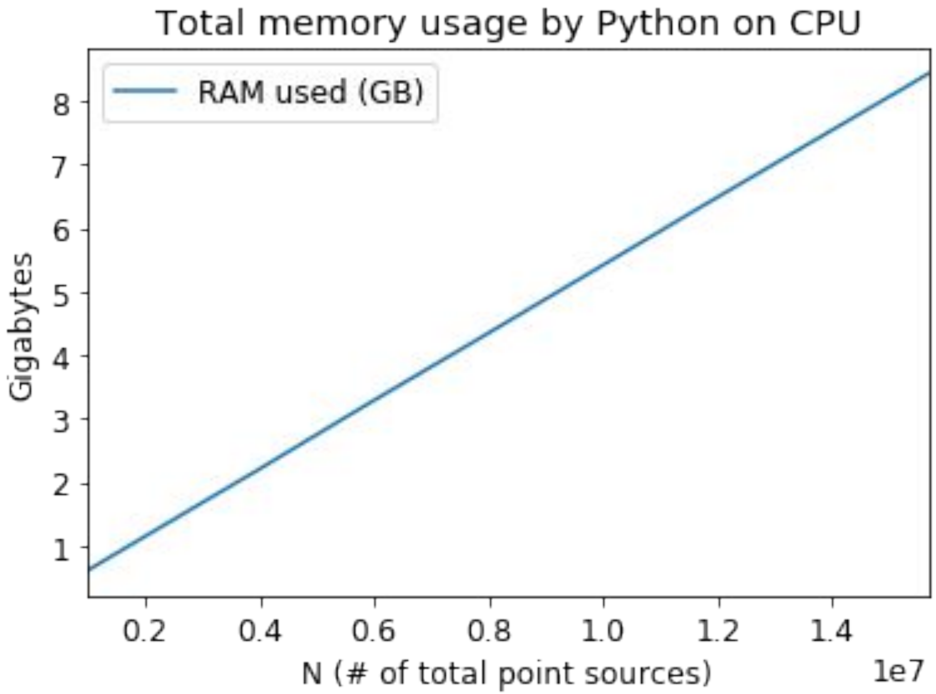
- Diagnosing performance is required to optimize an algorithm
  - CPU usage
  - VRAM usage
  - Memory usage
- We found that runtime scales $O(N^2)$ as a function of point sources used
- We also found that VRAM usage scales linearly as a function of point sources used

# Analyzing Runtime




| N (# of total point sources) | total-time (hours) |
|---|---|
| 980000 | 0.142171 |
| 1960000 | 0.585482 |
| 2940000 | 1.320947 |
| 3920000 | 2.345460 |
| 5880000 | 5.268576 |
| 7840000 | 9.575953 |
| 11760000 | 21.491627 |
| 15680000 | 37.175367 |

# Analyzing Runtime

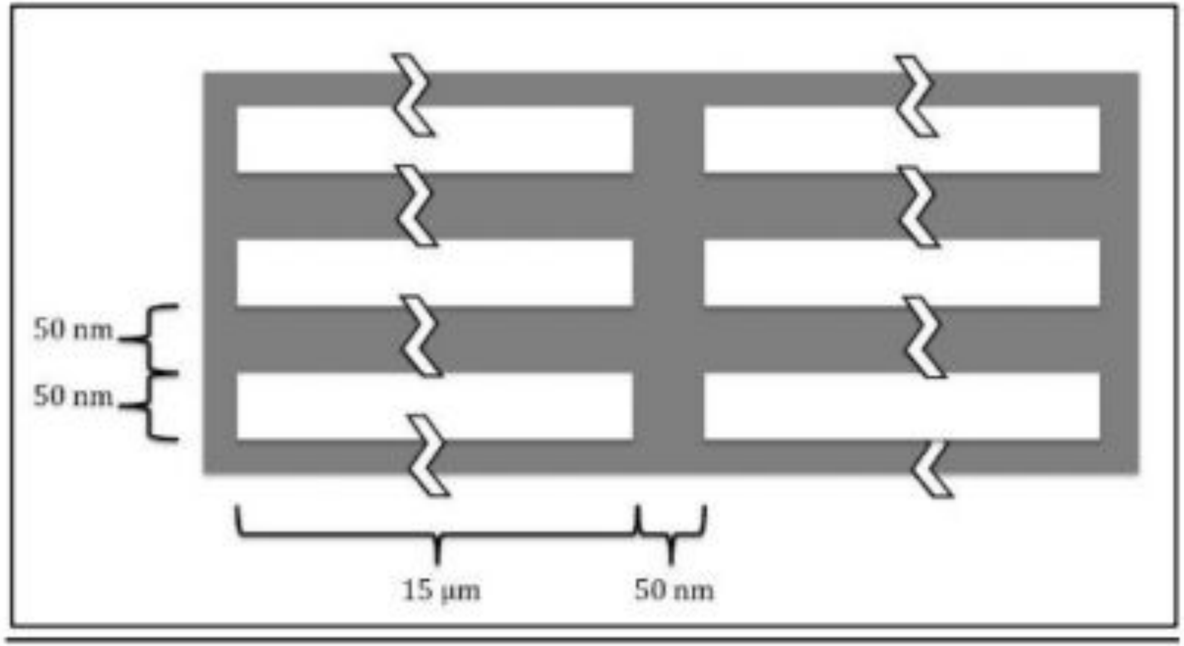



| N (# of total point sources) | RAM used (GB) |
|---|---|
| 980000 | 0.599099 |
| 1960000 | 1.121924 |
| 2940000 | 1.643728 |
| 3920000 | 2.162176 |
| 5880000 | 3.223385 |
| 7840000 | 4.260962 |
| 11760000 | 6.360155 |
| 15680000 | 8.429974 |

# Parameter Optimization

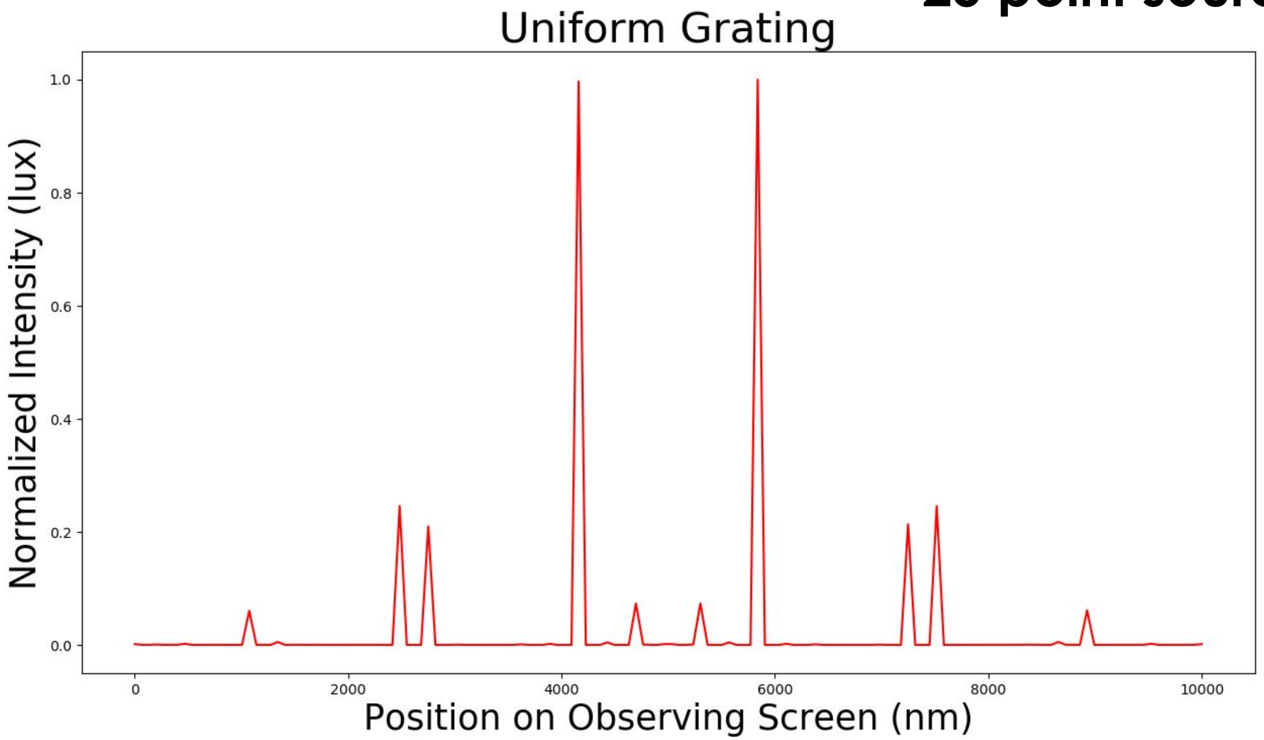
- ❑ Ran the simulation with varying source point parameters
  - ❑ When trends in results stop changing is indicative of the most accurate results
  - ❑ Ideal testing parameter
    - ❑ Increase in source points would not yield more accurate or different results
- ❑ Intensity graph stops changing at about 300 source points per slit length

