ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPMA021

OPTIMIZATION OF AN IMPROVED SASE (iSASE) FEL*

L. Gupta†, Cornell University, CLASSE, Ithaca NY 14853, USA
K. Fang, J. Wu, SLAC National Accelerator Lab, Menlo Park CA, 94025, USA

Abstract

In order to improve free electron laser technology for the future LCLS II at SLAC, a new strategy for creating radiation with increased temporal coherence is under development. The improved Self-Amplified Spontaneous Emission (iSASE) FEL utilizes phase shifters which allow for the spontaneously emitted radiation to interact with and stimulate more electrons to radiate coherently. Five phase shifters were simulated, with 34 normal-conducting undulators and focusing-defocusing quadrupoles as an LCLS II FEL lattice using the FEL software Genesis 1.3. Two general schemes, one providing a total phase shift of arbitrary distribution, the other providing a sequential or distributed phase shift, were simulated and optimized using a simulated annealing algorithm. The results suggest that the phase shifters must provide a total shift comparable to the bunch length, and the shifts must be distributed with one large shift, followed by smaller shifts.

INTRODUCTION

A new frontier in fundamental science research, with applications in biological, material, and various other physical sciences, is the use of free electron lasers, or FELs. Only a few FELs exist at various particle accelerator facilities around the world, including the Linear Coherent Light Source (LCLS) at SLAC, and new designs are being developed for use in conjunction with improved accelerators. Specifically, the LCLS II at SLAC will use superconducting technology that could produce brighter hard x-ray FELs than is currently possible at existing FEL facilities. Currently, the LCLS FEL has been able to produce hard x-rays that allow for angstrom resolution imaging [1]. However, the bandwidth of the current LCLS FEL is large relative to that of a transform limited laser. As there is need for highly coherent FEL radiation, FELs must be improved to provide such radiation to users.

Improved SASE (iSASE)

A new strategy for constructing FELs is the improved Self-Amplified Spontaneous-Emission (iSASE) undulator, which can overcome the limitations of a SASE FEL [2, 3]. The key disadvantage that must be overcome in the SASE FEL is the limited slippage that occurs; therefore increasing the slippage would increase the temporal coherence of the emitted radiation. The slippage is artificially increased in the iSASE FEL by adding phase shifters, that increase the path travelled by the electron bunch [2]. By increasing the path length of the electron bunch, the radiation, which is not affected by the phase shifter, continues on a straight trajectory and is able to “catch-up" to the head of the electron bunch. Due to this improvement, the randomly emitted radiation is able to stimulate further coherent radiation from the entire bunch, which increases the overall temporal coherence of the FEL radiation [2, 3]

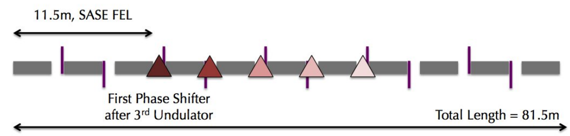

Figure 1: The base-lattice layout for the simulated FEL; the first phase shifter was placed after the third undulator, with focusing and defocusing quadrupoles maintaining the beam optics through the FEL.

The iSASE FEL has only been in development at SLAC for a short period of time, yet has already been shown to work as the theory predicts in both simulations and experimentally [2]. Because the initial simulations show that the iSASE FEL could produce coherent radiation, the next step in the design process is to optimize the chicanes within the undulator system. The program Genesis 1.3, with improvements made for the current simulation requirements, can be used to simulate an iSASE FEL and return information about the radiation that would be generated in such an FEL undulator system [2–4]. In order to design an efficient and effective iSASE FEL, the chicane lengths and positions within the FEL must be optimized such that the temporal coherence and the brightness of the radiation are maximized, and the radiation bandwidth is minimized. The integration of an optimized iSASE FEL with the LCLS II at SLAC could therefore be a significant development in FEL technology.

SIMULATION SET-UP

In order to optimize the phase shifter strengths for an LCLS II type, normal conducting FEL, a lattice the following lattice was set-up. First, the base-lattice was created with 34 undulators and 33 quadrupoles set up in a focusing-defocusing layout, over the 81.5 m long FEL.The lattice also included five phase shifters, the first of which was placed after the third undulator (three gain lengths), creating essentially a short SASE FEL with known slippage length, l_{slip}. Each phase shifter consists of four bending magnets, and is 40 cm long. A general schematic is shown in Fig. 1. Once the lattice was constructed, the focusing and defocusing strengths for the lattice were calculated and the beta functions for the beam were simulated in Tao, the tool for accelerator optics, which runs using Bmad (charged particle simulation subroutine library). Once the beta function

* Supported by US DOE FWP- 2013-SLAC-100164 and DOE SULI.
† lg344@cornell.edu

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matching was complete, the base-lattice could be constructed in the FEL simulation software Genesis 1.3. The following parameters were used in setting up the lattice for optimization.

