ADAPTIVE 3-D UV-LASER PULSE SHAPING SYSTEM TO MINIMIZE EMITTANCE FOR PHOTOCATHODE RF GUN AND NEW LASER INCIDENCE SYSTEM

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Abstract

We developed an adaptive 3-D shaping (both temporal (1D) and spatial (2D)) short pulse (80 fs~40 ps) UV-laser system as an ideal light source for yearlong stable generation of a low-emittance electron beam with a high charge (1~2 nC/pulse). In its current form, the laser's pulse-energy stability has been improved to 0.2~0.3% (rms; 10 pps, 0.4 TW in femtosecond operation) at the fundamental wavelength and 0.7~1.4% at the third-harmonic generation. Such improvement reflects an ability to stabilize the laser system in a humidity-controlled clean room. The pulse-energy stability of a mode-locked femtosecond oscillator has been continuously held to 0.3% (p-p) for 4.5 months (1% for 10 months), 24 hours a day. In addition, the ideal spatial and temporal profiles of a shot-by-shot single UV-laser pulse are essential to suppress emittance growth in an RF gun. We apply a deformable mirror that automatically shapes the spatial UV-laser profile with a feedback routine, based on a genetic algorithm, and a pulse stacker for temporal shaping at the same time. The 3D shape of the laser pulse is spatially top-hat (flattop) and temporally a square stacked chirped pulse. Using a 3D-shaped laser pulse with a diameter of 0.8 mm on the cathode and pulse duration of 10 ps (FWHM), we obtain a minimum normalized emittance of 1.4 π mm mrad with a beam energy of 26 MeV. We found that the last mirror in the vacuum to make normal incidence is an obstacle for the electron beam. Therefore, we developed the optical elements for a new hollow laser incidence with an axicon final focusing. We fixed temporal parameters with the present mechanical pulse stacker and prepared a new UV-pulse stacking system (fixed parameters) consisting of three birefringence α-BBO crystal rods.

INTRODUCTION

We have been developing a stable and highly effective UV-laser pulse as the light source of a photo-cathode RF gun [1] that in turn provides a high-brightness electron beam source to achieve future X-ray light sources (FEL (free electron laser), Compton back scattering, etc.) since 1996 at SPring-8 (Synchrotron Radiation Research Group). The electron source for several X-ray FEL projects [2-4] requires a very-low-emittance (high-brightness) electron beam as low as 1 π mm mrad. One of the most reliable candidates for this high-brightness electron source is a photocathode RF gun. This type of gun generates an electron beam pulse from a photocathode illuminated by a laser pulse. Our development of this gun is oriented toward a yearlong stable system for user experiments. It is necessary for the copper cathode of this RF gun to have a UV-laser pulse with a pulse width of ~10 ps and a photon energy of ~4 eV. Since we started to develop the laser test facility, two issues related to the laser light source have arisen. One is the energy stability of the UV-laser light source. Therefore, we have stabilized the third-harmonic generation (THG) of a CPA (chirped pulse amplification) Ti:Sapphire terawatt laser system (Figure 1) as the laser light source for the SPring-8 RF gun.

The other problem concerns the spatial and temporal laser profiles. To minimize the beam emittance of a photocathode RF gun, the laser pulse shape should be optimized three-dimensionally. Over the past six years at SPring-8's test facility for the photocathode laser light source, several 3-D shaping systems have been developed from combinations of spatial (transverse: x-, y-axes) and temporal (longitudinal: z-axis) pulse shaping methods (Figure 1). The spatial profile has to be modified with a microlens array [5] or a deformable mirror (DM) [6]. In addition, the temporal profile has to be modified with a spatial light modulator (SLM) [6-7] or the pulse stacker described in this paper. One of the candidates for a reliable 3-D laser pulse shape has been the cylindrical shape (spatially top-hat and temporally square pulse). With a square-shaped 9-ps laser pulse, the lowest beam emittance of 1.2 π mm mrad at 1.0 nC/pulse has already been achieved by J. Yang et al [7]. Previously, we have demonstrated a UV-laser spatial profile shaped as a quasi top-hat (flattop) with a deformable mirror used to automatically optimize it with a feedback routine based on a genetic algorithm. Using this top-hat laser pulse (diameter of 1.0 mm on the cathode) with a pulse duration of 5 ps (note: temporally, not square), we could obtain low-emittance beam generation of 1.7 π mm mrad [6] at a net electron charge of 0.1 nC/pulse. However, the beam emittance at high charge was much larger. This indicates that a 5-ps laser pulse is too short for the laser spot diameter of 1 mm. (The charge density is too high.)

