ADAPTIVE SHAPING SYSTEM FOR BOTH SPATIAL AND TEMPORAL PROFILES OF A HIGHLY STABILIZED UV-LASER LIGHT SOURCE FOR A PHOTO-CATHODE RF GUN

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ABSTRACT

We have been developing a stable and highly qualified UV-laser pulse as a light source of an rf gun for an injector candidate of future light sources. Our gun cavity is a single-cell pillbox, and the copper inner wall is used as a photo cathode. The CPA
(chirped pulse amplification) Ti:Sapphire laser system is operated at a repetition rate of 10 Hz. At the third-harmonic generation (central wavelength: 263 nm), the laser pulse energy after a 45-cm silica rod is up to 850 μJ/pulse. In its present status, the laser’s pulse energy stability has been improved down to 0.2~0.3 % at the fundamental and 0.7~1.4% (rms; 10pps; 33,818 shots) at the third-harmonic generation, respectively. This stability has been held for one month 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 kept at 50~60% in a clean room to reduce damage to the optics. In addition, we prepared a deformable mirror for spatial shaping and a spatial light modulator based on fused-silica plates for temporal shaping. We are applying both of the adaptive optics to automatic optimization of the electron beam bunch to produce lower emittance with the feedback routine. Before the improvements, the electron beam produced from a cathode suffered inhomogeneous distribution caused by the quantum efficiency effect and some pulse distortions caused by its response time. However, we can now freely form any arbitrary electron beam distribution on the surface of the cathode.

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1. INTRODUCTION

We have been developing a photo-cathode rf gun [1] as a highly qualified electron beam source for future X-ray light sources (ERL (Energy Recovery Linac), FEL (Free Electron Laser), Compton back-scattering, etc.) since 1996 in a test facility at the SPring-8 site. Future X-ray light sources will require an electron beam source with a low emittance of \(\sim 1\pi \text{mm}\cdot\text{mrad}\) at a charge of more than 1 nC/bunch. Our development of this type of gun is oriented toward a long-lived stable system for use in experiments. It is necessary for the copper cathode of an rf gun to be illuminated by a UV-laser pulse with a pulse width of \(\sim 10\) ps and a photon energy of \(\sim 4\) eV.

When we started constructing the test facility, we faced two problems concerning the laser light source. One was the energy stability of the UV-laser light source. Generally, stabilization of the system should be controlled first passively and then actively. However, we completed only passive stabilization with respect to the laser system. The other was the spatial and temporal laser profiles. The quality of the laser beam is essential to the stabilization of it and the generation of a low-emittance electron beam.

It is essential to optimize the spatial and temporal profiles of a shot-by-shot single laser pulse in order to suppress the emittance growth of the electron beam emitted from a photo-cathode rf gun. This laser shaping project has proceeded in two steps since the beginning of 2002. Specifically, higher stability of the pulse energy was required and a homogeneous Silk-hat (cylindrical, flattop) with spatial and rectangular temporal profiles of the UV-laser light source must have been generated.

In the first spatial shaping test run, we shaped the laser spatial profiles with the use of a microlens array. Consequently, the horizontal emittance significantly improved from 6 to \(2\pi \text{mm}\cdot\text{mrad}\) at a beam charge of 0.1 nC/bunch. The experimental data obtained represented a new record for the minimum emittance of an electron beam from a single-cell-cavity rf gun [2].
In the next test run, we simultaneously applied both types of adaptive optics to automatically shape the spatial and temporal UV-laser profiles with a feedback routine. We prepared a deformable mirror for spatial shaping and a spatial light modulator based on fused-silica plates for temporal shaping. Both adaptive optical elements were installed in the system. In addition, in conjunction with Hamamatsu Photonics K.K. we are developing an optical shaping and transport system for a backward illumination system to be incorporated into a transparent diamond cathode for industrial or medical applications. We are responsible for developing fourth-harmonics generation (FHG: 197 nm) of a Ti:Sapphire laser as a light source for the diamond cathode and for its shaping techniques.

The fiber bundle is a useful system for shaping both spatial and temporal profiles. It is also an ideal user-friendly laser transport from the laser light source to the cathode. The operating wavelength of the fiber bundle used in this experiment (Ceram Optec Industries, Inc.) was tested between 197 and 1,100 nm. At present, our FHG currently under development oscillates with a pulse energy of 20 µJ/pulse after pulse shaping.

We review the development processes of our beam quality control systems in the remainder of this paper.