# Parameter Optimization



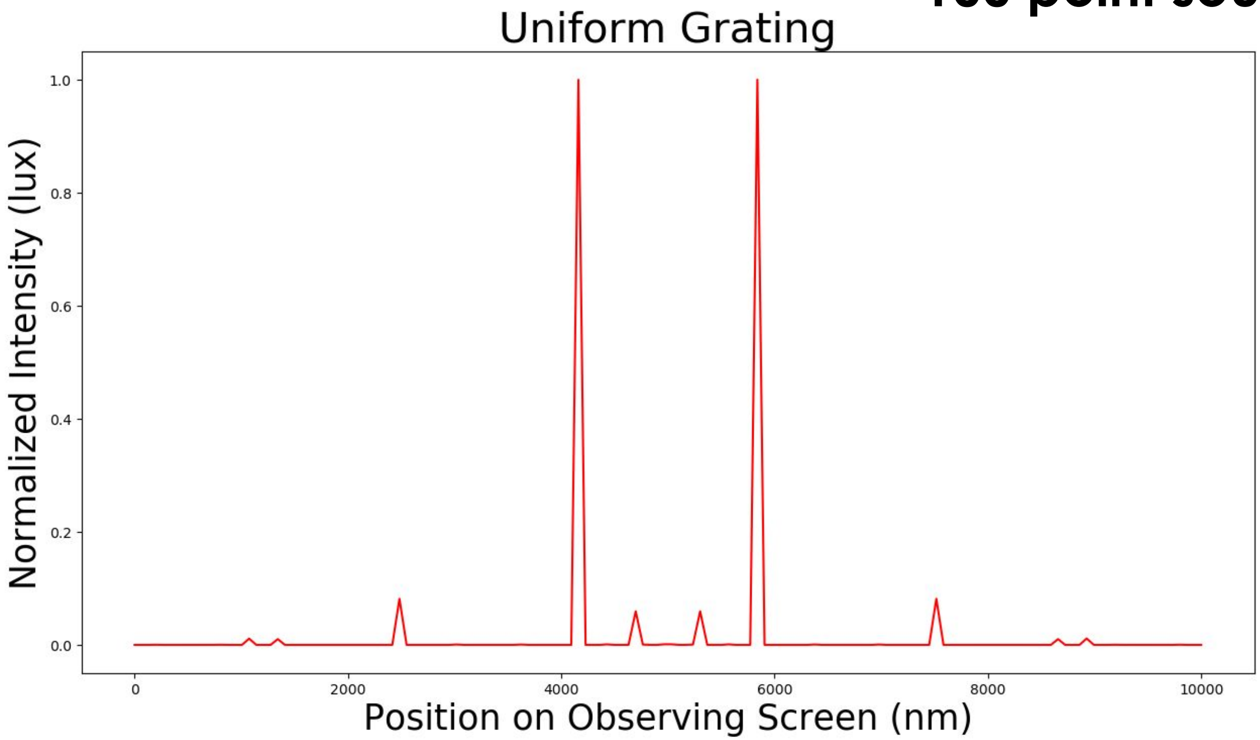
# Parameter Optimization

**25 point sources**



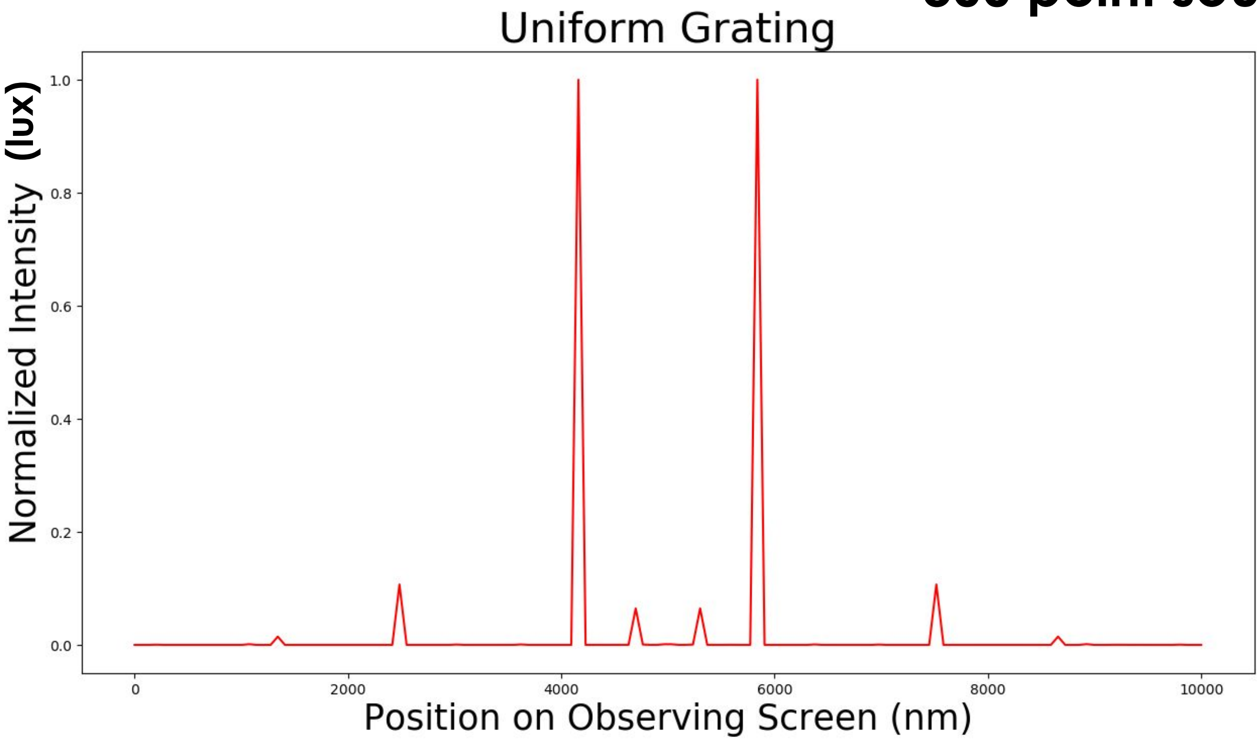
# Parameter Optimization

**100 point sources**



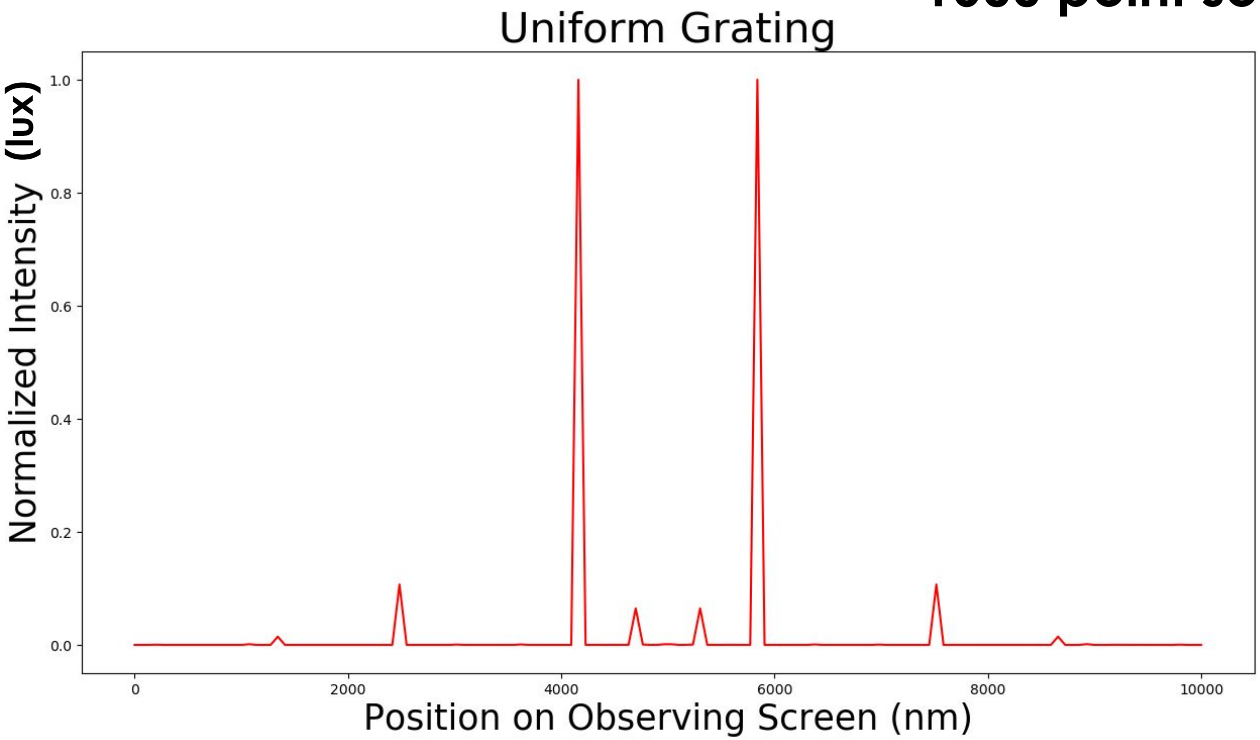
# Parameter Optimization

**300 point sources**



# Parameter Optimization

**1600 point sources**



# Identifying Realistic Parameters

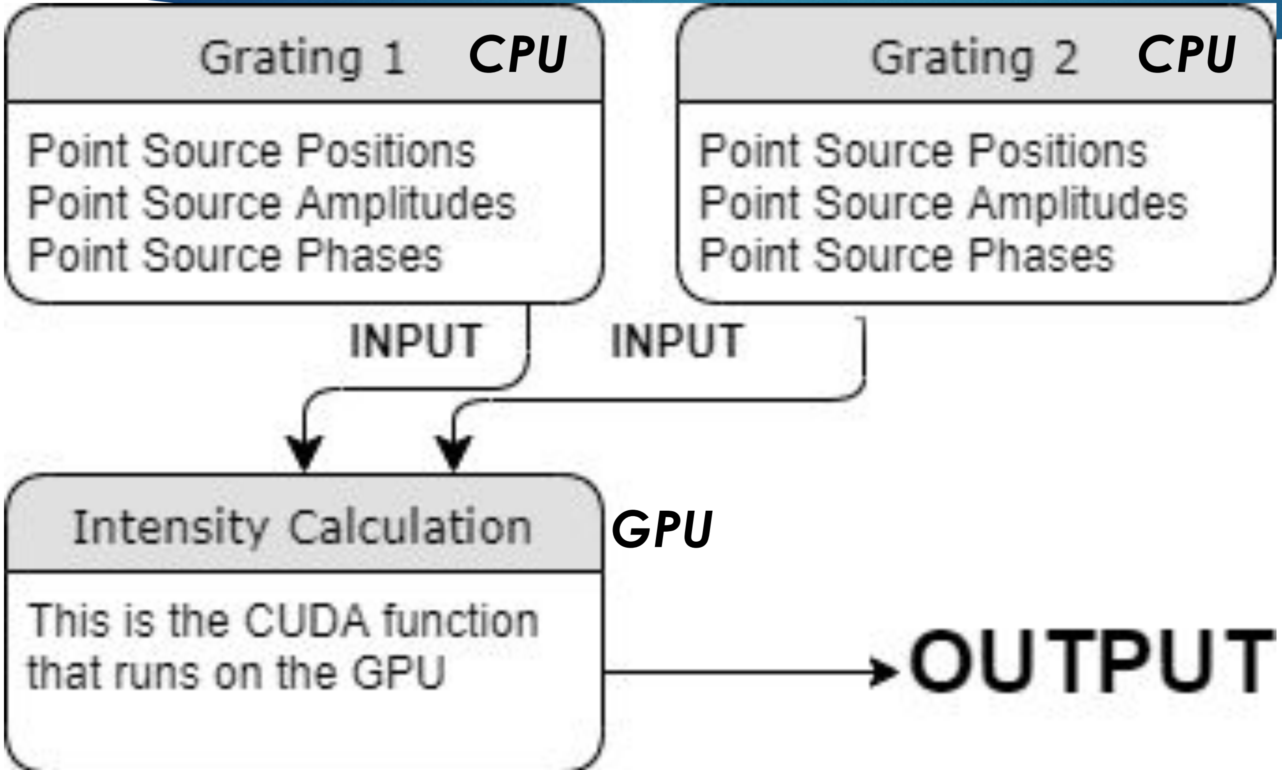
| | |
|---|---|
| Source points per slit | 300 |
| Slit length | 150um |
| Slit width | 50nm |
| Total Slits | 66,399,336 |

- The right parameters are crucial in understanding what kind of runtime the simulation has

# Input Data Generation

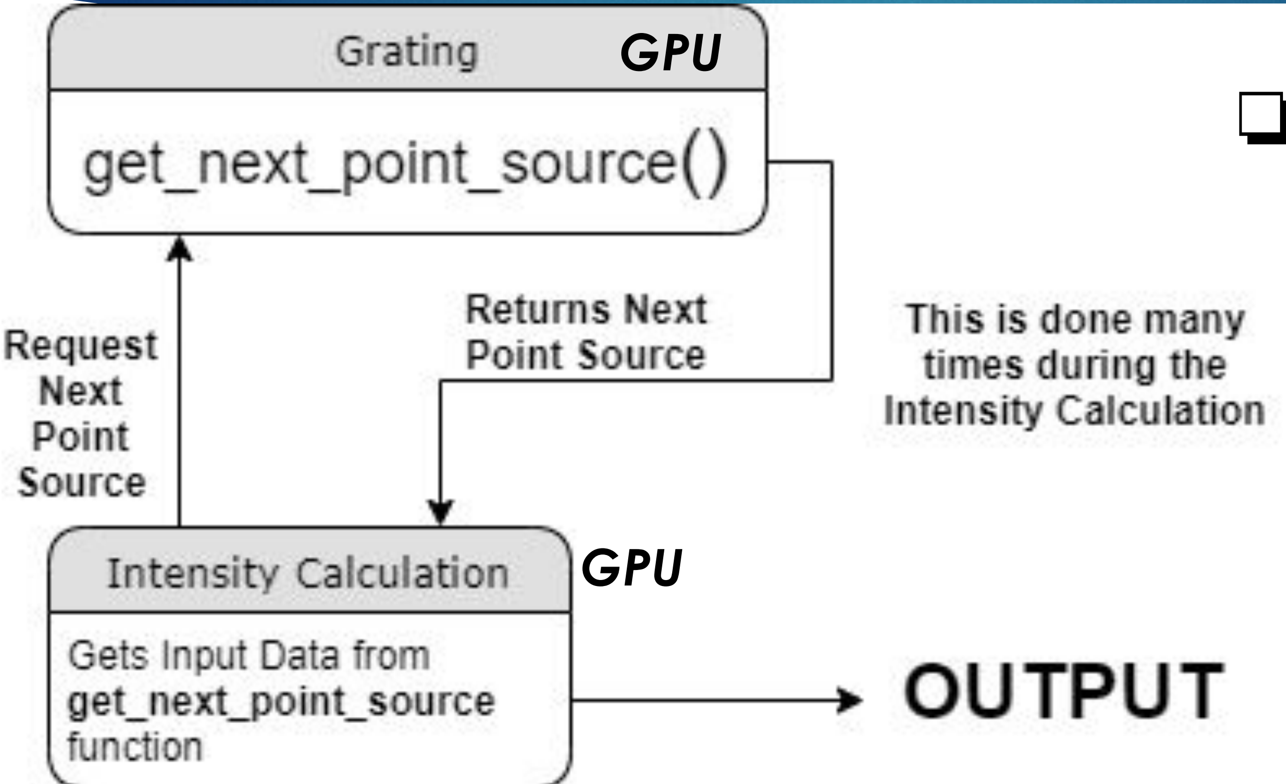
- Issue in how data is passed
  - Huge amount of data needs to be passed into the CUDA kernel function and stored on the GPU
- Possible solution by generating data on GPU as it is being requested

# Input Data Generation




- Objects that the gratings generate to pass to the CUDA function
  - Positions
  - Amplitudes
  - Phases

# Input Data Generation




- This shows the proposed solution where it will generate while the CUDA function is running.

# Generating data on the GPU vs CPU

- Pros of generating data on the GPU
  - GPU memory can be used entirely for output, instead of input
  - Opportunity to rewrite the flawed grating library
- Cons
  - Possible runtime increase
  - It would be difficult to generate arbitrary grating structures and still take advantage of parallel processing to decrease runtime

