Limit of brightness of synchrotron radiation facilities imposed by self-heating of long undulators

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Abstract

As an electron beam moves through the storage ring of a synchrotron, radiation is deposited on undulators. If too much radiation is deposited, it could cause an electron beam to lose cohesion. Before any research is conducted, time-consuming calculations must be performed to determine how much radiation will be produced. This research performed at Brookhaven National Laboratory's National Synchrotron Light Source - II aims to decrease the amount of time these calculations take. Python in Jupyter Notebooks was used to calculate the power on plane when the gap, length, period, and energy of a synchrotron accelerator are varied from 2-7 mm, 1.5-5 m, 10-23 mm, and 2-6 GeV, respectively. The results were displayed as 1D and 4D plots with curve-fits. The quality of the equation for the curve-fit equation of the 4D plot was determined using a chi-square calculation. The maximum brightness at 10 keV was found. The radiation increased when the gap was decreased, the length of the beam was increased, and the speed of the beam decreased. The maximum brightness was produced when L = 4.4 m and p

= 0.015 mm. Decreases the amount of time a calculation takes from 20 seconds per calculation to milliseconds.

Introduction

Brookhaven National Laboratory's National Synchrotron Light Source II (NSLS-II) is a user facility that provides photons. To generate the greatest number of photons, scientists seek to build devices that are longer, have a smaller period, a smaller gap, and a larger magnetic field. The beamlines at NSLS II use wavelengths from infrared radiation to x-rays. A key component of any synchrotron, however, are the accelerators. Accelerators keep electrons moving in a beam close to the speed of light in a 3 GeV storage ring. To prevent electrons from colliding with other particles, the electrons move in a vacuum.

One key component of the storage ring in a synchrotron are the undulators. Undulators cause the electron beam to "wiggle" using magnets, which produces synchrotron radiation. The power (P) as a function of gap (g), length (L), period (p)–where one period consists of two poles and two magnets– and energy (En) eventually enters a danger zone: if too much synchrotron radiation is deposited, the sections of the undulator closest to the electron beam will become too hot, while the rest of the magnet will remain cold, triggering a danger situation in which the beam loses cohesion. The electron beam could be moving with anything from 10 to 60 kW of energy in a very, very narrow gap. If the electron beam collides with the undulator, the resulting accident could shut down NSLS-II for up to a week. An additional issue is that each calculation for the power density to prevent a shutdown requires 20 seconds per calculation. Performing a large number of calculations could take hours, or even days.

Literature Review

Inside an undulator one finds magnets, poles, and coils. The coils' being resistance superconductivity is dependent upon the undulator period, the gap, the dimensions of the coils, and coil density. No undulator with a short-period is driven by resistive coils due to the ohmic heating in the coil (Kim, 2005, 605). When the coil gap is small in a short-period undulator, it is necessary to use a superconducting coil due to steel. This is commonly used in undulators, because of the nonlinear nature of B(H) data (Poole & Walker, 1980, 488). The peak magnetic field is $B_0 = 3.33\ e^{[(-g/p)\ (5.47\ -\ 1.8\ (g/p))]}$ (Kim, 2005, 605; Halbach, 1983).

Due to synchrotron radiation and image current, an undulator's performance could suffer from the large heat load from the electron beam. Whereas the image current decreases the minimum power to elicit an avalanche meltdown, it is the synchrotron radiation itself that is responsible for any potential avalanche meltdown (Huang *et al.*, 2014, 162). Since an accident occurred in which a stainless-steel magnet sheet fused, Cu-Ni foil, as opposed to stainless-steel foil, may be more likely to avoid the heating issue (Kitamura *et al.*, 2004). However, long undulators with small gaps still face an issue: the tail of the undulator will face more synchrotron radiation than its head. The head and tail of the undulator must receive similar synchrotron radiation to avoid a meltdown (Huang *et al.*, 2014, 162). Should an undulator be prepared with a large gap, a small amount of power will be generated from synchrotron radiation, and the foil and magnet will remain stable. Conversely, should an undulator be prepared to a smaller gap, the proximity of the foil to the synchrotron radiation beam will cause the heating power to increase rapidly (Huang *et al.*, 2014, 163).

