ADVANCED METAHEURISTIC ALGORITHMS FOR LASER OPTIMIZATION

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A laser is one of the most important experimnetal tools. In synchrotoron radiation field, lasers are widely used for experiments with Pump-Probe techniques. Especially for Xray-FELs, a laser has important roles as a seed light source or photo-cathode-illuminating light source to generate a high brightness electron bunch. The controls of laser pulse characteristics are required for many kinds of experiments. However, the laser should be tuned and customized for each requirement by laser experts. The automatic tuning of laser is required to realize with some sophisticated algorithms. The metaheuristic algorithm is one of the useful candidates to find one of the best solutions as acceptable as possible. The metaheuristic laser tuning system is expected to save our human resources and time for the laser preparations. I have shown successful results on a metaheuristic algorithm based on a genetic algorithm to optimize spatial (transverse) laser profiles and a hill climing methode extended with a fuzzy set theory to choose one of the best laser alignments automatically for each experimental requirement.

Keywords: XFEL, ERL, synchrotron radiation, photo-cathode, EO-sampling, genetic algorisms, metaheuristics, laser shaping, laser alignment

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1. Introduction

A laser pulse is characterized in its pulse energy, pulse chirp, spectral distributions (both of intensity and phase), 3D-profile (both of spatial and temporal), wavefront distortion, M^2-value, pointing stability, timing jitter, etc. When we use a laser on our own purposes, we have to optimize some of these laser characteristics at the same time. However, these laser pulse characteristics are not perfectly independent of each other. In this case, it is almost impossible to determine the best solution uniquely by mathematical formulae. The metaheuristic algorithm is powerful methodology to find some of the acceptable and the most preferable solutions with searching better parameters. Many kinds of metaheuristic algorithms have been proposed and applied widely. I utilised a genetic algorithm [1] and a simulated annealing methode [2] to optimize 3D laser pulse shape, and a hill climing methode with a fuzzy set theory [3] to align a laser to reliable path for each experiment at advanced photoinjector test facility in SPring-8.

Applying any kind of metaheuristic algorithm, a great number of system's parameter must be introduced. Making the probability higher to find some solutions as good as possible, it is necessary to increase freedom of its searching space. For instance, optimizing laser shape, I introduced adaptive optics to increase the parameters of laser system as shown in Fig. 1 (Deformable Mirror (DM) [1] for spatial (transverse) shaping & glass (fused silica)- plate-based Spatial Light Modulator (SLM) [4] for temporal (longitudinal) shaping).

In this paper, I review mainly adaptive optical system developed with metaheuristic algorithms for controlling 3D laser pulse shape and laser alignment. I completed system to manipulate 3D laser pulse shape as an illuminating light source for a photo-cathode RF gun [5]. In low-emittance electron beam generation, the experimental requirements for laser spot size on the

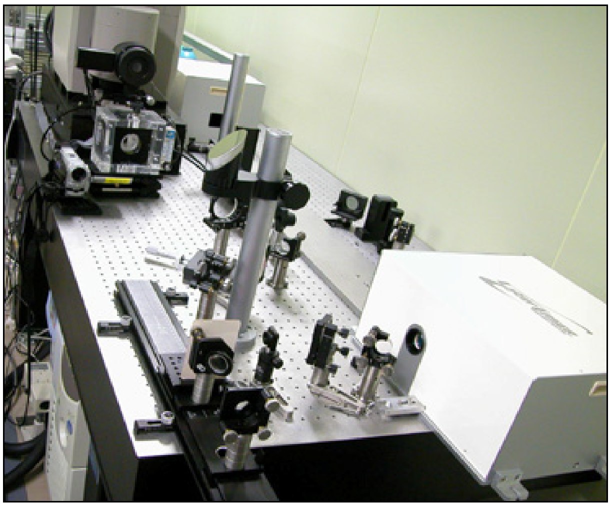

Figure 1. Adaptive-optic complex [4] for shaping both spatial and temporal laser profiles in Photo-cathode test fasility at SPring-8 (Spatial shaping: DM as an adaptive actuator & UV-CCD camera (laser profiler) as a monitor; Temporal shaping: SLM with a grating pair as an adaptive actuator & Streak Camera (Fesca-200; Hamamatsu Photonics K.K.) as a monitor).

