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FINITE ELEMENT ANALYSES OF SYNCHROTRON RADIATION INDUCED STRESS IN BERYLLIUM SYNCH-LIGHT MIRRORS*

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Abstract

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, resulting in a significantly reduced thermal stress and distortion on the mirror surface. In this paper, we describe a Finite Element Analysis method of accurately simulating the SR-induced thermal stress on the beryllium mirrors at the Cornell Electron Storage Ring at various particle beam conditions. The simulations consider the energy dependence of X-ray attenuation in beryllium. The depth-dependent distribution of the power absorbed by the mirror is represented by separate heating zones within the mirror model. The results help set the operational safety limit for the mirrors—ensuring that the SR-induced thermal stress is below the elastic deformation limit—and estimate the mirror surface distortion at high beam currents. The simulated surface distortion is consistent with optical measurements.

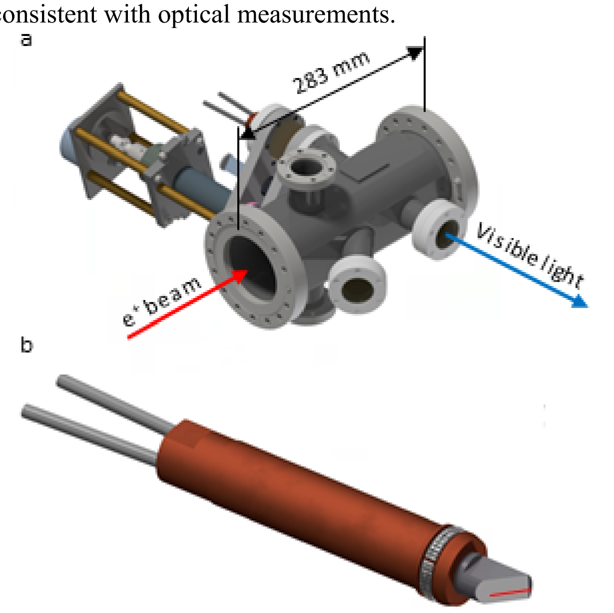

Figure 1: The Synch-Light mirror: a) the vacuum chamber assembly as configured for beam size measurements and b) the beryllium mirror mounted on the water-cooled copper mount; the red strip gives the approximate location of SR deposition. A motorized stage allows mirror to be retracted when not in use.

INTRODUCTION

The Cornell Electron Storage Ring (CESR) utilizes visible light reflected from water-cooled retractable Synch-Light beryllium mirrors (see Fig. 1) for transverse and longitudinal beam size measurements [1], as well as for aligning the Optical Stochastic Cooling (OSC) experiment [2]. These mirrors are retractable and may be deployed during Cornell High Energy Synchrotron Source (CHESS) operation, therefore, we needed to set an operational beam current limit to avoid damaging the mirrors with Synchrotron Radiation (SR) heating. Since SR heating would deform the mirror surface, we also needed to determine the relationship between the stored beam current and the surface deformation in order to set a current limit for accurate measurements that use the mirrors. The beam size measurements and the OSC experiment were originally meant to occur at a beam current of around 10 mA, however, the design current for recently upgraded CHESS is 200 mA [3] and CESR is usually operated at 100 mA.

Beryllium is a high-strength, high thermal conductivity material. Because it is a low-Z metal, it scatters and absorbs the majority of SR in the bulk of the material, rather than very near its surface. The SR may also pass through the material. This behaviour is convenient for thermal management, but it presents difficulties for accurately simulating the thermal stress and the deformation of the material. In this paper, we discuss a straightforward method for performing Finite Element Analyses (FEA) on Be components illuminated by SR. This method takes into account the spectral power distribution of the incident SR as well as the spectral dependency of the attenuation cross sections in the material.

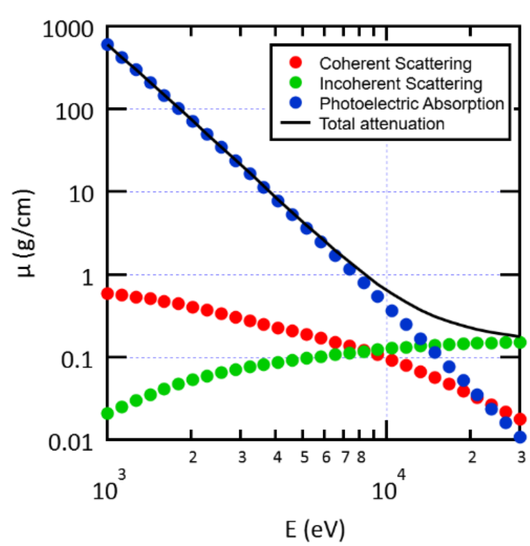

Figure 2: Attenuation cross sections for Be in the spectral region of interest.