Open Source Code for Advanced Radiation Simulation (OSCARS) can be used to calculate the power density in an undulator. Additionally, "OSCARS is capable of computing spectra, [and] flux" (Hidas, 2018, 309). Using OSCARS significantly reduces the time required to complete the necessary pre-experimental calculations. OSCARS computations can be applied to both magnetic and electric fields. Moreover, "source fields may be time dependent, static, or any combination therein" (Hidas, 2018, 309). Using OSCARS, particle beams are defined by particle mass, energy, current, position, and direction. Additionally, it is possible to include the emittance, beta function, and energy speed (Hidas, 2018). The present study seeks to model power deposition from generic but complicated in-vacuum undulator models using a fitted functional form, thus improving the calculations of these quantities by orders of magnitude. This would allow for more complicated and detailed design and for greater understanding of design consequences.

Methodology

The radiation deposited when the gap, length, period, and energy are varied from 2-7 mm, 1.5-5 m, 10-23 mm, and 2-6 GeV, respectively. To do so, Python through Jupyter Notebooks was used to calculate the power on a plane, and a 1D plot was created for each parameter. Subsequently, a curve fit equation was determined for each plot. Afterward, 4D plots were created. Whereas for the 1D curve fits a different equation was determined for each parameter, one equation had to be able to create a curve fit for all four parameters for the 4D plot. To verify the quality of the 4D curve fit equation, a chi square calculation was used. Finally, the maximum brightness, or concentration of photons, at 10 keV was found.

Current Results

1D Plots and Curve Fits

As displayed in figures 1 and 1.1, as the gap decreases, the deposited radiation decreases. The equation found to best fit the data was $P(g) = a_0e^{-a1 \cdot g}$, where a_0 and a_1 are coefficients. As displayed in figures 2 and 2.1, as the period of the electron beam increases, the radiation deposited will increase. The equation found to fit the data was $P(p) = a_0p + a_1$, or the equation of a straight line. A_0 and a_1 are coefficients As displayed in figures 3 and 3.1, as the length of the electron beam increases, the radiation deposited will increase. The equation found to best fit the data was $P(L) = a_0L^4$, where a_0 is a coefficient. Finally, as displayed in figures 4 and 4.1, as the energy of the beam increases, the radiation deposited decreases. The equation found to best fit the data was $P(En) = a_0e^{-En \cdot a_1}$, where a_0 and a_1 are coefficients.

