ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMF056



# BRIGHTNESS DEPENDENCE INVESTIGATION AND OPTIMIZATION FOR THE HEPS*

Y. Jiao†, M. Li, X. Y. Li, Key Laboratory of Particle Acceleration Physics and Technology, IHEP, CAS, Beijing 100049, China

*Abstract*

The High Energy Photon Source (HEPS) is an ultralow-emittance, kilometer-scale storage ring light source to be built in China. To maximize the photon spectral brightness, one of the most important performance parameters of the light source, we investigated the dependence of brightness on different parameters, such as the natural emittance, coupling, beta functions of the undulator section, and length of the undulator section. Based on this study, we optimized the HEPS lattice by using brightness as an optimizing objective.

## INTRODUCTION

In an electron storage ring light source, the photon spectral brightness is one of the most important performance parameters, providing a measure of the radiation quality. In modern storage ring light sources, emittance is minimized and insertion devices (IDs), e.g., the undulators, are widely adopted to reach a high brightness.

There are many literatures discussing the evaluation of brightness in a ring-based light source (e.g., [1-5]). Here we will follow the definition in Ref. [3], where the effect of energy spread was taken into account.

The spectral brightness $B$ of a planar undulator at $\lambda_n$, the $n$th harmonic of wavelength of $\lambda$, is defined as

$$B = \frac{F}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}. \quad (1)$$

where $F$ is the angular-integrated photon spectral flux in the forward direction, and $\Sigma_x$ and $\Sigma_{x'}$ ($\Sigma_y$ and $\Sigma_{y'}$) are the convoluted size and divergence of the photon beam and electron beam in horizontal (vertical) plane,

$$F = \frac{\pi}{2}\alpha N_u \frac{\Delta w}{w}\frac{I}{e} K^2 \xi [J_{\frac{n+1}{2}}(\frac{K^2\xi}{4}) - J_{\frac{n-1}{2}}(\frac{K^2\xi}{4})]^2. \quad (2)$$

$$\Sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y} + \sigma_{r0}^2 Q_s^2}, \Sigma_{x',y'} = \sqrt{\varepsilon_{x,y}/\beta_{x,y} + \sigma_{r'0}^2 Q_a^2}. \quad (3)$$

$$\sigma_{r0} = \sqrt{\lambda_n L_u / 8\pi^2}, \quad \sigma_{r'0} = \sqrt{\lambda_n / 2L_u}. \quad (4)$$

$$Q_a(d) = [\frac{2d^2}{-1+\exp(-2d^2)+(2\pi)^{1/2} d\, \mathrm{erf}(2^{1/2}d)}]^{1/2}. \quad (5)$$

$$Q_s(d) = 2[Q_a(d/4)]^{2/3}. \quad (6)$$

where $\alpha$ is the fine-structure constant, $N_u = L_u/\lambda_u$ is the period number with $L_u$ being the undulator length and $\lambda_u$ the undulator period, $I$ is the average beam current, $K$ is the undulator strength parameter, $\xi = n/(1+K^2/2)$, $\varepsilon_{x,y}$ and $\beta_{x,y}$ are the electron beam emittances and beta functions (in Eq. (3) beam waist is assumed), $d = 2\pi n N_u \sigma_\delta$ with $\sigma_\delta$ being the rms energy spread of electron beam.

When $Q_{a,s} = 1$, the above formulas reduce to those that is derived by assuming negligible energy spread (e.g., in [4]). From the above, the 'matching condition' that maximizes the brightness for a fixed emittance is that the beta functions is about $L_u/2\pi$.

Along with the continuous advance in accelerator technology and unceasing pursuit of higher quality photon beam, the so-called diffraction-limited storage ring (DLSR [6]) light sources, were proposed around the world, to push the brightness and coherence beyond the existing third generation light sources.

For the High Energy Photon Source (HEPS), a 6-GeV, kilometre-scale DLSR light source to be built around Beijing, north of China, the lattice has been evolved for ten years [7].

Global optimization was performed to explore optimal performance for the HEPS lattice. In the first stage of optimization of the HEPS hybrid 7BA lattice, emittance and dynamic aperture (DA) were optimized [8-14], with constraints on the ID beta functions to avoid beta functions too far away from the optimal values. However, it was noticed that the optimization tended to look for solutions with ultralow emittances but not very low beta functions, which is mainly due to the fact that a larger beta helps to reach a larger DA.

It was then considered to use the brightness rather than the emittance as an optimizing objective. Before doing so, we investigated the dependence of the brightness on different related parameters, such as the natural emittance, coupling, beta functions at the ID section, and the ID section length, hoping to get some hints on direction of effective lattice optimization.

