STATUS OF SPRING-8 PHOTOCATHODE RF GUN FOR FUTURE LIGHT SOURCES

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Abstract

Since 1996, we have been researching a photocathode single-cell pillbox rf gun for future light sources, and to date have achieved a maximum field gradient of 187 MV/m with a chemical etching processed cavity. For the last three years, we have been focusing on the development of a stable and highly qualified UV laser source for the rf gun. The UV laser pulse (10 Hz) energy is 80 μJ/pulse at the entrance window. The energy stability (rms) of the laser has been reduced to 0.2~0.3% at the fundamental and 0.7~1.3% at the third harmonic generations. This stability can be held continuously for two months, 24 hours a day. The improvement is the result of the stabilization of the laser system in a humidity-controlled cleanroom. In addition, the ideal spatial and temporal profiles of a shot-by-shot single laser pulse are essential to suppress the emittance growth of the electron beam from the rf gun. We prepared a deformable mirror for spatial shaping and a spatial light modulator based on fused silica plates for temporal shaping. With a computer-aided deformable mirror, we obtained a minimum horizontal normalized emittance of 1.74 mm mrad with a beam energy of 28.8 MeV, holding its net charge to 0.09 nC/bunch. We applied the variable quadrupole method to evaluate the emittance. The 3D shape of the laser was spatially flattop with a 1 mm diameter on the cathode and temporally a function of sech(t) with a pulse duration of 5 ps (FWHM). This laser pulse was illuminated on the copper cathode with normal incidence. We are currently preparing both adaptive optics to automatically optimize the electron beam parameters for lower emittance with a feedback routine.

INTRODUCTION

Since 1996 in a test facility at SPring-8, we have been developing a photocathode rf gun [1] as a highly qualified electron beam source to produce future X-ray light sources. Until 2002, our previous experimental setup was a feasibility study of the gun cavity to investigate beam emittance just after the rf gun. This previous system was limited to studying the complete system including gun cavity and the first accelerating structure. To develop a long-lived stable complete system as a highly qualified electron beam source with lower emittance, the rf gun test facility was upgraded and constructed between 2003 and 2004. We remodeled the shielding room and installed one accelerating structure, beam diagnostic systems, and a humidity-controlled cleanroom to stabilize the complete laser system.

At the beginning of our study, we faced two problems concerning the laser light source. One was the energy stability of the UV laser light source. By 2004, we had only completed passive stabilization with respect to the laser system. The other was the spatial and temporal laser profiles. The 3D shape of the laser beam is essential to its stabilization and the generation of a low emittance electron beam. It is important to optimize the spatial and temporal profiles of a shot-by-shot single laser pulse to suppress the emittance growth of the electron beam emitted from a photocathode rf gun. This laser shaping project has proceeded in two steps since 2002. Our first target on the 3D shape of a UV laser pulse was a homogeneous Top Hat (cylindrical, flattop) with spatial and rectangular temporal profiles.

In the first spatial shaping test run, we shaped the laser spatial profiles with a microlens array. Consequently, the horizontal emittance significantly improved from 6 to 2 π mm•mrad with a beam energy of 3.1 MeV, maintaining its net charge at 0.1 nC/bunch [2]. Note that these measurements were done using a ‘double slits’ scanning method under oblique laser incident with an incident angle of 66 degrees.

In the next test run, we are simultaneously applying 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. Also in 2005, laser transport for normal laser incidence was completed, which is reliable for ideally shaped laser pulses.

In addition, in conjunction with Hamamatsu Photonics K.K. we are developing a transparent diamond cathode for industrial or medical applications. For this backward illumination system, we developed an optical element based on fibre bundles as a laser 3D shaping and transport system [3]. We have also developed a fourth harmonics generation (FHG: 197 nm) of a Ti:Sapphire laser as a light source for the diamond cathode. At present, our FHG currently under development oscillates with a pulse energy of 20 μJ/pulse at maximum after pulse shaping with a spatial light modulator.

We review the development processes of our laser beam quality control systems for generating lower emittance in the remainder of this paper.

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 (THG) 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. For the shot-by-shot optimization of each laser pulse profile, the laser system was passively stabilized by environmental controls because of the humidity-controlled cleanroom [3]. At present, the 1 hr pulse energy stability of the THG was improved to 0.7~1.4% (rms; 10 pps; 33,818 shots), which is sufficient for automatic optimization with adaptive optics for laser shaping. To keep long-term mode-locking stability, in 2005 a new oscillator laser (Femtosource Synergy; Femtolasers Produktions GmbH) was installed in our system. Without any active control of the pumping direction drift, its mode-locking remained stable at a locked repetition rate of 89.25 MHz for two months. At the moment, we are optimizing the parameters of the active control program (Femtoalign; Femtolasers Produktions GmbH) for our environmental condition. The temperature fluctuation and drift in our cleanroom are too small for the original program to actively control the pumping direction. We expect that its stability can be greatly extended with an optimized active control system.