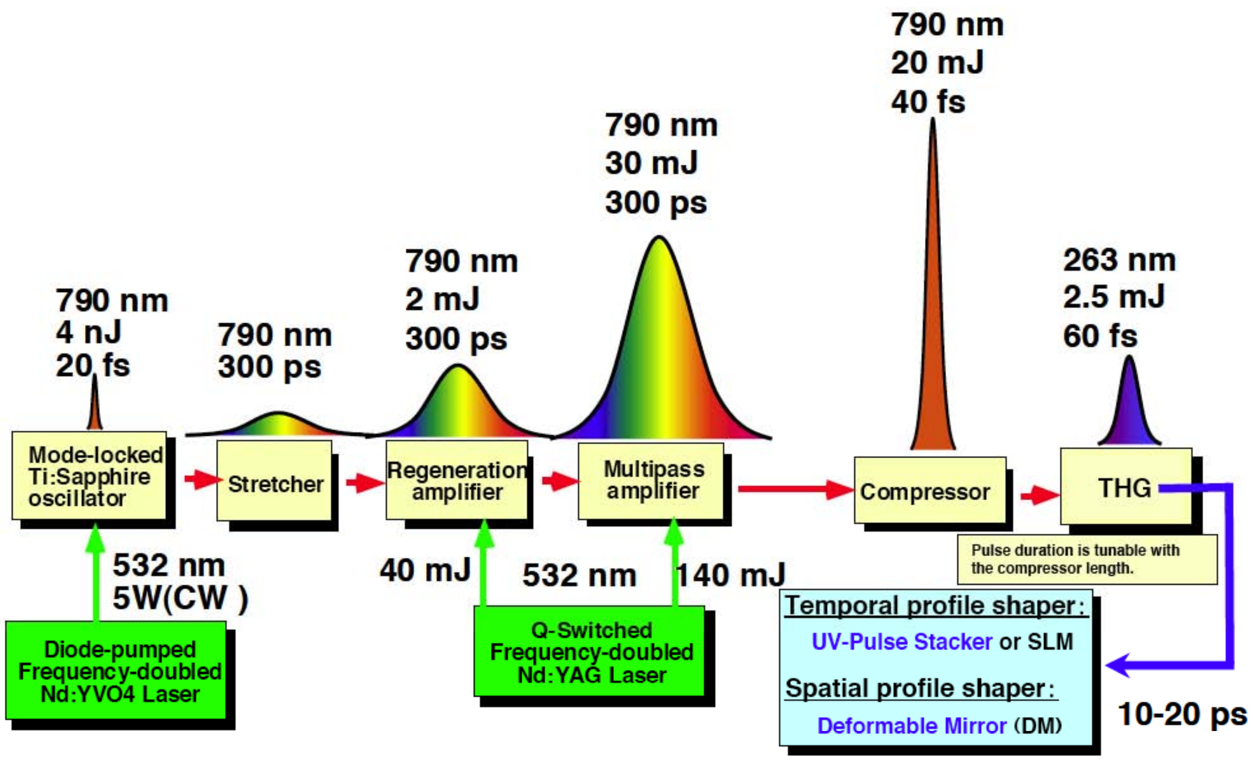
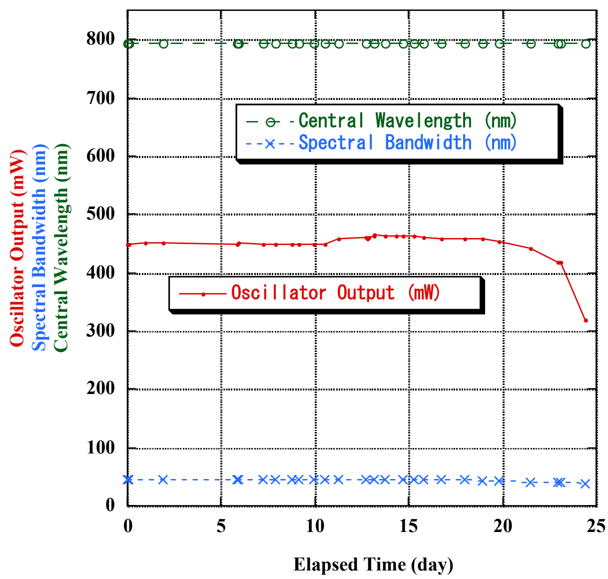


Figure 1: Laser pulse growth and three-dimensional (spatially (2D) and temporally (1D)) shaping process: the pulse duration of THG (263 nm) depends on the group delay dispersion (GDD) introduced by AO-modulator (DAZZLER: FASTLITE) after the stretcher (790 nm). To obtain a 20-ps pulse by stacking eight micro chirped pulses (three stages of pulse stackers), micro chirped pulse duration should be optimized to 2.5 ps at the cathode by changing GDD with DAZZLER (also possible with shifting compressor length).

Therefore, we prepared longer square laser pulses of 10 and 20 ps generated by stacking equivalently split 2.5-ps Gaussian chirped pulses to obtain lower emittance in a higher-charge region. Three stages of pulse stacking can generate a 20-ps pulse from eight 2.5-ps micro chirped pulses. The purpose of introducing longer laser pulses is to make the laser spot size on the cathode smaller while still decreasing the charge density. The small beam size helps to decrease the initial (thermal) emittance, and the small charge density suppresses the space charge effect. A 3-D particle tracking simulation predicted that smaller beam emittance could be obtained with a laser pulse length of about 20 ps at 1.0 nC/pulse [8]. This simulation result implies an important prediction, i.e. that electron pulse length can be maintained around 10 ps with both 10- and even 20-ps laser pulse lengths, due to electron bunch compression during its acceleration in the RF cavity.