## BRIGHTNESS DEPENDENCE

A program based on Eqs. (1-6) was written, which can calculate the brightness as a function of natural emittance $\varepsilon_0$, coupling factor $\kappa$ ($\kappa = \varepsilon_y/\varepsilon_x$, $\varepsilon_x+\varepsilon_y = \varepsilon_0$), beta functions at the centre of ID section, ID section length $L_s$ and the electron beam energy spread.

For a quick comparison, other related parameters were fixed and several assumptions were considered based on the HEPS design,

* Work supported by by NSFC (11475202, 11405187, 11205171)
† email address: jiaoyi@ihep.ac.cn

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMF056

- Photon energy of 20 keV (0.62 Å) at fundamental harmonic of the undulator radiation was specially considered. The electron beam energy was set to 6 GeV. The undulator parameters were fixed, i.e., $\lambda_u$ = 11.28 mm, undulator gap $g$ = 4 mm and $K$ = 0.7214, except the undulator period, $N_u = floor[(L_s–1)/\lambda_u]$, where $floor[x]$ gives the nearest integer to $x$ toward negative infinity.
- Although the beam energy was used as a variable parameter in the program, it was assumed to be constant, $\sigma_\delta = 8\times10^{-4}$.
- In the parameter scan, 'zero current' electron beam parameters were used, while the beam current was set to 200 mA without considering the collective effects (e.g., the intrabeam scattering) at high current. This is not self-consistent, but was believed to not greatly affect the result for the parameter tuning range of interest.

Based on the HEPS lattice design, we considered the cases with $L_s$ of 5 m and 6 m, $\varepsilon_0$ of 20 pm, 40 pm and 60 pm, and $\kappa$ of 0.1 and 1. For each case, the beta functions were scanned in the range of [0.1, 10] m, with a step of 0.1 m. Study indicated that the beta functions of 1~1.1 m in both $x$ and $y$ planes result in the maximum brightness (see Fig. 1 for an example), which are close to (but not equal to) the theoretically predicted 'matching condition', $L_{ID}/2\pi$. The values of the available maximum brightness, in unit of $10^{22}$ ph/s/mm$^2$/mrad$^2$/0.1%BW, under different cases are summarized in Table 1.

Table 1: Maximized Brightness Under Different Cases

| $L_s$ (m) | $\varepsilon_0$ (pm) | $\kappa$ | Max. $B$ |
|---|---|---|---|
| 5 | 20 | 0.1 | 14.6 |
| 5 | 20 | 1 | 12.9 |
| 5 | 40 | 0.1 | 8.3 |
| 5 | 40 | 1 | 6.4 |
| 6 | 40 | 0.1 | 9.4 |
| 6 | 40 | 1 | 7.4 |
| 6 | 60 | 0.1 | 6.3 |
| 6 | 60 | 1 | 4.5 |

Keeping other parameters unchanged, the brightness can be increased by ~15% with a 20% increase in $L_s$ (from 5 to 6 m with $\varepsilon_0$ of 40 pm); the brightness can be increased by at least 50% or 75% with a 33% or 50% decrease in $\varepsilon_0$ (from 60 to 40 pm with $L_s$ of 6 m, or from 40 to 20 pm with $L_s$ of 5 m); a 'flat' beam ($\kappa$ = 0.1) promises a higher brightness than a 'round' beam ($\kappa$ = 1), whatever the $\varepsilon_0$ is; in addition, as shown in Fig. 1, the effect of small beta functions is obvious. For example, by changing the beta functions from (8, 5) m to (1, 1) m, one can achieve an increase in brightness by a factor of ~80%.

## BRIGHTNESS OPTIMIZATION

In the following, tradeoffs between different parameters will be discussed from the lattice design point of view.

From the above, it seems more efficient to increase the brightness by reducing the emittance or the beta functions at the ID section than increasing the ID section length. Nevertheless, experience indicated that either emittance reduction or beta function minimization will lead to more difficulty in DA optimization.

One possible way may be using a shorter ID section length so as to get a larger arc length (for a fixed circumference of the ring), which benefits emittance reduction [14] and helps to achieve higher brightness as a net effect of the reduction in both $L_s$ and $\varepsilon_0$. Nevertheless, such a choice implies a lower photon spectral flux, which is undesirable for the users who care much about the flux.

Another possible way is to combine the reduction in emittance and beta functions at the ID section, i.e., decreasing both parameters to such a level that an adequate DA is still available.

