REVIEW OF ADVANCED LASER TECHNOLOGIES FOR PHOTOCATHODE HIGH BRIGHTNESS GUNS

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Abstract

We developed an adaptive 3D shaping UV pulse laser system (based on a Ti:S laser) as an ideal light source for yearlong stable generation of low-emittance electron beams with a charge of 1 nC/bunch. From 2005 onwards, the laser's pulse-energy stability was continuously kept at <1.4% for THG (263 nm) for several months (flashlamp lifetime). In addition, in order to suppress the emittance growth caused by the space charge effect, the 3D cylindrical “beer-can” shape of the laser pulse was optimized spatially as a top-hat (flattop) and temporally as a square stacked chirped pulse. We utilized a deformable mirror that automatically shapes the spatial profile with a feedback routine, which is based on a genetic algorithm, and an UV pulse stacker consisting of three birefringent Alpha-BBO crystal rods for temporal shaping at the same time. Using this “beer-can” 3D-shaped laser pulse, so far we have obtained a minimum horizontal normalized emittance of 1.4 π mm mrad. In 2006, we proposed a laser-induced Schottky-effect-gated photocathode gun for the realization of a water bag beam in Luiten’s scheme by using Z-polarization of the laser on the cathode. A hollow laser incidence was applied with convex lens focusing after passing the beam through a radial polarizer. According to our calculations (NA=0.15), a Z-field of 1 GV/m needs 1.26 MW at peak power for the fundamental wavelength (790 nm) and 0.316 MW for the SHG (395 nm).

INTRODUCTION

Since 1996, we have been developing a stable and highly effective UV laser pulse as the light source for a photo-cathode RF gun [1] which in turn provides high-brightness electron beams for future X-ray light sources at SPring-8. The electron source for several X-ray FEL projects [2-4] requires electron beams with very low emittance (high brightness), often as low as 1 π mm mrad, and a charge of 1 nC/bunch. 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. The development of this gun is oriented toward the creation of a yearlong stable system for user facilities. Since we started developing the laser test facility in 2001, two issues related to the source of laser light have arisen. One is the energy stability of the UV laser light source. In this regard, we successfully stabilized the third-harmonic generation (THG) of a CPA (chirped pulse amplification) Ti:Sapphire terawatt laser system as the laser light source for the SPring-8 RF gun. From 2005 onwards, the laser's pulse-energy stability was continuously kept at <1.4% for THG (263 nm) for several months limited by flashlamp lifetime. This improvement reflects the ability to stabilize the laser system in the pumping sources (Q-switched YAG) of the amplifiers with a temperature-controlled base plate in a clean room where the relative humidity was maintained at 55%. This system keeps dust particles away from the charged optical elements (typically insulator) and thus avoids burn-out damage with the laser incidence.

The other problem concerns the spatial and temporal laser profiles. In order to minimize the beam emittance of a photocathode RF gun, the laser pulse shape should be optimized in three dimensions. One of the candidates for a reliable 3D laser pulse shape has been the cylindrical “beer-can” shaped (spatially top-hat and temporally square) pulse. Over the past seven years, at the test facility for photocathode laser light sources at SPring-8, several 3D shaping systems in the UV region have been developed from combinations of spatial (transverse: x-, y-axes) and temporal (longitudinal: z-axis) pulse-shaping methods (Fig. 1). It was necessary to modify the spatial profile with a microlens array [5] or a deformable mirror (DM) [6], as well as to alter the temporal profile with a spatial light modulator (SLM) [6] or a pulse stacker. In its current form, we have applied a deformable mirror which automatically shapes the spatial profile with a feedback routine based on a genetic algorithm and a UV pulse stacker consisting of three or four birefringent Alpha-BBO crystal rods for temporal shaping at the same time [7]. In 2006, we demonstrated a cylindrical 3D UV laser pulse with the shaping system described above. By precisely optimizing the 3D shape of the laser pulse, we are striving toward the generation of a beam with as high a brightness and as low an emittance as possible. The perfect homogeneity of temporal stacking is automatically optimized with a feedback routine between a AOPDF UV pulse measurement (spectral phase interferometry in the UV region) and a high-resolution DAZZLER as a micro pulse shaper. Using this “beer-can” 3D-shaped laser pulse (diameter: 0.8 mm; pulse duration: 10 ps), so far we have obtained a minimum horizontal normalized emittance of 1.4 π mm mrad [7].