DEVELOPMENT OF YEARLONG STABLE LASER LIGHT SOURCE

We chose the THG of a CPA Ti:Sapphire terawatt laser system (repetition rate of 10 Hz) as the laser light source for the SPring-8 RF gun. At THG (central wavelength: 263 nm), the femtosecond UV-laser pulse energy is up to 2.5 mJ/pulse. In its current form, the laser's pulse energy stability has been improved to 0.2~0.3% (rms; 10 pps, 0.4 TW in femtosecond operation) at the fundamental and 0.7~1.4% at the THG. At the first stage of development, this stability had been held for 1.5 months continuously, 24 hours a day. The improvements we had passively implemented were to stabilize the laser system as well as the environmental conditions. We introduced a humidity-control system that maintained humidity at 55% (fluctuating by less than 2% (p-p)) in a clean room to reduce electrostatic charge on the optics. This system keeps dust particles away from the optics and thus avoids burn-out damage. The temperature was kept constant at 21±0.3˚C (p-p), monitored on the laser table. The improvement in THG stability results from the ability to stabilize the laser pumping sources (Q-switched YAG) of the amplifiers with a temperature-controlled base plate in this humidity-controlled clean room. This base plate for YAG stabilization maintained temperature at 25˚C (fluctuating by less than 0.1˚C % (p-p)). In addition, we are testing a feedback system to control the long-term drift of the YAG laser due to the lifetime of the flash lamp, which is now limited to continuous operation of around five months (in our record, 119,380,846 shots at max.) while maintaining the high stability of the laser's pulse energy as mentioned above.



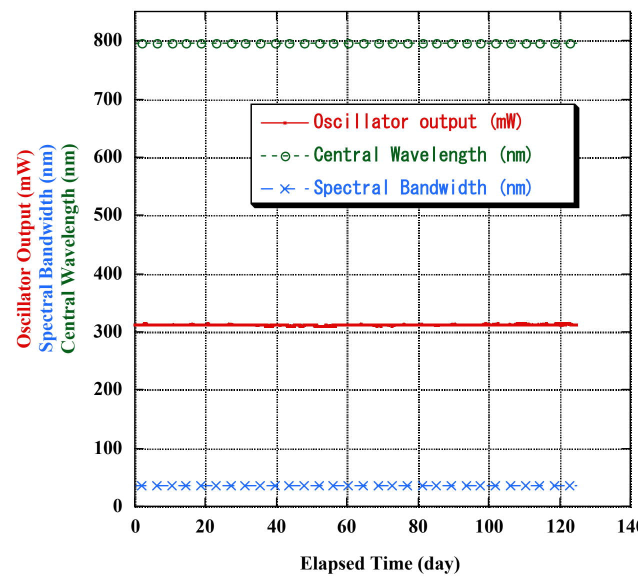


Figure 2: Improvement in laser oscillator's long-term stability (left: just passive, right: full-active, Femto-align & Femto-lock): With full-active feed-backing, the mode-locking and spectral distribution has been kept constant.

Aside from long-term drift of the pumping source YAG, the long-term stability of the total laser system (in THG) depends only on the stability of mode-locking at the oscillator laser. A new oscillator laser (Femtosource Synergy; Femtolasers Produktions GmbH) was installed in our system in April 2005. This oscillator was passively stabilized with a temperature-controlled base plate (21±0.1˚C (p-p)). In the first long-term continuous operation test run, its mode-locking was kept stable without any active stabilization for one month (left figure of Figure 2). However, laser parameters did not remain constant. This indicates that pointing of the pumping laser or laser self-focusing in the crystal (due to change in cavity length) causes drift in the long term (1~2 weeks). When the geometrical configuration of the laser cavity changes with these drifts, its mode-locking becomes unstable. Therefore, for the second test run, we introduced two active feedback systems (Femto-align and Femto-lock; Femtolasers Produktions GmbH) to lock the geometrical configuration of the laser cavity.

Femto-align is designed to compensate for long-term instabilities caused by environmental sources of interference such as thermal deformations or pump-pointing drift. It avoids mode-locking failures and reduces unexpected fluctuations. It monitors the output power and optimizes operations whenever deviations occur. The active controlling mirror can compensate for long-term instabilities of the total laser system. On the other hand, Femto-lock is a sub-ps-jitter synchronization for the oscillators. It allows locking the round-trip frequency of the oscillator pulses to a given reference RF-source (ROHDE & SCHWARZ GmbH & Co. KG: SMHU). The system comprises a fast piezo translator (PZT) in combination with a wide-range translation stage. This arrangement allows the unit to compensate for fast fluctuations (~kHz) as well as for slow long-term drifts (e.g. mechanical deformations due to temperature drifts). This combination of feedback guarantees drift-free yearlong operation.

In the second long-term continuous operation test run, the oscillator was actively stabilized by utilizing both Femto-align and Femto-lock, and it was operated at the locked repetition rate of 89.25 MHz. This long-term stability test had to be stopped for maintenance of the infrastructure. The pulse energy stability of the mode-locked femtosecond oscillator with a temperature-controlled base plate (21±0.1˚C (p-p)) was held at 0.3% (p-p) for 4.5 months continuously, 24 hours a day (right figure of Figure 2). Except for momentary line drop due to natural disasters (thunderbolts, etc.) or infrastructure maintenance, this oscillator has continuous yearlong operation while maintaining constant laser parameters (pulse energy, pulse duration, spectral distribution, etc.) The laser parameters have been kept constant without any sign of instability. This indicates that the drifting deformations of the laser's geometrical configuration could have been locked within the stable region of mode-locking.

3D SHAPING EXPERIMENT WITH UV-LASER PULSE

The 3D UV-laser pulse shaping system combined with a deformable mirror (transverse: 2D) and a chirped pulse stacker (longitudinal: 1D) is shown in Figure 3. Utilizing the long-term stable UV-laser source described above, this system can generate a 3D cylindrical laser pulse. Note that the original micro chirped pulse is optimized in its shape and pulse duration with DAZZLER (AO-modulator) at the fundamental. We explain both shaping techniques in the following.

