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Conceptual design of Hefei advanced light source*

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Abstract The conceptual of Hefei Advanced Light Source, which is an advanced VUV and Soft X-ray source, was developed at NSRL of USTC. According to the synchrotron radiation user requirements and the trends of SR source development, some accelerator-based schemes were considered and compared; furthermore storage ring with ultra low emittance was adopted as the baseline scheme of HALS. To achieve ultra low emittance, some focusing structures were studied and optimized in the lattice design. Compromising of emittance, on-momentum and off-momentum dynamic aperture and ring scale, five bend acromat (FBA) was employed. In the preliminary design of HALS, the emittance was reduced to sub nm·rad, thus the radiation up to water window has full lateral coherence. The brilliance of undulator radiation covering several eVs to keVs range is higher than that of HLS by several orders. The HALS should be one of the most advanced synchrotron radiation light sources in the world.

Key words SR light source, diffraction limited emittance, brilliance, coherence, lattice, dynamic aperture

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1 Introduction

Hefei Light Source is the first dedicated synchrotron radiation light source in China, which was designed and constructed in the later 1980s and began regular operation in 1991. At present, 16 beamlines are in operation and above 150 registrated users are doing experiments at NSRL. Several hundreds experiments are completed every years.

HLS is spectrally stronger at VUV and soft X-ray, and superconducting wavelength shifter is used to extend the available radiation to hard X-ray. Comparing with fast developing third generation light sources, the performance of HLS is lagged behind. Some inherent factors limit the enhancement of HLS performance, such as large beam emittance and less number of insertion devices, which prevent from providing brilliant undulator radiation to users. Upgrade proposal of HLS, where emittance is lowered to several nm·rad and ID number is increased to 7, was studied theoretically[1]. But its performance can't achieve advanced level in the world due to low beam energy and short ID length. For the increasing demand of SR users, an idea of advanced VUV and soft X-ray light source, named Hefei Advanced Light Source, was developed in future plan of NSRL. In the following sections, the design consideration and preliminary lattice design will be presented briefly.

2 Features of advanced light sources

According to user requirements and the development trends of light sources, some specific features would be attached to the advanced light source, including higher brilliance, better lateral coherence, controllable polarization, correct photon energy, good stability, etc. Some users need synchrotron radiation with ultra short pulse and/or ultra high brilliance[2].

Undulator radiation would be the main source with its high brilliance, controllable polarization and adjustable photon energy. The brilliance of undulator radiation is:

$$B=\frac{N_{\rm ph}}{4\pi^2\sigma_{\rm Tx}\sigma_{\rm Tx'}\sigma_{\rm Ty}\sigma_{\rm Ty'}({\rm d}\omega/\omega)}\,, \tag{1}$$

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where N_{ph} is photon flux, $\sigma_{\mathrm{Tx,Ty,Tx',Ty'}}$ are horizontal and vertical source parameters, which are dependent on the electron and undulator parameters[3]. The effective measures enhancing brilliance are to increase photon flux and to decrease beam emittance. When beam emittance approaches zero, the source geometrical parameters are determined by diffraction effects, and the brilliance reaches diffraction limited brilliance $\left(N_{\mathrm{ph}}\cdot(4/\lambda^2)\right)/(\mathrm{d}\omega/\omega)$, which is determined by radiation wavelength.

Transverse coherence is relevant to emittance. When emittance is smaller than diffraction limited emittance:

$$\varepsilon_{x,y} \leqslant \lambda/4\pi, \tag{2}$$

where λ is radiation wavelength, radiation will show interesting diffraction and interference properties. The user-concerned wavelength is shorter; the diffraction limited emittance is smaller. According to the dependence of brilliance and coherence on emittance, reducing emittance is the design key of the advanced SR light source.

There are different methods to produce ultra short SR pulses: in linac-based light source, laser-driven electron gun and magnetic compression techniques are employed to obtain ~100 fs pulse; while in ring-based light source, laser slicing or crab cavity techniques are adopted to achieve sub-ps pulse.

At present, three advanced light source schemes are focused on. The first one is the linac-based FEL, such as LCLS and X-FEL[4, 5], whose advantages are ultra high peak brilliance and ultra short SR pulse, while served users are limited by low repetition frequency of linac. The second one is linac-based ERL, such as CHESS, and APS-upgrade, whose advantages are very high average brilliance, better coherence and more served users, while some key techniques are under study[6, 7]. The third one is ultra low emittance storage ring, such as NSLS II with 0.55 nm·rad[8], whose advantages are high brilliance and have more served users and mature techniques, but the shortage is that it is difficult to obtain ultra low emittance due to quantum excitation in storage ring. For reducing emittance, the large ring is necessary to adopt more dipoles, where severe nonlinear problems are the main obstacles in the ring lattice design.

3 Design consideration of HALS

HALS is intended to be an advanced VUV and soft X-ray light source with higher brilliance, whose emittance is smaller than 0.2 nm·rad allowing production coherent SR in water window (minimum photon wavelength is 2.5 nm); number of ID is more and length of ID is moderate. One limitation on circumference is that, HALS can be located on NSRL campus.

