ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB075

PROPOSAL OF THE SOUTHERN ADVANCED PHOTON SOURCE AND CURRENT PHYSICS DESIGN STUDY*

Sheng Wang†[1], Jianliang Chen[1], Yanliang Han[1], Liangsheng Huang[1], Yi Jiao, Biaobin Li[1],
Zhiping Li[1], Weihang Liu[1], Xingguang Liu[1], Xiaohan Lu[1], Shouyan Xu[1] and Yu Zhao[1],
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China,
[1]also at Spallation Neutron Source Science Center, Dongguan 523808, China

Abstract

It has been considered to build a mid-energy fourth generation storage ring photon source neighbouring the China Spallation Neutron Source, in Guangdong Province, the south of China. The photon source is named as the Southern Advanced Photon Source (SAPS). Preliminary physics design studies on the SAPS have been implemented for a few years. In this paper, we will describe considerations of technical roadmap and key parameter choice for this photon source, and introduce the up-to-date lattice designs and related physics studies on the SAPS.

INTRODUCTION

Early from 2016, scientists from the Institute of High Energy physics (IHEP), have proposed to build a mid-energy fourth generation storage ring photon source neighbouring the China Spallation Neutron Source (CSNS), in Guangdong Province, the south of China. This photon source, together with the CSNS, is expected to able to benefit multi-discipline scientific researches in the south of China.

In the past few years, several meetings were held to discuss the main goals and roadmap of this photon source, and great efforts were made to apply for the R&D project for this photon source, which is named Southern Advanced Photon Source (SAPS).

In the meantime, preliminary design studies are under way. In current stage the main parameters of the photon source, like the beam energy and circumference have not been fixed yet. And for the injector, two candidate options, i.e., Linac and booster, a full energy Linac are both under consideration. This brings challenges but also great freedom to the design studies. It is expected that with iterative design and optimization, the overall design goals of the SAPS will become gradually clear.

Up to now, we have produced several candidate lattices for the SAPS storage ring and the injector. The design experience of the High Energy Photon Source [1] (HEPS, also built by IHEP) provides many helpful information and references. In addition, we also started studies on related physics issues in such an ultralow emittance ring photon source, such as the lattice calibration, collective effects and injection schemes. The status of the SAPS design studies is presented in this paper.

PHYSICS DESIGN STUDIES

Candidate Ring Lattice Design

One candidate lattice for the SAPS storage ring has been worked out, with a beam energy of 3.5 GeV and a circumference of 1080 m. It is composed of 36 7BA cells.

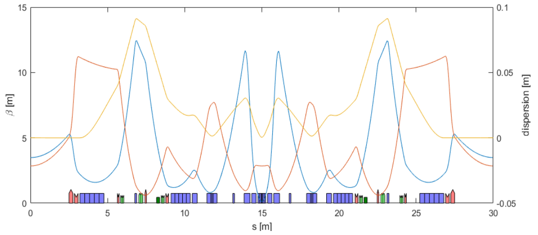

Figure 1: Layout and optical functions of the candidate lattice designed for the SAPS. The blue, red, green, dark green blocks represent dipoles, quadrupoles, sextupoles and octupoles, respectively.

In this lattice design, we basically followed the Hybrid Multi-bend achromat (H-MBA) concept [2], which was firstly proposed and adopted in the design of the ESRF upgrade project. Based on the H-7BA, we added some combined function dipoles such as longitudinal gradient bends (LGBs) [3] and high-gradient horizontally focusing anti-bends (ABs) [4] to further improve the performance. Firstly, we replace the third and fifth dipoles in each achromat with novel combined function dipoles (like those in Elettra-II [5]) and change the fourth dipole to an LGB whose central slice has a magnetic field up to 2 T. Each of the novel combined function dipoles consists of high-field (up to 1.05 T without transverse gradient) dipole in the middle and moderate-field (0.31 T with transverse gradient up to 20 T/m) dipoles on both sides. In addition, neighboring the LGB, there are two dipoles combined with horizontally defocusing gradient and two ABs, like the unit cell in SLS-II [6]. Then we replace two quadrupoles within the dispersion bump to those ABs. Considering the experience [7] in the HEPS design that the lattice parameters are more relevant to the horizontal phase advance of one pair of sextupoles, and less relevant to the vertical one, the vertical phase advance between the one pair of the sextupoles is not matched to nπ but treated as a free variable during the design and optimization process.

