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# EVOLUTIONARY MANY-OBJECTIVE OPTIMIZATION ALGORITHM FOR LARGE-BANDWIDTH FREE-ELECTRON-LASER GENERATION

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*Abstract*

X-ray free-electron lasers (XFELs) are leading-edge instruments in a wide range of research fields. Besides pursuing narrow bandwidth FEL pulses, the large-bandwidth XFEL pulses are very useful in various spectroscopy experiments, multi-wavelength anomalous diffraction, and X-ray crystallography. Overcompression operation scheme can be utilized to generate electron beams with large energy chirp which is benefit for bandwidth broadening. Recently, an evolutionary many-objective (having four or more objectives) algorithm, NSGA-III, was used to optimize the electron beam parameters in the overcompression including energy chirp, energy spread, current profile, peak current, and projected emittance. In this paper, combining with the Xie's semianalytical estimate formula, the NSGA-III is utilized to find an optimal working point of linac by optimizing the XFEL pulse properties directly. Start-to-end numerical simulations based on the Shanghai soft X-ray Free-Electron Laser user facility parameters demonstrate that a full bandwidth of 4.75% can be generated.

## INTRODUCTION

X-ray free electron lasers (XFEL) are capable of providing x-ray pulses with high peak brightness, narrow bandwidth spectrum and ultra-fast time structure. Besides pursuing narrow bandwidth XFEL pulses, large-bandwidth XFEL pulses are demanded for several certain types experiments such as X-ray absorption spectroscopy, multi-wavelength anomalous diffraction and X-ray crystallography.

The FEL wavelength is decided by the resonance condition [1]:

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2}), \quad (1)$$

where $\lambda_u$ is the undulator period length, $\gamma$ is the mean Lorentz factor of the electrons, and $K$ is the undulator field parameter. Therefore, the XFEL bandwidth is related to the electron beam energy chirp and the undulator field parameters. In principle, making different parts of a transverse tilted electron beam experience different magnetic fields [2, 3] or utilizing an energy-chirped electron beam can broaden the XFEL bandwidth. While the beam tilt always needs additional hardware elements like the transverse deflecting structure or de-chirper device. The beam energy chirp can be achieved by just changing operation parameters of the acceleration sections. One natural way to obtain energy chirp is to let the electron bunch be accelerated at the off-crest phase, however, it at the cost of the beam energy. Overcompression [4–7] is a promising scheme to increase correlated energy spread of electron beams. In this scheme, electron bunches are overcompressed in one bunch compressor and the sign of the energy chirp of the electron bunches are changed. Therefore, the wakefields of the subsequent rf structures will increase the beam energy chirp. One of the crucial problem for the overcompression scheme is how to find an optimal working point of the linac where electron beams can generate XFEL pulses with large bandwidth while other properties like pulse energy and power profile can be maintain. The recent paper [7] utilized an evolutionary many-objective algorithm, NSGA-III [8], to optimization electron beam parameters and analyze the dependencies between these parameters. However, the optimization of the electron beam is difficult to analyze the relations between radiation pulse properties, which is also important for exploring the limitations of an operation scheme. As an extended work, in the following sections, based on the Shanghai soft x-ray free-electron laser (SXFEL) user facility [9] parameters, the NSGA-III is used to optimize the XFEL pulse properties directly.

## OPTIMIZATION STRATEGY

The SXFEL user facility is under construction at Shanghai, which is the first X-ray FEL in China. The SXFEL user facility consists of a two-stage seeded FEL line and a SASE line. This optimization is to design the large-bandwidth mode for the SASE line. The layout of the SXFEL user facility linac and the SASE line are presented in Fig. 1. 0.5 nC electron beams are generted and accelerated to 130 MeV in the injector. Downstream of the injector are the main linac including one S-band (L1), one X-band (LX), and two C-band (L2, L3) accelerating sections. And there are two magnetic chicanes between these accelerating sections to further compress the electron bunches. To let the overcompressed electron beam be accelerated in more rf structures, turning off the second bunch compressor and utilizing single bunch compressor are considered in this optimization. To produce high qualities XFEL pulses, angle of the first bunch compressor, phases and voltage of the L1 and LX are selected as optimization variables. The corresponding optimization objectives are pulse energy, bandwidth, and power distribution.