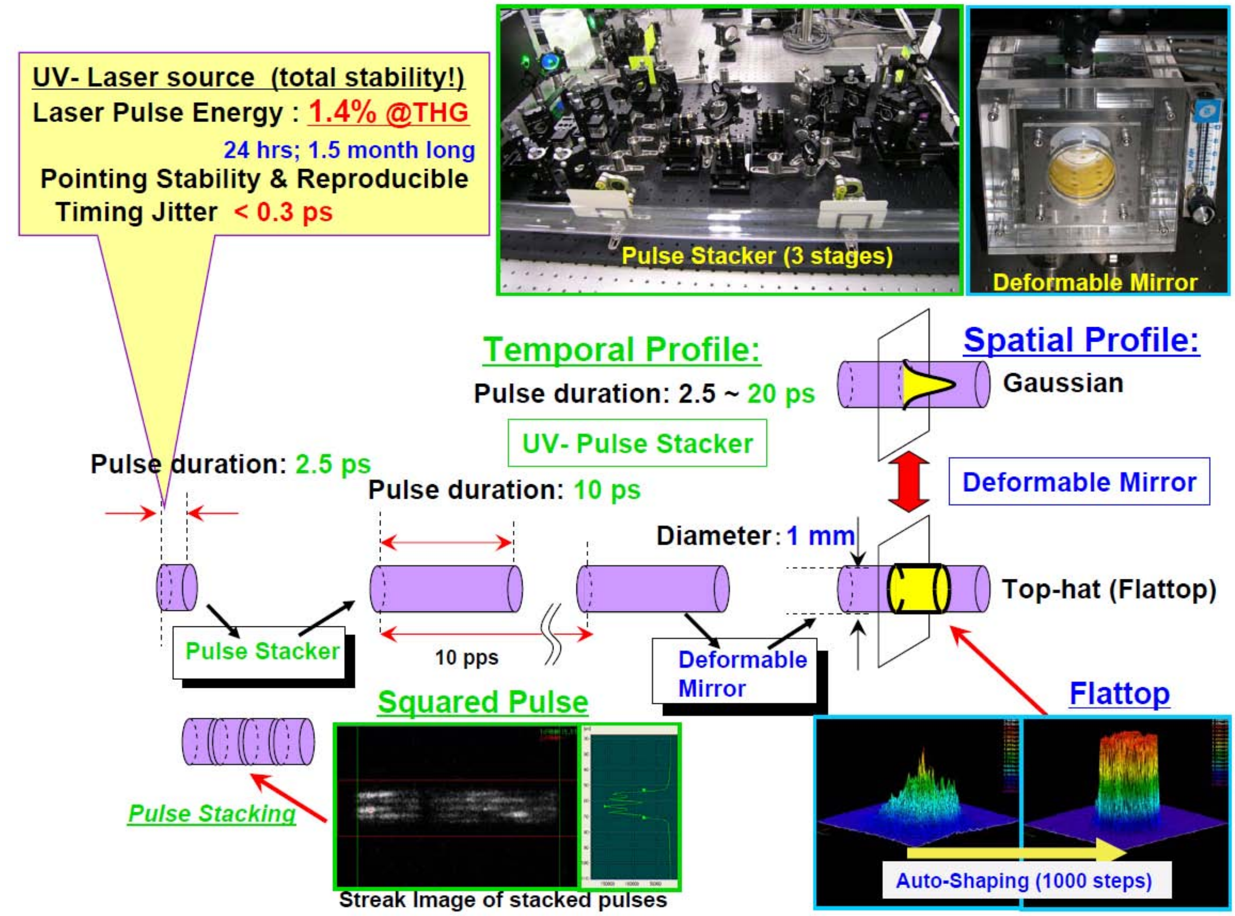


Figure 3: Three-dimensional (spatially (2D) and temporally (1D)) UV-laser pulse shaping system: the 3D shaping system consists of a deformable mirror (DM) and a chirped pulse stacker. These two shaping techniques can be optimized independently because there is no interference between them. The schematic drawing of pulse stacking shows 10-ps pulse generation by stacking four 2.5-ps micro chirped pulses (two stages of pulse stackers).

Top-hat spatial profile optimization with computer-aided deformable mirror

We used a computer-aided deformable mirror (top-right photo in Figure 3) as a spatial shaper. This deformable mirror 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. The outermost layer of the reflective membrane is protected with an MgF_2 coating to maintain reflectivity at about ~80% in the ultraviolet 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 255 V in steps of 1 V, making it possible to shape arbitrary spatial profiles in a total of 256^{59}($\sim 10^{141}$) forming possibilities. However, such high adjustability makes manual as well as simple algorithm adjustment impossible.

Closed loop system for spatial shaping

A closed loop system is essential for a deformable mirror to optimize the laser's spatial profile automatically. We use a PC to control the electrode voltage of the deformable mirror and to measure the spatial profile with a laser profile monitor (Spiricon, Inc.: LBA300-PC). Laser light is reflected with deformation by the deformable mirror and monitored with the profile monitor, whose analyzing program can provide many parameters to evaluate the characteristics of beam profiles. The program is remotely controlled by Active-X [9] control (Object Linking and Embedding), so we could control the deformable mirror while monitoring the laser beam parameters.

