COMPARISON OF SIMULATIONS AND ANALYTICAL THEORY OF RADIATION HEATING ON THE ADVANCED PHOTON SOURCE SUPERCONDUCTING UNDULATOR*

Laura Boon†, Purdue University, West Lafayette, IN 47907, USA
Roger Dejus, Katherine C. Harkay and Mark Jaski, ANL, Argonne, IL 60439, USA

Abstract

Synchrotron radiation can potentially introduce large heat loads on the beam chamber of the superconducting undulator (SCU0) at the Advanced Photon Source (APS). With the photon absorber mask, a well-aligned centered beam in the upstream bending magnet allows only a small amount of radiation power, less than 1 W, to intercept the walls of the beam vacuum chamber in the cryostat, assuming no photon scattering. But beams with vertical orbit errors, especially, can deposit much higher heat loads on the beam chamber, above 100 W. An analysis was carried out to calculate the power on the vacuum chamber when the beam has an orbit error through the upstream bending magnet. This paper presents these analytical results compared to simulations that were performed using a 3D photon tracking code, Synrad3d.

INTRODUCTION

As part of the Advanced Photon Source Upgrade project [1], a test superconducting undulator (SCU0) was developed at Argonne National Laboratory [2]. The test SCU0 was installed in December 2012 [3]. To reduce heating on the superconducting coils, the beam chamber is thermally isolated from them. The cryo-coolers used to cool the beam chamber are able to handle up to 40 W of power (at 20 K) from transient and continuous wave sources. Radiation from the upstream dipole produces high amounts of power that can be incident on the beam chamber inside the SCU0 cryostat. SCU0 is in the downstream end of the straight section in sector 6, see Fig. 1. The upstream end of the straight section has a hybrid permanent magnet undulator (HPM). A photon absorber (PA) in the downstream end box of the HPM is used to shield the beam chamber outboard wall from direct, on-axis radiation.

CALCULATIONS

The power incident on the SCU0 beam chamber from primary photons can be calculated through ray tracings and analytically. Ray tracings are 2D projections of the dipole radiation fan on the 3D vacuum system layout. Ray tracings do not typically include the vertical distribution of the dipole radiation. So analytical calculations were performed to include the photon vertical distribution. Figure 2 shows the elliptical shape of the beam chamber in the SCU0 cryostat. The shape was taken into account for all the calculations and simulations shown in this paper. All calculations assume a beam current of 100 mA. Beam orbits are referenced to the dipole exit.

Ray Tracings

The layout of the radiation fan is seen in Fig. 1. By applying an off-axis electron beam orbit through the radiation source, the horizontal steering offset (x) and angle (x') limits can be determined. The steering limit is defined by when the radiation fan begins to intercept the outside edge of the beam chamber. The steering limit defined by ray tracings is shown in Fig. 3 (red dotted line). Due to the wide horizontal aperture of the beam chamber, only for very large steerings is there a concern about radiation heating. For positive offsets the photon absorber shields the beam chamber. The power incident on the beam chamber is calculated as follows. The APS main dipole magnet generates 6.65 kW of synchrotron radiation power per 100 mA. The horizontal fraction of energy that is incident on the SCU0 chamber is calculated using α/θ_{dipole} where $\theta_{dipole} = 77.54$ mrad is the full bending angle and α is the angle subtended by the SCU0 chamber. The power incident on the beam chamber is greatest for an electron beam that has a negative orbit offset. The power on the outside edge ranges from 0.3 W to 22.8 W. The power increases for larger negative offsets.

Analytical Calculations

The radiation heating load is calculated analytically using the method described in [4]. The following equation is integrated over the vertical opening angle in which the photon beam is incident on the beam chamber:

$$F = P_0 \frac{1}{(1+X^2)^{5/2}} \left[1 + \frac{5}{7} \frac{X^2}{1+X^2} \right]. \quad (1)$$

In Eq. 1, P_0 is the fraction of total power produced by the dipole magnet that passes the photon absorber, and $X = \gamma\psi$, where γ is the relativistic factor, and ψ is the vertical opening angle between the radiation source and the SCU0 beam chamber.

