ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG03

TEMPORAL PROFILE SHAPING FOR A DISPERSIVE SECTION USING A MULTI-OBJECTIVE GENETIC ALGORITHM

Z. Sun†, T. Xin, X. Li, C. Meng, O. Xiao, Z. Liu
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
also at University of Chinese Academy of Sciences, Beijing, China
Z. Song, Tsinghua University, Beijing, China

Abstract

The importance of shaping temporal profiles in accelerator physics is highlighted by a wide range of applications, such as plasma acceleration and improved performance in free electron laser applications. In our study, we focus on controlling the dispersion in a bunch compressor and the energy chirp of the beam entering the compressor to achieve diverse temporal profiles. The transmission of electron beams through dispersive regions, like bunch compressors and transport lines, can significantly impact the beam's temporal profile. we propose the application of a multi-objective genetic algorithm to address this one-to-many problem. After multiple optimization iterations, we obtained several feasible solutions for controlling the dispersion section and various energy chirps to achieve desired temporal profile.

INTRODUCTION

The development of advanced accelerator applications, such as free-electron lasers, terahertz radiation sources, and plasma accelerators, has brought into sharp focus the need for precise control over the temporal profiles of electron beams [1]. These applications benefit from tailored current profiles, which are essential for achieving optimal performance.

For instance, for achieving high transformer ratios in plasma acceleration, specialized electron beam profiles are crucial. This typically involves using a longitudinally asymmetric driver beam with a triangular shape, featuring a gradual increase in density at the head and a sharp decrease at the tail to ensure minimal and uniform decelerating field experienced by the driver beam. Additionally, employing a longitudinally trapezoidal distribution for the beam to be accelerated allows for a flatter longitudinal wakefield at the location of the accelerated beam, enabling the production of a low-energy-spread beam for high transformer ratio acceleration [2]. Moreover, the removal of current spikes is essential for improving the operation of free-electron lasers, emphasizing the importance of advanced beam shaping techniques in accelerator physics to design optimal current profiles for various FEL applications. To meet these demands, shaping the temporal profiles of electron beams is essential, highlighting the significance of advanced beam shaping techniques in accelerator physics.

† sunzheng@ihep.ac.cn

Several robust methods have been developed for shaping the temporal profile of beams. One common approach involves directing an electron beam with a specific energy distribution through an energy dispersion section, such as a bunch compressor comprising several bending magnets, and possibly additional sextupoles and octupoles. By selecting an appropriate combination of dispersion terms in the compressor and an initial beam with a specific energy chirp, it is possible to achieve the desired custom temporal profile.

Research indicates that due to the highly nonlinear nature of this process, multiple combinations of dispersion terms may result in the same target profile, making temporal shaping inherently a one-to-many problem [3]. Stochastic optimization techniques such as genetic algorithms (GA), particle swarm optimization (PSO), and extremum seeking (ES) have been found to offer more effective solutions to these one-to-many problems [4-5]. However, these algorithms often converge to the first solution found, especially with insufficient population sizes, potentially overlooking other more feasible solutions. This limitation has motivated the search for an algorithm that can maintain solution diversity and avoid premature convergence to local optima.

The introduction of the NSGA-III algorithm has tackled these challenges by implementing an enhanced ranking method for the final rank layer [6]. This advancement facilitates rapid convergence while maintaining a diverse array of solutions, effectively addressing the complexities of optimization problems. By utilizing NSGA-III, our goal is to optimize both the temporal profile at the bunch compressor's exit and its focusing performance. Our aim is to achieve temporal profile shaping without sacrificing the beam charge, thereby offering a variety of feasible design choices.

TEMPORAL PROFILE SHAPING

For a bunch compressor, an electron beam with small emittance and large energy spread, a Taylor map that represents the final longitudinal coordinate z_f of a charged particle as a Taylor series of the initial coordinates can be simplified as [7]:

$$z_f = z_0 + R_{56}\delta(z_0) + T_{566}\delta(z_0)^2 + U_{5666}\delta(z_0)^3 + ... \quad (1)$$

$$\delta(z_0) = h_1 z_0 + h_2 z_0^2 + h_3 z_0^3 + ... \quad (2)$$

where $\mathbf{z_0}$ is the initial longitudinal coordinate with respect to the bunch central, R_{56}, T_{566}, and U5$_{666}$ are the first-, second- and third-order longitudinal dispersion terms

