MULTI OBJECTIVE GENETIC OPTIMIZATION FOR LINAC LATTICE OF PAL XFEL*

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Abstract

There are a large number of variables and objectives in design of XFEL linac lattices. Recently, most of accelerator physics field, are applying the multi-objective genetic algorithm (MOGA) for these kinds of problems. MOGA was applied to the PAL XFEL linac lattice design. Longitudinal position of all components was fixed before applying MOGA. RF parameters of RF cavities and bending angles of bunch compressors are selected as variables. Various beam parameters computed by ELEGANT were used as objectives. By using MOGA, new linac lattice designs with 2 and 3 bunch compressors was generated and their beam properties are presented in this paper.

INTRODUCTION

Recently, multi-objective genetic algorithm (MOGA) is being applied to a wide range of science fields, and it is being used in the accelerator physics field too. I. V. Bazarov and C. K. Sinclair used MOGA for the optimization of the high brightness dc gun photoinjector [1] and L. Emery used MOGA for optimization of damping ring for the ILC [2]. And in the FEL field, R. Bartolini et al. used MOGA for optimization of beam dynamics in linac drivers for free eletron lasers [3].

As shown in Ref. [3], applying MOGA to the design of X-ray free electron laser (XFEL) can be effective way. XFEL requires high quality electron beams. Electron beams should have a large peak current, small slice emittance, and small energy spread. These beam properties are determined by a large number of machine parameters, such as RF parameters of RF cavities and configuration of magnetic compression stages. Thus, there are a lot of variables and objectives for design of XFEL linac. Furthermore, there are conflicts between objectives, for example, the large peak current and small slice emittance. In this case, i.e. the case of multi-variables and multi-objectives, applying the multi-objective genetic algorithm (MOGA) can be an effective method [4].

When the number of magnetic bunch compression stages and its position are fixed, it is not straight forward to determine the machine parameters of RF cavities and magnets. Longitudinal phase space manipulation with magnetic bunch compression stages and wakefield induced energy spreads are non-linear processes. The LiTrack code can help us to find machine parameters in a short time without time consuming to the transverse optics design [5]. However, the LiTrack code does not offer exact machine parameters, because it does not include collective effects of electron beams.

MOGA with ELEGANT [6] can offer machine parameters with considering collective effects of electron beams in a relatively short time and with relatively small human efforts. We used the genetic optimizer script written by M. Borland and H. Shang. One may find description on thet algorithm used in this script in Ref. [3], [4], and [7]. We used 4 best children to generate 16 next generations.

In this paper, we fixed longitudinal positions of all components and applied MOGA with ELEGANT from the injector end to the linac end to find machine parameters of components. We found the machine paramters for lattices with 2 and 3 magnetic bunch compression stages, and we presemt resulting electron beam properties..

VARIABLES AND OBJECTIVES

There are a lot of machine parameters in a linac lattice including the length and strength of quadrupoles and dipole magnets for transverse focusing and bunch compression, RF parameters of RF cavities, and longitudinal positions of all components. The largest numbers of variables arise from quadrupole magnets for transverse focusing. Including machine parameters of quadrupole magnets in the MOGA is inefficient, and there is a way to exclude them. To do that, we can determine parameters of quadrupole magnets before applying the MOGA.

First, we fixed the longitudinal position and length of all components. And then, we put matching sections before and after the bunch compressors. At this configuration, we can easily find the strength of all quadrupole magnets which gives appropriate transverse optics. To find parameters of quadrupole magnets, we

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used the simplex optimization of ELEGANT, and resulting transverse optics were satisfactory.

In addition, we fixed RF parameters of cavities in linac-4 (see Fig. 1). Their variation range is not wide for the effective use of RF energy. And their effects on electron beam properties are restricted, because there is no bunch compressor after them. We applied MOGA from the injector end to the linac end, and variables are summarized in Fig. 1. Basic longitudinal positions and lengths of all components are determined based on design of Ref. [8].

