SIMULATION AND OPTIMIZATION OF SPS-II LINAC

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Abstract

Siam Photon Source II (SPS-II), the new 3-GeV synchrotron light source project in Thailand, has been designed based on an accelerator system consisting of a 150-MeV injector linac, a full-energy booster synchrotron and a storage ring based on a Double Triple Bend Achromat (DTBA) lattice. A turn-key linac system has been used in an injection system of many synchrotron facilities, and thus it is considered for the SPS-II project. Preliminary beam dynamics simulation and optimization of the SPS-II linac are necessary for investigating achievable beam parameters which can be used for study of beam injection through a transfer line to the booster. Multi-objective genetic algorithm (MOGA) has been used in design and optimization of many accelerators including a linac system for synchrotron light sources, similar to the SPS-II linac. In this paper, results of beam dynamics simulation and MOGA optimization of the SPS-II linac are discussed.

INTRODUCTION

SPS-II project, is a project to build a new 3-GeV synchrotron light source in Thailand. The project aims to become a synchrotron facility to support synchrotron user community not only in Thailand but also in South East Asia. The SPS-II storage ring was designed based on DTBA lattice which provides moderately low beam emittance but double the number of straight sections per cell resulting in more than 20 straight sections for insertion devices (IDs) [1].

In the current design, an injection system of SPS-II was designed based on a conventional injection system consisting of a low-energy injector linac and a full-energy booster. This will allow the project to rely on conventional technologies, reduce the total project cost and increase the proportion of components developed and fabricated domestically. A 150-MeV injector linac has been adopted and tested recently at new synchrotron facilities such as TPS [2] and Sirius [3]. Thus, SPS-II plans to also adopt a 150-MeV injector linac based on a turn-key linac system [4]. However, the SPS-II storage ring and booster were designed based on RF system operating at RF frequency of 119 MHz [5] which is different from other modern storage rings. This leads to some design differences of the injector linac. Although the SPS-II linac will be a turn-key system, design and simulation of the linac have been done in order to study achievable beam parameters from the linac to be used in simulation of other parts of the machine, e.g. transfer lines and beam injection to the booster.

Design of the 150-MeV linac, and preliminary beam dynamics simulation and optimization of the SPS-II linac will be discussed in the following sections.

DESIGN AND MAIN PARAMETERS

The SPS-II injector linac has been designed [4] with main components as follows:

- Triode gun with 119-MHz voltage modulation at the grid level to produce a chopped beam
- Subharmonic prebuncher (SHB) operating at 476 MHz
- S-band buncher (BCH) operating at 2856 MHz
- Four S-band accelerating structures (ACC1-4).

The layout of the SPS-II linac for beam dynamics simulation and optimization in this work is shown in Fig. 1.

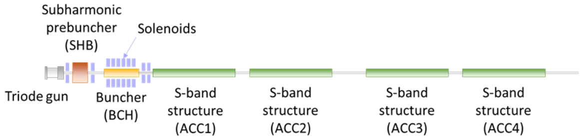

Figure 1: Schematic layout of the SPS-II linac.

The SPS-II linac aims to support beam injection for different operations of the storage ring, for example, normal user operation based on a uniform fill, and user request operations and machine developments based on other specialized filling patterns. Thus the linac should be able to operate in multi-bunch mode (MBM) and single bunch mode (SBM). Table 1 lists main parameters according to design specifications of the SPS-II linac.

Table 1: Main Parameters of the SPS-II Linac

Parameter	**Value**
Beam energy	150 MeV
Normalized emittance	$\leq$ 50 mm·mrad
RMS energy spread	$\leq$ 0.5%
Bunch train charge (MBM)	> 6 nC
Bunch charge (SBM)	$\geq$ 1.5 nC
Bunch train duration (MBM)	150-600 ns
Bunch duration (SBM)	< 1 ns
Repetition rate range	1-5 Hz
Nominal repetition rate	2 Hz

SIMULATION AND OPTIMIZATION

Beam Dynamics Simulation

Multi-particle beam dynamics simulations of the SPS-II linac have been done with PARMELA [6]. Since the beam dynamics simulation is done starting from an electron gun at low beam energy, calculation of space-charge effects should be included in the simulations. In this work, beam dynamics simulations were performed by using a chopped beam from the triode gun as an initial beam distribution with uniform transverse and longitudinal distribution.

