USE OF MULTI-OBJECTIVE METHODS FOR CHOOSING UNDULATORS FOR STORAGE RINGS *

M. Borland†, ANL, Argonne, IL 60439, USA

Abstract

Users of storage ring light sources generally rely on undulators to provide the highest brightness. Choice of the optimal undulator period is complicated by the fact that users do not operate at a single photon energy or place equal weight on operation at all photon energies of interest. In addition, some users may be best served by a double- or triple-period revolver device. In this paper, we present a method of narrowing the choice of undulator periods based on multi-objective techniques. Applications are shown in the context of the Advanced Photon Source upgrade.

INTRODUCTION

A major component of the Advanced Photon Source (APS) upgrade is provision of new undulators in order to maximize flux and brightness for specific experimental programs. Originally, APS beamlines were provided with a standard "Undulator A" device, having a period of 3.3 cm and total length of 2.4 m. Over time, additional single-period periods have been developed for specific needs. As part of the upgrade, we are exploring provision of additional single-period devices, but also of a number two-period revolvers and superconducting undulators (SCUs). With these expanded choices comes the need to quickly and reliably determine the best device for a given experimental program.

The particular advantage of a revolver is that it provides two (or more) undulator periods within the space normally occupied by a single undulator. However, the choice of the best periods is not necessarily obvious. In this paper, we present a method for choosing undulator types and periods in order to maximize performance within the limits presented by beamline front ends.

The APS presently operates at 100 mA, but will move to 150 mA and possibly 200 mA as part of the upgrade. Due to power and power density limits in the front ends, the optimum for one current may well not be optimal for another. At the very least, we should optimize for 150 mA and keep an eye on performance at 200 mA. The software described here was configured to allow determining optimal choices for all three currents. Another variable is the type of front end, since that determines the specific power and power density limits.

Another complication is that not all devices have the same magnetic length. In particular, SCUs have a magnetic length 0.9 m shorter than hybrid permanent magnet (HPM) devices, due to the need for thermal transitions to and from cryogenic temperatures.

We've assumed that these choices will take one of several combinations, as follows

- Canted front end (CFE) in a 4.8-m-long short straight. Each half of the canted straight accommodates a 2.1-m HPM device or a 1.2-m SCU.
- CFE in a 7.7-m-long long straight section (LSS). Each half of the canted straight accommodates a 3.55-m-long HPM or 2.65-m-long SCU.
- High-heat-load front end (HHLFE) in a short straight with a 4.8-m HPM or 3.9-m SCU.
- HHLFE in a long straight in an LSS with a 7.7-m HPM or 6.8-m SCU.

Long revolvers are challenging mechanically and may involve restrictions on the period of the device; for the present analysis, we assume that periods up to 35 cm are possible. Note that due to front-end limitations, the longest device may not always be the best.

METHOD

The basic idea of our method is to analyze all possible choices and select those that will best satisfy users of the beamline. We assume that a given beamline will be interested in working over a specific set of photon energy bands and that the desired quantity to optimize is the brightness. (The same technique can readily be applied to flux or flux density.) For example, a beamline might want to operate in the bands from 20-25 keV, 30-35 keV, and 50-60 keV.

We assume that the dominant consideration is to have the narrowest possible spectral gaps within the bands of interest, where a spectral gap is defined as a region with brightness below 10^{15} photons/s/mm^2/mrad^2/0.1%BW. Ideally, there should be no spectral gaps. We then assume that users are interested in maximizing the average brightness over each band, but also in maximizing the minimum brightness over each band. These will not necessarily be achieved for the same conditions. Because of these potentially conflicting goals and the potential conflict between optimization for several energy bands, a multi-objective approach using non-dominated sorting is needed. Choice C_1 is said to dominate choice C_2 if C_1 is better than C_2 in all performance measures. In general, we may find that one choice dominates the other or that neither dominates, in which case each choice is superior in at least one performance measure. For any set of choices C_i, one or more choices always have the property of not being dominated by any

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

† borland@aps.anl.gov

other choice. It is from these "non-dominated" choices, also known as the "Pareto-optimal set," that the best options may be drawn.

