ELECTRON CLOUD ISSUES FOR THE APS SUPERCONDUCTING UNDULATOR*

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Abstract

The Advanced Photon Source (APS) Upgrade calls for the design and development of a superconducting undulator (SCU) at APS, a 7-GeV electron synchrotron. The heat load is a critical parameter in designing the cryosystem for the SCU. Operation of an SCU at ANKA shows a heat load and pressure rise that may be consistent with beam-induced multipacting from an electron cloud. For this reason, a study was undertaken to minimize the contribution to the heat load by a possible electron cloud at the APS. We focused on analyzing the photon absorption on the chamber walls that can potentially give rise to photoelectrons. Preliminary tracking of the photon flux using the code synrad3d for the APS SCU chamber is presented, and possible ways to mitigate the photo-electrons are discussed.

INTRODUCTION

A key goal for the APS Upgrade is to provide high photon brilliance at high photon energies. Superconducting undulator (SCU) technology can potentially outperform permanent-magnet technology in terms of the peak magnetic field at small period length. An important challenge in designing an SCU system is to minimize the heat load for the cryosystem. Preliminary estimates of the total beam-related heat load were presented elsewhere [1]. Included in the total was an estimate of electron cloud heating of 2 W, caused by electrons being accelerated into the walls by the beam field, resulting in secondary emission of more electrons. The electron-cloud generation code posinst [2] was used for these calculations.

There is growing evidence suggesting that the existing electron-cloud generation models are incomplete for electron beams [3-5]. For these reasons, we investigated the possible contribution to the beam-induced heat load by the photo-emitted electrons. A key step in this analysis is a calculation of photon absorption in the SCU chamber.

We used the synrad3d code [6] to track synchrotron radiation in 3D for both primary and secondary photons that scatter on the chamber walls before being absorbed. Through a combination of simulation parameters and post-processing, a strategy was developed to potentially minimize the absorbed photon power and, subsequently, photoelectron generation.

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SYNRAD3D

Synrad3d is a photon production and propagation code that utilizes the Better Methodical Accelerator Design (BMAD) and radiation integrals to determine initial positions and momenta of each marco-photon [6]. For this analysis up to 300k macro-photons were generated and comparisons of their absorbed positions were made with and without reflections allowed.

The chamber wall is a simplified model of one sector of the APS ring. This simplification assumed no ante-chamber in the main vacuum chamber. The antechamber for the standard insertion device (ID) was modelled as an extension of the beam chamber. By ignoring the ante-chamber we were able to avoid extended convex chamber shapes. The issues associated with convex or arbitrary chamber shapes are addressed in the next section. The top and side views of the chamber are shown in Figs. 1 and 2. The SCU chamber cross-section is shown in Fig. 3.

In Synrad3d all photon reflections are specular and elastic. The reflection probability is based on data from the Berkeley Center for X-ray Optics [6].

For this analysis we are only concerned with photons absorbed in the SCU cryostat. All photons without enough energy to produce photoelectrons are ignored, so an energy cut of 4 eV was used, a value representing the chamber work function.

Validation of Arbitrary Wall

Synrad3d uses each photon's momentum vector to determine its position a distance Δs downstream. If the photon is outside the chamber wall then synrad3d calculates the point at which it exited the chamber and whether it was absorbed or reflected. In the case of a convex arbitrary chamber wall shape, such as the photon absorbers marked A, B in Fig. 1, photons can potentially pass through undetected. To confirm that no photons were behaving in this way the chamber wall file was validated by artificially lengthening A and B and changing the distance between photon position checks to Δs = 0.01 m. In the chamber analyzed the absorbers are modelled as 5-cm long instead of the actual ~0.5 cm. This change did not affect the validity of the final results because all photons that would be reflected are preserved, but the probability that a photon would pass through the chamber wall is decreased. In addition to lengthening the absorbers, the distance between photon checks was set to 1 cm, a length shorter than the modeled absorber. It was found that the small Δs resulted in the same photon absorption locations as the larger, default Δs = 3 m. Values of Δs of 0.1 m and 1 m were also checked resulting in the same outcome. Therefore, all the analysis shown uses $\Delta s = 3$ m in order to decrease the computation time with no essential changes to the final result.