Table 1: FEL Simulation Parameters, (for an LCLS II type FEL with normal conducting undulators)

Parameter	**Simulation Value**
Beam Energy	4 GeV
Peak Beam Current	800 A
$\epsilon_{x,n}/\epsilon_{y,n}$	0.3 μm/ 0.3 μm
λ_u	0.026 m
λ_r	3 Å
FEL Parameter ρ	0.0003
Undulator Parameter K	0.9095
Bunch Length	16 μm
Gain Length (L_G)	3.5 m
β_x/β_y	17.9 m/ 8.0 m
Macro-particles	5120

The optimization process utilized a simulated annealing algorithm, which “cools" or converges to a solution by means of an exponentially decreasing annealing schedule [5]. As the temperature decreases, the solution at each iteration must highly statistically significant in order for it to be recorded as an improved solution. This algorithm was ideal for this optimization as it does not require a differentiable function, and allows the solution to be perturbed in any direction in the variable space [3,5]. The radiation bandwidth by the end of the FEL process for the optimal solutions are presented below.

RESULTS AND DISCUSSION

A general scheme for the phase shifter strengths was developed as a starting point for the optimization. There were two approaches to consider: providing an equally distributed shift or providing a sequential shift in each shifter (Fig. 2). In the first scheme, the phase shift in each phase shifter was not as important as the total shift provided to the electron beam once it has passed through all of the shifters. This is referred to as case A, in which each shifter initially provided the same amount of phase shift [6]. The second scheme, case B, provides shifts in unequally distributed shifts, to test whether the order and magnitude of the shifts must also be considered in the lattice design. The initial set up provided in case B was therefore a reverse geometric configuration, in which the shift decreases in a geometric series starting at 16 l_{slip}. The initial slippage within the FEL, l_{slip} was calculated numerically; thus the phase shifts “strengths" are in units of $l_{\text{slip}} = 290\lambda_r$. From the optimization process, the optimal phase shifter strengths for both cases were simulated in Genesis, and the bandwidth ω/ω_r, where $\omega_r \approx 10^{20}$ Hz, of the radiation over the length of the FEL was plotted. In Fig. 3 the final radiation bandwidth of the iSASE FEL can be seen in comparison to the SASE FEL for the optimal solu-

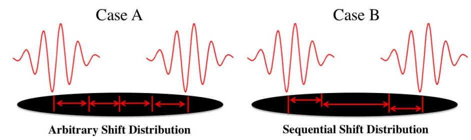

Figure 2: For case A, each phase shifter initially provided the same shift: $3\,l_{\text{slip}}$ for $l_{\text{slip}} = 290\,\lambda_r$. For case B, the initial phase shifter settings varied in a geometric sequence in which the five shifters provided $16\,l_{\text{slip}}$, $8\,l_{\text{slip}}$, $4\,l_{\text{slip}}$, $2\,l_{\text{slip}}$, and $1\,l_{\text{slip}}$ shifts respectively.

tion in case A. The RMS bandwidth of the iSASE FEL was about 4.42 times smaller for the iSASE spectrum. Similarly, in Fig. 4 the final radiation bandwidth of the iSASE FEL in case B resulted in a 4.32 times smaller RMS radiation bandwidth than the SASE FEL spectrum. In both cases, the reduction of the side bands was significant, but in case B, remnants of the frequency comb which is created in the intermediate stages of the FEL (shown in Fig. 5) remain at the end of the FEL process.

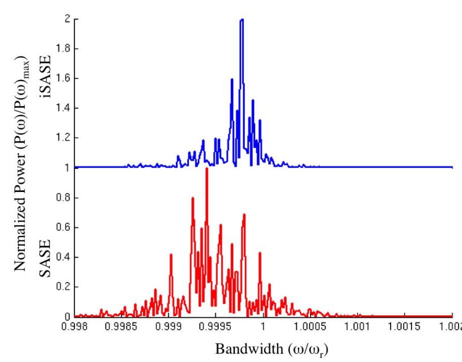

Figure 3: The radiation bandwidth at the end of the FEL process for case A shows a peak near the target radiation frequency in the iSASE spectrum, as compared to the less sharp SASE spectrum. The RMS bandwidth of this solution is about 4.42 times smaller than the SASE bandwidth.