The lattice is optimized with the multi-objective particle swarm optimization (MOPSO) [8, 9] and multi-objective genetic algorithm (MOGA) [10, 11]. Experience [12] in HEPS has shown that a combination of MOPSO

---

*work supported by Guangdong Basic and Applied Basic Research Foundation(2019B1515120069)
† wangs@ihep.ac.cn

and MOGA is more effective than using only either of them. In the optimization, all tunable variables except the lengths of the quadrupoles and long straight sections are optimized to find some feasible solutions between the emittance and ring acceptance (a normalized quantity with the dynamics aperture (DA) and momentum acceptance (MA)). Finally, a design with an emittance of 31.8 pm·rad is obtained [13]. The layout and optical functions of one period are shown in Fig. 1, and the main parameters of the storage ring are summarized in Table 1. In the candidate design for SAPS, the horizontal and vertical phase advances between the sextupoles are 3π and 2.5π, respectively. Moreover, the MA is about 4% and the DA for on-momentum particles is about 5 mm in the horizontal and 4 mm in the vertical (tracked for 1024 turns), sufficient for on-axis injection.

Table 1: Main Parameters of the Candidate Design

Parameters	**Values**	**Unit**
Beam energy	3.5	GeV
Natural emittance	31.8	pm·rad
Circumference	1080	m
Natural energy spread	1.10×10^{-3}	
Length of straight section	5	m
RF frequency	166.7	MHz
RF voltage	1.2	MV
Corrected chromaticity (H/V)	1	
Momentum compaction factor	1.37×10^{-5}	
Harmonic number	600	
Natural bunch length	4.6	mm
Betatron tune (H/V)	81.23/64.18	
Radiation energy loss per turn	0.898	MeV/turn
Damping partition ($x/y/z$)	1.55/1/1.45	
Damping time ($x/y/z$)	18.1/28.1/19.3	ms

Injector Option A: Linac and Booster

The injector option of a low energy Linac and a booster has been adopted by many synchrotron photon facilities [1, 14-16] due to its robustness and lower cost, compared to other options like full energy Linac and the energy ramping storage ring.

In our preliminary design for this option, the Linac consists a DC thermionic electron gun, a bunching section and an accelerating section. The electron gun can provide electron bunches at 50 Hz with energy of 150 keV, bunch length of about 1.6 ns. The bunch charge can be varied for different working modes of the storage ring. The bunching section includes two sub-harmonic cavities, one pre-buncher, one main-buncher, one S-band Linac and several focusing solenoids. This section can compress the bunch length and accelerate the bunch energy to about 50 MeV. In the accelerating section the electron energy will be boosted from 50 MeV to 150 MeV and the bunch length is further reduced using velocity bunching. The layout of the low energy Linac system is shown in Fig. 2. Details are given in another paper [17].

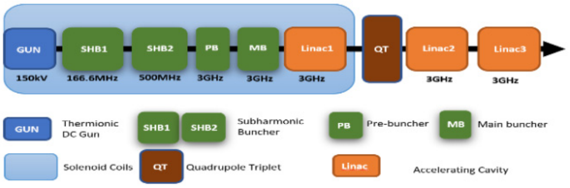

Figure 2: The Layout of the low energy Linac system of the injector option A.

The booster is assumed to be a 1 Hz synchrotron. Electron bunches coming from the 150 MeV Linac will be accelerated, then extracted and injected into the storage ring. The current design of the booster has a three-fold structure lattice with a circumference of 240.5 m, including 60 dipole magnets and 78 quadrupole magnets. Each super-period, as shown in Fig. 3, consists of nine identical TME cells and two matching cells to make dispersion-free long straight sections. The booster will be located in a separate tunnel from the storage ring.