In this optimization, the ASTRA and ELEGANT are used to tracking electron beams in the injector and main linac separately. The calculation of the objectives are based on the ELEGANT simulations where one hundred thousand

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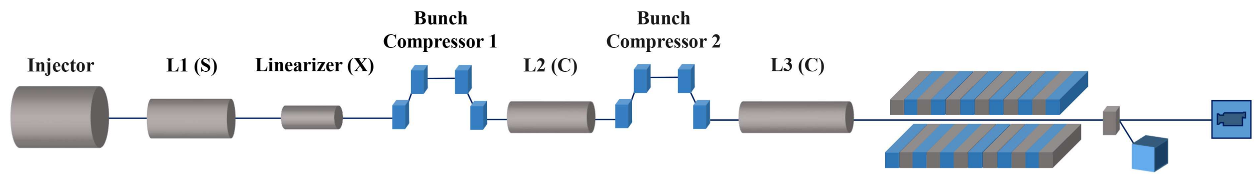


Figure 1: Layout of the SXFEL user facility linac including the injector section, S-band sections (L1), one X-band linearizer (LX), C-band sections (L2, L3) and two bunch compressor chicanes (BC1, BC2).

macroparticles are used. One electron bunch from the simulation results will be divided into 100 slices. The saturation power of the radiation generated by one electron slice is calculated by the semianalytical estimate formula [10]:

$$P_{sat} \approx \frac{1.6}{(1+\Lambda)^2} \rho P_{beam}, \tag{2}$$

where the $\Lambda$ can be calculated by the Xie's fitting formula [11]. Therefore, the radiation energy generated by each electron slice can be obtained. The pulse energy is defined as the sum of the slice energy. The XFEL wavelength generated by each slice is calculated by the Eq. (1). Treating 2% of the peak slice energy as a cut-off value. The bandwidth is defined as the relative wavelength between the two cut-off slice on the two sides of an electron bunch. In this optimization, the sum of the radiation energy of the middle 50 slices divided by the whole pulse energy is treated as the FEL power profile factor. The lager power profile factor means the lasing part are more concentrate on the central part of the electron beam. In addition, the coherent synchrotron radiation (CSR) effect is strong in the overcompression. The slice misalignment caused by the CSR will reduce the pulse energy and this effect cannot be expressed by Eq. (2). Therefore, the horizontal projected emittance of the electron beam is treated as the fourth objective and the two quadrupoles in the first bunch compressor are added to the optimization variables to eliminate the CSR effect. To analysis the relations between these objectives and find the optimal solution, the NSGA-III is used to optimize the four objectives simultaneously. The population and iteration in the algorithm are set 300 and 100 to ensure the convergence of the solutions.

## OPTIMIZATION RESULTS

The Pareto-optimal front and its projection at several two-dimensional surfaces in the last generation are shown in Fig. 2. The pareto front (Fig. 2 (top left)) shows that the horizontal projected emittance of most solutions are well optimized and does not correlate with other three objectives. As shown in the Fig. 2 (top right), the bandwidth and pulse energy are two conflicting objectives. The pulse energy is quite low when the bandwidth is larger than 5%. The Fig. 2 (bottom left) the Fig. 2 (bottom right) present the dependencies between the power profile and pulse energy, bandwidth which show that the larger profile factor corresponds to larger