In the amplification system, the laser pulse is amplified to 30 mJ/pulse after the multi-pass amplifier and then compressed to 80 fs at the compressor to generate THG at a central wavelength of 263 nm.

At the present state of development, long-term stability within two months depends only on the mode locking stability of the oscillator laser. Continuous operation lasting more than two months is limited by the lifetime of the flash lamp for the amplifiers. Within two months, the overall laser system can remain stable for long-term operation with pulse energy stability, as mentioned above. Therefore, we are preparing a feedback system to control long-term drift due to the lifetime of the flash lamp.

LASER PROFILE SHAPING SYSTEMS

Fused Silica Rod as a UV Laser Pulse Stretcher

This femtosecond UV laser pulse is sent through two 45 cm long silica rods that are used as UV pulse stretchers from 80 fs to the 10 ps region. The laser pulse energy through one 45 cm long silica rod is a maximum 850 μJ/pulse. Note that its output pulse energy and pulse duration depend on the laser fluence at the entrance of the silica rods: it can stretch the pulse to 22 ps long at a fluence of 2.6 mJ/cm^2 (see Figure 1). However, due to the nonlinear process in the first few millimeters, some hot spot structures appear on the laser spatial profile [3]. This nonlinear process is essential to broaden the spectral bandwidth. The spectrally broadened laser pulse is stretched by the dispersion of the silica rod. Our efforts are hampered by the low efficiency of laser transport after the silica rods, because laser quality significantly deteriorates due to the nonlinear process in the silica rod. We can send just 10% of the original laser pulse energy to the cathode. Based on our experience, this stretching method simplifies the creation of a picosecond pulse from the femtosecond, but it is not a reliable method for a light source of rf gun.

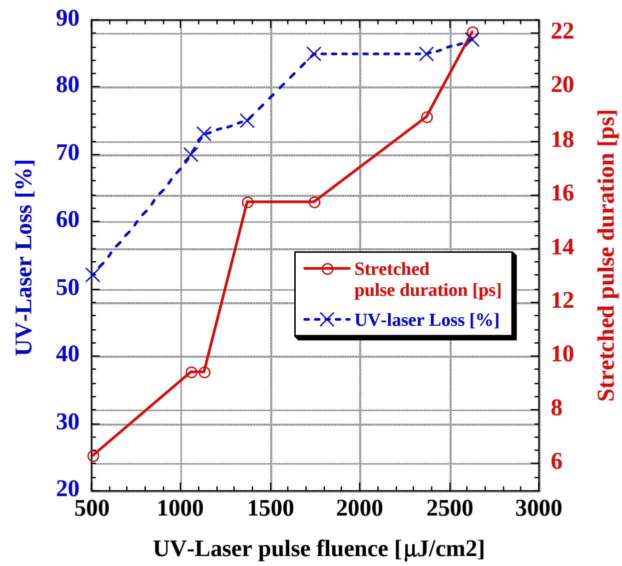

Figure 1: THG pulse duration and pulse energy loss vs. Incident laser fluence at the entrance of silica rod (90 cm)

Deformable mirror and SLM as 3D shaping

Consequently, we need to develop other pulse shaping and stretching methods in the UV region instead of the aforementioned silica rods. One candidate is spatial light modulator (SLM) based on fused silica plates (Cyber Laser Inc.). It is possible to directly shape the UV laser pulse. The first test was done in the fundamental wavelength region using a SLM based on fused silica plates. We are preparing a programmable pulse shaping system with SLM for active feedback. The temporal profile is going to be monitored with a streak camera. After generating a 10 ps pulse, THG was generated with pulse energy of 170 μJ/pulse. Its conversion efficiency from the fundamental laser was 8%.

We used a computer-aided deformable mirror as a spatial shaper [3]. 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 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 60~70% 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 250 V in steps of 1 V, making it possible to shape any laser spatial profile for a total of 250^{59}($\sim 10^{141}$) forming possibilities. However, such high adjustability makes manual as well as simple algorithm adjustment impossible. Thus, this spatial shaping method needs a sophisticated algorithm, which we developed, based on this genetic algorithm to control the deformable mirror.