2. LASER STATUS UNDER A CONTROLLED ENVIRONMENT

Configuration of CPA - Ti: Sa Laser System

The UV-laser light source for the rf gun consists of a mirror-dispersion-controlled Ti:Sapphire laser oscillator (Femtolasers Produktions GmbH) operated at a repetition rate of 89.25 MHz, a chirped pulse amplification system (Thales Lasers Co., Ltd.) operated at a repetition rate of 10 Hz, and a third-harmonic generator system. The fundamental laser oscillates at a central wavelength of 790 nm with a spectral bandwidth (FWHM (full-width at half maximum)) of 40–50 nm. This spectral bandwidth strongly influences the pulse duration after the compressor. If the BBO crystal thickness is not matched with the
laser pulse duration, the laser spatial profile deteriorates (see the original worse laser profiles on the left-hand side in Figs. 5 and 7). The laser spatial profile at the optimized condition is homogeneous as shown on the left-hand side of Fig. 1.

In the following amplification system, the laser pulse is amplified up to 30 mJ/pulse after the multi-pass amplifier, and then compressed down to 80 fs at the compressor to generate THG at a central wavelength of 263 nm. This UV-laser pulse is sent through a 45-cm long silica rod that is used as a UV-pulse stretcher from 80 fs to the 10-ps region. The laser pulse energy through the silica rod is 850 µJ/pulse at maximum. Note that its output pulse energy and pulse duration depend on the laser fluence at the entrance of the silica rod: it can stretch the pulse to 11-ps long at a fluence of 1.8 mJ/cm². However, due to the nonlinear process in the first few millimeters, some hot-spot structures appear on the laser spatial profile (see the right-hand side of Fig. 1). This nonlinear process is essential to broaden the spectral bandwidth. The spectrally broadened laser pulse is stretched by the dispersion of the silica rod.

The best short-term pulse energy stability (rms) of the original laser system was 2% for the fundamental and 3% for the THG. However, the original THG stability deteriorated to 10% (rms) within a few days of its optimal tuning. This original system could not maintain a homogeneous laser spatial profile for long periods of operation, mainly due to tiny pinpoint damage on the dichromatic mirrors, mismatching between the compressed pulse duration and THG (BBO) crystal thickness, and misalignments in the compressor and THG sections.

*Environmental control system for the laser*

In principle, we planned only passive stabilization of the system. We considered environmental controls in the clean room to reduce optical damage accidents and constructed a new humidity-controlled clean room in 2003, and then re-installed the total laser system in this room in 2004. The relative humidity of this new clean room at room temperature is in the region of 50–60% fluctuating by less than 2% (p-p). The
temperature is kept constant at 21 (±0.3) on the laser table. Also, the laser pumping sources are stabilized with a temperature-controlled base plate. As a result, the short pulse energy stability of the laser has been improved, with a reduction to 0.7~1.4% (rms; 10 pps; 33,818 shots) at the THG (263 nm). This stability was held for one month continuously without any significant tuning over the last six months. In this improvement we just passively stabilized the system.

At the present state of development, long-term stability within two months depends only on the stability of mode locking at the oscillator laser. Continuous operation lasting more than two months is limited by the lifetime of the flash lamp for the amplifiers. If the oscillator is stable without out-of-mode locking, the overall laser system can remain stable for long-term operation with short-pulse energy stability as mentioned above.

3. TESTED OPTICAL ELEMENTS FOR LASER-PROFILE SHAPING

Microlens array as a spatial homogenizer

We applied several microlens arrays as a homogenizer for the first test run [2]. This microlens array is a collection of small hexagonal convex lenses with a pitch of 250 µm. The transmission of this optical array is about 80% in the ultraviolet region, which makes it possible to shape any laser spatial profile into a Silk-hat (cylindrical, flattop) by combining the array with a convex lens. The main difficulty in utilizing this optical system is the manner in which the homogenized laser profile transports toward the cathode surface while focusing.

Deformable mirror and Spatial Light Modulator (SLM) as a 3D-shaping

Consequently, we used a deformable mirror (upper-left in Fig. 3) as a spatial shaper for the second test run. This deformable mirror consists of an aluminum-coated, multilayer silicon nitride membrane and 59 small hexagonal mirror-actuators behind the reflective membrane with a center-to-center distance between the actuators of 1.75 mm. The
outermost layer of the reflective membrane is protected with an MgF$_2$ coating to keep reflectivity at about 70% in the ultraviolet region. Adjusting the voltages between the control electrodes on the boundary actuators performs fine adjustment of each mirror-actuator; the adjustable region of the control voltages is between 0 and 250 V in steps of 1 V. This makes it possible to shape any laser spatial profile with a total of $250^{59}(\sim 10^{141})$ forming possibilities. However, such a high adjustability makes manual as well as simple algorithm adjustment impossible. Thus, this spatial shaping method needs a sophisticated algorithm. One concept for a sophisticated program based on this genetic algorithm for a deformable mirror has been developed through a joint project [3].

To control the temporal parameters of the laser pulses, we are preparing a programmable pulse shaping system in the fundamental wavelength region using a spatial light modulator (SLM) based on fused-silica plates (Cyber Laser Inc.: right in Fig. 3). The temporal profile is measured with a streak camera.