Figure 1

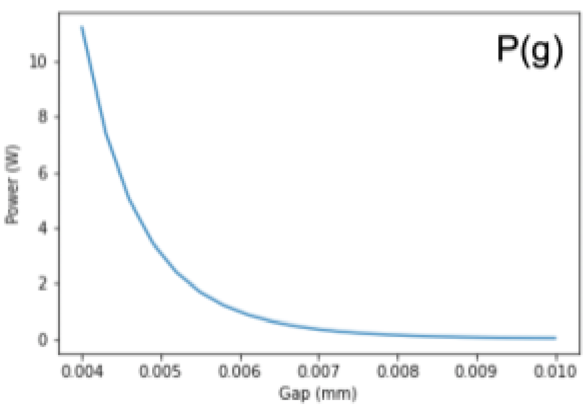


Figure 1.1

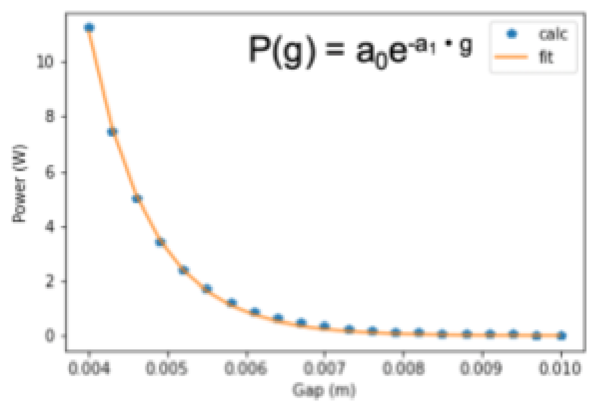


Figure 2

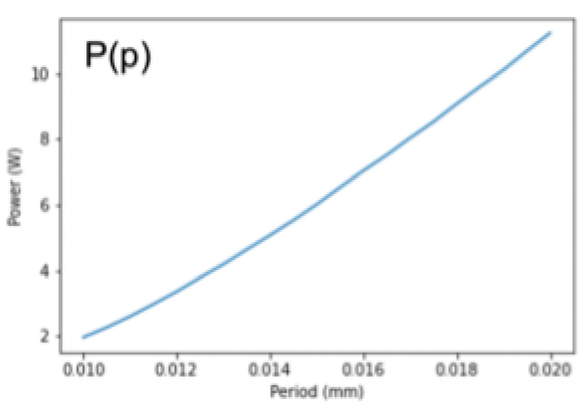


Figure 2.1

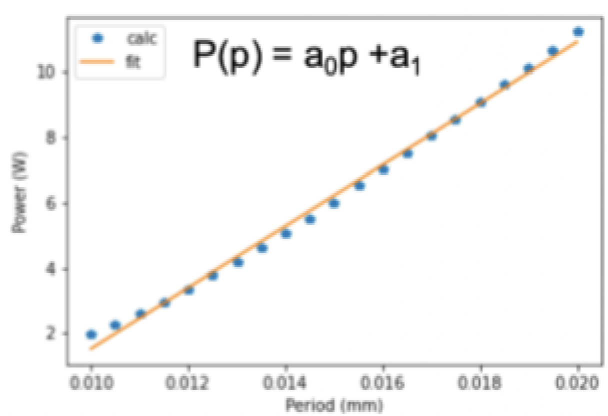


Figure 3

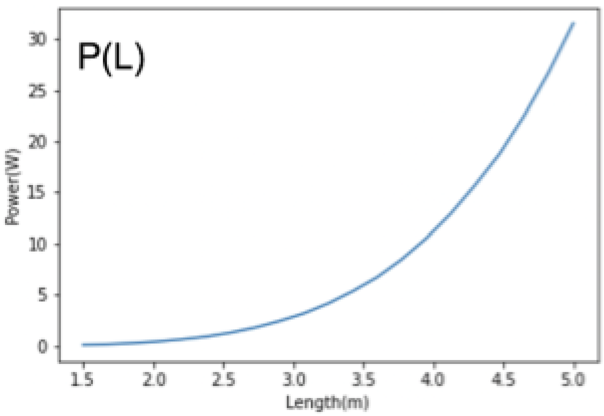


Figure 3.1

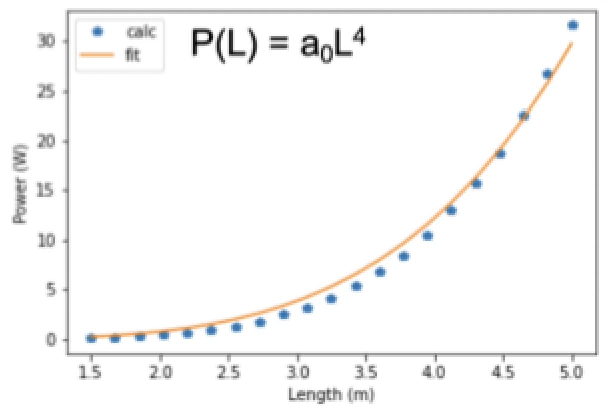


Figure 4

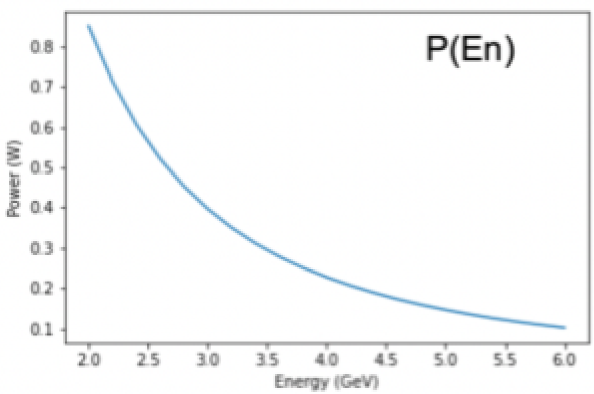
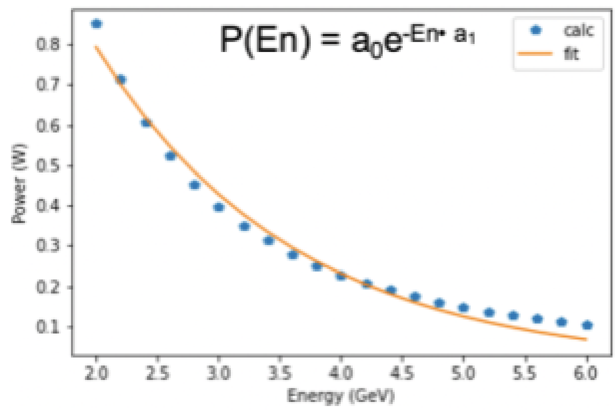