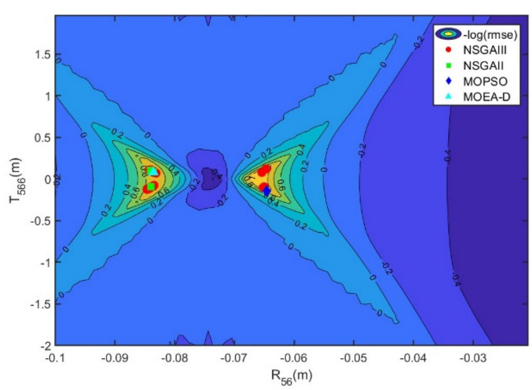
15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG03

respectively, $\delta = {(E - E_0)}/{E_0}$ represents the energy deviation relative to the nominal beam energy, and h_1, h_2 and h_3... are the first-, second- and third-order energy chirps respectively. It can be observed that by controlling the initial energy chirps of the beam and the dispersion terms of the bunch compressor, we can achieve arbitrary temporal profile of beams at the exit of the chicane.

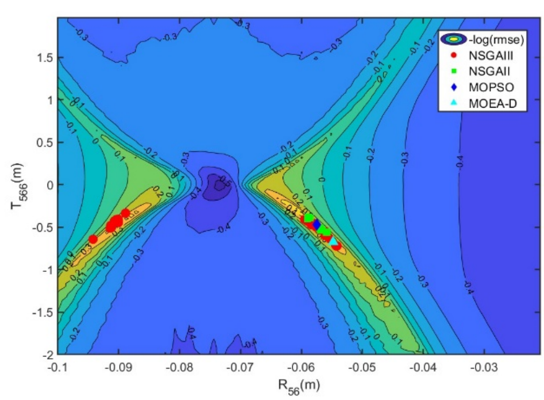
Therefore, we conducted two simulations to validate the optimization algorithm's ability to solve one-to-many problems and quickly provide initial information for the beam bunch and chicane.

Solving One-to-Many Problems

In this study, we used the same initial beam energy chirp as in Ref [5], with a temporal profile following a standard Gaussian distribution. We shaped temporal profile at the exit of the chicane solely by controlling the dispersion terms. In order to validate that the NSGAIII algorithm we used can solve such one-to-many problems, we compared it with the NSGAII, MOPSO, and MOEA-D optimization algorithms. Figure 1 shows the results for the dispersion terms R_{56}, T_{566}, and U_{5666} for the target temporal profile of uniform profile and double-horn profile.



(a) uniform profile



(b) double-horn profile

Figure 1: Solving one-to-many problems using NSGAIII, NSGAII, MOPSO and MOEA-D optimization algorithms.

In Figs.1 (a) and (b) show the convergence results of grid search and four algorithms for optimizing uniform and double-horn profile, respectively. Contour lines represent the negative logarithm of the mean squared difference between the final profile and the target profile.

It can be observed that directly controlling the dispersion terms R_{56}, T_{566}, and U_{5666} is an effective way to achieve temporal profile shaping of the beam. Since equations (1,2) are analytical, for different target temporal profile, this means that we can always find a set of dispersion term combinations to achieve the desired temporal profile. A certain degree of symmetry is observed in the negative logarithm of the mean squared difference between the final profile and the target profile obtained through grid scanning in Fig.1. This indicates that even though the same profile is achieved at the chicane exit, different combinations of chicane parameters can be utilized. This validates that the problem falls under the category of one-to-many problems, where for the same target values, there exist multiple potential optimal solutions corresponding to them. This also demonstrates the performance of the NSGAIII algorithm we used, as it converges to the global optimal solution region when solving this one-to-many problem, with the solution set of dispersion terms exhibiting higher diversity.

Chicane and Initial Energy Chirp Design

When studying the beam dynamics of a beamline, we not only want to determine the parameters of the chicane but also obtain more information about the beam, such as the energy chirp. By combining the known energy chirp with precisely designed chicane parameters, we can quickly achieve temporal shaping of the beam. The energy chirp can be adjusted based on the beamline elements upstream of the chicane, such as higher harmonic cavities. Below, we demonstrate using the NSGA-III algorithm to provide multiple sets of different energy chirp and chicane magnet parameter combinations. To manipulate the dispersion terms of the bunch compressor more flexibly, we adopt a structure similar to that in Ref [7], which consists of dipoles and sextupoles, with the potential inclusion of quadrupoles and octupoles. Additionally, the magnets are arranged in mirror symmetry to ensure that the horizontal dispersion can reach zero at the end of the compressor.