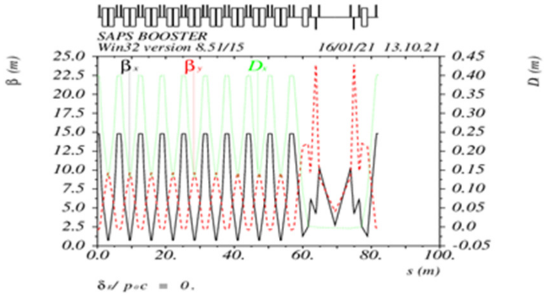

Figure 3: Layout of the booster TME lattice and the optical functions along the lattice.

Injector Option B: Full Energy Linac

Both X-ray Free Electron Laser (XFEL) and Diffraction Limited Storage Ring (DLSR) are the 4th generation photon sources and currently being built or planned around the world. Thus, in the early design stage, it is better to keep the option of full energy Linac injector for the DSLR in case the XFEL plan is foreseen in the future. In fact, Max-IV [18], Spring-8-II [19] and another 3 GeV photon source project in Japan [20] adopt this option for the same reason. SAPS is a mid-energy-range DSLR. With similar undulator design as the CompactLight project [21], the generated photon can cover the soft X-ray region and part of the hard X-ray region [22]. Thus, the Linac of this option has been designed in such a way that it can be used as an XFEL while fulfilling the needs of the storage ring.

C-band RF photo gun has been chosen for Compact-Light project to provide small emittance beam (0.15 µm normalized). In order to generate hard X-ray at relatively lower energy like SAPS, the period of the undulator should be short and the emittance from the electron beam should be small. Thus C-band RF gun is chosen for SAPS too. At the same time, C-band accelerating structures have been widely chosen in recent XFEL projects like SACLA in Japan [23], swissFEL [24] in Switzerland and SXFEL [25] in China, also in the above-mentioned 3 GeV photon source project in Japan. For the option of the full energy Linac of SAPS, we consider a full C-band Linac, except for the linearizer part, making it an advanced solution.

A preliminary full energy Linac delivering 3.5 GeV electron beam working in the XFEL mode has been designed [26], as shown in Fig. 4. The whole Linac includes two-stage beam compression, at 300 MeV and 1.5 GeV, respectively. However, compressed beam with a current intensity of several kiloamperes is not suitable for beam transport and injection to the SAPS ring due to large radiation loss. One possible solution is putting the second Bunch Compressor (BC) after the final energy like Max-IV or bypassing the second BC during injection. Another choice is making the bunch longer in the transport line from the Linac to the ring, like that in SACLA [19].

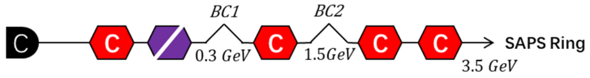

Figure 4: Full energy Linac injector for SAPS.

Injection Consideration

Conventional off-axis injection scheme generally requires that the storage ring provides a large dynamic aperture at the level of 10 mm. For the SAPS storage ring, the small dynamic aperture of 5 mm makes it difficult to use off-axis injection scheme.

The novel on-axis transverse injection scheme [27] requires dynamic aperture of only few millimeters, which is compatible with the SAPS storage ring. The cost for this on-axis injection is that there is no beam accumulation and thus large bunch charge from the injector.

Moreover, the on-axis longitudinal injection scheme [28] is also under consideration. This scheme allows bunch accumulation so that the requirement for single bunch charge is not critical. Especially in the case of the full energy Linac option, the single bunch charge is typically lower to ensure a small beam emittance. The challenge of this on-axis injection scheme is even faster injection kicker (compared to on-axis transverse injection) with the state-of-art technology.

Error Study

A large number of ultra-high gradient quadrupoles and sextupoles in the SAPS storage ring design lead to tight tolerance of beam parameters to magnetic errors. Therefore, it is essential to evaluate the effect of various magnetic errors on lattice parameters.

At present, the SAPS error study covers some common errors in practical accelerator (in brackets are typical setting in simulation):

- Alignment offsets in three directions (30 µm in rms) and rolling angles (100 µrad in rms)
- Magnetic field errors: dipole (3×10^{-4}), quadrupole (2×10^{-4}) and sextupole (3×10^{-4}).

Different random seeds are generated for the SAPS lattice error study. Beam optical parameters, closed orbit information, and dynamic aperture are recorded and analyzed. It is found that for the errors listed above, the alignment error has dominant contribution to DA reduction. More details are shown in [29].