Figure 4.1



4D Plots and Curve Fits ——

Whereas the 1D plots only show a single parameter per plot as a function of the radiation deposited, the 4D plots show a single parameter per plot as a function of the radiation deposited with the other 3 variables set as a constant. Therefore, the 1D plots required a different equation for each parameter, while the 4D plots required one equation for all parameters. This equation was found to be $P(g, p, L, En) = a_0 \cdot En^2 \cdot 3.33 \cdot 3^{(-g/p(5.47 - 1.8(g/p)))} \cdot L^{a_1} \cdot g^{a_2} \cdot (En + a_3)^{a_4}$, where a_0, a_1, a_2, a_3 and a_4 are all coefficients. This equation was based upon Halbach's peak magnetic field equation. A chi-square calculation was used to determine the quality of the curve-fits using this functional form, which was equal to about 0.198.

For all the 4D plots, the orange dots are the calculation, and the blue line is the curve fit. Figure 5 is the plot when gap varies, while the period, energy, and length are set constant at 23 mm, 3 GeV, and 3 m, respectively; figure 6 is the plot when period varies, while the gap, energy, and length are set constant at 3 mm, 3 GeV, and 5 m, respectively; figure 7 is when the length varies, while the gap, period, and energy are set constant at 2 mm, 10 mm, and 3 GeV, respectively; figure 8 is when the energy varies while the gap, period, and length are set constant at 2mm, 10 mm, and 4 m, respectively.

Figure 5

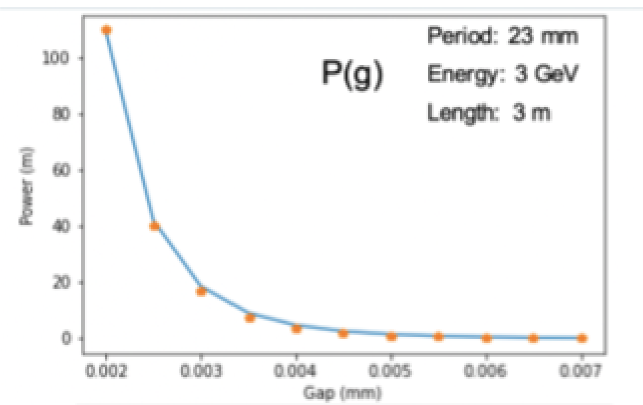


Figure 6

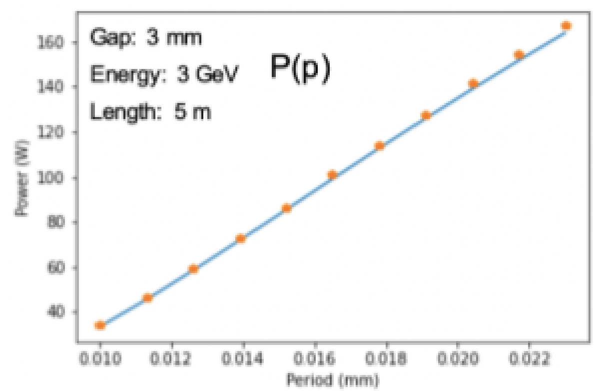


Figure 7

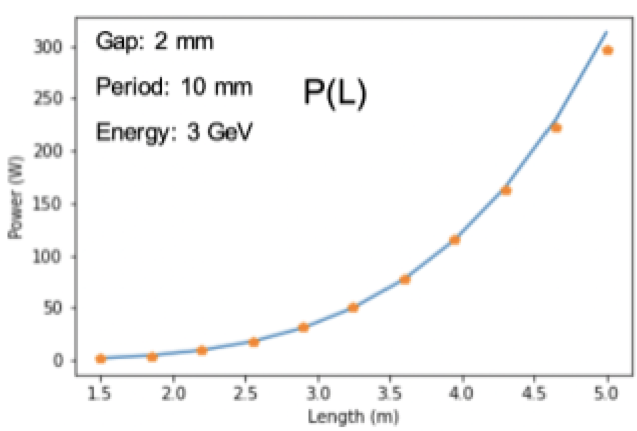
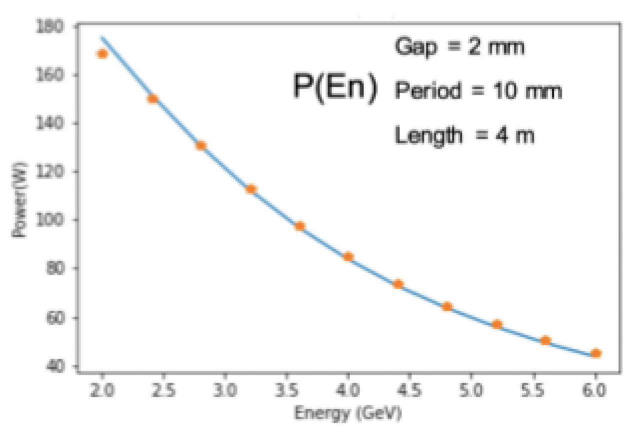