A part of the results found by the algorithm is shown in Fig. 2, depicting different initial beam longitudinal phase space distributions. It can be observed that these distributions include both linear and nonlinear energy chirp, which can be controlled by beamline elements upstream of the chicane. This means that we can adjust different energy chirps based on different parameters of the chicane to achieve shaping. Additionally, multiple optimal solutions can also generate different energy spreads at the chicane exit to match the requirements of downstream beamline elements. For example, the beam at the entrance to the plasma desires an energy spread below 1%. Not only the need for energy spread, but also different qualities of beam bunches can be provided, such as transverse phase space, transverse distribution, etc., to meet different experimental requirements. Of course, the most important thing is to ensure the requirement for stable transmission in the subsequent beamline.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG03

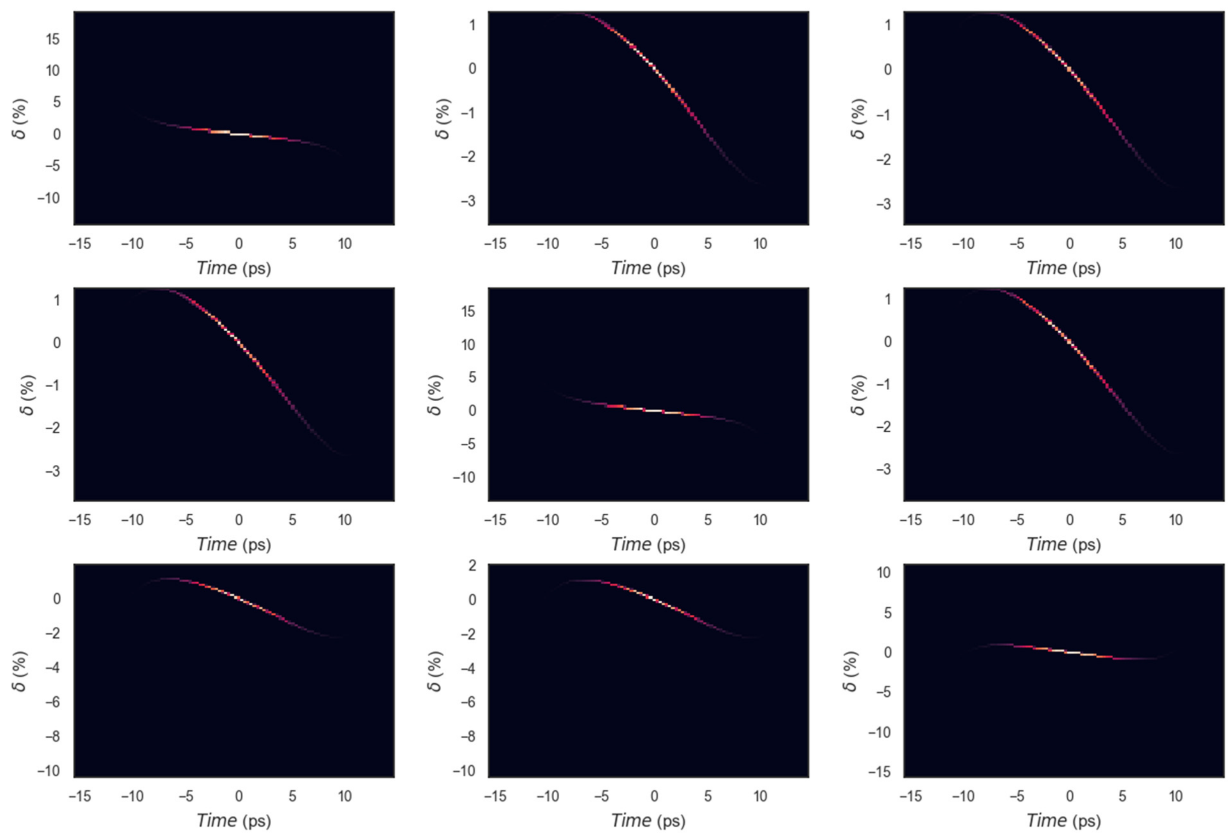
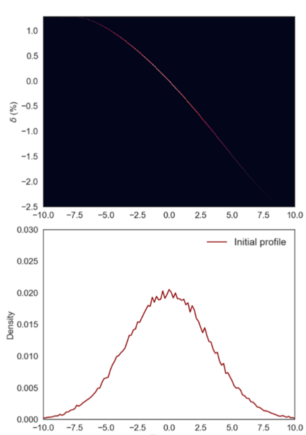
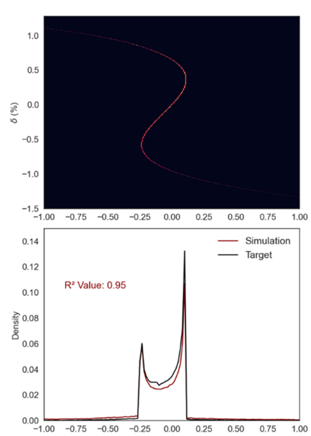


