Finite Element Analyses of Synchrotron Radiation Induced Stress in Beryllium Synch-Light Mirrors

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IPAC21
12th International Particle Accelerator Conference
Virtual Edition
May 24th-28th, 2021

Introduction

Mirrors made of high purity beryllium are used in particle accelerators to extract synchrotron radiation (SR) in the visible range for transverse and longitudinal particle beam profile measurements. Be is a high-strength, high-thermal-conductivity material. As a low-Z metal, it allows high energy photons to penetrate the mirror body, so that majority of the SR power is dissipated within the bulk or transmitted through, resulting in a significantly reduced thermal strain on the mirror surface. In this paper, we describe a Finite Element Analysis (FEA) method of accurately simulating the SR-induced thermal stress on the beryllium mirrors at the Cornell Electron Storage Ring (CESR) at various particle beam conditions. The simulations consider the energy dependence of X-ray attenuation in beryllium. The simulated surface distortion was confirmed by optical measurements.

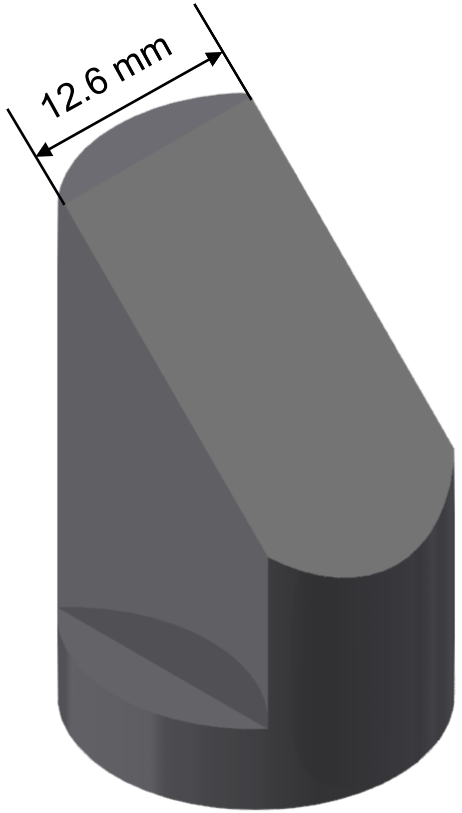

fig 1: Render of a Synch-Light Be mirror. The beryllium is I-70H grade polished to 1/10 λ at 500 nm.

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CESR Synch-Light Mirrors

- Mirror surfaces at a 45^{o} angle to the direction of positron beam propagation; reflects visible light at a right angle.
- Mirrors are retractable via motor and water-cooled.
- Used to observe the transverse and longitudinal beam sizes for CESR.
  - SR from a magnet with a bending radius R of 140.6 m.
  - 34.0 W of incident SR power from 100 mA stored at 6.0 GeV.
- Used for alignment of the Optical Stochastic Cooling (OSC) experiment.
  - SR from a magnet with a bending radius of 58.6 m.
  - 84.9 W of incident SR power from 100 mA stored at 6.0 GeV.
- We needed to set the maximum operational beam current that would not damage the mirror surface as well as understand the relationship between beam current and mirror surface deformation for optical measurements.