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MOGA Optimization

One main optimization algorithms which has been widely used in design and optimization of particle accelerators is multi-objective genetic algorithm (MOGA) because it is suitable for solving multi-objective optimization problems with capability to search a diverse set of solutions. Non-dominated sorting genetic algorithm II (NSGA-II) [7] is a suitable type of MOGAs which has been used extensively in both storage ring design and linac design as reported in [8-10] to provide non-dominated solutions simultaneously as a Pareto-optimal set of solutions. The main features of NSGA-II are an elite approach to carry the best solutions to the next generations, crowding distance to maintain solution diversity, and emphasis on non-dominated solutions.

SPS-II Linac Optimization

This work uses PARMELA to perform beam dynamics simulation of the linac and uses NSGA-II to optimize parameters of the linac. A Python script was written to run a PARMELA simulation, get parameters which are chosen as objective functions from the simulation result, and then optimize these objective functions with NSGA-II by using the Python module Pymoo [11]. The optimization was done with 4 objective functions: normalized emittance, beam energy, RMS energy spread and transmission efficiency at the end of the linac as listed in Table 2. The optimization objectives are to minimize normalized emittance and RMS energy spread, and to maximize beam energy and transmission efficiency. Constraints of the optimization were set corresponding to the target values in Table 2. There are 17 parameters for the optimization including phase and peak field of SHB, phase of BCH, phase of accelerating structures, and peak field of solenoids as listed in Table 3.

Table 2: Objective Functions and Targets of MOGA Optimization

Objective Function	**Target**
Final normalized emittance	< 50 mm·mrad
Final beam energy	≥ 150 MeV
Final RMS energy spread	≤ 0.5%
Transmission efficiency	> 80%

Table 3: Main Parameters at the End of SPS-II Linac

Parameter	**Range**
Phase of SHB	[-180, 180]°
Peak field of SHB	[0.1, 0.3] MV/m
Phase of BCH	[-180, 180]°
Phase of ACC1-4	[-180, 180]°
Peak field of solenoids (10)	[0, 0.05] T

PRELIMINARY OPTIMIZATION RESULT

The MOGA optimization of the SPS-II linac was done based on 10,000 macro-particles for beam dynamics simulations and 200 populations in each generation. The results of 100 generations of the MOGA optimization in Fig. 2 show the evolution trend of the objective functions towards lower normalized emittance, lower energy spread, higher transmission efficiency, and beam energy more than 150 MeV. The constraints of normalized emittance, beam energy and transmission efficiency are satisfied but energy spread is still higher than 0.5%.