Algorithm for automatic control

This spatial shaping method with adaptive optics requires a sophisticated algorithm. We developed software based on a genetic algorithm (GA) to automatically optimize the deformation of the deformable mirror (DM). The set of voltages of whole DM-electrodes are treated as chromosomes in their application. At first, we prepared 50 chromosomes as the initial population and used the MGG (Minimal Generation Gap) method to select the surviving chromosomes. The 59 DM-electrode voltages are applied independently in the range of 0 to 255 V, and these were coded to 59 elements in a chromosome.

In this type of deformable mirror (electrostatic actuator), the displacement in the central region of the membrane is proportional to the square of the electrode voltage. In the initial population, applied electrode voltages (chromosome element values) were randomly selected from the set of discreet voltages (0, 42, 70, 93, 113, 131, 147, 162, 176, 189, 201, 213, 225, 236, 250 V) to linearly change the displacement. In this procedure, chromosomes are treated as follows.

(1) Make a Family consisting of four chromosomes: Two chromosomes are selected randomly from the initial population to make the family, and these chromosomes are placed as “Parents.” Then, the other two chromosomes as “Children” are generated through the crossover of the chromosomes of the “Parents.” In our program, we prepared three different methods of crossover: random crossover (in our case “58-point crossover”), one-point crossover, and two-point crossover. Thus, four chromosomes are prepared and treated as “Family,” which is called “Generation” in GA. The mutation rate was set 1% of the total number of generations.
(2) Drive the deformable mirror and obtain results of the laser parameters from measurements of the laser’s spatial profile. In the MGG method, the four chosen chromosomes in the family are compared, and the two best chromosomes survive as superior. Drive the deformable mirror by setting the chromosomes of four members of the “Family” (in the order “Father,” “Mother,” two “Children”) and obtain each result of beam parameters calculated from the analysis program of the laser profile monitor. The beam parameters of the laser’s spatial profile are obtained for evaluation in the following step.
(3) Evaluate the resulting parameters using a fitness function. These results are scored by a fitness function defined by top-hat beam shaping. The fitness function is a linear combination of the nine parameters shown in Table 1 with each coefficient as weight. If a chromosome is more highly scored in the evaluation of the fitness function for top-hat, it will be promoted to a higher position in the ranking of “Family.” Thus, in this ranking, the chromosomes are ordered by comparing values of the fitness function.
(4) The two best chromosomes are selected as superior and then returned to the population. This procedure makes one generation step forward, and the population is renewed to initiate the next generation.