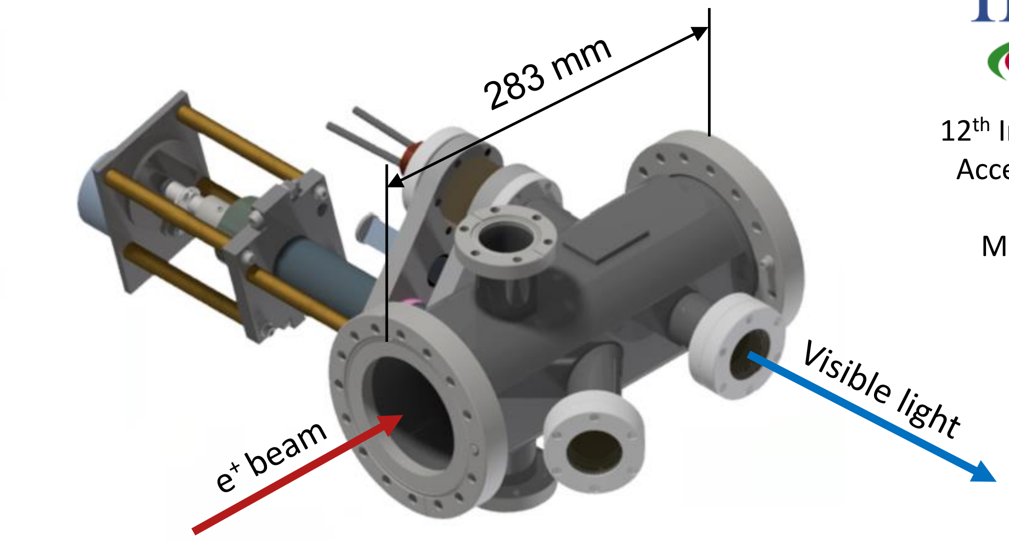

fig 2: Render of the CESR Synch-Light vacuum chamber.

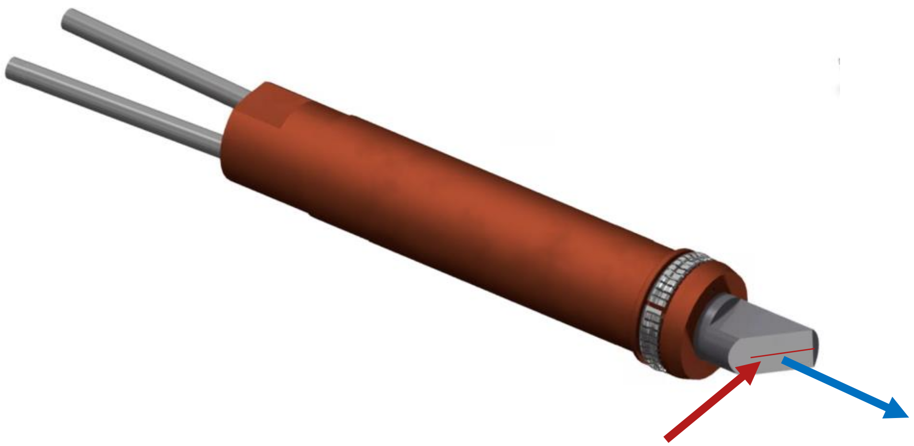

fig 3: Render of a Synch-Light Be mirror with a cooled mirror mount and RF fingers. The red stripe gives the approximal dimensions and location of the SR strip.

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Determining the SR power distribution

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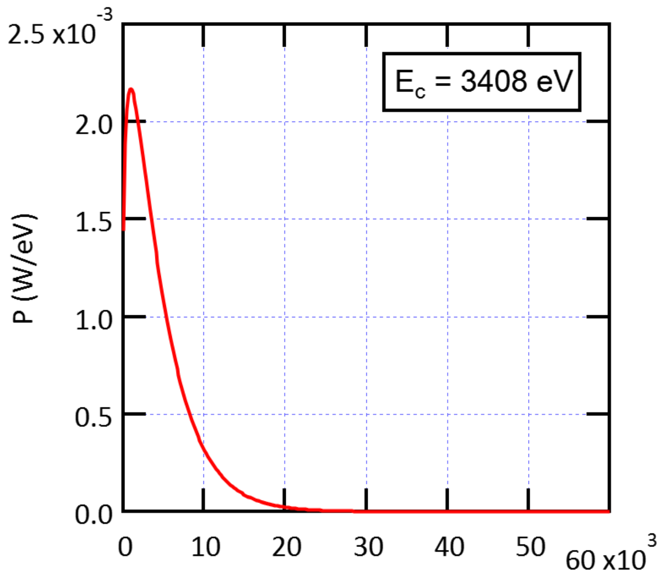

fig 4: Spectral power distribution of SR from a R = 140.6-m magnet with 100 mA stored at 6 GeV.