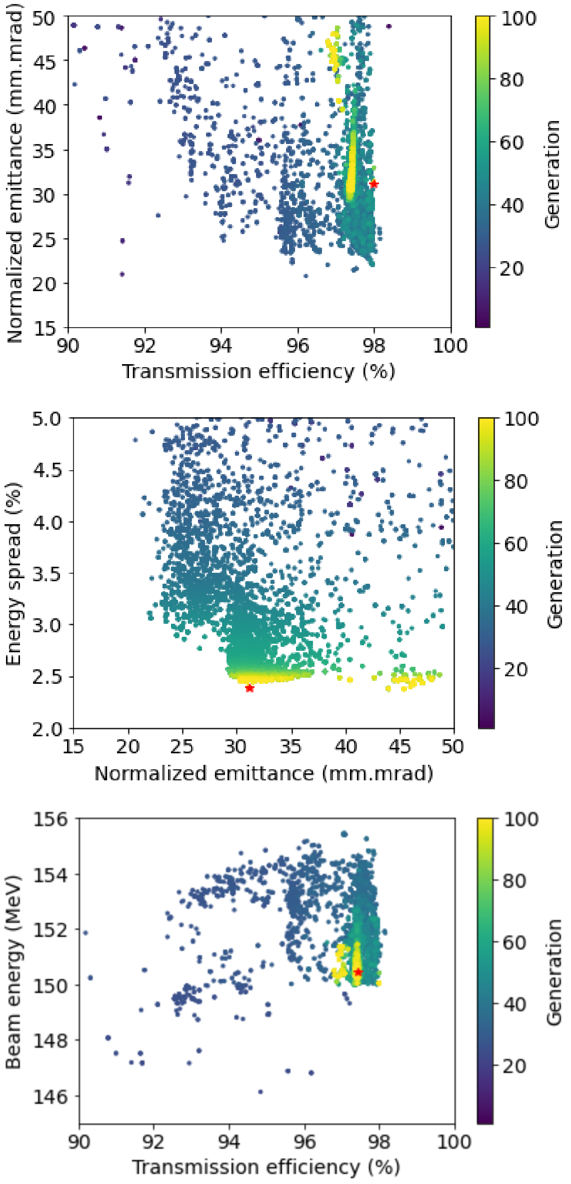

Figure 2: Results of the MOGA optimization. Plots show the evolution trend of 4 objective functions across 100 generations.

A solution with normalized emittance of 30.4 mm·mrad, RMS energy spread of 2.5%, beam energy of 150 MeV, and transmission efficiency of 97.4% was chosen and shown as a red star in Fig. 2. The objective functions of the MOGA optimization along the linac are shown in Fig. 3. Beam bunching in the buncher leads to beam losses which can be clearly seen by a decrease in transmission efficiency together with a fluctuation of the normalized emittance and a large increase in the energy spread.

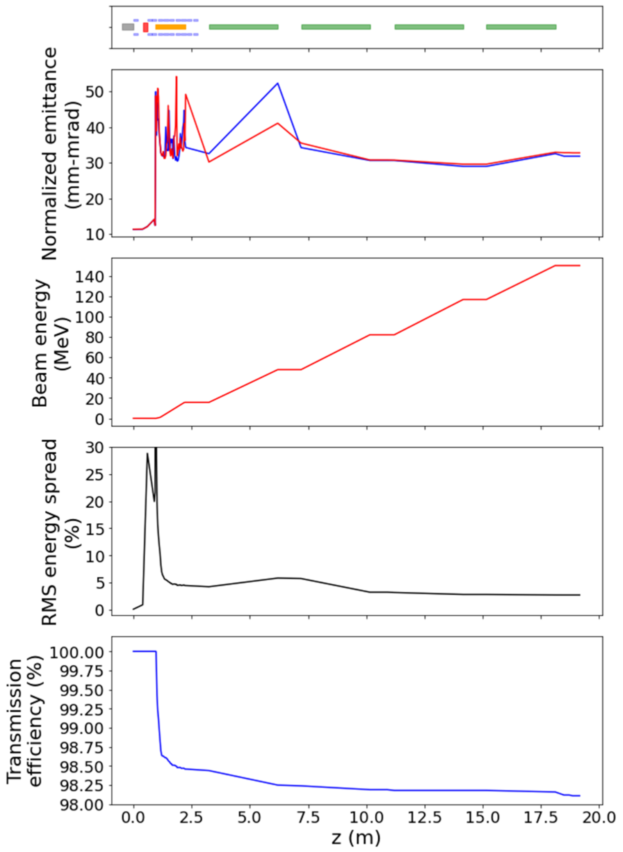

Figure 3: Plots of the objective functions along the SPS-II linac corresponding to the chosen solution (the red star in Fig. 2).

Horizontal and longitudinal phase spaces with corresponding beam distributions at the end of the linac are shown in Fig. 4. A macro-pulse beam from the gun has been modulated and transformed into two micro-bunches at the end of the linac. However, the beam distribution in time shows that most of electrons are in the 2nd micro-bunch.

CONCLUSION

The NSGA-II type MOGA optimization of the SPS-II linac was done with 4 objective functions, 4 constraints and 17 parameters. The optimization targets of normalized emittance below 50 mm·mrad, beam energy higher than 150 MeV and transmission efficiency higher than 80% can be achieved. Energy spread is minimized but cannot achieve the target value of below 0.5%.

The MOGA optimization of the SPS-II linac should be done further in order to satisfy all objectives and constraints. This can be done by running the MOGA optimization with more number of generations and including peak field of accelerating structures as parameters.