The analysis has two steps: data preparation and determination of optimum choices for a specific requirement. First we describe the data preparation for HPM devices. For each current (100, 150, and 200 mA), each front-end and straight-section combination, and a series of device lengths consistent with the straight section length, perform the following steps:

1. Vary the device period from 17 mm to 55 mm in 1 mm steps.
   (a) Compute the maximum K value based on measured performance for APS devices for three magnetic gaps: 10.5 mm, 10.75 mm, and 11.0 mm.
   (b) Run `sddsbrightness` [1] and `sddsfluxcurve` [2] to get power density and total power as a function of K, along with brightness and flux density for harmonics 1 through 17. These data are interpolated to obtain brightness as a function of photon energy at 0.1-keV intervals from 0 to 120 keV.
   (c) Limit the photon energy range for each harmonic to account for the power and power density limits of the chosen front end.
   (d) Multiply the brightness for each harmonic by values that approximately account for the effect of typical phase errors [3].
   (e) Compute the brightness envelope over all harmonics. This eliminates the overlap and gives a single curve of maximum brightness vs photon energy. Gaps in the spectrum are represented by zero values.
2. Choose in turn the data for each device period from 17 to 35 mm (35 mm is the maximum period allowed for revolvers). Loop over all periods that are shorter than or equal to the chosen period. For each pair of periods, compute the maximum brightness available from either undulator as a function of photon energy.

These computations are fairly time-consuming, so a Linux cluster is used. Having completed this step, we now have several thousand data files covering various choices of beam current, front-end type, straight-section length, and device length. Each file tells us, for any pair of undulator periods, the maximum brightness available as a function of photon energy when front-end limits are taken into account. Data for single-period superconducting devices is obtained in a similar fashion.

The next step is to choose the optimum devices for a specific set of photon energy bands. This is performed with a graphical user interface (GUI) based on Tcl/Tk and SDDS. The fast non-dominated sorting algorithm of Deb [4] is implemented in the program `sddssort`. The user first selects the beam current, front-end type, and straight-section type, as well as providing a list of lower and upper limits for any number of energy bands. The software then collects all the relevant data files and computes a series of performance measures for device choice c and each band b: G_{cb}, the total number of points in spectral gaps; $B_{cb,m}$, the minimum brightness in the band; and $B_{cb,a}$, the average brightness in the band.

Because absence of gaps is very important, an initial non-dominated sort is performed to select those choices with the best values of G_{cb}. In most cases, it is possible to find several choices for which there are no gaps. Following this, a second non-dominated sort is performed on $B_{cb,m}$ and $B_{cb,a}$. The resultant list of top choices is displayed to the user, along with graphs of the performance for each. Because all the data are generated ahead of time, it takes at only about 10 s to produce a result. Figure 1 shows the interface.

A feature of this algorithm is that it will avoid choosing period pairs that have brightness gaps in the energy bands of interest. If gaps are in fact acceptable, then this should be indicated to the algorithm by splitting up the energy bands to exclude the regions where gaps are acceptable.

EXAMPLES

We ran the selection algorithm for a series of energy bands that seemed potentially interesting. For ease of comparison, we used a short straight section, an HHL front end, 10.75-mm magnetic gap, and 150-mA beam current in all cases. Table 1 shows the results. In reality, users would specify the energy bands they are interested in, but these results illustrate the approach. Figures 2 through 4 show examples of optimized brightness curves.

ALTERNATE SELECTION METHOD

An alternate method that we explored involves a different algorithm for choosing the best combination of periods. The idea of this algorithm is that at each photon energy (with 0.1-keV spacing) we find which choice delivers the highest brightness. We call this the dominant choice for that photon energy. We then count how many times each choice is dominant in the energy bands of interest. The "best" pair is the one that dominates the most times.

Although this algorithm is easily implemented, it does not produce satisfactory results. The reason is that it is possible to dominate at a significant number of points while also providing very poor performance in a significant number of points. Hence, the other algorithm is preferred.

CONCLUSION

A method was presented for optimizing the choice of devices for maximizing beamline performance. The method relies on simply computing all the brightness curves for each possible choice of periods, then finding the Pareto-optimal choices. Several applications of the method were

ISBN 978-3-95450-115-1

Table 1: Examples of optimized device choices for 150 mA, HHL front end, 4.8 m straight, and the indicated energy bands. Brightness values are in units of photons/s/mm^2/mrad^2/0.1%BW.