# Achievements

- Measured and analyzed the simulation runtime and identified multiple bottlenecks
  - Runtime increases $O(N^2)$ as a function of total number of point sources
  - Memory usage in the GPU scales linearly as a function of total number of point sources

# Achievements

- ❑ Identified the lower limit for the number of point sources per slit (300) that still produce realistic diffraction patterns
- ❑ Documented setup, installation, and prior code

# Challenges

- Some code left by last semester was poorly documented making parts hard to understand
- Did not have a full understanding of the physics in the simulation to completely validate the code
- Some terms are used interchangeably for no reason and it makes it confusing
    - i.e. slit length vs slit height

# Future Work

- Allow gratings to be generated in a pseudo-random pattern
- Include outside variables
  - Effect of gravity
  - Incorporation of defective slits

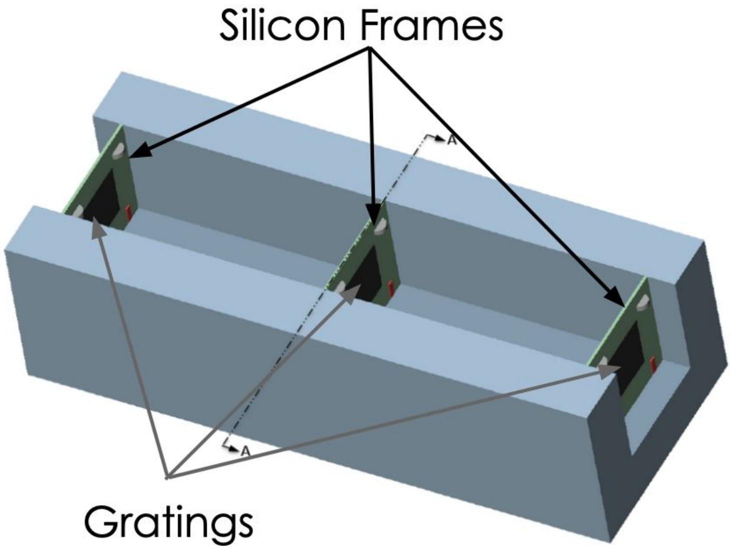
# Future Work

- Consideration in how to optimize the CUDA kernel
  - Methods in storing the output
    - Storing the output solely within the GPU to free up space.
    - Partitioning the results properly before the next calculation

# Flexure Hinges

# Purpose

- Gratings will be mounted within Silicon frames in the interferometer
- Frames need to be able to move gratings for alignment
    - 2 Rotational
    - 1 Translation
- Flexure hinges incorporated into frames allow for precise controlled movement