Figure 2: Different longitudinal phase space distributions of initial beam.



(a) input beam



(b) final beam

Figure 3: Longitudinal phase space distribution and temporal profile. (a) and (b) correspond to the beam at the entrance and exit of the chicane.

Figure 3 shows the optimization results of the NSGA-III algorithm with a target profile of double-horn profile. The Fig. 3 (a) displays the longitudinal phase space distribution of the beam at the entrance of the chicane, where the energy chirp of the bunch is nearly linear, with an energy spread of approximately 3.5%. The Fig. 3 (b) depicts the beam at the exit of the chicane, which exhibits a nonlinear energy chirp with an energy spread of approximately 2.5%. The temporal profile closely resembles the double-horn profile of the target profile, which is a complex example provided in Ref [7]. The correlation coefficient between the final profile and the target profile is 0.95, indicating a high degree of similarity between the two profiles.

CONCLUSION

We have demonstrated the process of optimizing energy chirp of the initial beam and the chicane parameters using the NSGA-III algorithm to achieve arbitrary temporal profile shaping. We found that controlling the dispersion terms in the chicane is an effective method to shape in order to achieve an arbitrary profile. Furthermore, the improved NSGA optimization algorithm can solve one-to-many problems and converge to the global optimal solution region. Lastly, for a specific target profile, we can achieve it by adjusting the magnet parameters of the bunch compressor and the energy chirp, which led to the design of upstream electron guns and pre-injection systems. This means that for experiments requiring temporal shaping, we will have a lot of flexibility to meet shaping requirements, while also providing the possibility of achieving better beam quality.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG03

REFERENCES

[1] Y. Ding *et al.*, "Beam shaping to improve the free-electron laser performance at the Linac Coherent Light Source", *Phys. Rev. Accel. Beams*, vol. 19, p. 100703, Oct. 2016. doi:10.1103/PhysRevAccelBeams.19.100703

[2] F. Lemery and P. Piot, "Considerations for an Efficient Terahertz-driven Electron Gun", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2664-2666. doi:10.18429/JACoW-IPAC2015-WEPWA070

[3] Jinyu Wan and Yi Jiao, "Machine learning-based direct solver for one-to-many problems on temporal shaping of relativistic electron beams," *Front. Phys.*, vol. 17, no. 6, p. 64601, Sep. 2022. doi:10.1007/s11467-022-1205-y

[4] D. J. Dunning, J. K. Jones, H. M. Castaneda Cort´es, and N. R. Thompson, "Multi-Objective FEL Design Optimisation Using Genetic Algorithms", in *Proc. FEL'19*, Hamburg, Germany, Aug. 2019, pp. 711-714. doi:10.18429/JACoW-FEL2019-THP065

[5] Y. Ding, K. L. F. Bane, and Y. M. Nosochkov, "Beam Shaping for High-Repetition-Rate X-Ray FELs", in *Proc. FEL'19*, Hamburg, Germany, Aug. 2019, pp. 661-664. doi:10.18429/JACoW-FEL2019-THP035

[6] K. Deb and H. Jain. "An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, part I: solving problems with box constraints," IEEE Transactions on Evolutionary Computation, vol. 18, no. 4, pp. 577-601, Aug. 2014. doi:10.1109/tevc.2013.2281535

[7] T. K. Charles, D. M. Paganin, M. J. Boland, and R. T. Dowd, "Beam by Design: Current Pulse Shaping Through Longitudinal Dispersion Control", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 644-647. doi:10.18429/JACoW-IPAC2017-MOPIK055