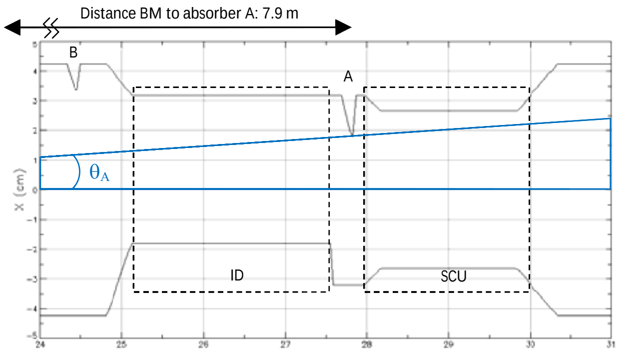

Fig. 1. Schematic of SCU chamber as modeled, plan view, and ray-tracing radiation fan from main dipole (BM).

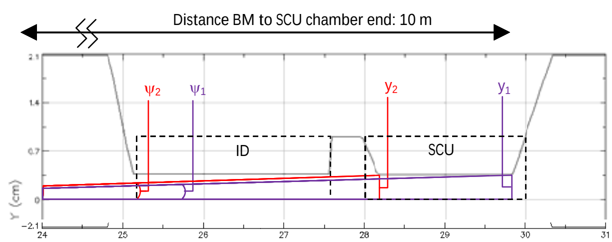

Fig. 2. Schematic of SCU chamber as modeled, elevation view, and ray-tracing of radiation fan showing opening angles of photons incident on the SCU chamber ends.

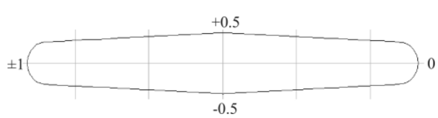

Fig. 3. SCU chamber cross-section (53 mm × 7.2 mm) with perimeter coordinates labeled; positive-x is p=0. Each grid line is 10 mm.

SCU CHAMBER MODELING

Synchrotron radiation from the main dipole (BM) and smaller bend magnets that bump the beam through the ID sections was included. The photon absorber labelled A (Fig. 1) is designed to stop the highest-energy primary photons from being absorbed in the SCU cryostat. The absorber labelled B is a standard end absorber.

Initial modeling was performed with primary photons only to compare with ray-tracing. The photon absorption spectra and distributions in the SCU chamber are shown in Figs. 4 and 5 as a function of *s*, the longitudinal and *p*, the perimeter coordinate, respectively. In this calculation, 100k macro-photons were used, and about 200 photons are absorbed on the chamber. The location of the end of the taper is marked in Fig. 4 near 0.2 m. About half of the photons are absorbed on the taper.

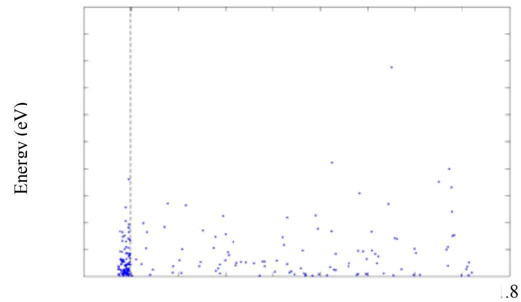

Fig. 4. Energy of absorbed photons vs. s, integrated over perimeter, primary photons only.