cathode should be optimized for all bunch charge densities. Therefore, I decided to develop an adaptive shaping system in spatial shaping. Note that the latest 3D UV-laser pulse shaping system was completed with a DM (transverse: 2D) assisted by a genetic algorithm and a chirped pulse stacker (longitudinal: 1D) [5]. The shape and pulse duration of the original micro chirped pulse of this pulse stacker is precisely optimized with DAZZLER (acousto-optic programmable dispersive filter (AOPDF)) in our present 3D pulse shaping system. On the other hand, a simulated annealing methode was developed to optimize square laser pulses with the glass (fused silica)-

plate-based SLM [5]. However, our development of this SLM for adaptive square shaping (up to 20 ps) in high energy (~ mJ) UV-pulse was discontinued in 2005. It could be operated as a square pulse shaper even for the cw-mode. The operation with high repatition rate is attractive for X-ray Free Electron Laser (XFEL) [6-8] and Energy Recovary Linac (ERL) [9]. However, long-term drifts and uncertain individual plate-twisting motions were not negligible to keep the phase masks of the intended square pulses.

2. Developments of genetic Algorithms for Deformable Mirror

The laser spatial profile was adaptively optimized with a genetic algorithm for a DM that consists of an aluminium-coated, multilayer silicon nitride membrane and 59 small mirror actuators behind the reflective membrane with a center-to-center distance of 1.75 mm between the actuators (left in Fig. 2). The reflective membrane is protected with MgF_2 coating to maintain reflectivity at about 80% in the UV region. Adjusting voltages between the control electrodes on the boundary actuators results in fine adjustment of each mirror actuator; the adjustable region of the control voltages is between 0 and 250 V in steps of 1 V, making it possible to shape the arbitrary spatial profiles for a total of 250^{59} ($\sim 10^{141}$) deforming possibilities. However, since such high adjustability makes manual as well as simple algorithm adjustment impossible, this spatial shaping method with adaptive optics needs a sophisticated algorithm. Under the collaboration with F. Matsui (Industrial Technology Centre of Fukui Prefecture), we developed software based on a genetic algorithm to adaptively optimize DM deformation.

The set of the voltages of all DM-electrodes is treated as chromosomes in this software. A closed loop system is essential for a DM to adaptively optimize the laser's spatial profile. I used a PC to control the electrode voltage of the DM and to measure the spatial profile with a laser profile monitor (LBA300-PC, Spiricon Inc.).

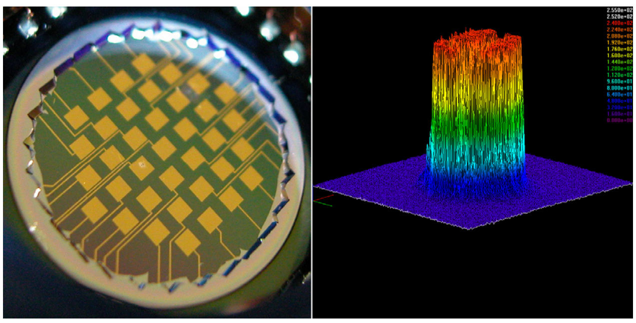

Figure 2. Result of spatial profile optimized to flattop (right) with a 59-ch DM: Mirror actuators behind the reflective membrane of a 37-ch type DM is shown in left as an example. Maximizing the fitting function consisted of laser profiling data analyzed with LBA300-PC, one of the best voltage sets applying to DM-actuators are searched by means of a metaheuristic method based on a genetic algorithm.

Laser light is reflected with deformation by the DM and monitored with a laser profile monitor, whose analyzing program can provide many parameters to evaluate the beam profile characteristics. I chose useful parameters to evaluate the flattop profiles and made a fitting function for the developed a genetic algorithm to optimize the profile toward an ideal flattop. The fitting function is a linear combination of flattop shaping parameters with certain optimal weights for fast convergence (see ref [2] for details). The value of this fitting function is returned as feedback to control the deformable mirror with the genetic algorithm. As a result, the laser profile on the cathode surface was spatially shaped as a quasi-flattop profile (right in Fig. 2). The laser spatial profile was remarkably improved by this shaping technique.