The radiation wavelength of undulator radiation is:

$$\lambda\left[\mathring{A}\right] = 13.056\frac{\lambda_{\mathrm{period}}}{nE^2}\left(1+\frac{1}{2}K^2\right), \tag{3}$$

where $\lambda_{\mathrm{period}}$ is period of undulator, n is harmonic number, K is strength parameter, E is beam energy。To produce brilliant short wavelength radiation, it is inclined to high beam energy and short undulator period. On the contrary, to produce high brilliant long wavelength radiation, it is apt to low energy and long period. According to current ID techniques, when the beam energy is 1.5 GeV, HALS can use undulator with period 100 mm to produce several eVs photons and use short period undulator to produce several keVs photons.

The achievable emittance is the main factor determining light source scheme. Assuming normalized emittance of linac is 1 μm·rad, the geometrical emittance is 0.34 nm·rad when energy is 1.5 GeV. According to MAX-IV and NSLS-II experiences, sub nm·rad emittance can be obtained in storage ring. Under predetermined energy, the emittance of linac has not obvious advantages. Associating with user number and technique maturity, storage ring with ultra low emittance was adopted as the baseline of HALS.

4 Lattice design of HALS

Lattice design is the most important issue in HALS physical design. Emittance and nonlinear performance are the main concentration in design study. Expression of emittance in storage ring is:

$$\varepsilon_{\mathrm{x0}}\,[\mathrm{nm\cdot rad}] = 1470\frac{(E\,[\mathrm{GeV}])^2}{J_x}\frac{F_1F_2\theta^3}{12\sqrt{15}}, \tag{4}$$

where θ is angle of dipole, J_x is horizontal damping partition number, F_1 is determined by specialized lattice, F_2 is ratio of achieved emittance to theoretical minimum emittance of specialized lattice.

Under limitation of circumference, the double bend acromat (DBA), triple bend acromat (TBA), quadruple bend acromat (QBA), five bend acromat (FBA), six bend acromat and seven bend acromat (SBA) were studied. DBA and TBA have more straight sections and are used in current light sources, but for our limitation, the achieved emittance is larger due to less dipole number. Multiple bend acromat ($M>3$) is more compact and factor F_1 is smaller,

Table 1. Basic parameters of HALS storage ring.

energy	1.5 GeV	circumference	392 m
beam intensity	500 mA	betatron coupling	5∼10%
straight section	7.6×18 m	natural energy spread	0.00022
tunes	29.32/10.29	bunch length	∼2 mm
momentum compaction	0.00047	natural chromaticity	−55/−51
radiation without ID	34 keV/turn	radiation with ID	∼300 keV/turn
emittance with DW	< 0.2nm·rad	emittance of bare lattice	0.27 nm·rad
harmonic number	648	momentum aperture	> ±3

whose disadvantage is number of straight sections. Considering the achieved emittance, the number and length of straight sections, FBA was adopted; where the dipole-quadrupole and quadrupole-sextupole combined function magnets were employed.

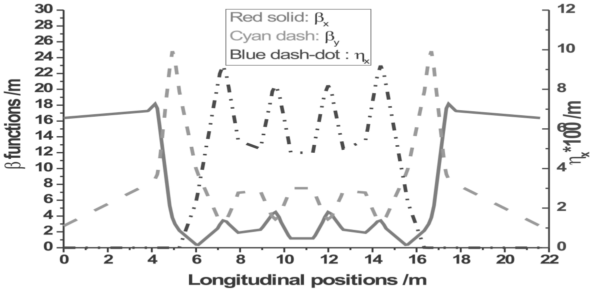

Fig. 1. Twiss parameters of HALS.

The MAD, OPA and BETA codes were used in linear and nonlinear optimization of the HALS storage ring. There is no distinct boundary between linear and nonlinear optimization. In linear optimization, emittance and Twiss function are the main purpose, while the position and strength of sextupoles are the main variables in nonlinear optimization except for adjusting the advance of betatron phase. Full symmetric lattice was adopted to avoid DA reduction. The basic parameters of HALS are listed in Table 1. The achieved emittance of bare lattice is 0.27 nm·rad，and a few damping wiggler is needed to achieve the design goal. Figs. 1 and 2 show the Twiss functions of one cell and brilliance curves. The brilliance of undulator radiation is very high and exceeds 10^{21} photons/s·mm^2·mrad^2·‰ BW, and the brilliance of dipole radiation is also considerable.

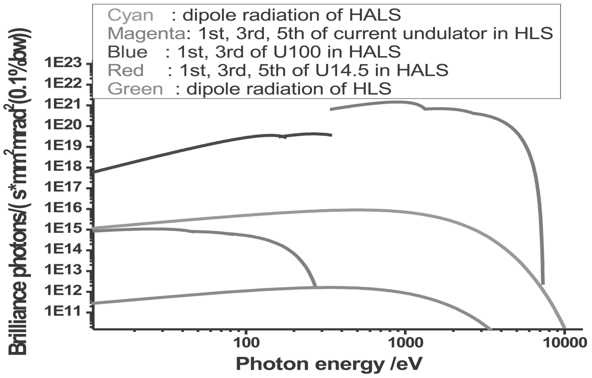

Fig. 2. Brilliance curves of HALS.

5 Conclusions

The preliminary physical design study of HALS shows that, the design goal can be achieved by ultra low emittance storage ring with acceptable dynamic aperture and momentum aperture, and the number and length of straight section are moderate, which are essential to produce high brilliance VUV and soft X-ray radiation. The maximum brilliance of HALS exceeds 10^{21} photons/s·mm^2·mrad^2·1‰ BW. The transverse coherence of HALS is better than that of most light sources. Beside the above introduction, detail studies of many issues and application procedure of HALS are underway.

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