The sidebands visible in Fig. 3 suggest that providing an initial shift which is the majority of the total provided phase shift (in this scheme the initial phase shift is $16l_{\text{slip}}$) can create a frequency comb, or a series of defined peaks in the frequency spectrum of the x-ray radiation at frequencies close to the desired frequency. It can be seen that the frequency comb is reduced to a single peak at the desired frequency, like in case A, by the end of the phase shifting and gain process.

The optimal phase shifter settings are presented in Fig. 6. It is clear that in case A, the initial solution did not provide enough of a shift, and a reduced bandwidth was attained by increasing the shift strengths. However, the shifters did not increase equally in strength, and the optimal solutions has a definite sequence, which resulted in a decreased radiation bandwidth relative to the initial configuration. Conversely,

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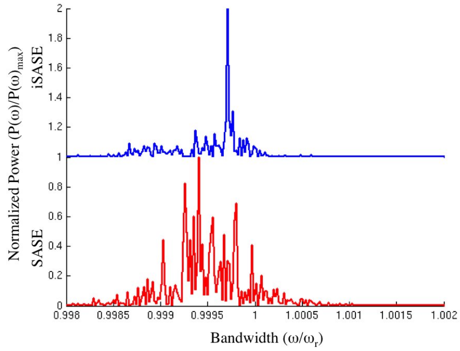

Figure 4: The radiation bandwidth at the end of the FEL process for case B shows a peak near the target radiation frequency in the iSASE spectrum, as compared to the less sharp SASE spectrum. The RMS bandwidth of this solution is about 4.32 times smaller than the SASE bandwidth.

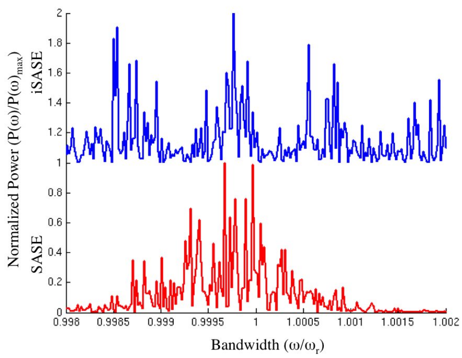

Figure 5: After the initial phase shifters, the radiation spectrum appears to have become a frequency comb, in which certain resonances have been amplified due to a large phase shift early in the FEL process.

the optimal configuration in case B retained the general configuration, suggesting that the initial solution provided a sufficient shift, and the configuration was also close to optimal. In both schemes at least one of the phase shifters was either significantly higher or lower than the other shifters. The effects of the large shift must be studied further, but likely contribute to the suppression of sidebands within the spectrum.

While these preliminary results need further investigation, such a phase shifting strategy could be used for providing users with a variety of coherent x-ray frequencies to choose from for their experiments.

CONCLUSIONS AND FUTURE WORK

The optimization of the improved Self Amplified Spontaneous Emission FEL led to an improved lattice design which

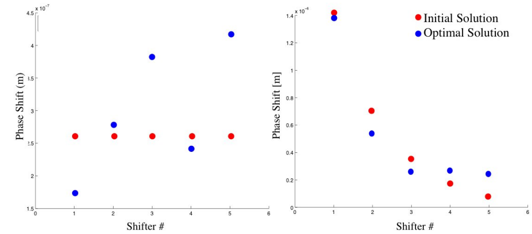

Figure 6: The initial and optimal phase shifter settings for case A (left) and case B (right) show that, in both cases, the total shift provided needed to be increased, and that the order of the provided shifts should not be arbitrary.

reduced the radiation bandwidth of the FEL radiation, and gave interesting insight into phase shifting strategies. It was seen in this study that the distribution of this shifts is important, and that the total shift provided must be increased. Further optimization is necessary to confirm whether these solutions are local minima, or could converge to a global minimum. Such optimization would include running more iterations, and varying other initial conditions, such as the undulator lengths in the shifting portion of the lattice (the first 35 meters). Because phase shifting delays the electron bunch, a misalignment of phase within the undulators could contribute to a diminished gain in power or minimization of bandwidth, and must be studied further.

ACKNOWLEDGEMENTS

This work was made possible by the DOE SULI program, and the the US DOE Office of Science Early Career Research Program grant FWP-2013-SLAC-100164. L.G. would like to thank Dr. Christopher Mayes of Cornell University for technical support.

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