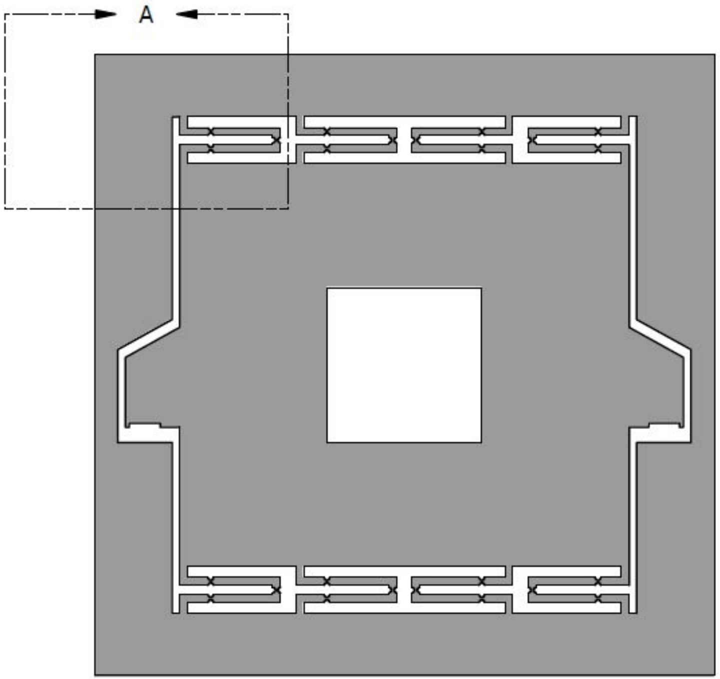


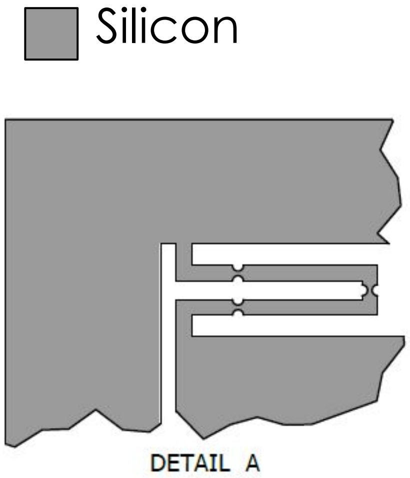
# Objective

- Previous group developed translational design with 3-notch hinges
- Adapt 3-notch design to work in a rotational design
- Achieve 0.5 degrees of rotation with a maximum of 5 N applied force from piezos

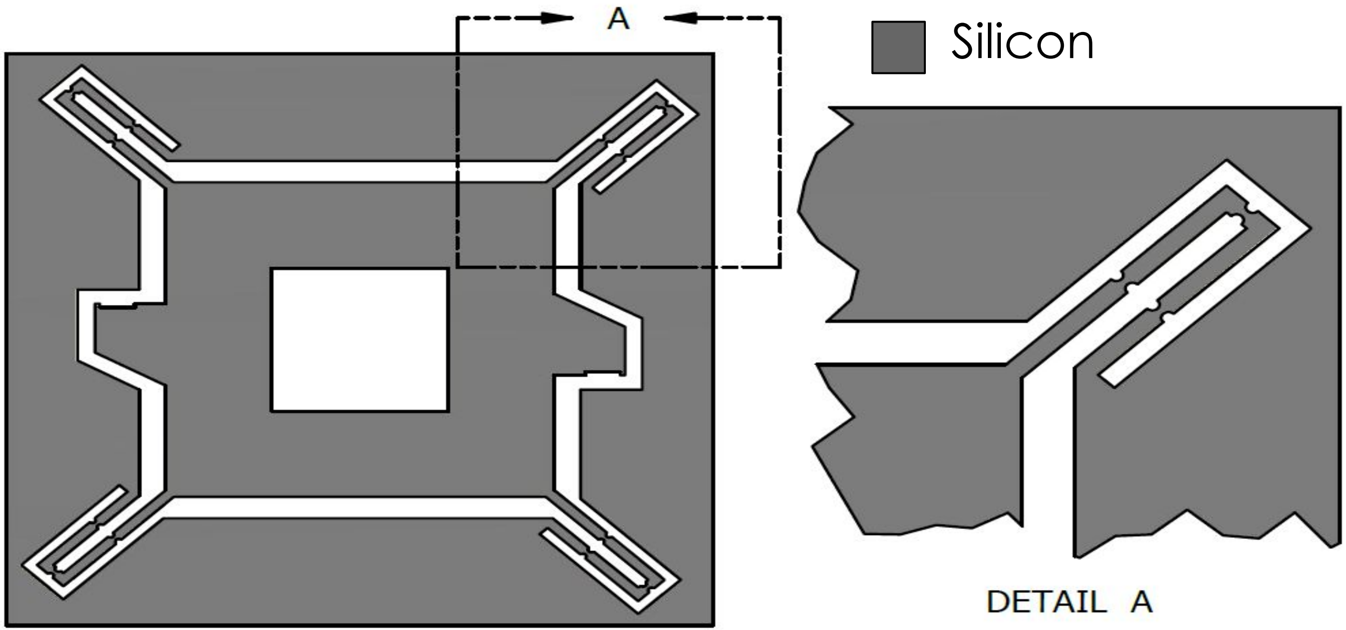
# Translational Design

(Previous Semester)



# Rotational Design



# Analytical Model

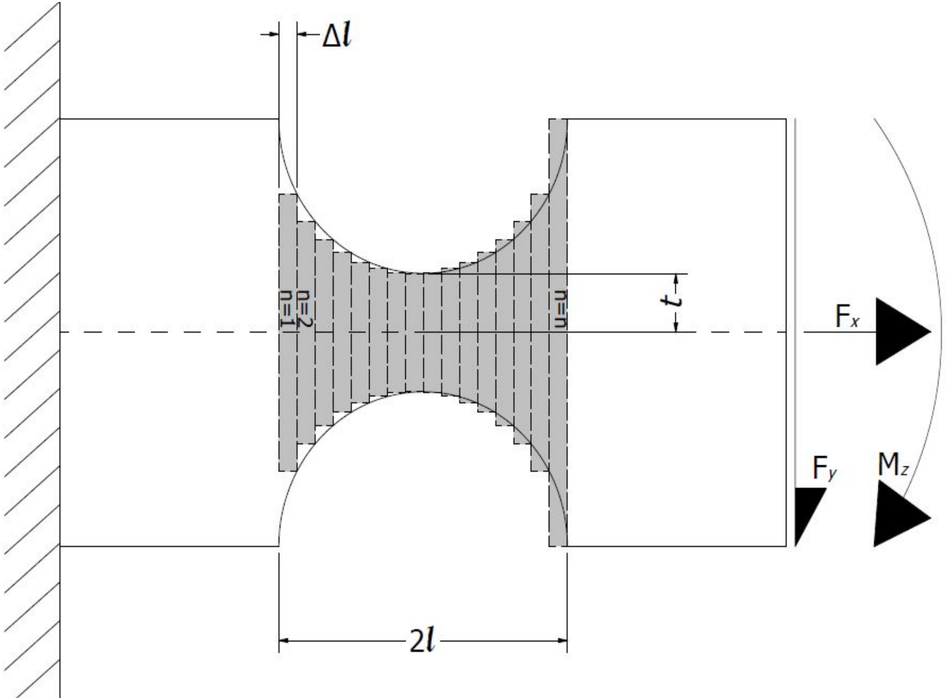
- Single notch hinges commonly modeled as cantilevers
- Cannot model 3 notch design as cantilever

Deflection Equations

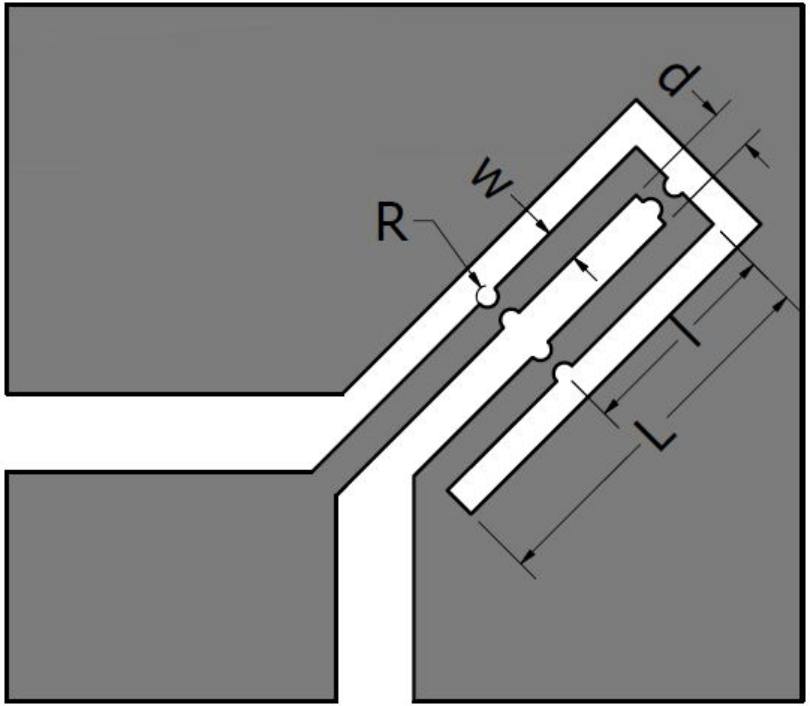
$$u_n = \frac{F_x \Delta l}{Ebt(n\Delta l)}$$

$$v_n = \frac{6[M_z + F_y(2l - n\Delta l)]\Delta l^2}{Ebt^3(n\Delta l)} + \frac{4F_y \Delta l^3}{Ebt^3(n\Delta l)}$$

$$\alpha_n = \frac{12[M_z + F_y(2l - n\Delta l)]\Delta l}{Ebt^3(n\Delta l)} + \frac{6F_y \Delta l^2}{Ebt^3(n\Delta l)}$$