IBS Effects

For SAPS which operates in the regime of low energy, ultra-small emittance and high luminosity, intra-beam scattering (IBS) that includes multiple small-angle coulomb scattering within the beam will lead to a remarkable increase in the 6D emittance of the bunch and thus greatly restrict the best performance of photon source.

The IBS introduced growth rates and equilibrium emittances in SAPS are calculated with the tool of ELEGANT [30], the algorithm of which is based on the Bjorken and Mtingwa's formula [31]. Simulation results indicate that the beam emittance is sensitive to the beam current intensity and the coupling factor. By using 3rd harmonic cavities for bunch lengthening and insertion devices for increasing damping, the IBS effect can be controlled and the growth rate of emittance will slow down significantly.

OTHER STUDIES

One of the attractive studies of the storage ring photon source is to break the time resolution limits of its radiation pulses and extend the time resolution to femtosecond or even sub-femtosecond levels. To achieve this goal in SAPS, a new scheme has been proposed by combining a few-cycle laser and a laser modulation scheme [32, 33]. The numerical results of the proposed scheme demonstrate the feasibility of obtaining a soft X-ray attosecond pulse with MW level peak power in SAPS. In addition, by adopting an optical cavity, the repetition rate of the attosecond pulse is expected to reach the level of MHz.

SUMMARY

A mid-energy 4th generation photon source was proposed to be built near the CSNS, in the south of China. The efforts of the lattice designs and related physics studies on the SAPS have been made. The basic design on the ring and injector has been worked out. Nevertheless, there is still a lot of work ahead to reach a satisfying and self-consistent physics design of the photon source.

REFERENCES

[1] Y. Jiao *et al.*, "The HEPS project", *J. Synchrotron Rad.*, vol. 25, pp. 1611-1618, 2018. `doi:10.1107/S1600577518012110`

[2] L. Farvacque *et al.*, "A low-emittance lattice for the ESRF", in Proc. 4th Int. Particle Accelerator Conf. (*IPAC'13)*, Shanghai, China, May 2013, paper MOPEA008, pp. 79-81.

[3] S.C. Leemann and A. Streun, "Perspectives for future light source lattices incorporating yet uncommon magnets", *Phys. Rev. Spec. Top-Accel. Beams*, vol. 14, pp. 030701, 2011. `doi:10.1103/PhysRevSTAB.14.030701`

[4] A. Streun *et al.*, "Design studies for an upgrade of the SLS storage ring", in *Proc. IPAC'15*, Richmond, USA, May 2015, paper TUPJE047, pp 1724-1727.

[5] E. Karantzoulis and W. Barletta, "Aspects of the Elettra 2.0 design", *Nucl. Instr. Meth. A*, vol. 927, pp. 70-80, 2019. `doi:10.1016/j.nima.2019.01.044`

[6] L. Liu *et al.*, "The Sirius project", J. Synchrotron Rad., vol. 21, pp. 904-911, 2014. `doi:10.1107/S1600577514011928`

[7] Y. Jiao and G. Xu, "DA optimization experiences in the de-sign of HEPS lattice", in *Proc. IPAC'18*, Vancouver, Canada, April 2018, paper TUPMF050, pp. 1367-1370.

[8] X. Pang and L.J. Rybarcyk, "Multi-objective particle swarm and genetic algorithm for the optimization of the LANSCE linac operation", *Nucl. Instr. Meth. A*, vol. 741, pp. 124-129, 2014. `doi:10.1016/j.nima.2013.12.042`

[9] Z. Bai, W. Li, and L. Wang, "Emittance optimization using particle swarm algorithm", in *Proc. IPAC'11*, San Sebastián, Spain, September 2011, paper WEPC109, pp. 2271-2273.

[10] 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, pp. 027001, 2017. `doi:10.1088/1674-1137/41/2/027001`

[11] L. Yang *et al.*, "Global optimization of an accelerator lattice using multi-objective genetic algorithms", *Nucl. Instr. Meth. A*, vol. 609, pp. 50-57, 2009. `doi:10.1016/j.nima.2009.08.027`

[12] Y. Jiao and G. Xu, "Comparing the Performance of MO-GA and MOPSO in Optimization of the HEPS Performance", in *Proc. IPAC'16*, Busan, Korea, May 2016, paper THPMB019, pp. 3266-3268.