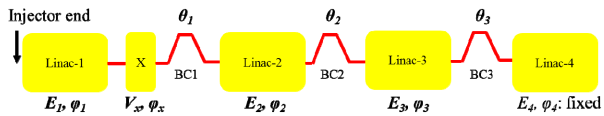

Figure 1: Summary of variables (bolded). $\boldsymbol{E}$ and $\boldsymbol{\varphi}$ are accelerating gradient and phase of RF cavities. $\boldsymbol{V}$ is energy gain of RF cavity. $\boldsymbol{\theta}$ bending angle of dipoles in the bunch compressors.

Objectives are various beam properties computed by ELEGANT. In this study, we used mainly quantities computed by "sasefel" function of ELEGANT with the Ming Xie model. Specific objectives are presented for each case.

MOGA FOR 3 MAGNETIC BUNCH COMPRESSION STAGES

As a first trial, we simplify the problem to confirm the possibility of MOGA on XFEL linac lattice design. We fixed bending angles of dipoles of bunch compressors as the value of Ref. [8]. Then, there are no variables to change the transverse optics .Thus we designed transverse optics before applying MOGA and fixed it. Finally, 8 variables (RF parameters of linac-1, 2, 3 and X-band in Fig. 1.) are included in MOGA.

Objectives for this case are large saturation power, short saturation length, and small current non-uniformity. The saturation length and power are computed by the "sasefel" function with the Ming Xie model in ELEGANT. Current non-uniformity is equivalent to the standard deviation of the RMS bunch length of each slice, which is normalized to the average of the RMS bunch lengths. The electron beam is divided into 10 slices to get the slice information and central 8 slices are used to calculate current non-uniformity.

Result of MOGA was shown in Fig. 2. As shown in Fig. 2, starting from the initial population with the poor saturation power and length, MOGA proceeds to the region of the large saturation power and short saturation length. Finally, MOGA is saturated around saturation power of a few GW and saturation length of 100 m. Considering current uniformity, we pick a best one, and its beam properties are shown in Fig. 3, in which peak current, current profile, slice emittance, energy spread, and longitudinal energy spread are almost the same with results of Ref. [8]. However, the phase of X-band of MOGA is different from Ref. [8]. The X-band phase of MOGA is -179.3°, but the X-band phase of Ref [8] is -169.5°. Near -180° is the more common value seen in other XFEL designs [9], [10]. This difference is intended one, to confirm that MOAG can find machine parameters within a different range from Ref. [8]. To do that, we set the variable range of X-band phase as from -178° to -180° and MOGA found machine parameters within that range.

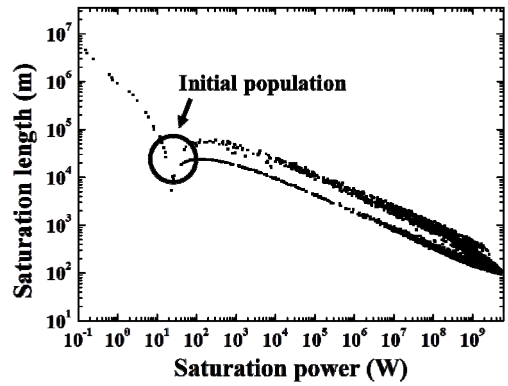

Figure 2: Saturation power and length simulated by MOGA.

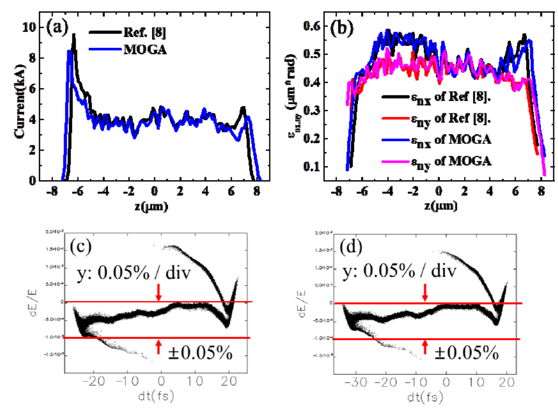

Figure 3: Start-to-end simulation result of Ref. [8] and best lattice generated by MOGA. (a) is current, (b) is normalized slice emittance, (c), (d) are longitudinal phase space of Ref. [8] and MOGA at the beginning of undulator.