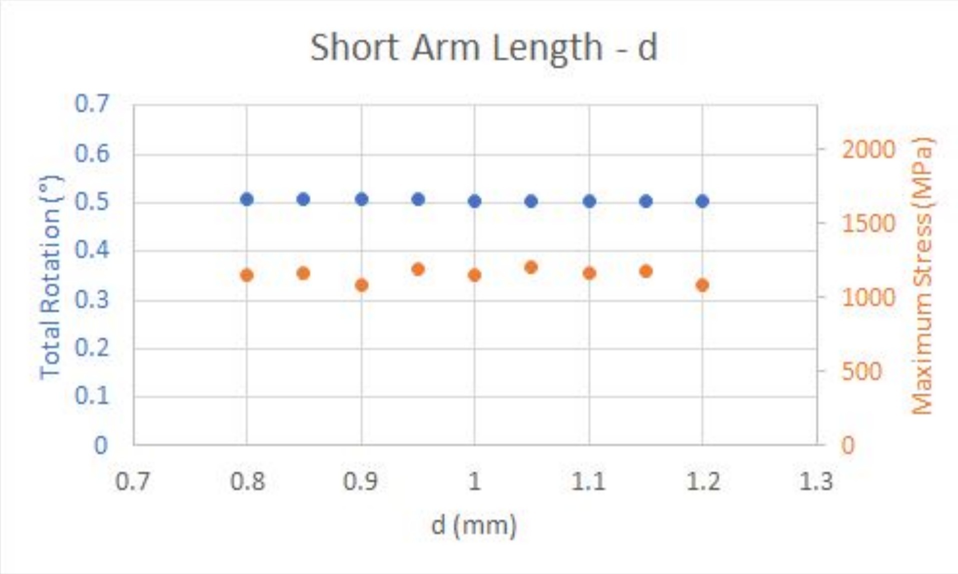


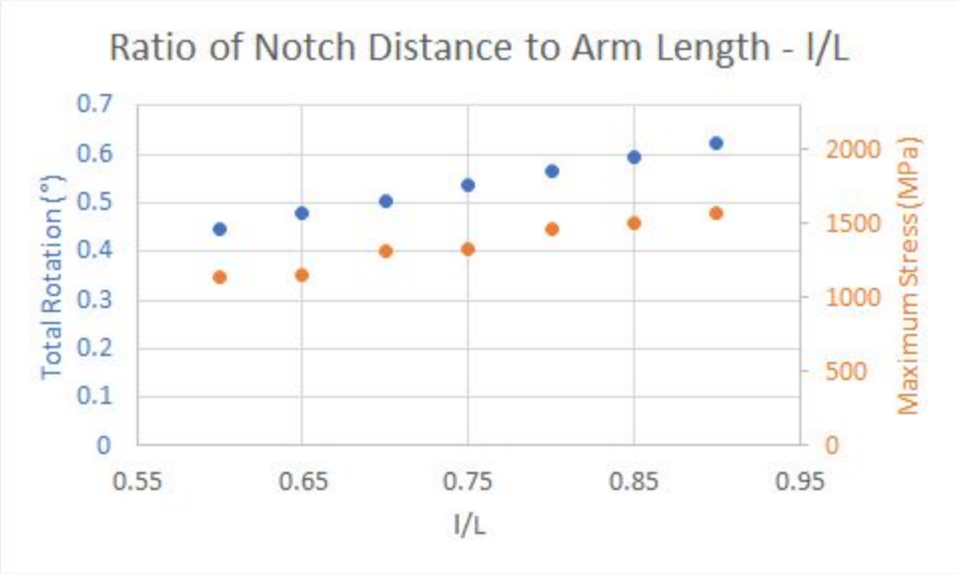
# Parameterization



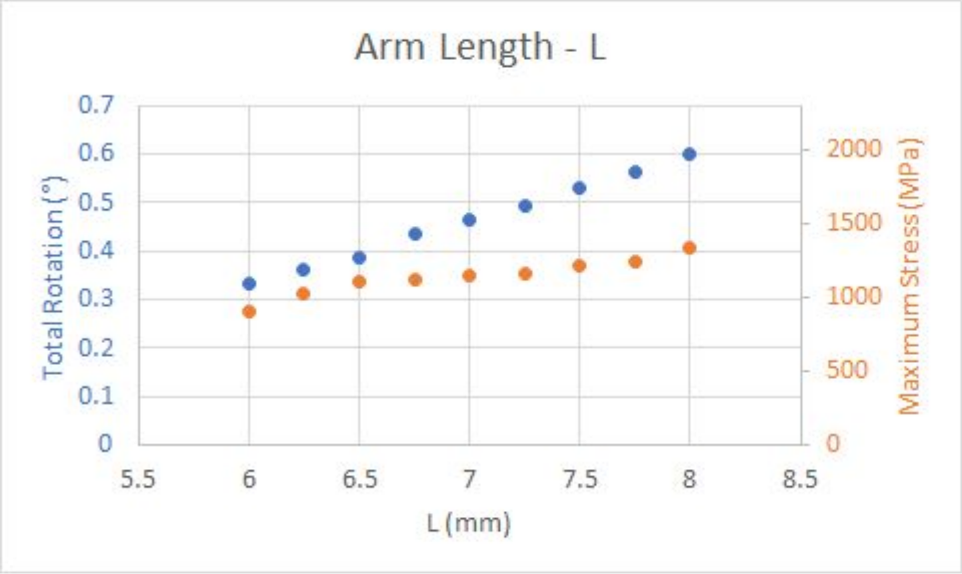

- Examine 5 different parameters
- Manipulate these parameters to achieve desired amount of rotation
- Silicon crystal orientation is held constant

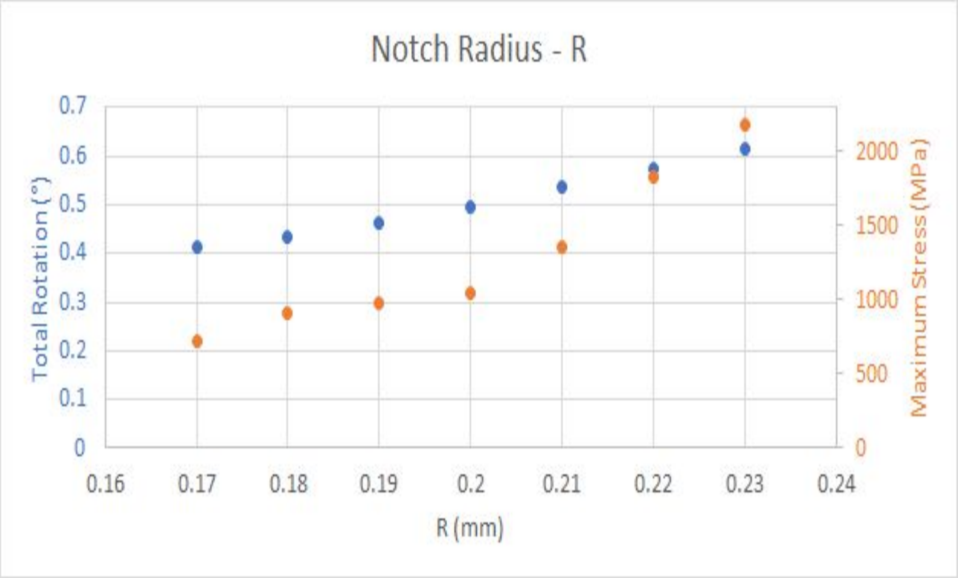
# ANSYS FEA Results



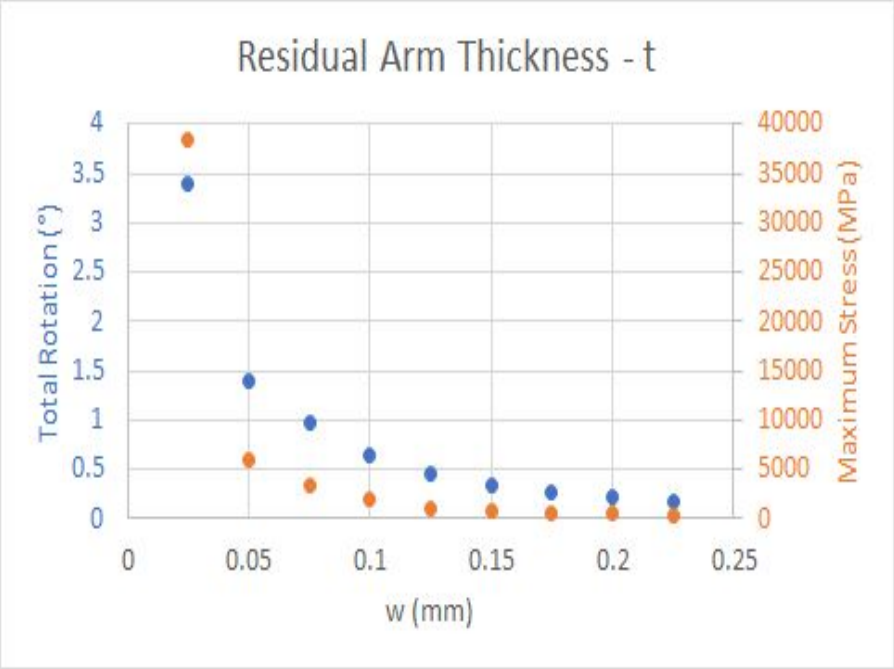



# ANSYS FEA Results



# ANSYS FEA Results




- Relations are linear except for residual arm thickness
- Residual arm thickness follows non-linear relation similar to model

$$\alpha_n = \frac{12[M_z + F_y(2l - n\Delta l)]\Delta l}{Ebt^3(n\Delta l)} + \frac{6F_y\Delta l^2}{Ebt^3(n\Delta l)}$$

# Conclusion

**Final Values**

| Parameter Name | Parameter Variable | Final Value |
|---|---|---|
| Notch Radius | R | 0.21 mm |
| Arm Length | L | 7.25 mm |
| Notch Distance | l | 70 % |
| Short Arm Length | d | 0.80 mm |
| Width | w | 0.65 mm |

- Hinges achieve 0.51° of rotation with 1151 MPa maximum stress at 5 N applied force
- Single crystal silicon yield strength as high as 7000 MPa but can be drastically reduced during manufacturing
- Arm thickness, notch radius, and arm length have largest effect on rotation
- Short Arm length has very little effect