Recently, another candidate for the generation of a reliable 3D pulse shape was proposed for even lower emittance values [8], which comprises an ellipsoid with equivalent fluence along the temporal axis. Such uniform 3D ellipsoidal distributions of charge are one of the ultimate goals in high-brightness beams due to their linear internal force fields. O. J. Luiten simulated a method for the actual production of such bunches, which are based on photoemission by femtosecond laser pulses [9]. In 2006, we proposed a laser-induced Schottky-effect-gated photocathode gun in order to realize a water bag beam in Luiten's scheme by using Z-polarization of the laser on the cathode [10,11]. A hollow laser incidence is applied with convex lens focusing after passing the beam through a radial polarizer. According to our calculations (NA=0.15), a Z-field of 1 GV/m needs 1.2 MW at peak power for the fundamental wavelength (790 nm) and 0.31 MW for the SHG (395 nm) [11]. This concept of laser-induced Schottky emission can be applied to photocathode RF and DC guns.

3D UV LASER PULSE SHAPING SYSTEM

The 3D UV laser pulse shaping system combined with a deformable mirror (transverse: 2D) assisted by a genetic algorithm and a chirped pulse stacker (longitudinal: 1D) is shown in Fig. 1. By utilizing the long-term stable UV laser source described above, this system can generate a "beer can" laser pulse. Note that the shape and pulse duration of the original micro chirped pulse is optimized with DAZZLER (AO-modulator) at the fundamental wavelength. We describe the pulse stacking rods consisting of three birefringent Alpha-BBO crystals below.

SPATIAL SHAPING WITH A 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 (see in Fig.1). The laser spatial profile was remarkably improved by this shaping technique.

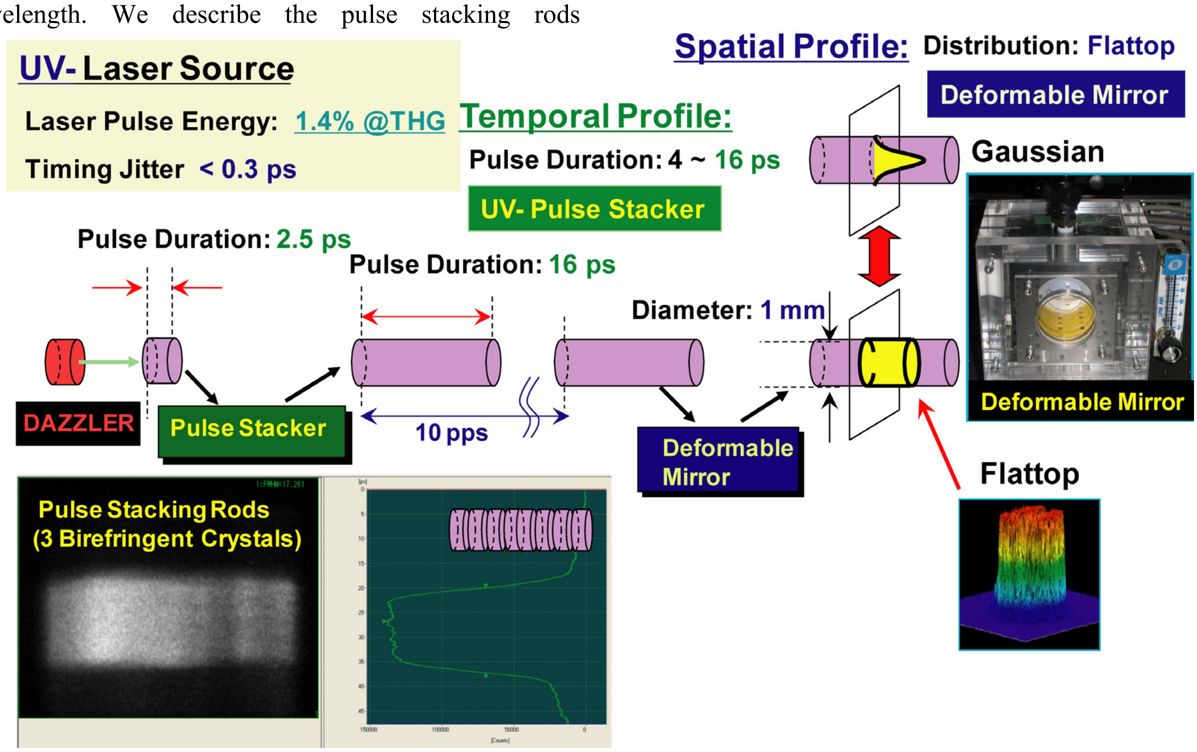

Figure 1: Three-dimensional UV-laser pulse shaping system: the 3D shaping system consists of a deformable mirror (DM) and chirped pulse stacking rods. These two shaping techniques can be optimized independently because there is no interference between them. The schematic drawing of pulse stacking shows 16-ps pulse generation by stacking eight 2.5-ps micro chirped pulses. The chirped 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 homogeneous square pulse by stacking chirped pulses in pulse stacker, the micro pulse duration is stretched 1.2~1.3 times longer than the optical delay between neighboring micro pulses at the cathode by the total amount of GDD during transport through transparent optical elements. Here 16-ps square pulse generated with three birefringent crystals in pulse stacking rods measured by streak camera (Fesca-200, Hamamatsu Photonics K.K.) is shown.