Figure 3 is a contour plot of the power incident on the SCU0 chamber when the beam has a horizontal offset. The vertical photon distribution is included in the calculation. Radiation intercepts the top and bottom of the beam vacuum chamber and not just the outside edge. Again the contour plot shows that large negative offsets through the

* Work supported by U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357

† lboon@purdue.edu

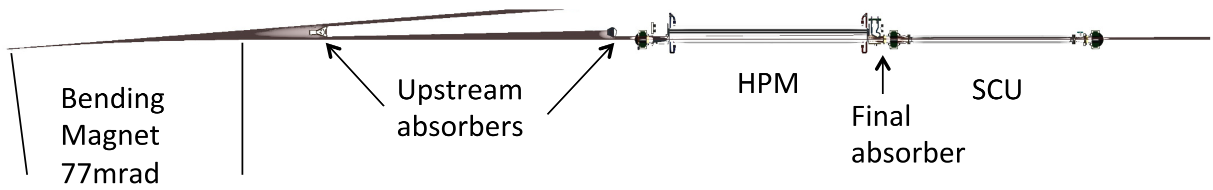

Figure 1: Top view schematic layout of the sector where the SCU0 is installed. The radiation is produced in the bending magnet, and photon absorbers are used to shield the SCU0 cryostat from direct radiation.

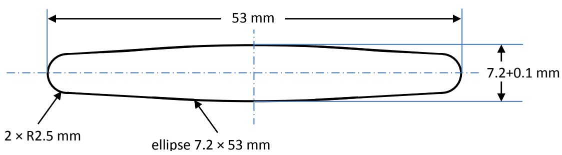

Figure 2: Elliptical shape of the beam chamber in the SCU0 cryostat.

dipole magnet produce the most power incident on the SCU0 beam chamber.

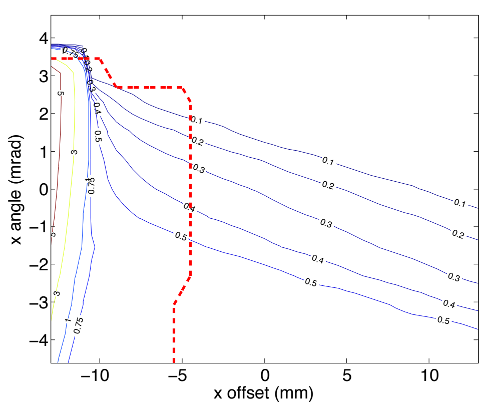

Figure 3: Comparison between ray tracings (dotted line) and analytical calculations (solid contours) of radiation power incident on the SCU0 beam chamber for a beam horizontally offset in the upstream bending magnet. To the left of the red dotted line is where radiation is incident on the outside edge of the SCU0 beam chamber. Power is shown in Watts. ($y = y' = 0$)

Figure 4 shows the power incident on the SCU0 chamber when the beam has a vertical steering error, offset (y) and angle (y') in the dipole magnet. Due to the small vertical aperture (7.2 mm) of the beam chamber, the incident power can reach over 100 W of power for relativity small vertical angles in the dipole. The vertical 'cut-off' of the heating on the SCU0 chamber is at 4 mm for two reasons. First, the upstream HPM has a vertical aperture comparable to that of the SCU0. This acts as a shield to the top and bottom of the SCU0 chamber. Second, the SCU0 chamber only has a vertical half aperture of 3.6 mm. Photons produced above that position will be absorbed in the taper before the SCU0 chamber.

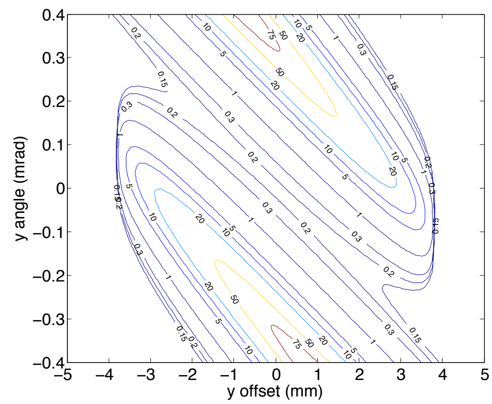

Figure 4: Power incident on the SCU0 cryostat for a beam that is off-axis vertically through the upstream bending magnet. Power is shown in Watts. ($x = x' = 0$)

The analytical results were compared with simulations in order to confirm our analytical model. Comparing Figs. 3 and 4, we note that vertical orbits in the dipole produce more heating on the beam chamber than comparable horizontal orbits. For this reason simulations were only done in the vertical plane.