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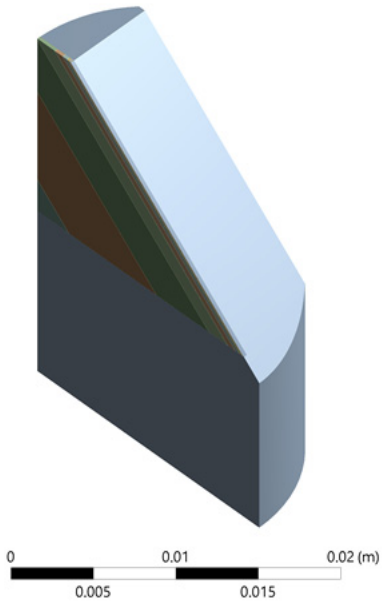

Figure 3: FEA model of the Synch-Light mirror used for simulating heating 140.6-m dipole magnet SR. The model used with 58.6-m dipole magnet SR differs in layer depth.

METHOD

The CESR beam size measurements are accomplished using a Synch-Light mirror downstream of a dipole magnet with a bending radius R = 140.6 m, while the OSC alignment occurs downstream of an R = 58.6 m dipole magnet. The spectral power distributions for each magnet were generated with XOP [4] and used the starting points for the simulations. The total power deposited by the SR is 34.9 W and 84.0 W for the 140.6-m dipole magnet and the 58.6-m dipole magnet, respectively. In each case I-70H beryllium polished to 1/10 wavelength at 500 nm is used.

The attenuation cross sections for Be were calculated using the XCOM utility from NIST [5]. Figure 2 shows the coherent scattering, the incoherent scattering, and the photoelectric absorption cross sections for Be in the spectral region of interest. It is important to note that the minimum energy accepted by XCOM is 1000 eV, while the spectral power distributions showed the power delivered at energies between 0 eV and 1000 eV as 5.8 W and 4.4 W for the 140.6-m dipole magnet and the 58.6-m dipole magnet, respectively. However, since the absorption cross section at 1000 eV is quite large and it dominates the scattering cross-sections, we assume that this power deposits on the surface of the mirror.

The simulations were performed in ANSYS Workbench 19.2 [6]. The model of the mirror and the water-cooled mount was simplified by utilizing the symmetry in the plane of CESR. The mirror mount was further simplified to a cylinder containing a cooling channel; these reductions in complexity were confirmed with simulation. Steady-State Thermal simulations were performed on the mirror and the mount, and the mirror heating data were transferred to Static Structural simulations; the mount was omitted in the latter to reduce computation complexity of the model.

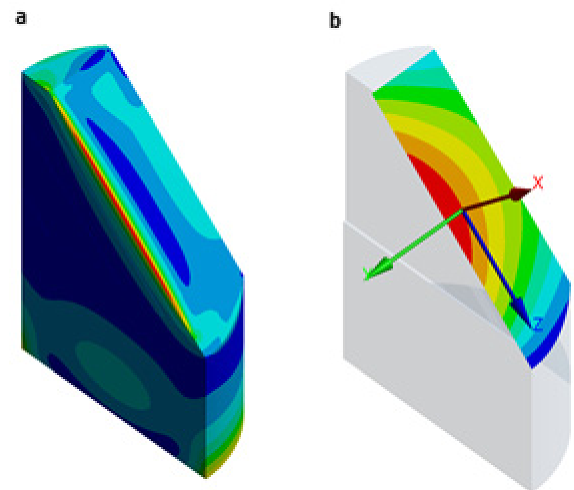

Figure 4: FEA results for SR from a 140.6-m dipole magnet with 100 mA stored at 6.0 GeV: a) the equivalent stress, and b) the surface deformation in the direction normal to the surface.

To account for the gradual attenuation of SR in beryllium, the portion of the mirror model where the SR impinges were subdivided into layers—ranging in depth from 15 µm to 20 mm—so that each layer attenuates 10% of the incoming power. The FEA model for the mirror illuminated by SR from the 140.6-m dipole magnet is given in Fig. 3; the 58.6-m dipole magnet possesses layers of different depth but is otherwise identical.

Each layer was meshed with elements sized to ensure that each layer is at least one 8-point tetrahedral element deep, therefore, possessing an internal integration point. The interfacing surfaces were forced to a mesh with the smaller elements of the two interfacing surfaces. The remainder of the model was meshed with 0.5-mm elements.

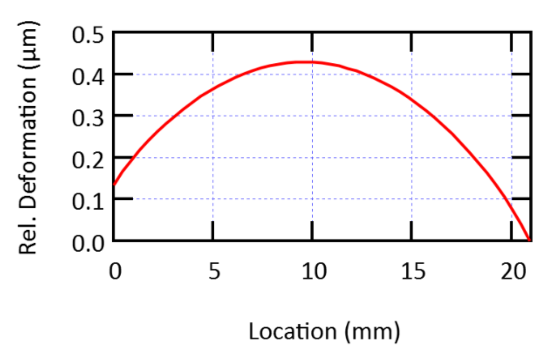

Figure 5: The relative normal deformation of the Synch-Light mirror illuminated by SR from a 140.6-m dipole magnet for 100 mA stored at 6.0 GeV.