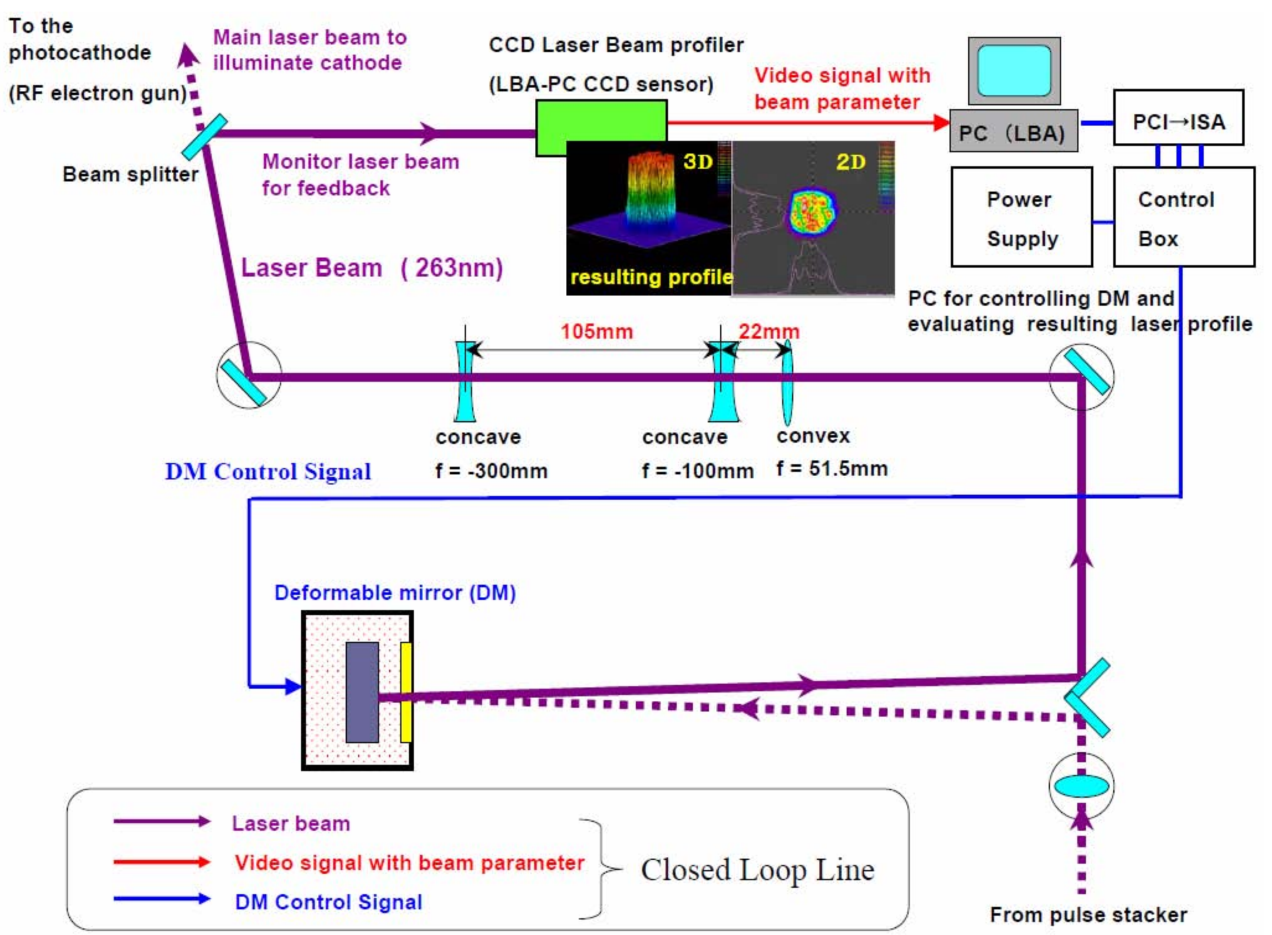


Figure 4: Closed control system for experiment: With evaluation of top-hat (flattop) profiles on laser profiler (LBA300-PC), the deformable mirror (DM) is automatically controlled to optimize the spatial profile toward the top-hat as a target profile.

Fitness function for genetic algorithm to optimize spatial profile through evaluation of beam parameters

We chose nine useful parameters [6] to evaluate the top-hat profiles. These parameters for top-hat shaping and their functions are shown in Table 1. A fitness function is made of the linear combination of these parameters. The fitness function is used as an index for the sophisticated program-based genetic algorithm. The more the laser profile is closed to the target profile (top-hat), the higher the value of the fitness function is. This is calculated for the spatial profile corresponding to each chromosome to evaluate the spatial profile, spot-size diameter, and centre position of the profile. Maximizing the value of the fitness function with the GA-program, the computer-aided deformable mirror optimizes the profile toward a target spatial profile such as the top-hat. The most representative parameter is the Top Hat Factor (THF) [10], where THF is defined as an integral function of the energy fraction as shown in Figure 5. After 2500 generation steps, an inhomogeneous spatial profile was improved to the quasi-top-hat profile shown in Figure 6.

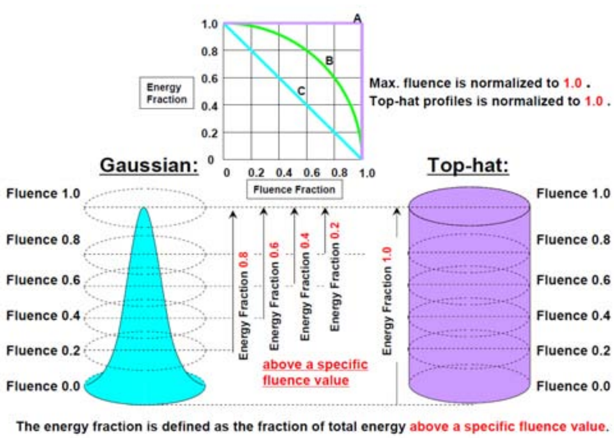


Figure 5: Top Hat Factor (THF) [10] for evaluation of Top-hat profiles: In the top figure, curve A is a Top-hat beam with THF of 1.0, curve C a Gaussian (conoidal) beam, and curve B is beam profile between Top-hat and Gaussian.

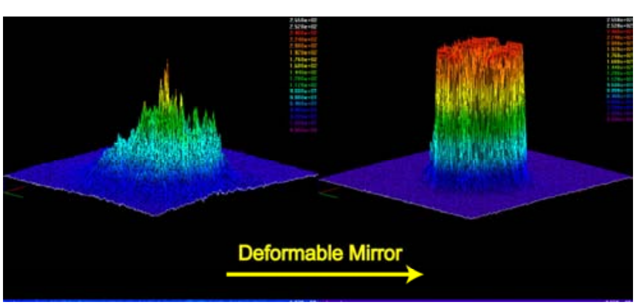


Figure 6: Result of spatial profile optimized to Top-hat with a deformable mirror (Laser profile monitor: LBA300-PC). The figures are normalised with the peak intensity to avoid saturation of laser profiler pixels.

Table 1: Parameters and their uses in fitness function to evaluate spatial profile optimization

Parameters of fitness function for top-hat (flattop) shaping with deformable mirror	
Beam Centre	Minimise the difference from the initial centre position (x, y)
THF	Maximise the Top Hat Factor (0~ 1) (Top-hat: THF=1.0; Gaussian: THF =0.5)
Effective Area	Maximise the integrated energy within the set circle area
Effective Diameter	Minimise the difference from the diameter of set circle
Flatness	Minimise the standard deviation divided by the average in a top-hat area
Peak-to-peak	Minimise the difference between the max. and min. in a top-hat area
Beam Diameter	Minimise the difference from the set diameter
Hot Spot	Minimise the max. in a top-hat area
Dark Spot	Maximise the min. in a top-hat area

SQUARE TEMPORAL PROFILE GENERATION (UV-PULSE STACKER)

Principle and configuration of chirped pulse stacker that is not affected by interference

A pulse stacker is composed of sets of half-wave plates and polarizing beam splitter cubes. One stage of the pulse stacker consists of a pair of a splitter and a half-wave plate. The full s-polarization is rotated to a 45-degree polarization with a half-wave plate. It is then divided into an s-polarized pulse and a p-polarized one with the first polarizing beam splitter at each stage. The p-polarized pulse is delayed with an optical delay line and then combined with the s-polarized pulse after using the next polarized beam splitter at each stage. Finally, as shown in Figure 7, the chirped laser pulse of 2.5 ps is stacked with optical delay at each stage to generate a longer square pulse. By stacking eight micro chirped pulses in three stages, we can obtain a 20-ps square combined pulse. The polarizing beam splitter cubes are the optical contact type (Showa Optronics Co., Ltd.), considering the high power density of the UV-laser pulse. The diagram of the optical system and timing chart of the pulse stacker with a three-stage configuration are shown in Figure 8. At every stage of this pulse stacker, the s-polarization pulse at the first splitter is always the origin of the optical timing delay (see timing chart of Figure 8). This makes it possible to keep the same origin of any timing delay, even if a 5-, 10- or 20-ps squarely combined pulse is generated by masking a p-polarization pulse at each corresponding stage.