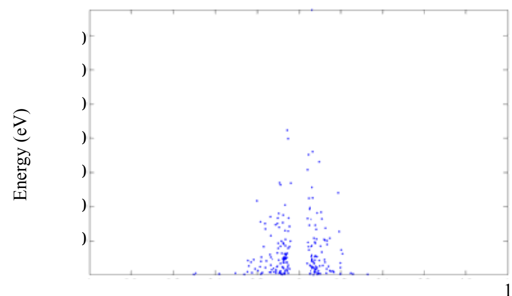

Fig 5. Energy of absorbed photons vs. chamber perimeter, integrated over s, primary photons only.

The tip of absorber A is 18 mm from the axis, giving an angle $\theta_A = 2.26$ mrad. The higher-energy photons are absorbed near the end of the chamber on the upper and lower surfaces. At the end of the chamber, the maximum horizontal extent of the radiation fan is 22.57 mm. The corresponding vertical aperture is $y_1 = \pm 2.57$ mm (Figs. 2, 3). Using this value of y, the vertical opening angle of the radiation at the end of the chamber is $\psi_1 = 3.53/\gamma$, where γ is the relativistic factor. An estimate for low photon energies at this opening angle gives $\varepsilon = \varepsilon_c / (\gamma\psi)^3 = 440$ eV, where $\varepsilon_c = 19.5$ keV is the critical energy. The absorbed photon energy spectrum in synrad3d is reasonably consistent with this estimate, with a small fraction of higher energies. The absorbed power is estimated in the analysis section.

Modeling with secondary photons included was carried out next. Of 300k macro-particles, about 10k were absorbed on the SCU chamber, with maximum photon energies reaching about 3 keV. Many of the high-energy photons clearly scatter off absorber A. It was also noted that the taper intercepted a significant fraction of photons, as seen for the primary photons in Fig. 4. We proceeded to model the taper with an anti-reflective surface, such as that used in the LHC beam shield to intercept photons at normal incidence [7]. This taper surface was modeled in post-processing by eliminating all photons that reflected on the taper. The results are shown in Figs. 6 and 7. The total number of macro-photons absorbed in the SCU chamber is now about 2k, a reduction factor of about 5. The photons absorbed on the taper are not shown in the graph but are included in this total. It should be noted that very few photons scatter into the p=±0.5 region.

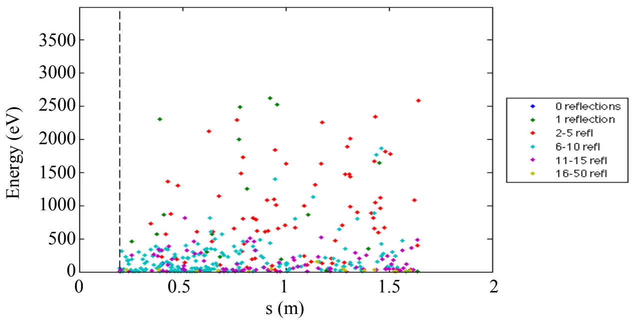

Fig. 6. Energy of absorbed photons vs. s, integrated over perimeter, secondary photons included. The taper is modeled as an anti-reflecting surface.

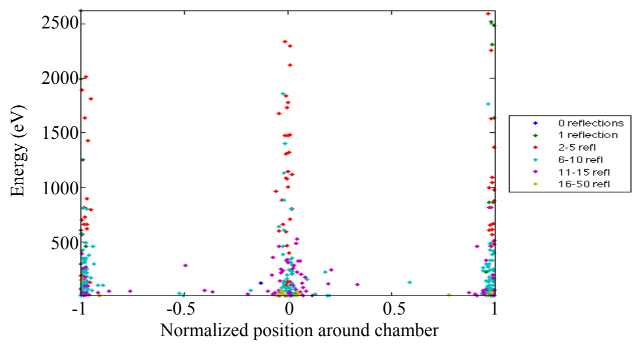

Fig 7. Energy of absorbed photons vs. chamber perimeter, integrated over s, secondary photons included. The taper is modeled as an anti-reflecting surface.