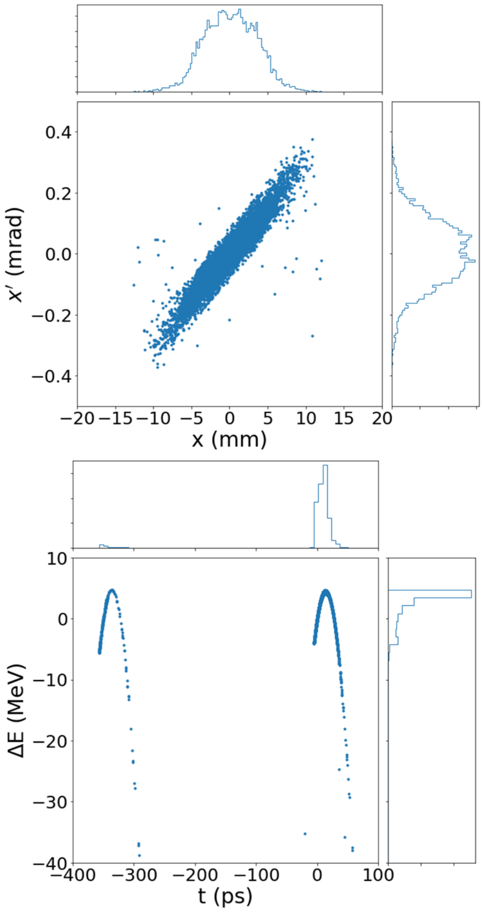

Figure 4: Horizontal phase space (top) and longitudinal phase space (bottom) at the exit of the SPS-II linac corresponding to the chosen solution (the red star in Fig. 2).

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REFERENCES

[1] P. Klysubun, T. Pulampong, and P. Sudmuang, “Design and Optimisation of SPS-II Storage Ring”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2773-2775. doi:10.18429/JACoW-IPAC2017-WEPAB086

[2] A. P. Lee *et al.*, “Technical Considerations of the TPS Linac”, in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper WEPC082, pp. 2186-2188.

[3] A. R. D. Rodrigues *et al.*, “Sirius Light Source Status Report”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2886-2889. doi:10.18429/JACoW-IPAC2018-THXGBD4

[4] T. Chanwattana *et al.*, “Update on Injector for the New Synchrotron Light Source in Thailand”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 435-437. doi:10.18429/JACoW-IPAC2021-MOPAB120

[5] N. Juntong *et al.*, “The New Design of the RF System for the SPS-II Light Source”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1110-1112. `doi:10.18429/JACoW-IPAC2021-MOPAB357`

[6] L. M. Young and J. Billen, “The Particle Tracking Code PARMELA”, in *Proc. PAC’03*, Portland, OR, USA, May 2003, paper FPAG029, pp. 3521-3523.

[7] K. Deb *et al.*, “A fast elitist multi-objective genetic algorithm: NSGA-II”, in *IEEE Transactions on Evolutionary Computation* vol. 6, no. 2, pp. 182-197, 2002.

[8] C. Sun *et al.*, “Optimization of the ALS-U Storage Ring Lattice”, in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 2959-2961. `doi:10.18429/JACoW-IPAC2016-WEPOW050`

[9] C. H. Yi, M.-H. Cho, S. H. Kim, W. Namkung, H.-S. Kang, and K.-J. Kim, “Multi Objective Genetic Optimization for Linac Lattice of PAL XFEL”, in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper TUPPC027, pp. 1224-1226.

[10] R. Bartolini, M. Apollonio, and I. P. S. Martin, "Multiobjective genetic algorithm optimization of the beam dynamics in linac drivers for free electron lasers," *Physical Review Special Topics - Accelerators and Beams*, vol. 15, no. 3, p. 030701, 2012. `doi:10.1103/PhysRevSTAB.15.030701`

[11] J. Blank and K. Deb, “Pymoo: Multi-Objective Optimization in Python”, *IEEE Access*, vol. 8, pp. 89497-89509, Apr. 2020. `doi:10.1109/ACCESS.2020.2990567`