[13] Y. Zhao, Y. Jiao, and S. Wang, "Design study of APS-U type Hybrid-MBA lattice for a mid-energy DLSR", *Nucl. Sci. Tech*, under review.

[14] M. Pont *et al.*, "Injector design for ALBA", *in Proc. EPAC'06*, Edinburgh, UK, June 2006, paper THPLS057, pp. 3413-3415.

[15] C. Christou and V.C. Kempson, "Operation of the diamond light source injector", *in Proc. PAC'07*, Albuquerque, New, USA, June 2007, paper TUPMN086, pp. 1112-1114.

[16] A.P. Lee *et al.*, "Technical consideration of the TPS Linac", *in Proc. EPAC'08*, Genoa, Italy, June 2008, paper WEPC082, pp. 2186-2188.

[17] Y. Han *et al.*, "Preliminary design of the low energy injector for the Southern Advanced Photon Source", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, paper TUPA045, this conference.

[18] N. Martensson and M. Eriksson. "The saga of MAX IV, the first multi-bend achromat synchrotron light source", *Nucl. Instr. Meth. A*, vol. 907, pp. 97–104, 2018. `doi:10.1016/j.nima.2018.03.018`

[19] T. Ishikawa, "SPring-8-II Conceptual Design Report", Japan, SPring-8-II, Nov. 2014.

[20] N. Nishimori, T. Watanabe, and H. Tanaka, "A Highly Brilliant Compact 3 GeV Light Source Project in Japan", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, paper TUPGW035, pp. 1478-1481.

[21] CompactLight project, `www.compactlight.eu`

[22] S. Di. Mitri *et al.*, "XLS Deliverables D2.2: FEL design with accelerator and undulator requirements", Italy, XLS-Report-2019-007, Dec. 2019.

[23] T. Shintake, "SACLA X-Ray FEL Based on C-Band Technology", in *Proc. IPAC'14*, Dresden, Germany, June 2014, paper THPPA02, 2014.6. pp. 2846-2851.

[24] R. Ganter *et al,* "SwissFEL Conceptual Design Report V19", Switzerland, PSI Bericht 10-04, 2011.

[25] Z. Zhao *et al.*, "SXFEL: A Soft X-ray Free Electron Laser in China", *Synchrotron Radiation News*, vol. 30:6, pp. 29-33, 2017. `doi:10.1080/08940886.2017.1386997`

[26] X. Liu, B. Li, Y. Jiao, and S. Wang. "Preliminary design of the Full Energy Linac Injector for the Southern Advance Photon Source". in *Proc. IPAC'21*, Campinas, Brazil, May 2021, paper TUPA046, this conference

[27] L. Emery and M. Borland, "Possible long-term improvements to the advanced photon source", *in Proc. PAC'03*, Portland, USA, May 2003, paper TOPA014, pp. 256-258.

[28] G. Xu *et al.*, "On-axis beam accumulation enabled by phase adjustment of a double-frequency RF system for diffraction limited storage rings", in *Proc. IPAC'16*, Busan, Korea, May 2016, paper WEOAA02, pp. 2032-2035.

[29] J. Chen *et al.*, "Magnetic Error Effects of The Storage Ring of The Southern Advanced Photon Source", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, paper THPAB104, this conference

[30] M. Borland, "Elegant: A flexible sdds-compliant code for accelerator simulation", Argonne National Lab., Illinois, United States, Rep. LS-287, Aug. 2000.

[31] J. D. Bjorken and S. K. Mtingwa, "Intrabeam Scattering", *Part. Accel.*, Vol. 13, pp. 115-143, 1983.

[32] W. Liu *et al.*, "Generation of coherent atto-second X-ray pulses in the Southern Advanced Photon Source", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, paper MOPAB055, this conference.

[33] C. Feng and Z. Zhao, "A Storage Ring Based Free-Electron Laser for Generating Ultrashort Coherent EUV and X-ray Radiation", *Sci. Reports* vol., 7, pp. 4724, 2017.