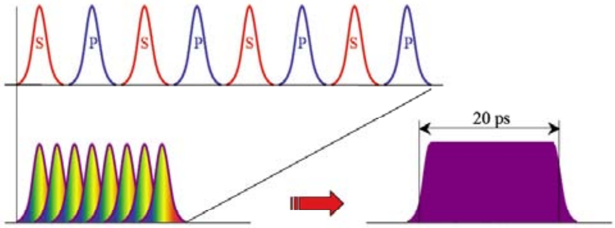


Figure 7: Principle of chirped-pulse stacking (8 pulses: three stages): Avoiding interference, the s- and p-polarized micro chirped pulses are alternatively stacked with the optical delay as long as the micro pulse duration.

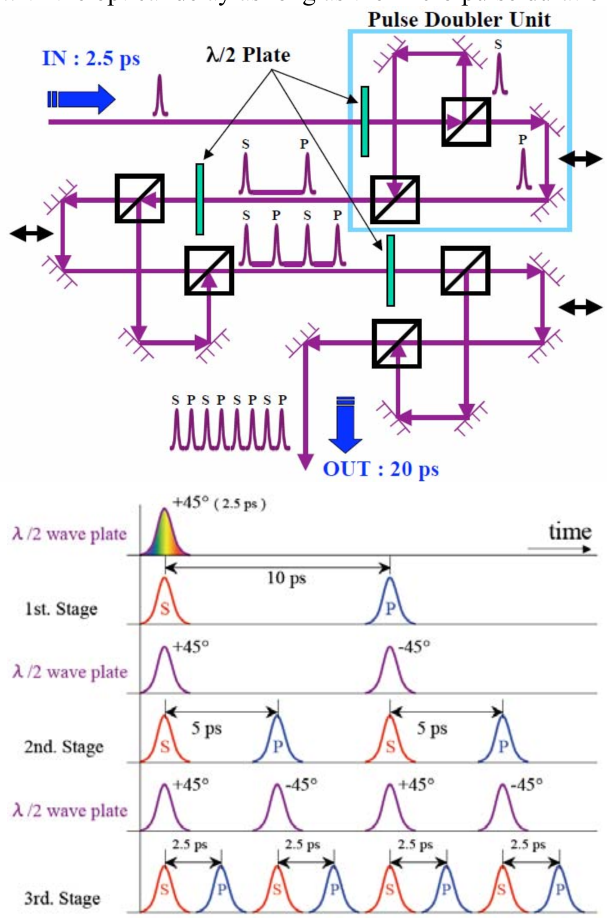


Figure 8: Optical system (upper) and timing chart (lower) of UV-laser pulse stacker: The drawings are shown in the case of three stages (pairs of polarizing UV-laser beam splitter cubes) of pulse stacker. The initial UV-laser pulse duration is set to 2.5 ps for generating a ~20-ps combined macro pulse. The pulse stacker kit is commercially available (http://www.luminex.co.jp/) under license from SPring8 /JASRI.

Finding the origins of optical delay lines

To generate a long pulse without any timing gap or overlap, the origins of the optical delay lines must be determined with a precision of less than 0.5 ps. The origin is defined here as the micrometer-level position in the delay line such that the s- and p-polarized pulses reach the cathode at the same time. The procedure determines the origin by utilizing the electron beam pulse generated at the photocathode as follows [8]. The energy of the electron pulse is measured for two laser pulses divided by each stage of the pulse stacker. The energy of the electron beam is measured as beam positions on a florescence profile monitor after a bending magnet downstream of the RF-gun cavity. To eliminate the positioning jitter and short time drift, the beam positions are measured 5000 times. The micrometer position of the p-polarized pulse is tuned as these two electron beam pulses come to the same position on the profile monitor after several iterations. The timing precision of the origin was about 0.5 ps, estimated from the position jitter distribution. After this procedure, with DAZZLER, micro chirped pulse duration is optimized to make the beam profile at the dispersion section homogeneous.

NEW FIXED 3D-SHAPING SYSTEM WITH HOLLOW LASER INCIDENCE

Through optimization with computer-aided DM and adjustable mechanical pulse stacker, we could improve the laser's 3D profiles and obtain their optimal parameters to minimize emittance. Using a 3D-shaped laser pulse with a diameter of 0.8 mm on the cathode and pulse duration of 10 ps (FWHM), we obtain a minimum horizontal normalized emittance of 1.4 π mm mrad with a beam energy of 26 MeV, holding its net charge to a 0.4 nC/pulse. At a higher net charge of 1.0 nC/pulse, the minimum beam emittance is 2.0 π mm mrad with equivalent diameter and a longer pulse duration of 20-ps (FWHM). However, vertical normalized emittance is around 1.5 times greater than horizontal. Considering the asymmetry of electrical field in the first coupler of the first accelerator tube, we rotated it 90 degrees to check the cause of the difference between x- and y- emittances. Consequently, the vertical emittance was greater than the other, as the emittance difference before the experiment with rotation of accelerator tube.