Table 1: Set Parameters and Usages for Fitting Function to Evaluate Spatial Profile Optimization [6]

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

SQUARE TEMPORAL SHAPING (CHIRPED UV PULSE STACKING)

Chirped Pulse Stacking Rods with Fixed Optical Delays

In order to avoid interference caused by stacking, the orthogonally polarized chirped pulses are alternatively stacked with the optical delay for a period of time as long as the micro pulse duration in generating a homogeneous electron bunch at the cathode. This method with introducing additional chirp to avoid interference as shown in Fig. 2 is referred to as “chirped pulse stacking”. In 2007, in order to fix the optical delays between neighbouring micro chirped pulses in the previously developed mechanical pulse stacker [8], we installed a new UV pulse stacking system consisting of three birefringent α-BBO crystal rods. The angle of rotation of each crystal rod against the incident polarization E_{in} is 45 degrees, as shown in Fig. 3.

A birefringent crystal works similar to a conventional retardation plate. This type of crystal introduces a certain temporal delay between two orthogonally polarized components of a linearly polarized incident beam. In polarized order to realize this temporal delay, the linearly incident beam E_{in} should meet the crystal surface with normal incidence. E_{in} is divided into two components being orthogonally polarized to each other (see Fig. 4). The first component E1 is polarized parallel to the x-axis, the second component E2 is polarized parallel to the y-axis. While propagating through the crystal, components E1 and E2 propagate extraordinary refractive index n_e and ordinary refractive index n_o, respectively. Due to the difference of the refraction indexes there will be a temporal delay Δt between E1 and E2 depending on the thickness d of the crystal and on the difference between the refraction indexes $\Delta n = n_e - n_o$. This temporal delay is given by the formula $\Delta t = d\, \Delta n / c$, where c is the speed of light. A very important constraint in our application is that there is no beam displacement between the two components E1 and E2, i.e. the two components should propagate collinearly inside and outside of the crystal without any spatial separation. They should propagate along the same path. This means that the crystal's optical axis must be located in the xy-plane.

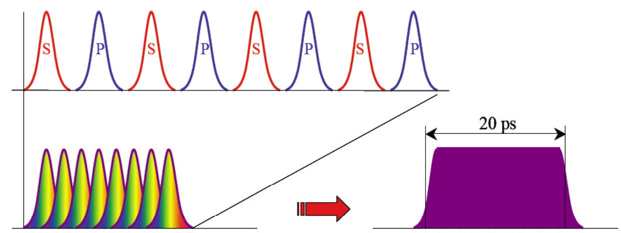

Figure 2: Principle of chirped pulse stacking (8 pulses: three birefringent crystal rods): For the purpose of avoiding interference, the orthogonally polarized chirped pulses are alternatively stacked with the optical delays in each birefringent crystal for a period of time as long as the micro pulse duration in generating a homogeneous electron bunch at the cathode.

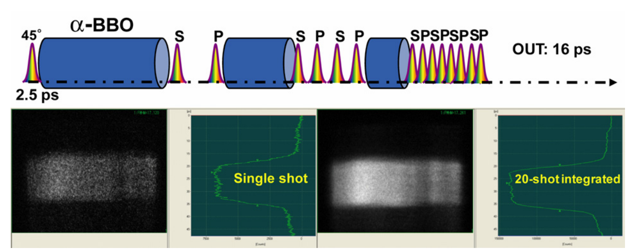

Figure 3: UV laser pulse stacking rods: The angle of rotation of each crystal against the incident polarization is 45 degrees. The drawings are shown in the case of three birefringent α-BBO crystal rods. This pulse stacking kit is commercially available (http://www.luminex.co.jp/) under a license from SPring8 /JASRI.

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 pulse duration, are applied to generate a homogeneous electron bunch at the cathode. To obtain longer square laser pulses of 16 ps with three birefringent crystals, each crystal should generate temporal delays of Δt = 2.0 ps, 4.0 ps, and 8.0 ps, respectively. In order to realize these values, the difference Δn of refraction indexes and the thickness d of the crystal must be adapted to each other. Even if a 4-, 8-

or 16-ps squarely combined pulse is generated by rotating crystal axis parallel to the incident polarization at each corresponding crystal.