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

Spatial shaping results with a computer-aided deformable mirror

The laser spatial profile was automatically optimized with self-developed genetic algorithms for a deformable mirror. We measured the profile with a laser profile monitor (Spiricon, Inc.: LBA300-PC) whose analyzing program can provide many parameters of beam profiles. We chose useful parameters to evaluate flattop profiles and made a fitting function for the developed genetic algorithm to optimize the profile toward an ideal flattop. These parameters for flattop shaping and their meaning are shown in Table 1. 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-hand side of Figure 2). The laser spatial profile was drastically improved by this shaping technique.

Table 1: Set parameters and usages for fitting function to evaluate spatial profile optimization

Fitting function parameters for flattop shaping	
Beam Centre	Minimize differences from initial centre position (x, y)
THF [4]	Maximize Top Hat Factor (0~ 1) (Flattop: THF=1.0; Gaussian: THF=0.5)
Effective Area	Maximize integrated energy within set circle area
Effective Diameter	Minimize differences from diameter of set circle
Flatness	Minimize standard deviation divided by the average in a flattop area
Peak-to-peak	Minimize differences between max. and min. in a flattop area
Beam Diameter	Minimize differences from set diameter
Hot Spot (max.)	Minimize max. in a flattop area
Dark Spot (min.)	Maximize min. in a flattop area

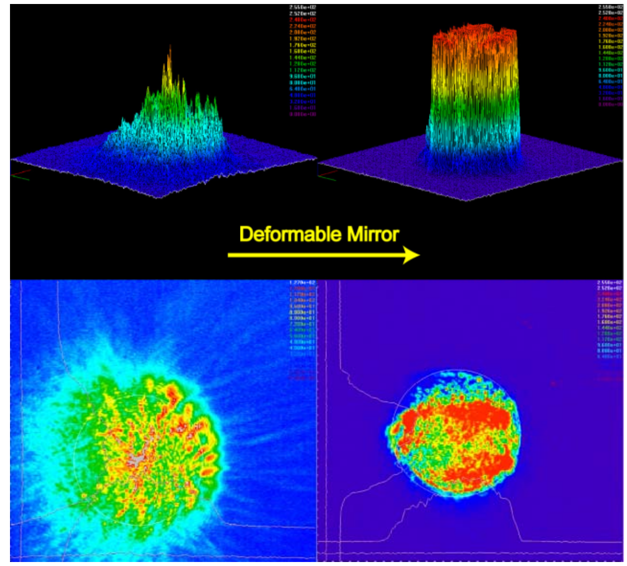

Figure 2: Spatial shaping results using deformable mirror and genetic-algorithm-based optimizations

EMITTANCE MEASUREMENTS WITH ADAPTIVE SPATIAL SHAPING

The electron energy at the exit of the gun cavity was 3.7 MeV with maximum electric field strength on the cathode surface of 157 MV/m. In the following accelerating structure, the beam was accelerated to 28.8 MeV. An initial RF phase of gun cavity was adjusted to 85 degrees, which is the optimum value for low emittance. Emittance measurements were performed with a variable quadrupole method by measuring the electron beam size while varying the quadrupole magnet strength. These data are fitted as a function of the magnet's strength of a singlet quadratic function. These measurements were automatically done by a sequence program developed with LabVIEW (National Instruments, Inc.). The experimental conditions of our test Linac and this emittance measurement method were written and discussed in [5] in detail.

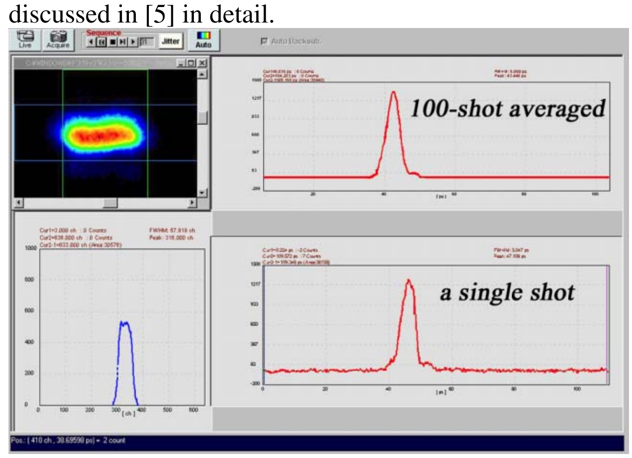

Figure 3: Streak image of UV laser pulse (THG)

The pulse duration was stretched to 5 ps (FWHM) with one 45 cm silica rod. The temporal profile of the UV laser was measured by a streak camera (Hamamatsu Photonics K.K. C6138 FESCA-200) with resolution of 500 fs (see Figure 3). We spatially shaped the laser beam using a deformable mirror. The laser beam profile on the cathode is shown in Figure 2. The laser beam diameter was estimated to be 1.0 mm. This shaped laser pulse was illuminated on the copper cathode with normal incidence with an incident angle of less than 2 degrees. We also performed experiments to shape the electron beam profile due to feedback of the video signal of the electron beam profile image to the computer-aided deformable mirror. It can compensate for the inhomogeneity of the cathode's quantum efficiency distribution.