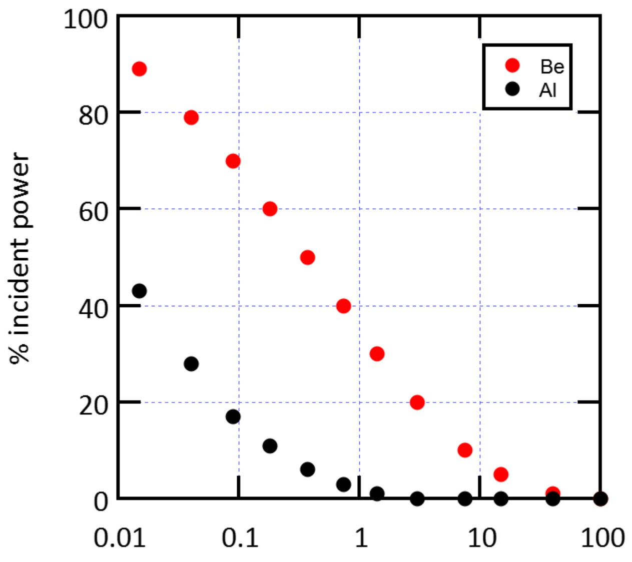

fig 5: A comparison of magnet SR transmission in beryllium and aluminum. The SR is from a R = 140.6-m bending magnet.

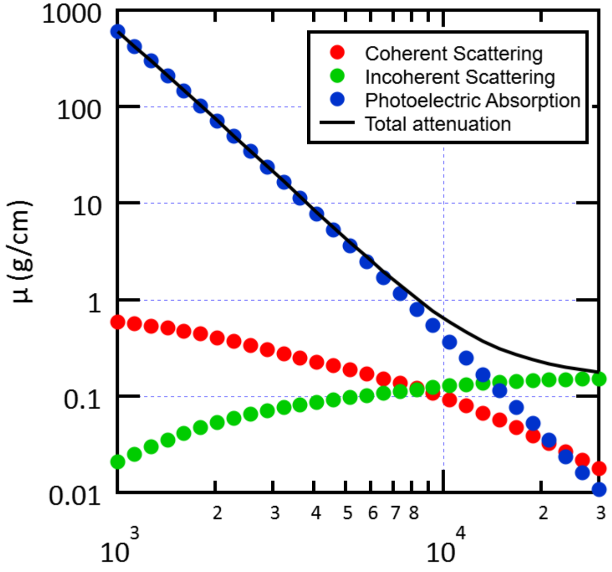

fig 6: Attenuation cross-sections for SR in Be.

- Unlike metals used in UHV chamber construction, Be attenuates the SR throughout its volume, rather than scattering or absorbing it near the surface.
  - The photon flux attenuates within the mirror as $I = I_0 \exp(-\mu \ell)$, where μ is the cross-section, and ℓ is the distance traveled.
- The absorption and scattering cross-sections are energy-dependent.
  - The XOP software from ESRF was used to determine the spectral distribution of the incident power.
  - The power scales linearly with positron beam current.
- The XCOM utility from NIST determines the attenuation cross-sections for SR in the spectral region of interest.