The power attenuated within the mirror volume was assigned to the heated layers as internal heat generation, with the power from light below the 1000 eV XCOM cut-off assigned to the surface of the first layer as heat flow. The contribution of Compton scattering was ignored, giving an additional safety margin. The simulations were performed

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at nine beam currents for each the 140.6-m dipole magnet used for CESR beam size measurements and the 58.6-m dipole magnet used for OSC alignment.

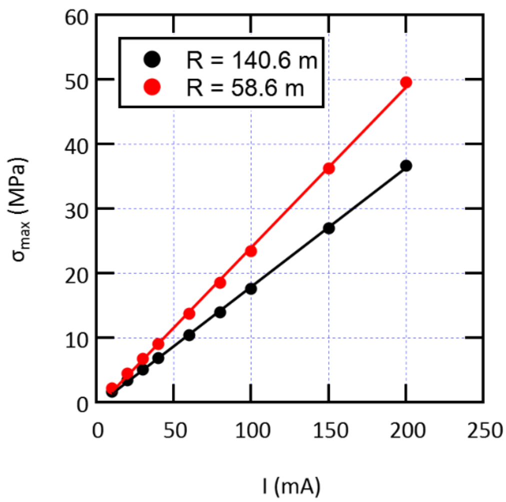

Figure 6: The maximum thermal stress on the Synch-Light mirrors for beam conditions simulated.

DISCUSSION

Figure 4 a shows the simulated stress map of the Synch-Light mirror illuminated with SR from a 140.6-m bending magnet with 100 mA stored at 6.0 GeV. Figure 4 b shows the deformation of the mirror surface in the direction normal to the surface for the same beam conditions. The maximum stress of 1.8×10^{7} Pa and the maximum deformation of 3.9×10^{-6} m occur in the vicinity of where the SR fan impinges.

Since the entire mirror-mount assembly undergoes thermal expansion, effectively pushing the mirror surface in the normal direction and only deviations from a flat surface change the optical behaviour of the mirror, it is helpful to extract the relative normal deformation, as given in Fig. 5. With the mirror illuminated by SR from a 140.6-m bending magnet with 100 mA stored in CESR at 6.0 GeV, simulations predict a maximum relative normal deformation of 0.43 µm.

Optical calculations that treat the deformed mirror as spherical predict a deformation of 0.21 µm. Since the deformation is only approximately spherical and the simulations ignore the Compton scattering, the agreement is acceptable and therefore this method of simulating the thermal behaviour of Be mirrors is valid. The optical calculations were performed for SR from a 140.6-m bending magnet at 100 mA stored at 6.0 GeV.

Figure 6 shows the maximum simulated stress on the Synch-Light mirror at various beam conditions, the maximum of 49.6 MPa is predicted for the OSC alignment mirrors (R = 58.6 m), with a 200-mA positron current stored at 6.0 GeV. The yield strength of optical-grade beryllium is 210 MPa. Therefore, we expect no plastic deformation of the mirrors if deployed at the CHESS design current of 200 mA.

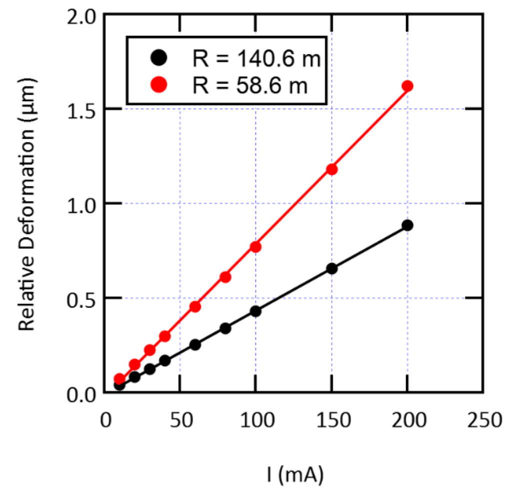

Figure 7: The maximum relative normal deformation of the mirror surface for beam conditions examined.

Figure 7 shows the relative normal deformation simulated for SR from the two bending magnets as a function of beam current. The maximum simulated deformation is 1.6 µm and is predicted for SR from a 58.6-m bending magnet with 200 mA stored at 6.0 GeV.

CONCLUSION

We have developed a straightforward method for simulating the thermal stress and deformation of beryllium mirrors irradiated by bending magnet SR. This method accounts for the spectral power distribution of the SR as well as the depth-dependent attenuation withing the mirror volume. Using this method, we have confirmed that the Synch-Light mirrors are safe to operate with a 100 mA positron current stored at 6.0 GeV and therefore the beam-size measurements and alignment may proceed parasitically during CHESS operation.

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