SIMULATIONS

Synrad3d [5] was used to calculate the power of photons incident on the beam chamber. The total power on the beam chamber was calculated from the incident photon distribution and energy [6]. To simulate an off axis beam through the dipole magnet, an optimization of the correctors' strength was completed using BMAD [7]. The simulations included the electron beam trajectory through the entire sector. Coupling in the sector sextupoles creates a horizontal offset in the electron beam orbit for vertical steering. The horizontal offset was minimized through the choice of correctors and tolerance value in the optimization. For comparison with simulations, the analytical calculations account for the residual offset in x as well as the intended vertical offset or angle trajectory through the magnet. In the simulations, any photon reflections off the beam chamber were ignored because reflections are not included

ISBN 978-3-95450-138-0

in the analytical model.

Figure 5 shows the comparison between the primary photon power calculated analytically and from the simulation. The incident power peaks at an offset of 2.8 mm. Then the power incident on the beam chamber drops to zero when the beam is offset more than 4 mm. The upstream undulator chamber shields the SCU0 beam chamber from the photon beam, similar to a photon absorber.

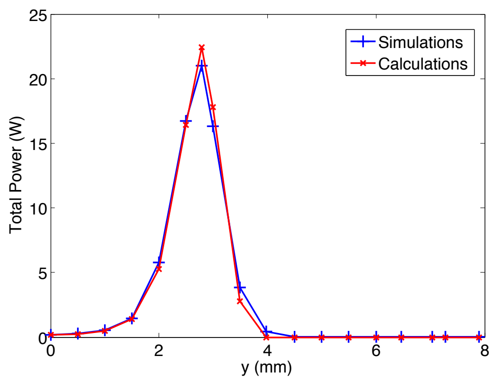

Figure 5: Analytical calculations and simulations of total synchrotron radiation power on the beam chamber wall for a vertical position offset in the upstream bending magnet.

Figure 6 is a comparison of analytical calculations and the corresponding simulations when an electron beam has a vertical angle through the upstream bending magnet. The incident power increases more slowly with just an angle offset in the electron beam. However, the maximum power is almost 4 times greater than an offset beam. The total power is greater for an angle because the highest-energy photons have the smallest opening angles from the electron beam trajectory. With an angle steering error the highest-energy photons intercept the beam chamber instead of passing though. Both sets of simulations have good agreement with the analytical values.

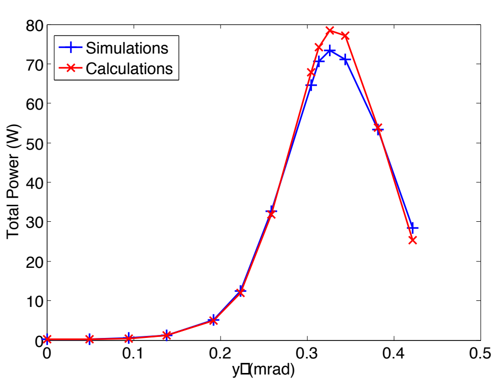

Figure 6: Analytical calculations and simulations of total synchrotron radiation power on the beam chamber wall for a vertical angle in the upstream bending magnet.

CONCLUSIONS

During user operation beam-position-limiting detectors are armed and limit the electron beam motion to ±0.85 mm in x and ±1.8 mm in y [8] at the exit of the bending magnet. According to the results shown here, the maximum power incident on the beam chamber is 25 W at these orbit limits, below the 40-W cooling capacity. Therefore, the greatest concern for radiation heating is during machine studies when the limits on beam motion are from the physical aperture of the beam chamber ($\pm 8 \times \pm 8.6$) mm [8]. Steering errors of this magnitude produce more radiation heating. To protect the SCU0 during machine studies, the current is turned off. Comparison of analytical calculations to simulations show that we have a good model for primary photon heating when the electron beam is off axis through the upstream bending magnet. In future work, photon scatting will be included in the analysis.

ACKNOWLEDGMENT

The authors would like to thank David Sagan and James Shanks for their guidance in running simulations in Synrad3d and BMAD.

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