3.1. Square Temporal Shaping (Chirped UV Pulse Stacking)

Low-emittance generation experiments require keeping cathode laser spot sizes and bunch charge densities with varying longitudinal (temporal) square bunch lengths. Therefore, I developed several pulse stacking systems to provide several different total bunch lengths of stacked square pulses. To avoid the interference caused by stacking, orthogonally polarized chirped pulses are alternatively stacked with an optical delay. The optical delay period should be 1.2~1.3 times longer than the micro chirped Gaussian pulse duration to generate a precisely homogeneous electron bunch at the cathode. This method, which introduces additional chirp to avoid interference is referred to as "chirped pulse stacking." In 2007, we installed a new UV pulse stacking system [5] that consisted of four birefringent Alpha-BBO crystal rods (Fig.3 (B)) to fix the optical delays between neighboring micro chirped pulses in the previously developed mechanical pulse stacker (Fig.3 (A)) [2]. The angle of rotation of each crystal axis against incident polarization is 45° to make twin pulses. Then a pulse train with equivalent intervals is connected smoothly with pulse stretching controlled in chirping. These Alpha-BBO crystal rods can be used as a pulse stacker in the super broadband wavelength region (189–3500 nm).

3.2. Homogeneous connection at the cathode with adaptive AO-modulator

To generate a long square pulse without any timing gap or overlap, optical delays in each birefringent crystal, which are ~20% shorter than the micro Gaussian pulse duration, are applied to generate a precisely homogeneous electron bunch at the cathode. Micro pulse lengths T [fs] at the cathode stretched by the dispersion of the transparent materials for UV-laser in pulse stackers and transportation are estimated by the following formula, where no nonlinear process is assumed to occur in the optical elements:

$$T = t_0\sqrt{1 + \left(4 \cdot \ln 2 \cdot GDD / t_0^{\,2}\right)^2} \;[fs],$$

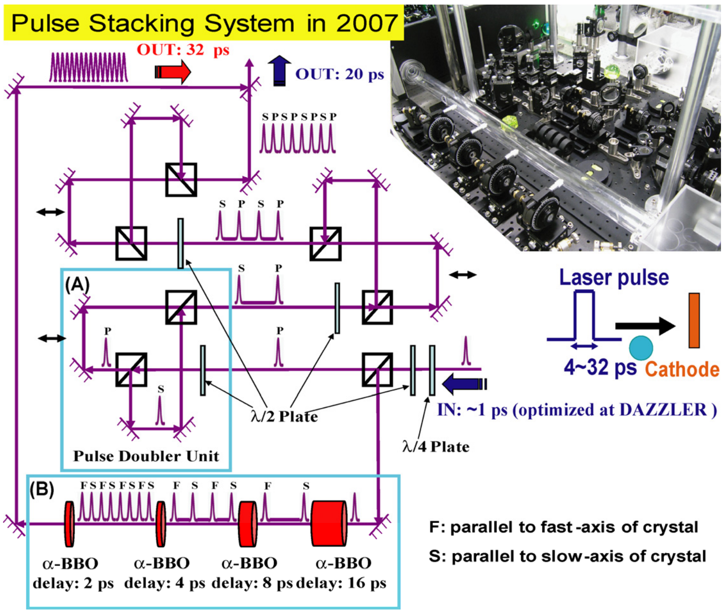

Figure 3. Drawing of UV-laser pulse stacking system [10]: (A) mechanical pulse stacker; (B) pulse stacking rods made of birefringent Alpha-BBO crystals. Initial UV-laser pulse interval is set to 2.5 ps for generating 5-, 10-, or 20-ps combined macro square pulses for three stages (pairs of polarizing UV-laser beam splitter cubes) of mechanical pulse stacker, while pulse stacking rods provide 4-, 8-, 16-, or 32-ps square UV-laser pulses.

where T and t_0 are the chirped pulse width and the pulse width of a Fourier-transform limited pulse, respectively. The UV-laser pulse intervals, which are usually set to 2.5 ps for the mechanical pulse stacker, were designed for a delay of 2.0 ps for the pulse stacking rods. To obtain smoothly squared combined macro pulses, micro pulse durations of 3.0±0.1 ps for the stacker and 2.5±0.1 ps for the birefringent rods should be prepared. We optimized a group delay dispersion (GDD) to roughly stretch the micro pulses with DAZZLER (HR-800, FASTLITE) and then additionally micro pulse shape for fine tuning with the depth and position of the dip in the spectra and the higher order dispersions up to the 7th.

I checked the electron bunch's homogeneity by measuring the electron energy spectra. The initial RF phase of the electron bunch was set near the zero-cross region to give quasi-linear energy chirp to the bunch generated at the cathode. The electron beam's energy is measured on the basis of the beam positions on a florescence profile monitor after they pass through a bending magnet downstream of the RF gun cavity. After introducing a second dispersion with DAZZLER, the micro chirped pulse duration is optimized so that the electron beam profile is homogeneous (lower right in Fig. 4) at the dispersion section [5].