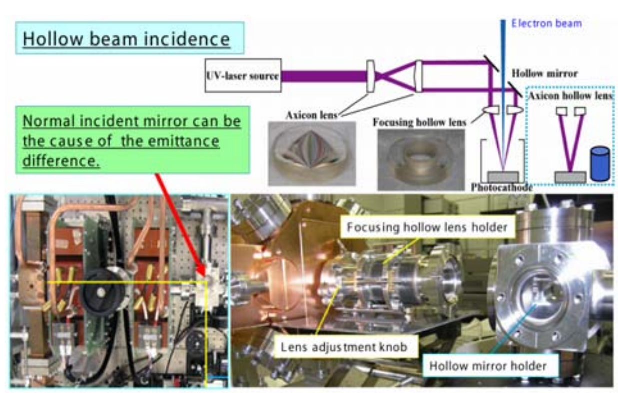


Figure 9: The present normal incident system (left) and new type of incidence with hollow optics (right): the final focusing axicon lens makes the spatial profile of the top-hat at its ray crossing (focus) point (top-right).

Then, we strongly doubt that the normal incident mirror can be the cause of the emittance difference. In particular, the higher charge the electron bunch is, the more significant the difference. Therefore, we developed a new hollow laser incidence system as shown in Figure 9. The hollow inside-out Gaussian laser beam is generated by an axicon lens pair, and then reflected at the hollow mirror for normal incidence through the hollow lens focusing to the photocathode.

In this new incidence system, the strategy for generating top-hat spatial shaping has to change. Up to now, we have obtained enough parameters to optimize the 3D laser pulse shape. There seems to be no difficulty in generating top-hat or homogeneous profiles with fixed (not-adaptive) optics. As shown in the upper right of Figure 9, using the axicon final focusing lens, there is a quasi-flattop region in the depth of a focus (ray crossing).

On the other hand, we fixed temporal parameters with the present mechanical pulse stacker and prepared a new UV-pulse stacking system (fixed parameters) consisting of three birefringence α-BBO crystal rods (Figure 10). When the incident ray injects with an angle to the optical axis, the extraordinary ray delays to an ordinary ray in a birefringence crystal. We utilize this delay in the same manner of the mentioned pulse stacker to generate a 20-ps square stacked chirped pulse. In this method, we rotate the crystal rods on the laser propagation axis independently to control polarisations and compensate angle of rotation, instead of using waveplates.

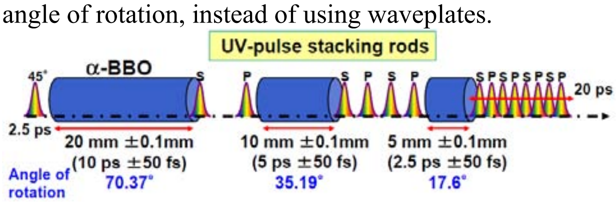


Figure 10: UV-laser pulse stacking rods: The angle of rotation of each rod is shown.

SUMMARY & FUTURE DEVELOPMENTS

For the shot-by-shot optimization of each laser-pulse profile, the laser system should be passively stabilized through environmental controls. At present, if the oscillator is stable without mode-locking failure, the overall laser system can remain stable for yearlong operation with the energy stability described in this paper. During this potentially continuous yearlong operation, every laser parameter was kept constant without any signs of instability.

We demonstrate a 3D shaping (both temporal (1D) and spatial (2D)) short pulse (5~20 ps) laser beam as an ideal light source for yearlong stable generation of a low-emittance electron beam with a high charge. At present, we apply a deformable mirror that automatically shapes the spatial UV-laser profile with a feedback routine, based on a genetic algorithm, and a pulse stacker for temporal shaping at the same time. The 3D shape of the laser pulse is spatially top-hat (flattop) and temporally a square stacked pulse. Using this 3D-shaped laser pulse (diameter: 0.8 mm; 10-ps pulse), we obtain a minimum horizontal normalized emittance of 1.4 π mm mrad.

This high-brightness electron source has maintained almost enough low emittance for X-ray FEL requirements during yearlong continuous operation. However, the vertical emittance is around 1.5 times greater than the other. To solve this, we developed a new incidence method with a hollow laser generator. We have already developed whole hollow optics. For this requirement of renewing 3D-laser pulse shaping, we have developed the hollow axicon final focus lens for spatial top-hat and UV-laser pulse stacking birefringence crystal rods for square macro pulse up to 20 ps.

Precisely optimizing the 3D-shape of the laser pulse, we are striving to generate a further high brightness beam with an emittance as low as possible. Recently, another candidate for a reliable 3D-pulse shape was proposed for even lower emittance [11], which is an ellipsoidal with equivalent fluence along the temporal axis. In this case, a microlens array or deformable mirror cannot help to generate such a three-dimensionally ellipsoidal distribution. A method using a fibre bundle is one solution to avoid the difficulty of adjusting different optical paths [12]. The fibre bundle is a practical system to shape both spatial and temporal profiles at the same time during laser-pulse transportation. The principle of this shaping method involves, in practice, thousands of pulse stackings in defusing the 3-D volume. However, it is difficult to make a smaller laser spot size of ~ 1 mm on the cathode for a realistic working distance of ~1 m in conventional cathode illumination. Therefore, we proposed this shaping technique for only a backward cathode illumination system to shorten the working distance. For this purpose, we are developing a transparent cathode with several materials [13].

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