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Simulation Highlights

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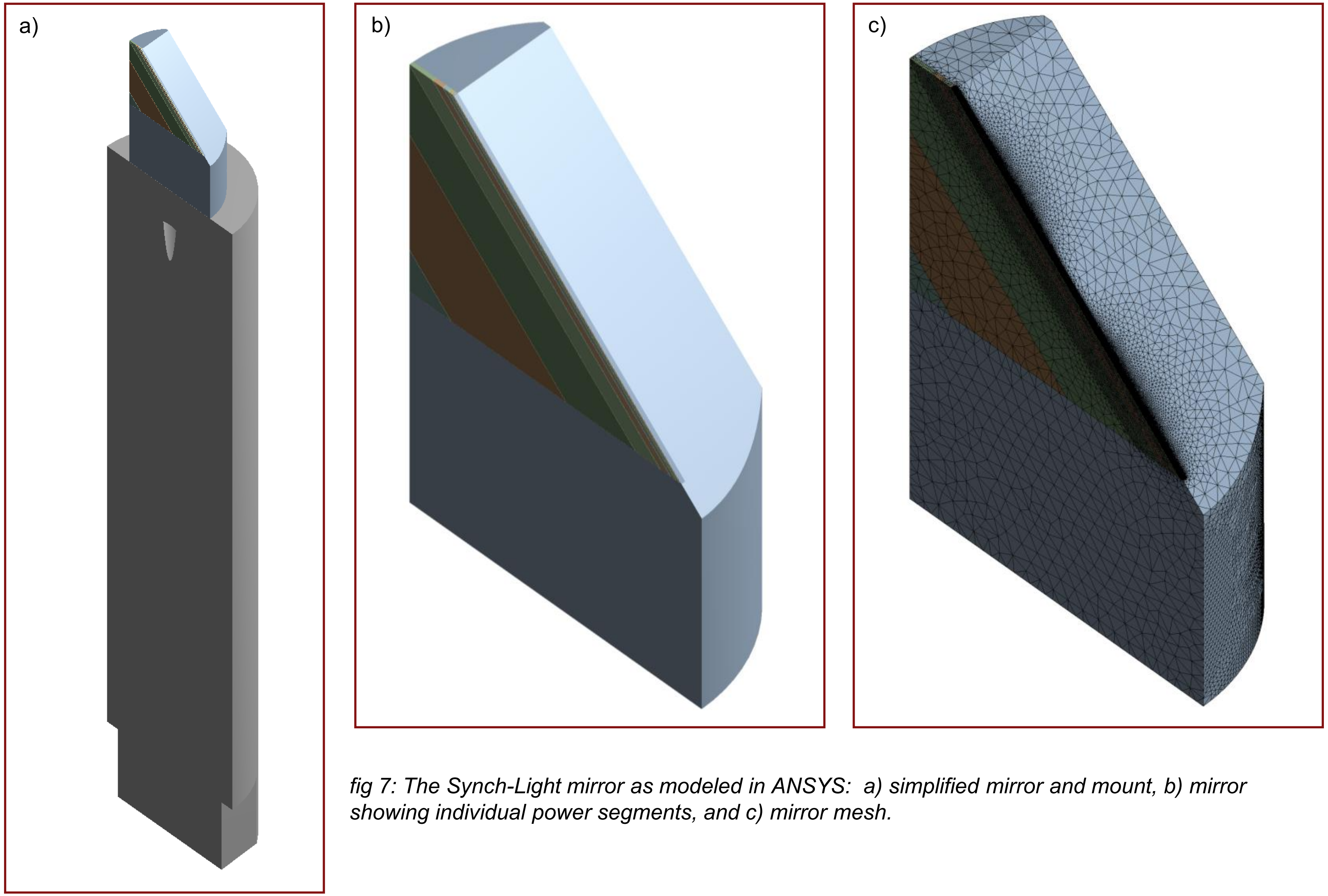

fig 7: The Synch-Light mirror as modeled in ANSYS: a) simplified mirror and mount, b) mirror showing individual power segments, and c) mirror mesh.

- The portion of the mirror directly in the path of the SR was subdivided into layers, each attenuating roughly 10 % of the incident power. The absorbed power was simulated as internal heat generation.
- Convective cooling by 29.4 ^{o}C water was applied to the cooling mount.
- Mesh element size was specified so that each heated segment is at least one 8-node tetrahedral element deep (i.e., possessing an internal integration point), with element size scaling with segment depth. The rest of the model was meshed with 0.5-mm elements.
- Interfacing surfaces were meshed with identical element sizes.