EXPERIMENTAL RESULTS

The results of horizontal and vertical emittance measurements and their fitting are shown in Figure 4. The minimum horizontal normalized emittance measured was 1.74 mm mrad with a net charge per bunch of 0.09 nC/bunch. By directly measuring electron beam profiles and with feedbacking, minimum emittance was not significantly improved.

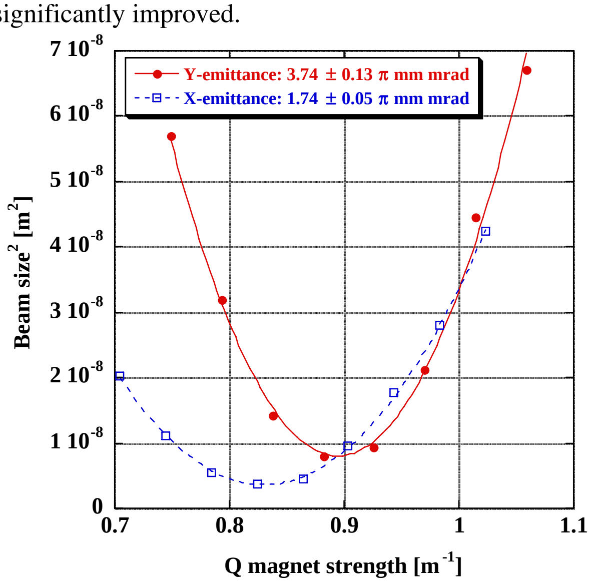

Figure 4: Measured beam size and fitted curve with a charge of 0.09 nC/bunch.

DISCUSSION & FUTURE PLANS

The special flattop shaping with computer-aided deformable mirror was successful to generate flattop or homogeneous profiles. Note that, this shaping was successful thanks to our long-term stable UV-laser light source: This shaping technique is quite far from shot-by-shot beam quality control. It takes 2 hours to optimize the laser profiles.

We are preparing 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.

We obtained the minimum horizontal normalized emittance of 1.74 π mm mrad with a beam energy of 28.8 MeV, holding its net charge to 0.09 nC/bunch. However, the minimum vertical one was 3.74 π mm mrad. According to our simulation result [2], we expected that the horizontal and vertical emittance become comparable under the condition with the normal laser incidence and roundly shaped laser spot on the cathode. As results, vertical emittance is twice worse than the other in our system. An asymmetric laser spot cannot explain such a difference between horizontal and vertical emittances. Figure 4 also shows deferent minimum beam sizes and their quadrupole magnet strengths. To understand these differences, we calculated back the beam envelopes in the 3-m long accelerating structure with using the transfer matrix of the accelerating structure and the Twiss parameters at the quadrupole magnet, which derived from the measurement data shown in Figure 4. These calculation results are shown in Figure 5. The horizontal and vertical beam envelopes cross a point nearby the entrance of the 3-m long accelerating structure. The crossing point indicates the round beam at the entrance. Actually, there are asymmetrical rf focusing forces in the input coupler, when injecting electron beam off-centers at the entrance of accelerating structure. The main cause of the aforementioned emittance deference must be the misalignment of injecting electron beam at the entrance of accelerating structure.

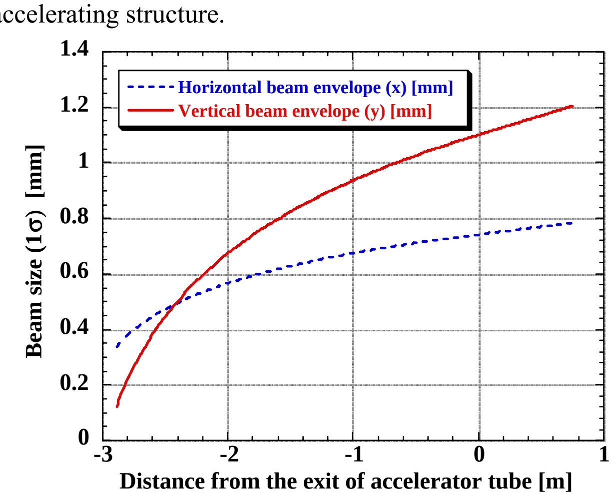

Figure 5: The beam envelopes calculated back in 3-m long accelerating structure

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