By precisely optimizing the laser pulse's 3D shape, I strive to generate a beam with as high a brightness and as low an emittance as possible. Farther perfect homogeneity of temporal stacking is planning with a feedback routine between an AOPDF UV-pulse real-time measurement using a UV-DAZZLER [spectral phase interferometry [11] for THG (264 nm)] and a high-resolution DAZZLER (HR-800, FASTLITE) as a micro laser pulse adaptive shaper in IR. Directly monitoring a generated electon bunch suracture with an electro-optic sampling (EO sampling) [12-13] in real time, it can be possible to optimized pulse stacking perfectly at the electron bunch generation with a metaheuristic feedback routine.

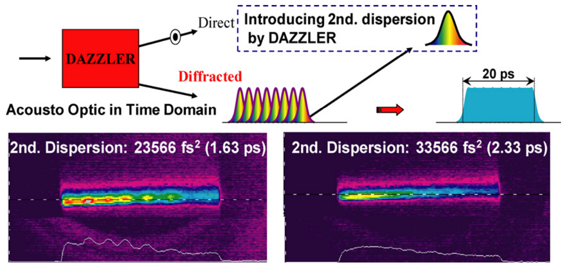

Figure 4. Generating a homogeneous electron bunch: Chirped pulse stacking made the connections between neighboring micro pulses smooth.

4. Auto-aligner with Fuzzy set theory

I have developed an auto-aligner for a large laser system together with Photo-Physics Laboratory Inc. since 2007. It is named Advanced Tactical Aligner (ATA), based on fuzzy set theory to find a better solution smoothly. It is principally one kind of hill climbing method. The fuzzy sets give certain step sizes according to their membership functions. The membership function is defined for each movement set. There are four movement sets classified by the achievement levels evaluated with a fitting function. They are a super fine-tuning set, a fine-tuning set, a rough-tuning set, and an out-of-target set, in the order of user-defined step size of movements to search. The membership functions can realize smooth movements to reach the most probable area implies the required solutions with a smoothly connected step size on the ambiguous "Fussy" boundaries between the classified sets.

I introduced several pairs of wedge plates (0.1 or 0.5 degrees of the wedge angles) mounted in remote-controlled rotary stages on the optical path of laser system. In the simple case, an analog signal of power meters or photodiodes are utilized as a fitting function to maximize with ATA system. To generate and keep laser profile, the fitting function is a linear combination of spatial laser shape parameters with certain optimal

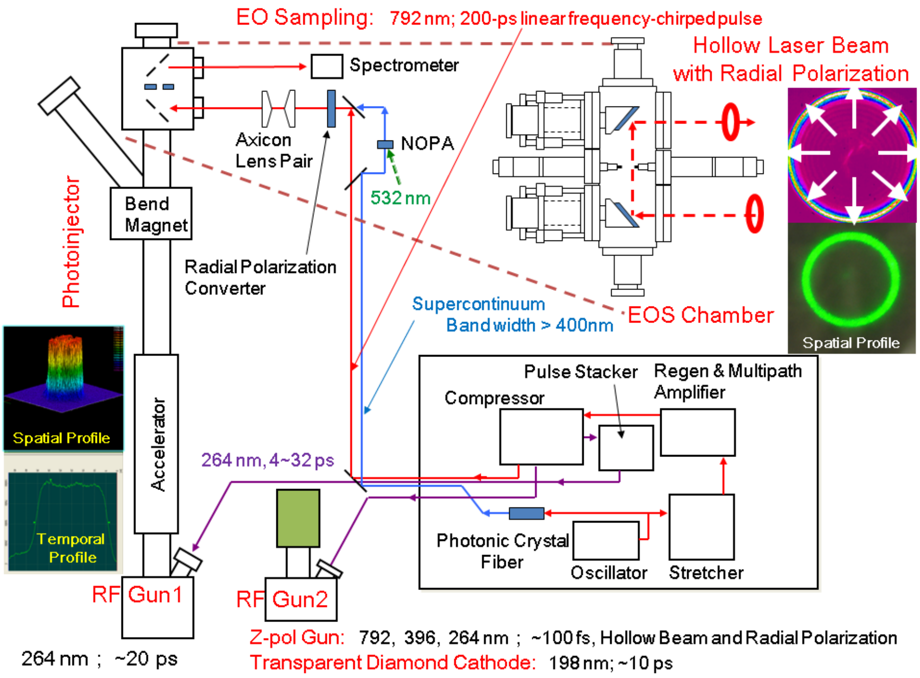

Figure 5. The present laser light distributions with swichng ATA system in the accelerator shirld room at advanced photoinjector test facility in SPring-8 (Photo-cathode illumination at the test photoinjector: 3D- cylindrically shaped 4-32 ps pulse with DM and pulse stacker @264 nm; Photo-cathode illumination at the RF gun 2: radial or athmuthal polarization @264, 396, 792 nm; Probe laser for 3D-EOS: linear frequency-charped 200-ps pulse and radial polarization @ 792 nm).