As shown in Fig. 2 and 3 MOGA can find machine parameters of RF cavities, and resulting beam properties are almost the same with Ref. [8] which is a result of manual job.

MOGA FOR 2 MAGNETIC BUNCH COMPRESSION STAGES

In previous section, we fixed bending angles of dipoles of bunch compressors to simplify the problem. To extent the capability of MOGA, bending angles of dipoles of

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bunch compressors are included as variables. Since we can change the configuration of bunch compressors, now we can try to find machine parameters far different from Ref. [8]. As an trial, we try to find machine parameters for the lattice with 2 magnetic bunch compression stages. The 2 magnetic compression stages configuration is the more common configuration seen in other designs [9], [10] and can offer shorter linac length due to the lack of the third magnetic bunch compressor.

In this case, we fixed accelerating gradient of lianc-1, 2, and 3 in Fig. 1 as the highest value (20 MV/m). And to make 2 magnetic bunch compression stages configuration, we turned off third bunch compressor (i.e. $\theta_3 = 0$ in Fig. 1). Objectives are to find the large saturation power and short saturation length. Constraints are the smaller energy spreads than 3×10^{-4} and smaller average normalized slice emittance than 0.5 μm·rad. Electron beams are divided into 60 slices to get the slice information.

Tendency of saturation power and length is similar to Fig. 2. And similarly to the case of 3 magnetic bunch compression stages, we pick the best one considering the longitudinal phase space shape and emittance. Beam properties of the best one is shown in Fig. 4.

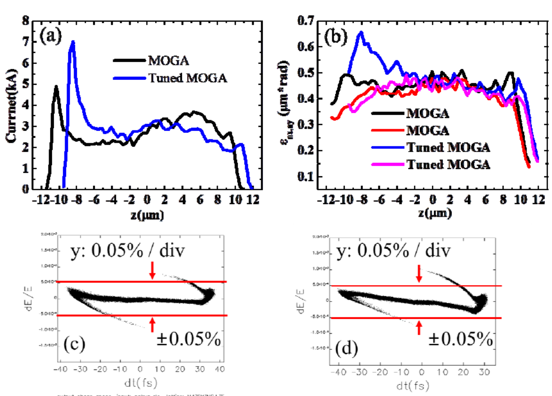

Figure 4: Start-to-end simulation result of best lattice generated by MOGA and manually tuned lattice from MOGA result. (a) is current, (b) is normalized slice emittance, (c), (d) are longitudinal phase space of MOGA and manually tuned lattice from MOGA at the end of linac.

As shown in Fig. 4, lattice generated by MOGA shows the similar level of beam properties with Ref. [8] in peak current, emittance, and longitudinal phase space. However, its current profile is quite non-uniform. To improve current uniformity, manual tuning on the X-band voltage was conducted, and its result is shown in Fig. 4. With some manual tuning with MOGA, the reasonable current profile, emittance, and longitudinal phase space shape are achieved.

As shown in Fig. 4, MOGA can generate a lattice with 2 magnetic compression stages which is far different from Ref [8]. And MOGA shows its capability on finding machine parameters with fixed longitudinal positions and lengths of components. This means that MOGA can find new operation modes automatically.

SUMMARY

Multi-objective genetic algorithm (MOGA) was applied to the PAL XFEL linac lattice design. MOGA can find machine parameters of RF cavities with fixed magnetic bunch compressor configuration and fixed longitudinal positions of all components. And found machine parameters can offer the similar level of beam properties with results by manual job.

Also, MOGA can find machine parameters with additional variables of bending angles of bunch compressors, and it gives reasonable beam properties. These results mean that once longitudinal positions of all components are fixed, MOGA can design the XFEL lattice automatically, and it can offer various operation modes. Furthermore, it is expected that if we set objectives more sophisticatedly, MOGA can be used to the optimization of specific electron beam properties as shown in Ref. [3].

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