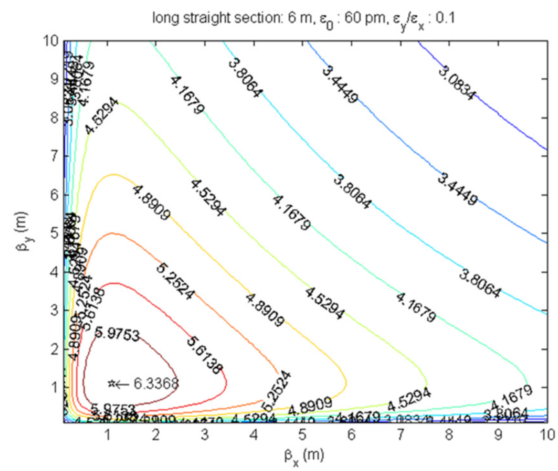


Figure 1: Brightness with respect to the beta functions, under the case with $L_s$ of 6 m, $\varepsilon_0$ of 60 pm and $\kappa$ of 0.1.

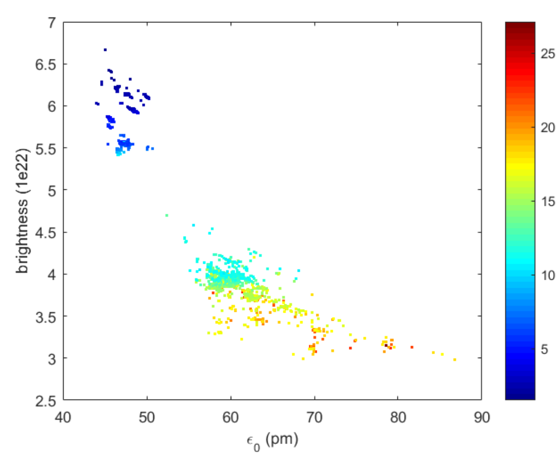


Figure 2: Optimized solutions for the HEPS lattice consisting of 48 identical hybrid 7BAs, projected to the space of ($\varepsilon_0$, $B$), with the colours representing different DA size.

This is actually what we did in the global optimization of the HEPS lattice consisting of 48 identical 7BAs [15], where a successive and iterative implementation of the PSO and MOGA algorithms (see [14] and references therein) were performed to avoid solutions being trapped in local optima. The final solutions are shown in Fig. 2. Note that the solutions promising very high brightness but

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMF056



with DA of a so small size that does not allow an efficient injection were gradually dropped out during the evolution. Figure 2 shows that the available maximum brightness is basically determined by the natural emittance of the lattice, and to achieve a lower emittance (a higher brightness) one needs to pay a price of a smaller DA. Further analysis (see Fig. 3) indicated that to obtain an adequate DA at an ultralow emittance, the beta functions at the ID could not be pushed down to very small values in both horizontal and vertical planes.

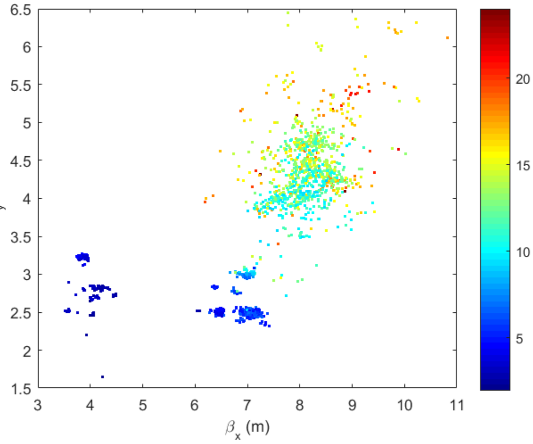


Figure 3: Optimized solutions for the HEPS lattice consisting of 48 identical hybrid 7BAs, projected to the space of ($\beta_x$, $\beta_y$) at the centre of the ID section. Different colours represent different DA size.

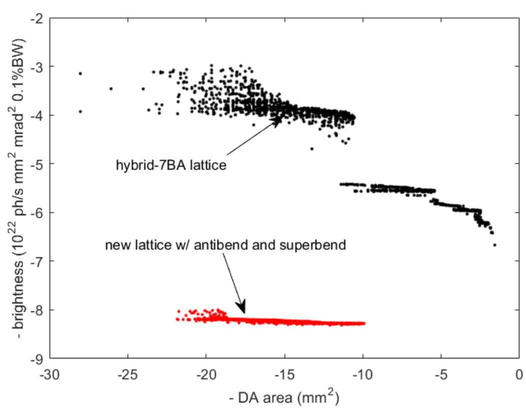


Figure 4: Optimized solutions (red dots) for the HEPS lattice by grouping the 48 hybrid 7BAs into 24 periods, the solutions for the HEPS lattice consisting of 48 identical hybrid 7BAs are also plotted for a comparison (black dots).