Analysis

The power absorbed in the SCU chamber including the primary photons only is estimated using the power distribution for a bending magnet:

$$\frac{d^2P}{d\theta d\psi} = 1.44 \times 10^{-18}\gamma^5 F(\gamma\psi) \text{ [W/mrad}^2\text{-mA]}.$$

The total power generated by each bending magnet into the full 78.5 mrad arc is 6.8 kW [8]. The fraction that passes absorber A is 2.26/78.5, or 200 W. For the vertical fan the power that remains outside an envelope covering the length of the SCU chamber, corresponding to the angles $(\psi_1 - \psi_2)$, where $\psi_2 = 4.34/\gamma$, is computed by integrating $F(\gamma\psi)$ [9]. The fractional power absorbed on the SCU chamber walls becomes 0.24%(200W) = 0.5 W.

The absorbed power including secondary photons has not yet been computed. It should be noted that about half the absorbed photons have very low energy and will contribute little to the total absorbed power.

The photoelectrons generated in the SCU chamber can potentially be accelerated by the beam and produce an additional heat source. Photons arriving at the walls at the same time as the electron bunch generate photoelectrons, but these are immediately driven back into the wall by the bunch field. Photons scattering in the x-plane travel an extra path length of ~53 mm, or 180 ps. The extra path length may be much shorter since the photons intercept the walls at almost grazing incidence. For an incident angle of 5 deg, the path length is 600 mm along s and 602 mm across the chamber, a difference of 2 mm, or 7 ps. The bunch length ranges between 20 ps and 40 ps and the bunch spacing between 2.8 ns and 153 ns. The path length difference for photons undergoing multiple scattering could be longer than the bunch length. Any photoelectrons that are produced can then potentially drift near the beam between bunch passages, and get a high-energy kick into the walls by the beam. Of course, photoelectrons cannot cross the SCU magnet field, which occupies 330 or 1150 m at the center of the SCU chamber.

FUTURE WORK

The results presented are very preliminary and more work is planned with a focus on reducing the absorbed secondary photons in the SCU chamber. Some initial plans include modeling absorber A with an anti-reflecting surface and adding a mask behind absorber A to intercept photons off the x-plane. Also in the future, the effect of beam missteering will be added. Calculation of the absorbed power including secondary photons will be developed. Further work will include analyzing the photons scattering back into the SCU chamber from the downstream end absorber. Additional physics including inelastic scattering will also be investigated. Finally, a more detailed analysis of photoelectron acceleration is planned using the incident angles from synrad3d.

SUMMARY

A preliminary qualitative analysis of the heat load due to photons and photoelectrons was presented for the APS SCU. Photon scattering from the upstream taper was found to significantly increase the photon absorption in the SCU chamber. Simulating an anti-reflecting surface in the tapers, such as that implemented for the LHC beam shield, reduced the photon absorption flux in the SCU chamber by almost a factor of 5.

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REFERENCES

[1] Y. Ivanyushenkov et al., to be published in Proc. 2010 Appl. Superconduct. Conf., Washington, D.C., 2LP1A-05.
[2] M.A. Furman, M.T.F. Pivi, Phys. Rev. ST Accel. Beams 5, 124404 (2002).
[3] S. Casalbuoni et al., Phys. Rev. ST Accel. Beams 13, 073201 (2010); 10, 093202 (2007).
[4] K.C. Harkay, R.A. Rosenberg, L.J. Loiacano, ICFA BD Newsletter 33, Apr. 2004 (http://www-bd.fnal.gov/icfabd/).
[5] J. Crittendon et al., to be published in Proc. 2010 ICFA Electron Cloud Workshop (ECLOUD10), Ithaca, NY.
[6] G. Dugan, D. Sagan, in Ref [5].
[7] N. Mahne et al., Appl. Surface Sci. 235, 221 (2004).
[8] A. Khounsary, B. Lai, Argonne Light Source Note LS-198 (1992).
[9] R. Dejus, private communication.