# Future Work

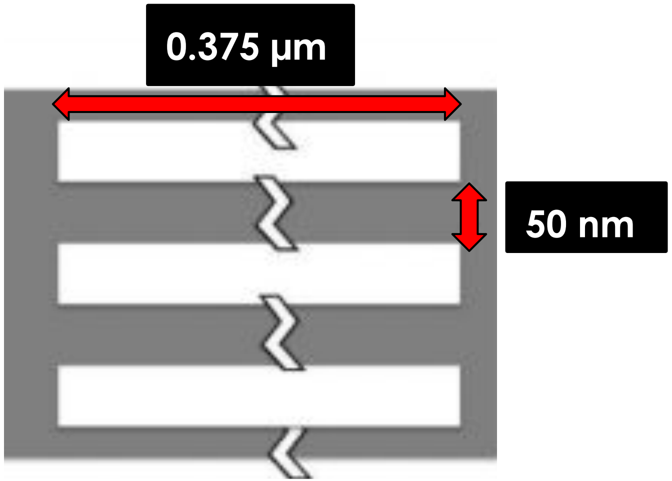
- ❑ Current system is idealized
- ❑ Measure the effects of unequal applied forces from piezo actuators
- ❑ Analyze out of plane deflection, potential for piezos to be misaligned
- ❑ Vary crystal orientation

# Nanogratings

# Initial Goals

- ❑ Run random vibrational analysis with ANSYS
- ❑ Interpret results
- ❑ Relate results to the design of nanogratings

# Cantilever Beam




- Modeled cantilever beam with a fixed end and a free end.
- Used dimensions of a grating strut from CAD file
- Thickness is two times grating height (2*50nm).

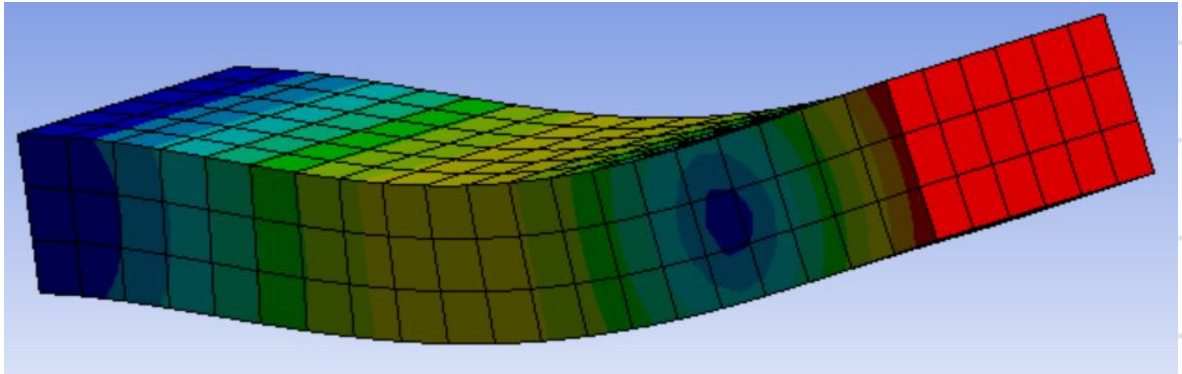
# Material Used

- Silicon Nitride
  - High temperature strength
  - Mechanical Fatigue resistance

# Cantilever Beam

# Cantilever Beam

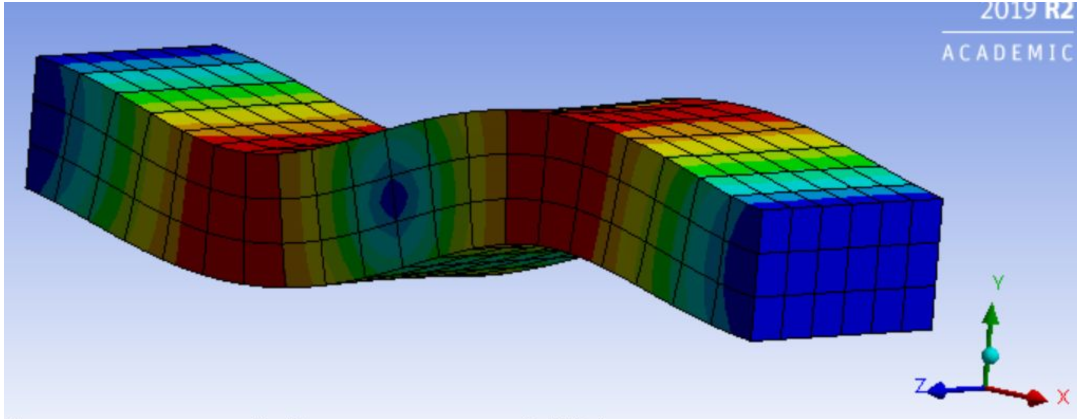
- Natural frequencies of beam:



| Frequency (Hz) |
|---|
| 5.56E+08 |
| 1.07E+09 |
| 3.14E+09 |
| 3.24E+09 |
| 5.34E+09 |
| 6.51E+09 |

# Cantilever Beam

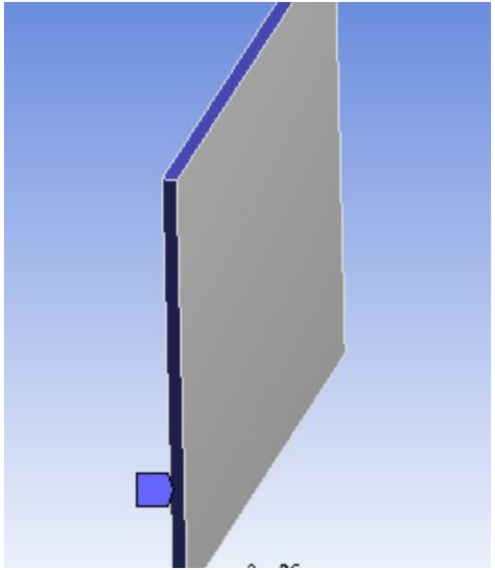
- Two fixed ends:




| Frequency (Hz) |
|---|
| 3.25E+09 |
| 5.07E+09 |
| 6.48E+09 |
| 8.04E+09 |

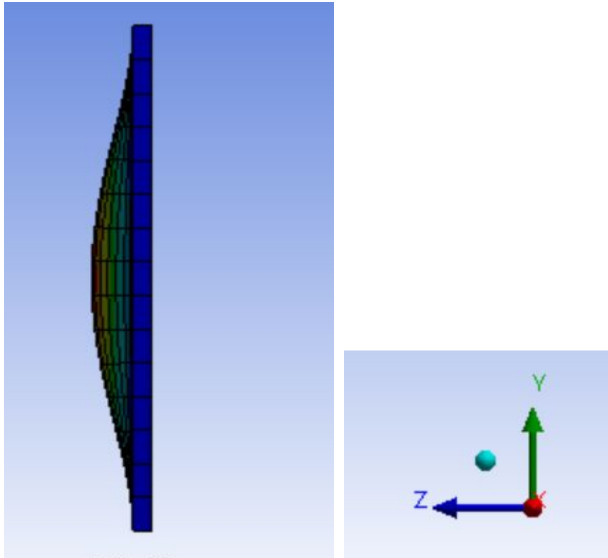
# Vibration Modes

- Modeled grating structure with no slits. (Fixed frame as Boundary Condition).
- Natural frequencies agree with Cantilever beam.