After discussing with beam line experts of the HEPS, we learned that user requirements on the radiation quality are really diverse. For example, some users prefer photon beam with as high as possible brightness; some users require high flux but not necessarily high brightness; and some users like wide covering range of the synchrotron radiation wavelength, and care about neither high flux nor high brightness.

So it was decided to look for an alternating high- and low-beta design, by grouping the 48 hybrid 7BAs into 24 periods. In this way, we can further push down the beta functions to the level as close to the 'matching condition' as possible for the highest possible brightness in one ID section, and match the beta functions of another section to moderate values to achieve an adequate dynamic aperture for at least the on-axis injection.

For this kind of lattice, global optimization was done, and the final solutions are shown in Fig. 4. It appears the conflict in pursing of the highest possible brightness and a large DA is greatly decoupled. At last, we reached a 34-pm lattice with alternating high- and low- beta sections and with antibends and superbends [16, 17]. The beta functions are about 2 m in the low-beta sections. A brightness of ~$8\times10^{22}$ ph/s/mm$^2$/mrad$^2$/0.1%BW can be achieved at the photon energy of 20 keV.

## ACKNOWLEDGEMENT

We sincerely thank the HEPS-TF IAC members and the colleagues of HEPS physics group for helpful discussions.

## REFERENCES

[1] K. J. Kim, in *Characteristics of Synchrotron Radiation*, *AIP Proc.*, No. 184, p.565-632, 1989.

[2] H. Onuki and P. Elleaume, "*Wigglers, Undulators and their applications,*" New York, USA: Taylor and Francis, 2003, p. 69-107.

[3] T. Tanaka and H. Kitamura, "Universal function for the brilliance of undulator radiation considering the energy spread effect", *J. of Synchrotron Rad.*, vol. 16, 380-386, 2009.

[4] Y. Cai *et al.*, "Ultimate storage ring based on fourth-order geometric achromats", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 054002, 2012.

[5] M. Borland *et al.*, "Lattice design challenges for fourth-generation storage-ring light sources", *J. of Synchrotron Rad.*, vol. 21, pp. 912-936, 2014.

[6] R. Hettel, "DLSR design and plans: an international overview", *J. Synchrotron Rad.*, vol. 21, pp. 843-855, 2014.

[7] Y. Jiao *et al.*, "Evolution of the lattice design for the High Energy Photon Source", presented at the 9th Int. Particle Accelerator Conf. (IPAC'18), Vancouver, Canada, Apr.-May 2018, paper TUPMF049, this conference.

[8] G. Xu, Y. Jiao, Y. Peng, "ESRF-type lattice design and optimization for the High Energy Photon Source", *Chin. Phys. C*, vol. 40, no. 2, p. 027001, 2016.

[9] Y. Jiao, "Improving nonlinear performance of the HEPS baseline design with a genetic algorithm", *Chin. Phys. C*, vol. 40, no. 7, p. 077002, 2016.

[10] Y. Jiao and G. Xu, "Exploring the ultimate linear and nonlinear performance of the HEPS hybrid 7BA design", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 2883-2885, doi:10.18429/JACoW-IPAC2016-WEPOW025.

[11] G. Xu *et al.*, "Recent physical studies for the HEPS project", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 2886-2888, doi:10.18429/JACoW-IPAC2016-WEPOW026

[12] Y. Jiao *et al.*, "Progress in the design and related studies on the High Energy Photon Source", *Physics Procedia*, vol. 84, pp. 40-46, 2016.

[13] G. Xu and Y. Jiao, "HEPS lattice design", in *1st HEPS-TF IAC meeting*, p. 12, 2016.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMF056

[14] Y. Jiao and G. Xu, "Optimizing the lattice design of a diffraction-limited storage ring with a rational combination of particle swarm and genetic algorithms", *Chin. Phys. C*, vol. 41, no. 2, p. 027001, 2017.

[15] Y. Jiao *et al.*, "Status of HEPS lattice design and physics studies", in *Proc. SAP2017*, Jishou, Hunan, China, Jan. 2018, pp. 7-9, doi.org/10.18429/JACoW-SAP2017-MOBH2

[16] Y. Jiao *et al.*, "Accelerator Physics studies for the High Energy Photon Source in Beijing", presented at the 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS'18), Shanghai, China, Mar. 2018, paper MOP2WB01, unpublished.

[17] G. Xu *et al.*, "Progress of lattice design and physics studies on the High Energy Photon Source", presented at the 9th Int. Particle Accelerator Conf. (IPAC'18), Vancouver, Canada, Apr.-May 2018, paper TUPMF052, this conference.