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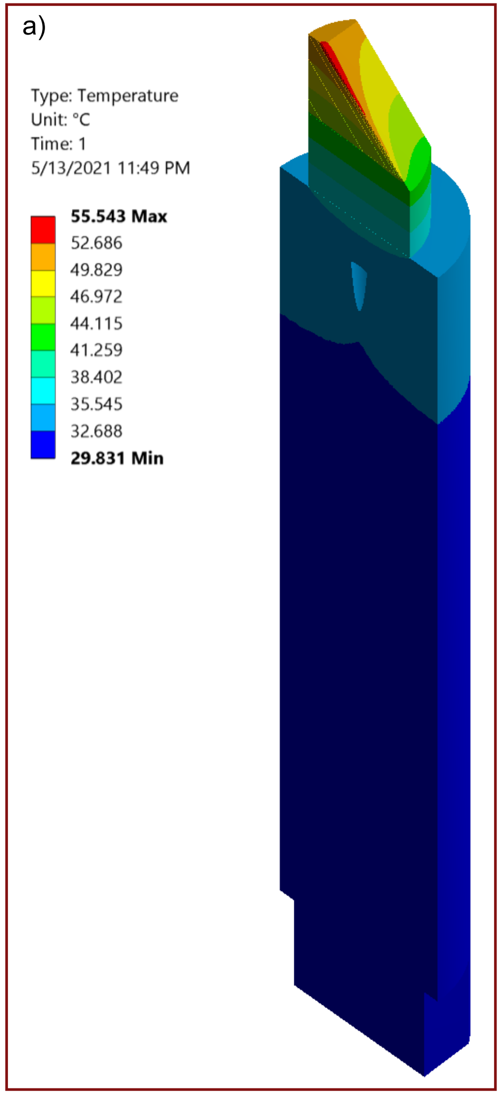
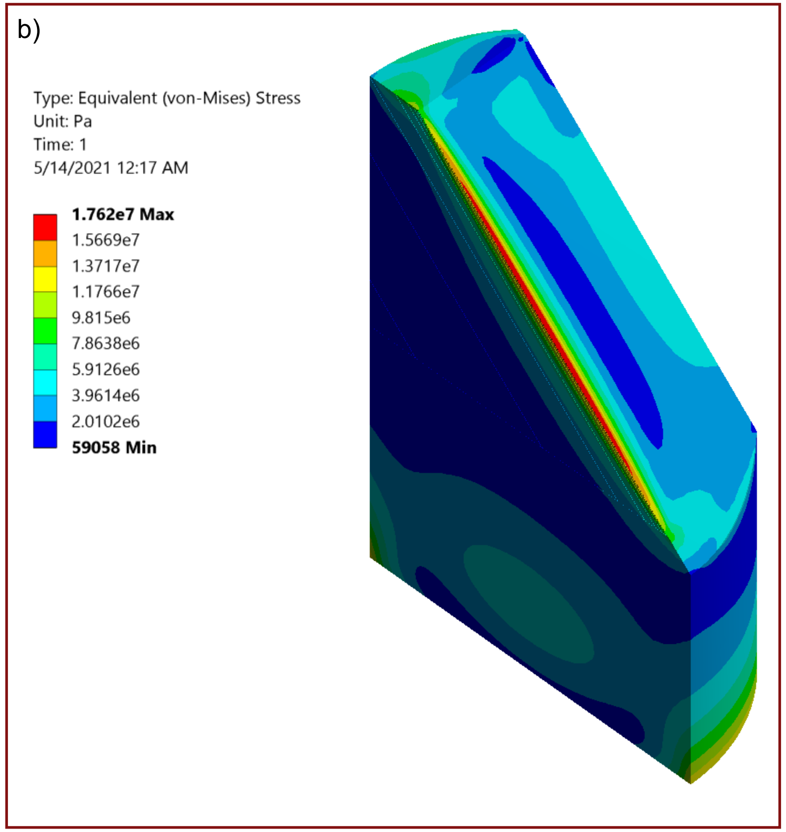
SR from R = 140.6 m magnet with 100 mA positron beam stored at 6.0 GeV