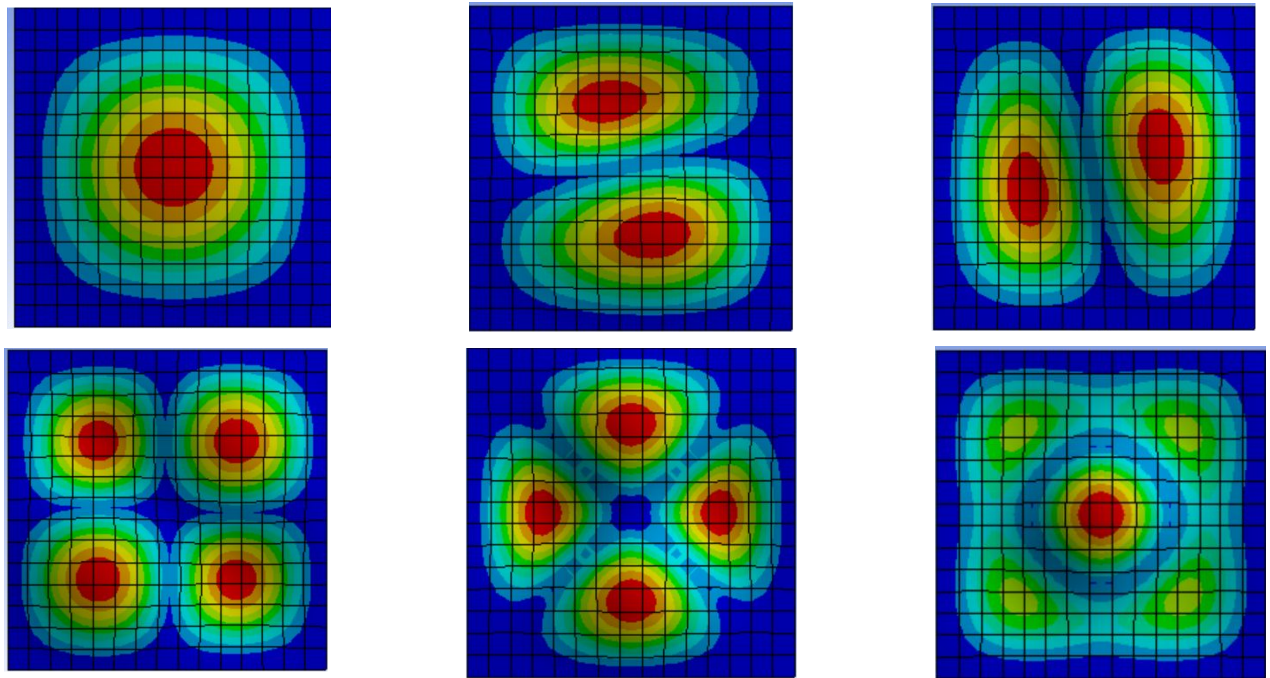
# Test Film





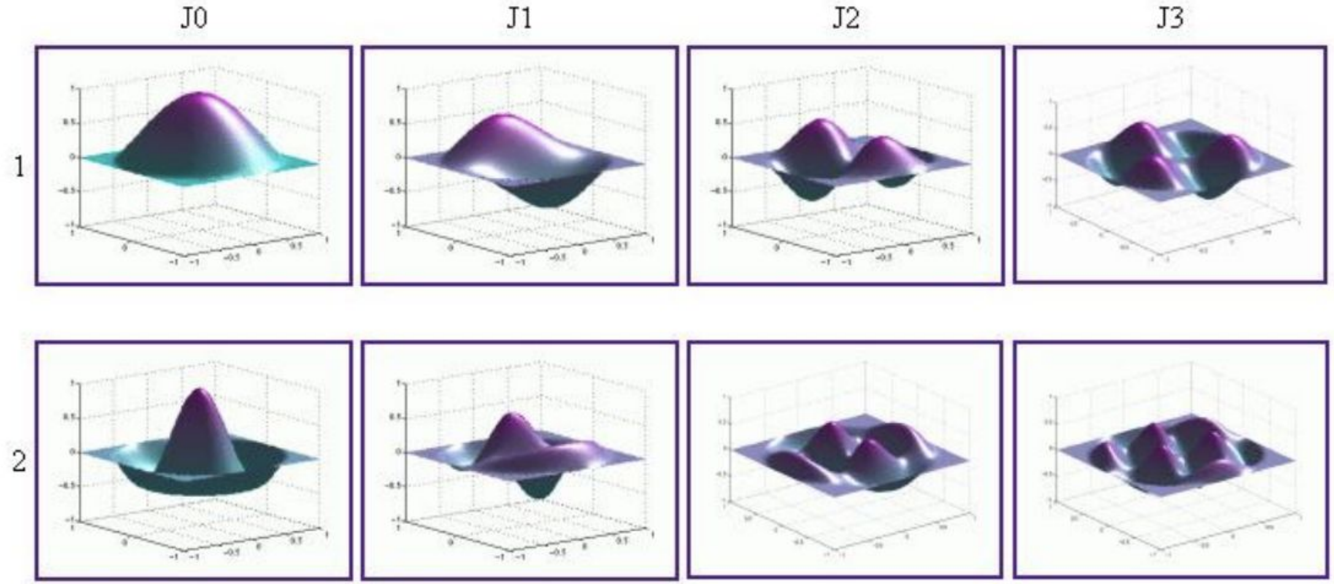

| Frequency (Hz) |
|---|
| 1.67E+08 |
| 3.38E+08 |
| 3.38E+08 |
| 4.95E+08 |
| 6.00E+08 |
| 6.03E+08 |

# Vibration Modes



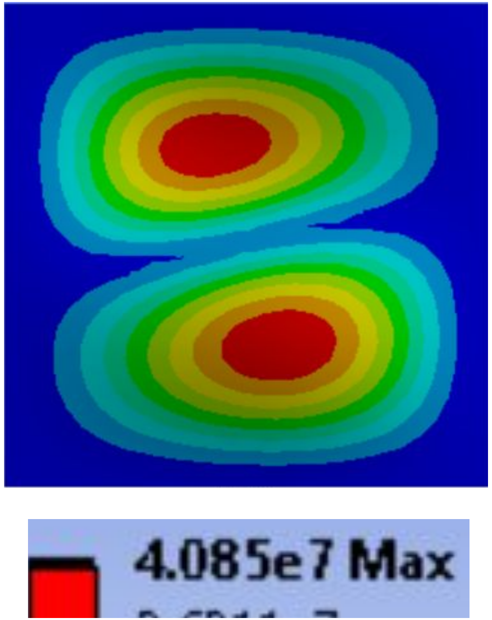
# Vibration Modes



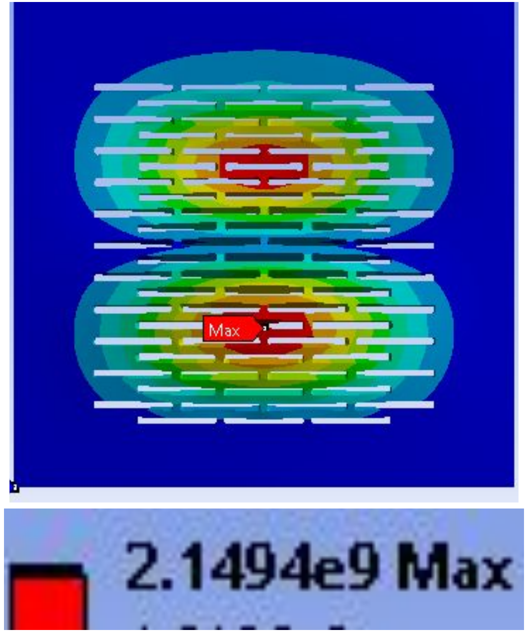


# Mode 2 Comparison

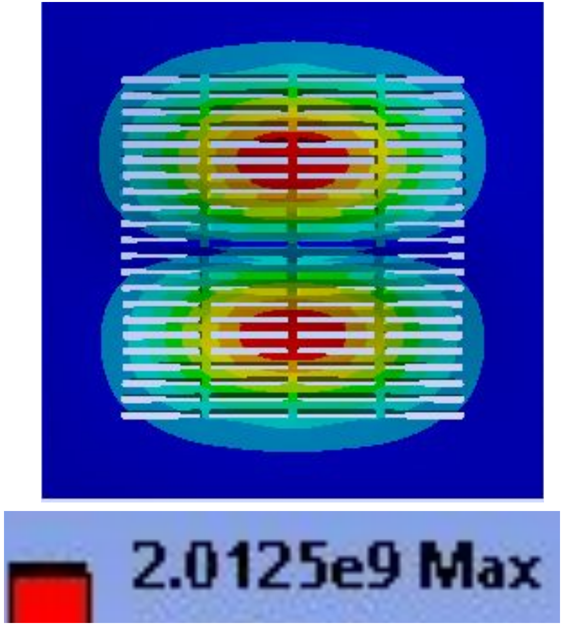
**Test Film (Student)**




**Ashlar (Full)**




**Columnar (Full)**

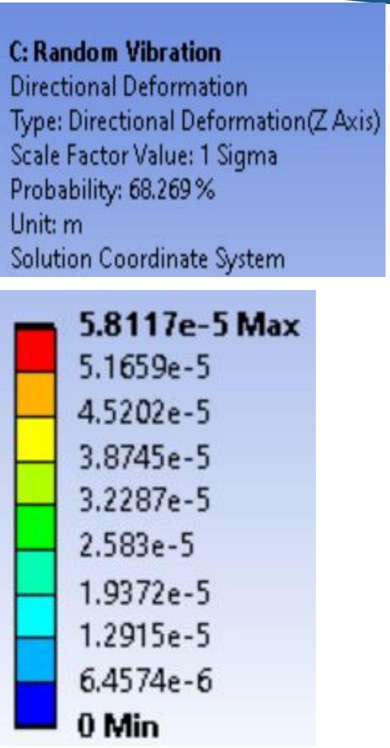


# Natural Frequencies (Hz)

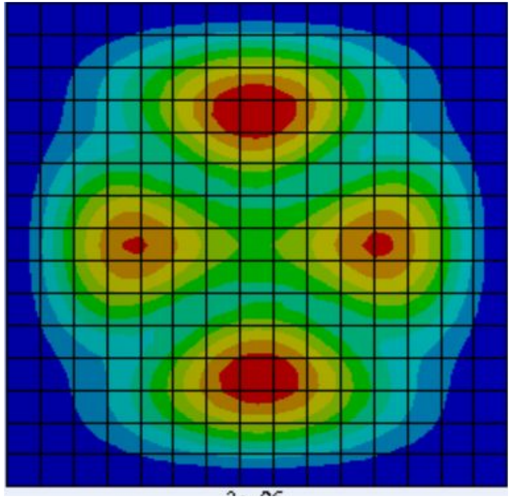


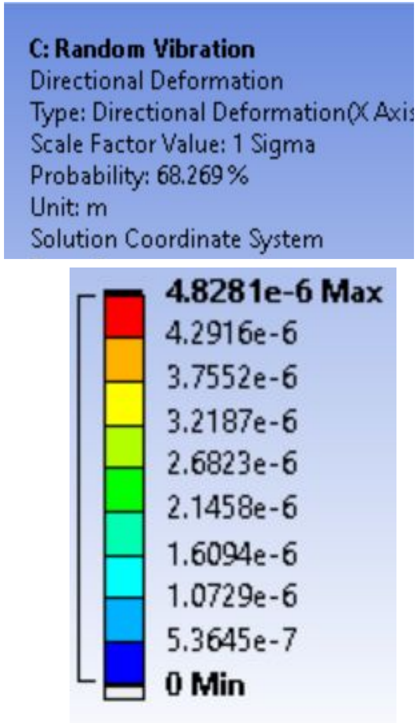
| C. Beam (1 Fixed) | C. Beam (2 Fixed) | Test Film | Ashlar | Columnar |
|---|---|---|---|---|
| 5.56E+08 | 3.25E+09 | 1.67E+08 | 4.60E+09 | 4.83E+09 |
| 1.07E+09 | 5.07E+09 | 3.38E+08 | 6.67E+09 | 7.88E+09 |
| 3.14E+09 | 6.48E+09 | 3.38E+08 | 9.45E+09 | |
| 3.24E+09 | 8.04E+09 | 4.95E+08 | | |
| 5.34E+09 | | 6.00E+08 | | |
| 6.51E+09 | | 6.03E+08 | | |