Figure 8



Brightness ——

The maximum brightness was achieved when the length of the electron beam is equal to about 4.4 m, and the gap is set to about 15 mm. In figure 9, at 10 keV, the red zone exceeds the radiation limit, the orange zone is below the radiation limit, but fails to produce any light, and the green zone will give off some light, with the blue dot being the maximum brightness. In figure 10, the histogram, each count represents a point on the plot of figure 9, and the blue line marks the maximum brightness. In figure 11, the graph shows the brightness of spectral peaks as the gap of an undulator is increased. For one point on the plot of figure 9, the optimal brightness is achieved in the third harmonic.

Figure 9

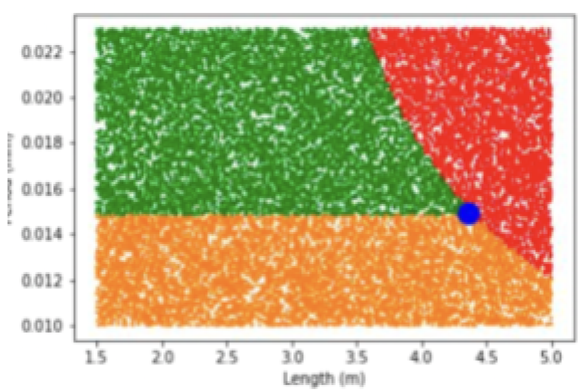


Figure 10

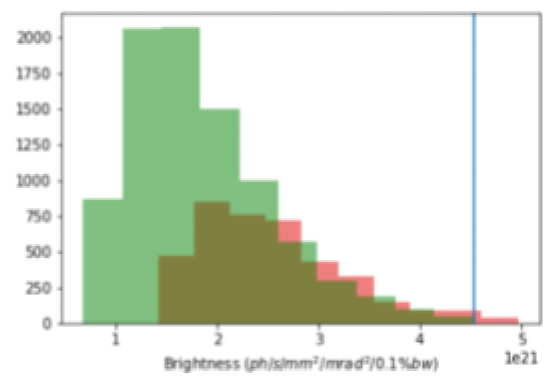
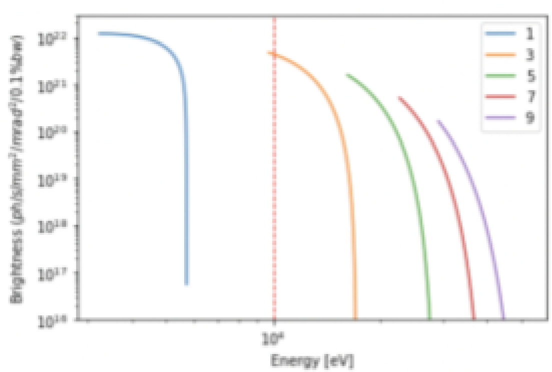


Figure 11



Conclusion

Should the aforementioned research be implemented in synchrotron facilities, the amount of time required to complete research would decrease significantly. As previously mentioned, the time typically required to compute the deposited radiation is 20 seconds per calculation. If this new code is enacted, the amount of time required to complete a calculation would decrease from 20 seconds to a fraction of a second. Decreasing the calculation time will naturally decrease the total amount of time it takes to complete research. This will allow more research in various fields to be completed.

Moreover, because scientists seek to build devices that are longer, have a smaller period, a smaller gap, and a larger magnetic field in order to maximize brightness, this research helps us to better understand the current limitations on devices that can be built. A narrower gap will increase the deposited radiation because the electron beam will be closer to the undulator. Similarly, a longer electron beam will also increase the deposited radiation because the electron beam will be closer to the undulator for a longer period of time. However, increasing the energy of the beam will decrease the deposited radiation because the electron beam will be close to the undulator for a shorter period of time.

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