weights. As the target laser profiles, flattop profile for photo-cathode illumination, and hollow beam profile of a probe laser for single-shot 3D EO-sampling (EOS) monitor [12-13]. The present laser distributions are shown in Fig. 5. ATA has been successful to tune the laser automatically to each experimental station downstream.

5. Summary

The metaheuristic algorithm is useful to find one of the best solutions as acceptable as possible on each occasion. Tuning laser is one of the effective cases to apply such a sophisticated algorithm. The metaheuristic laser tuning system is expected to save our human resources and time for the laser maintenance and preparation in user's experiments. I have shown successful results on a genetic algorithm to optimize spatial (transverse) laser profiles and a hill climing methode extended with a fuzzy set theory to choose one of the best laser alignments automatically for each requirment at the experimental points downstream.

References

[1] H. Tomizawa, H. Dewa, H. Hanaki, "Development of automatically optimizing system of both spatial and temporal beam shaping for UV-laser pulse," Proc. of LO'03, St. Petersbrug, Russia, 30 June -04 July 2003, (2004) 47–55.

[2] H. Tomizawa, H. Dewa, H. Hanaki, F. Matsui, "Development of yearlong maintenance-free terawatt Ti:Sa laser system with 3-D UV-pulse shaping system for THG," *Russ. J. Quant. Electron.* (2007) 697–705.

[3] H. Tomizawa, "Advanced laser pulse shaping," Plenary Talk at ICFA Advanced Accelerator and Beam Dynamics Workshop, HBEB'09, Maui, Hawaii, 17 November 2009.

[4] H. Tomizawa, T. Asaka, H. Dewa, H. Hanaki, T. Kobayashi, A. Mizuno, S. Suzuki, T. Taniuchi, K. Yanagida, F. Matsui, "Development of adaptive feedback control system of both spatial and temporal beam shaping for UV-Laser light source for RF gun," Proc. of LINAC'04, Luebeck, Germany, 16-20 August 2004, (2004) 207–209.

[5] H. Tomizawa, "Adaptive 3-D UV-laser pulse shaping system to minimize emittance for photo-cathode RF gun," Invited talk at FEL'07, Novosibirsk, Russia, 26-31 August 2007; *Proc. of FEL'07*, (2008) 298–305.

[6] *TESLA Technical Design Report, PART V, The X-Ray Free Electron Laser*, ed. G. Materlik, Th. Tschentscher, March 2001.

[7] *Linac Coherent Light Source (LCLS) Conceptual Design Report*, SLAC-R-593, April 2002.

[8] *SCSS X-FEL Conceptual Design Report*, RIKEN, May 2005.

[9] I. Ben-Zvi, I.V. Bazarov, "Summary, Working Group 1: Electron guns and injector designs," Workshop on ERL 2005, Newport News, VA, USA, March 2005, *Nucl. Instrum. Meth. Phys. Res. A* **557**, (2006) 337–344.

[10] H. Tomizawa, "Review of advanced laser technologies for photo-cathode high-brightness guns," Invited talk at LINAC'08, Victoria, British Columbia, Canada, 29 September - 3 October 2008; Proc. of LINAC'08, (2009) 1090-1094.

[11] E. Cormier, L. Corner, E.M. Kosik, I.A. Walmsley, A.S. Wyatt, "Spectral phase interferometry for complete reconstruction of attosecond pulses," *Laser Phys.* **15,** No. 6, (2005) 1–7.

[12] H. Tomizawa, H. Hanaki, and T. Ishikawa, "Non-destructive single-shot 3-D electron bunch monitor with femtosecond-timing all-optical system for pump &probe experiments," Proc. of FEL'07, Novosibirsk, Russia, 26-31 August 2007, (2008) 472–475.

[13] H. Tomizawa, A. Maekawa, M. Uesaka, "Novel single-shot EO-based 3D bunch charge distribution monitor with femtosecond resolution," ICFA Advanced Accelerator and Beam Dynamics Workshop, HBEB'09, Maui, Hawaii, 18 November 2009.