# Directional Deformation

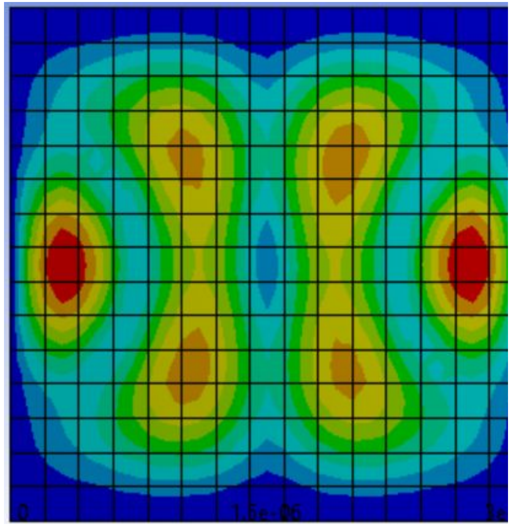


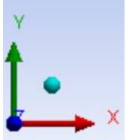

Z-Direction (m)






X-Direction (m)





# Accomplishments

- Determined the range of natural frequencies for nanograting structures.
  - Done through simulating cantilever beam and film.
- Provided documentation for future semesters on how to proceed.

# Challenges

- ANSYS only displayed >6 frequency modes when solving Modal Analysis.
- Elapsed Time >> CPU time, need more RAM or better hard drive configuration for all modes to show.

# Future Work

- Secure more RAM/Change hard drive config.
  - Allows Random Vibration analysis on all structures.

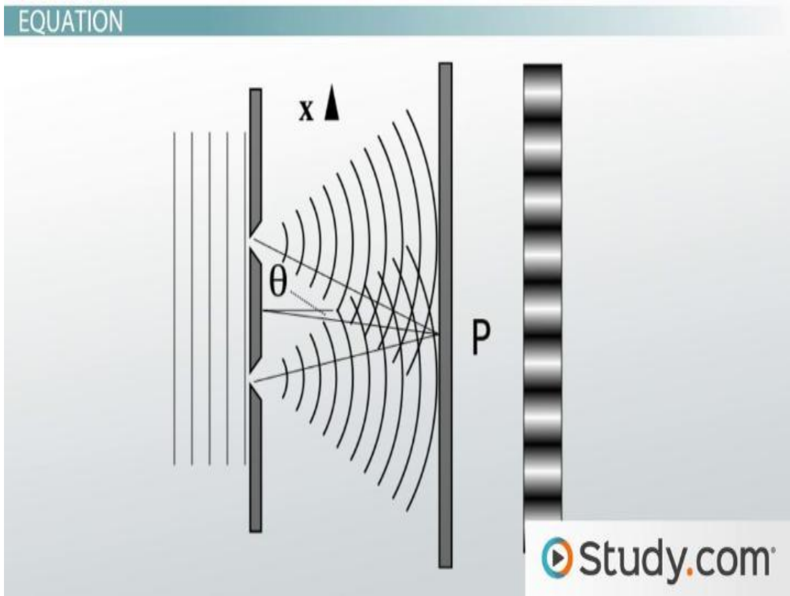
# X-Ray Calibration

# Goals

- Find a suitable code that can effectively simulate a grating rather than a few slits
- Generate a uniform grating that can produce accurate results
- Run an analysis on the diffraction pattern formed

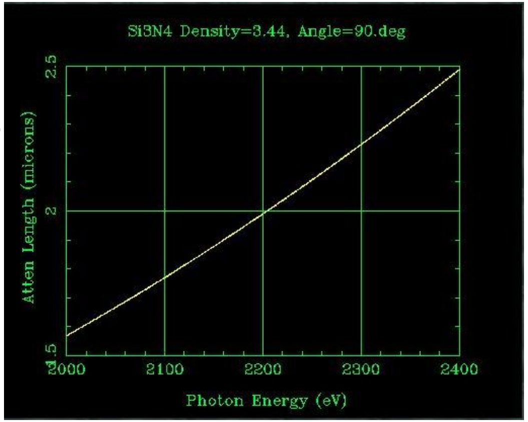
# Background

- X-ray Calibration code from UCL(University College London)
- Simulates x-ray propagation through a two dimensional uniform grating
  - Used to correct misalignment in gratings
  - Simulate properties of a muonium beam



# Attenuation Length

- Parameters are crucial in simulating the right x-ray energy and determining x-ray absorption length
- 2,215 eV is needed to achieve an attenuation length of the proposed 2 microns
- Using Planck's equation, a wavelength of 0.56nm is determined to be suited for our case




$$E = \frac{hc}{\lambda}$$

$E$ = energy

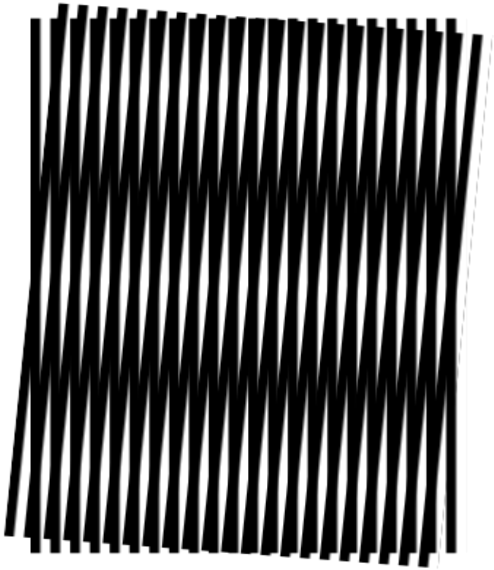
$h$ = Planck's constant

$c$ = speed of light

$\lambda$ = wavelength

# Moire Pattern

- Helps correct misalignment in multiple gratings
- Taking an x-ray image of multiple gratings to observe defects
  - One grating image means it is aligned



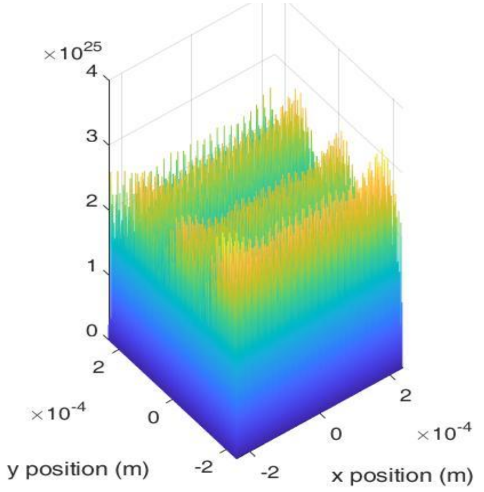
# Analysis of Diffraction Pattern

- Investigated *Wavepy*, a Python library for data analyses of coherence and wavefront measurements at synchrotron beamlines
  - Covers Single-grating Talbot Interferometry analysis
  - Requires TIFF image file to run

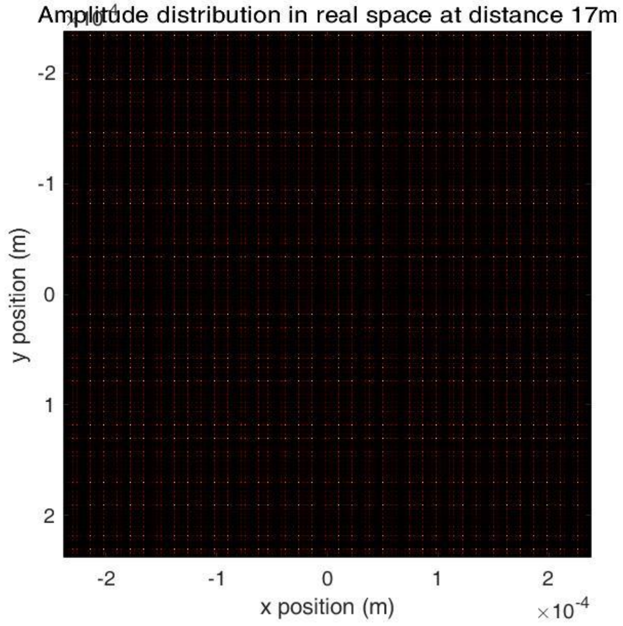
# Simulation of X-ray Propagation

- UCL diffraction code uses Matlab plotting to represent waveforms in the Fourier domain.
- Previous group maxed 10 slits at 100 pixels high
- Increased amount of slits to 51 at 20 pixels high, however grating is not uniform yet

# Intensity Distribution of 51 slits




Intensity Distribution at real space distance of 17m



# Future Work

- Need to account for three dimensional space regarding thickness of the grading
- Make more uniform grating by collaborating with nanogratings group
- Look into *pyXSFW* for a full x-ray simulation code & analysis simultaneously

# Public Outreach

# Purpose

- Raise awareness for work invested in this IPRO
- Raise funding as  result of increased publicity

# Plan/Future Work

- Strategies to raise more awareness
  - Reaching out to engineering groups for an event
  - Create website and brochures summarizing IPRO and impact
- Follow up with strategies and influencing people
- Present to Chicago Society for Space Studies and Adler

# Accomplishments

- Created a website summarizing this IPRO’s work and achievements using Wix
- Created brochures to hand out during events using Adobe Spark
- Created a contact list of people to reach out to plan events

# Future Work

- ❑ Update the website of the work done in the future semester
- ❑ Plan an event with ASME about this IPRO
- ❑ Plan an event with Chicago Society for Space at Adler

# Questions?