We installed a deformable mirror and an SLM while developing a sophisticated program to examine the spatial and temporal shaping ability of inhomogeneous original UV-laser profiles.

*Silica fiber bundle as a spatial homogenizer and pulse shaper*

The fiber bundle is a practical system for shaping both spatial and temporal profiles during laser pulse transportation. This method, however, suffers the large disadvantage of not being able to produce an ideal spot size on the cathode from a realistic working distance. Therefore, we proposed this technique for the backward cathode illumination system only. The fiber bundle, with a diameter of 8 mm, is a collection of 1,300 small fiber strands with fused ends (see Fig. 4).

4. EXPERIMENTAL RESULTS FOR SPATIAL SHAPING
Results and effects of spatial shaping with microlens array (in first test run)

The left-hand side of Fig. 5 shows the laser spatial profile without homogenization. The profile was spatially shaped by a microlens array into a quasi-Silk-hat profile (see the right-hand side of Fig. 5). These profiles were measured with a laser beam profiler (Spiricon Inc., LBA300-PC). Spatial homogenization improved the emittance from 3.3 to 2.3 $\pi$ mm•mrad at a beam charge of 0.1 nC/bunch. While it was not perfectly Silk-hat-shaped, the laser profile was greatly improved.

Result of spatial shaping with deformable mirror (in second test run)

The laser spatial profile was automatically optimized with self-developed genetic algorithms for a deformable mirror. The profile was spatially shaped as a quasi-Silk-hat profile (Fig. 6). The laser spatial profile was improved by this shaping technique.

Result of spatial and temporal shaping with fiber bundle for backward illumination

A fiber bundle was used to passively shape the laser spatial and temporal profile for the backward cathode illumination. The profile was spatially shaped into a perfectly homogeneous one with a 90-cm long fiber bundle (see Fig. 7). This shaping technique is based in practice on pulse stacking with 1,300 different optical paths. The 80-fs laser is shaped as a quasi-Gaussian profile with a pulse duration of 16 ps (FWHM). This 16-ps pulse shape does not change down to the input laser pulse energy of 60 nJ/pulse, indicating that this pulse shaping (or stretching) is not based on a nonlinear effect like the silica rod. Instead, the pulse duration mainly depends on the length of the fiber bundle and the mapping of its fiber strands.

5. DISCUSSION & FUTURE PLANS

Comparing the results of the spatial profiles among the different tested optical elements shown in Figs. 5-7, we can see that each method was successful. Especially, there seems to be no difficulty in generating flattop or homogeneous profiles. However, recently
another more ideal 3D-shape was proposed [4], which is an ellipsoidal with equivalent fluence along the temporal axis. In this case, the microlens array or deformable mirror cannot realize this ellipsoidal. In [4] a pulse stacker is proposed as a solution that makes it possible to realize an ellipsoidal beam pulse. It is not, however, simple to adjust. The method using a fiber bundle is one solution to avoid the difficulty of adjusting different optical paths. For shaping an ellipsoidal profile, it is necessary to combine that method with some adaptive optics to control the laser spatial distributions. Automatic optimization with a deformable mirror can be helpful with genetic algorithms if the ideal profile is within its search range. Considering the response time of photocathodes and reliable adjustability of the optics, we do not yet have a clear solution for generating this ideal ellipsoidal pulse.

For the shot-by-shot optimization of each laser pulse profile, the laser system should be passively stabilized by environmental controls. At present, the 1-hr. pulse energy stability of the THG has been improved to 0.7~1.4%, which is sufficient for shot-by-shot automatic optimization with adaptive optics. To test long-term mode-locking stability, a new oscillator laser (Femtosource Synergy; Femtolasers Produktions GmbH) was installed in our system in April 2005. During testing, its mode-locking has been kept stable with the locked repetition rate of 89.25 MHz for one month. We are expecting that its stability will keep for more than three months. In addition, we are preparing a feedback system to control long-term drift due to the lifetime of the flash lamp.

In future, we plan to apply both adaptive optics to automatically optimize the electron beam bunch for lower emittance with a feedback routine. With this procedure, we expect ideal electron beam profiles to be generated with compensation for some of the optical distortions and the inhomogeneous distribution of the quantum efficiency on the cathode surface. However, it is important to clarify the phenomena related to laser incidence on the cathode, and we will thoroughly investigate this together with cathode surface physics.
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FIGURE CAPTIONS

Figure 1: THG profiles before and after the silica rod as a UV-pulse stretcher

Figure 2: THG rms stability of 1.4% for 33,818 shots

Figure 3: Adaptive-optics complex for shaping both spatial and temporal laser profiles

Figure 4: The fused surface structure of the fiber bundle

Figure 5: Homogenization results with microlens array

Figure 6: Spatial shaping result with a deformable mirror

Figure 7: Homogenization results with the fiber bundle

REFERENCES


Figure 1