Band List keV	Number of choices in Pareto-optimal set	Sample device	Min. Brightness SU	Min. Ave. Brightness SU
10-30	5	4.8m Rev. 26+29mm	6×10^{19}	1×10^{20}
30-100	1	3.9m SCU 21mm	2.5×10^{18}	2.4×10^{19}
12.66 + 5-40	2	4.8m Rev. 24+30mm	3×10^{19}	9.9×10^{19}
12.66 + 31.8	2	3.9m SCU 21mm	8.4×10^{19}	8.4×10^{19}
12.66 + 31.8 + 5-40	6	4.8m Rev. 24+30mm	3.0×10^{19}	3.6×10^{19}
20-25 + 35-40	3	3.9m SCU 24	3.7×10^{19}	4.1×10^{19}
20-25 + 60-75	4	2.0m SCU 18	6.7×10^{18}	1.1×10^{19}

shown. The software is quick to run since the intensive calculations are done ahead of time on a Linux cluster.

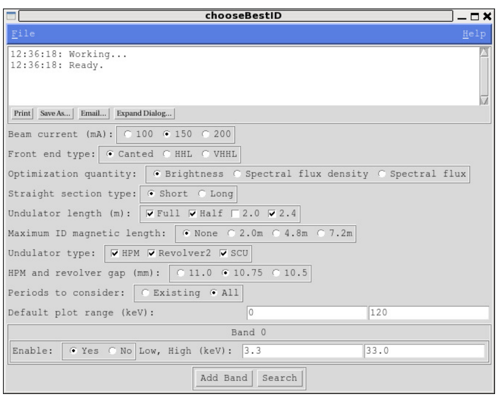

Figure 1: Graphical user interface for multi-objective selection of optimal insertion devices.

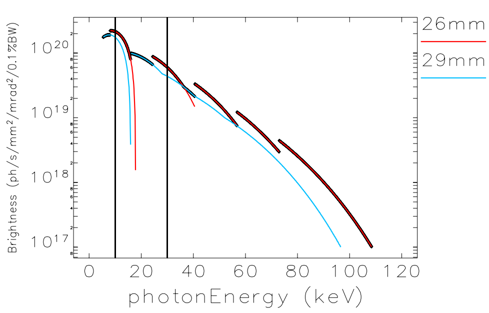

Figure 2: Brightness curves for optimal revolver ID 10-30 keV for APS with high-heat-load optics at 150 mA. The target region is shown by the vertical lines.

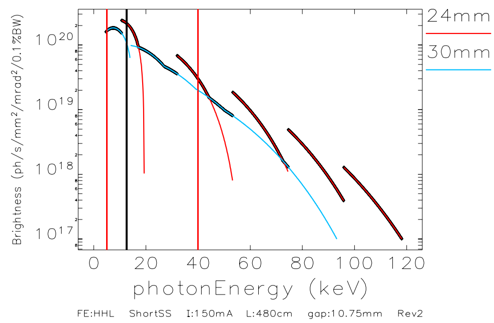

Figure 3: Brightness curves for optimal revolver ID for 12.66 keV and 5-40 keV for APS with high-heat-load optics at 150 mA. The target regions are shown by the vertical lines.

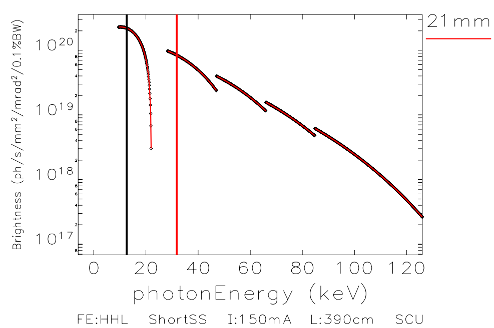

Figure 4: Brightness curves for optimal revolver ID for 12.66 keV and 31.8 keV for APS with high-heat-load optics at 150 mA. The target regions are shown by the vertical lines.

REFERENCES

[1] M. Borland *et al.*, Proc. PAC 2003, 3461-3463 (2003).

[2] M. Borland, H. Shang, R. Dejus, unpublished program.

[3] R. Dejus, Private communication.

[4] K. Deb *et al.*, KanGAL Report No. 2000001 (2000).