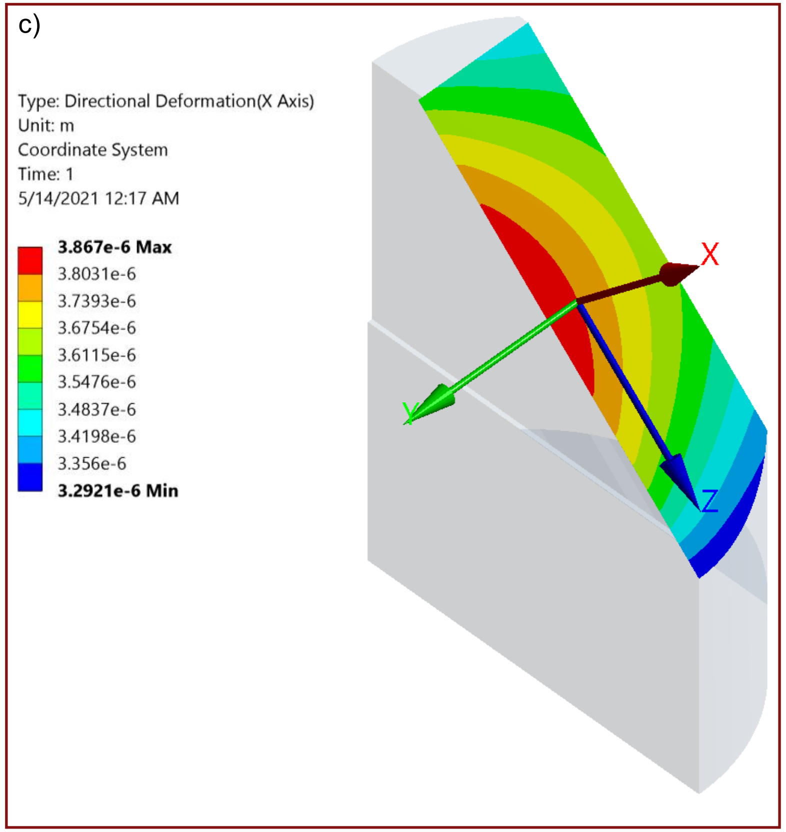


fig 8: Simulation results for SR from a R = 140.6 m magnet with a 100-mA positron beam stored at 6 GeV: a) temperature of the mirror and mount, b) equivalent stress on the mirror, and c) mirror surface deformation in the direction normal to the surface. Similar calculations were performed for the OSC beam conditions (R = 58.6 m).

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Relative deformation due to SR from R = 140.6 m magnet with 100 mA positron beam stored at 6.0 GeV

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- Since the entire mirror undergoes thermal expansion, it is useful to examine the relative deformation (i.e., the difference between the point of least deformation and the point of most deformation) along the SR strip and normal to the mirror surface.
- The peak relative deformation is 0.43 µm and the shape of the deformation curve is roughly paraboloid.
- Optical measurements, assuming that the deformation of the mirror surface is spherical, inferred a relative deformation of 0.21 µm.

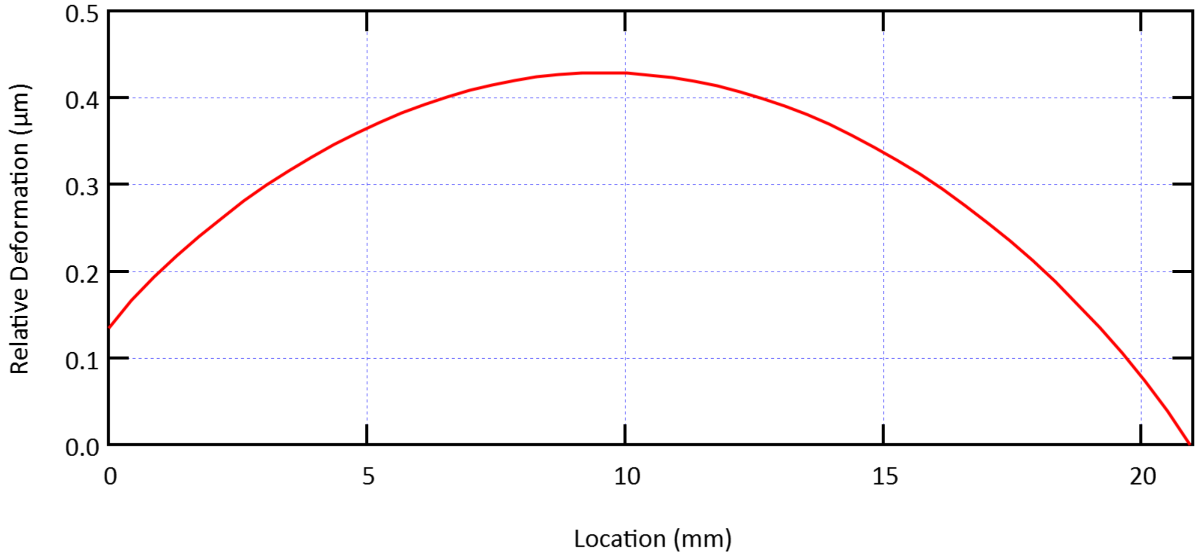

fig 9: Relative normal deformation of the mirror surface due to SR from R = 140.6 m bending magnet with 100 mA stored at 6.0 GeV. The 0 mm location is defined as the farthest point from the mirror mount.

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Results Summary

- FEA performed for mirrors illuminated with SR from a R = 140.6 m bending magnet—used for CESR beam size measurements—and from a R = 38.6 m—used for alignment of the OSC experiment.
- The calculations were performed at several beam currents up to the CESR design current of 200 mA.
- The yield strength of Be used is 210 MPa, therefore the deformation predicted is elastic for all beam conditions examined.
- The deformation results establish a relationship between beam condition and surface deformation.