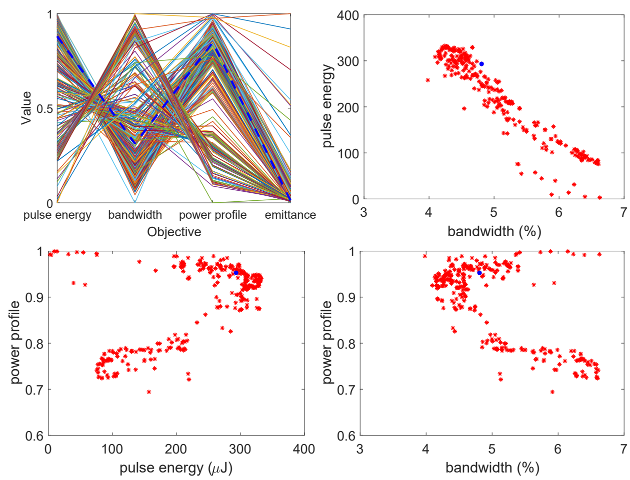


Figure 2: Parallel coordinate plots of the Pareto-optimal front and its two-dimensional projection on several planes.

pulse energy and narrower bandwidth for most cases. The optimization results of the electron parameters presented in [7] can be used to further understand this optimization results. Those electron beams with poorer current profile always lead to poorer power profile of the XFEL pulses and larger energy chirp, i.e., larger XFEL bandwidth, which finally cause the bandwidth and pulse energy are two conflicting objectives.

After weighing the four objectives, as the blue dashed line shown in the pareto front (blude points in other two-dimensional surfaces), a solution with a pulse energy of 293 µJ and a bandwidth of 4.8% is selected for the large bandwidth operation mode of the SXFEL user facility. Based on the parameters of the selected solution, ELEGANT simulation with one million macroparticles and the time-dependent GENESIS simulation are performed to verify the electron beam and the XFEL pulse generation. As shown in the Fig. 3 (top left and right), the selected electron bunch with a 1175 A peak current and an energy chirp of 2.5%. The FEL simulation results show that the corresponding pulse energy is 386 µJ and the bandwidth is 4.75% (including a 2% cut).

## CONCLUSION

In this paper, the NSGA-III is used to optimize pulse properties for large bandwidth XFEL pulses generation. The optimization results show that pulse energy and bandwidth are two contradictory objectives. In addition, the power

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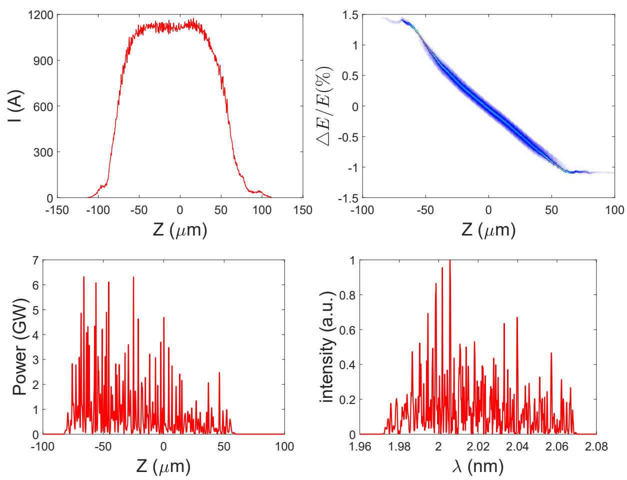


Figure 3: Current profile (top left), longitudinal phase space (top right) of the chosen electron beam and the power distribution (bottom left), spectrum (bottom right) of the XFEL pulse.

profile has a strong correlation with the pulse energy and bandwidth. Considering the broad bandwidth XFEL demands including the larger pulse energy, bandwidth and profile factor, a solution that generates XFEL pulse with 386 µJ and 4.75% full bandwidth is selected for the SXFEL user facility. Comparing with the electron beam optimization [7], this optimization can be used to further explore the dependencies between different pulse properties in the overcompression mode and makes it much easier to choose suitable solutions for the large bandwidth operation mode. At the same time, this optimization results can be further understood by the electron beam optimization results.

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