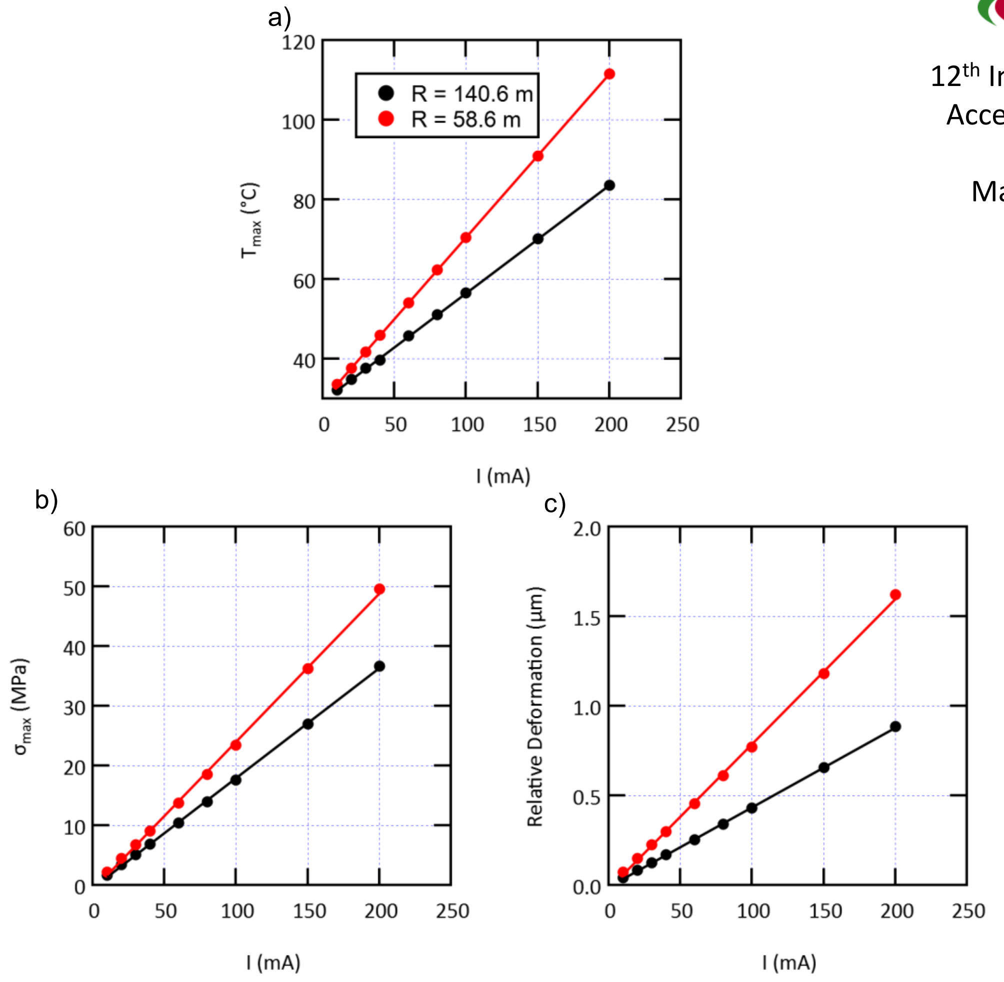

fig 10: Simulation results for SR illuminating the Synch-Light mirrors, using R = 140.6 m and R = 58.6 m bending magnets as sources: a) maximum temperature on the mirror surface, b) the maximum stress on the mirror surface, and c) maximum relative deformation on the mirror surface.

Conclusion

We have developed an FEA method for calculating the stress and the deformation on a beryllium mirror surface. The method takes into account the spectral distribution of the incident SR as well as the depth-dependent power distribution due to SR attenuating within the mirror volume. These results, verified by optical measurements, show that the Synch-Light beryllium mirrors would not be damaged under CESR beam conditions and describe the relationship between beam conditions and mirror surface deformation.

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Acknowledgements

The authors would like to thank Dr. Suntao Wang for performing the optical calculations used to verify the simulations results. We would also like to thank the CESR and OSC teams.

Funding

The work presented here was supported by the following agencies and grants.

Air Force Research Laboratory // FA8650-19-25220
Directorate for Mathematical and Physical Sciences // DMR-1829070
National Institute of General Medical Sciences // 5P30GM124166-02
Empire State Development - NYSTAR // C150153