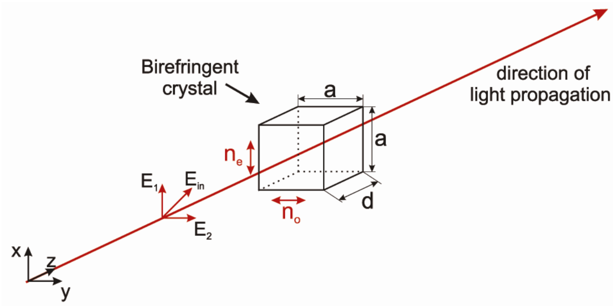

Figure 4: Optical delay in a birefringent crystal.

Homogeneous Connection at the Cathode

In order to generate a long pulse without any timing gap or overlap, optical delays in each birefringent crystal which are as long as the micro pulse duration are applied in generating a homogeneous electron bunch at the cathode. The stretching factor due to the total amount of GDD during the transport through transparent optics should be taken into account. We checked the homogeneity of the electron bunch by measuring the electron energy spectra. The energy of the electron beam 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. Introducing a second dispersion with DAZZLER, the micro chirped pulse duration is optimized in order to make the electron beam profile at the dispersion section homogeneous (lower right in Fig. 5).

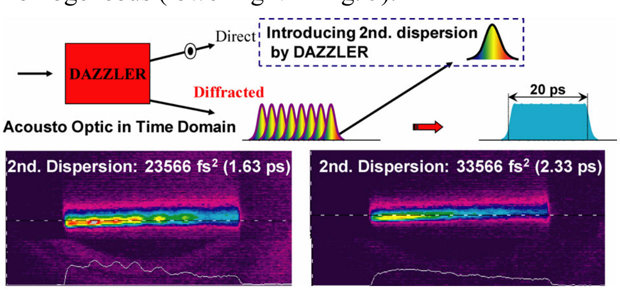

Figure 5: Generating homogeneous electron bunch: we optimized GDDs to roughly stretch the micro pulses with DAZZLER (HR-800, FASTLITE) and then additionally micro pulse shape for fine tuning with the depth and position of the dip in the spectra and the higher order dispersions up to the 4th.

FUTURE Z-POLARIZATION SCHOTTKY EMISSION GUN WITH HOLLOW LASER INCIDENCE

We propose a laser-induced Schottky-effect-gated photocathode gun using the Z-polarization of the laser source [10, 11]. The existence of radial polarized laser propagation modes has been theoretically predicted, and such modes were recently demonstrated. Focusing a radial polarized beam on the photocathode, the Z-polarization of the laser is generated at the focal point. The generated Z-polarization field can easily exceed an electrical field of 1 GV/m with the fundamental wavelength from compact femtosecond Ti:Sa laser systems. According to our calculations (NA=0.15, 60% hollow ratio, inside-out Gaussian beam), a Z-field of 1 GV/m needs 1.3 MW of peak power for the fundamental wavelength (790 nm) and 0.32 MW for the second harmonic generation (SHG). In a 1 GV/m field, the work function of the copper cathode decreases by ~2 eV [10,11]. This Schottky effect can be used as a gate of the photo-emission process, as shown in Fig. 6.

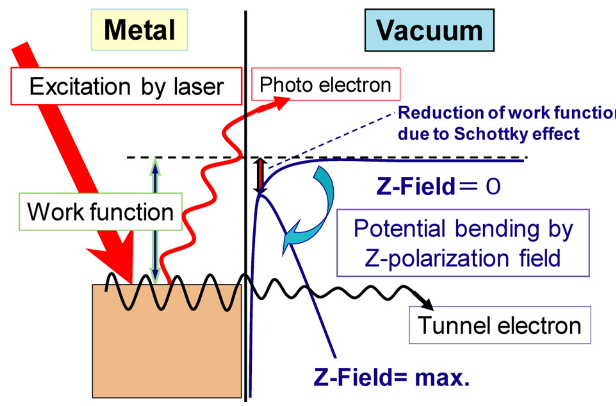

Figure 6: The principle of laser-induced Schottky-effect-gated photocathode gun: The important question was whether a femtosecond temporal response of the cathode is possible. Due to this temporal response issue, we started the feasibility tests with several metal cathode candidates.

We performed the investigation with a plane-field emitter assisted by laser radiation field and obtained indirect evidence of such laser field effects through comparison between normal and oblique incidences to the cathode. It is well known that the oblique incidence produces higher QE than normal incidence. This fact cannot be explained only with Brewster's angle. However, multi-photon absorption should be taken into account in the case of intensive laser focusing on the cathode. The Z-field component exists in the case of P-polarization incidence, but not in S-polarization, as shown in Fig. 7. This indicates that the laser field can assist the Schottky effect on the cathode.

Up to now, we have only discussed focusing radial polarization for maximizing the Z-field on the photocathode. On the other hand, the Z-polarization becomes zero if an azimuth polarized beam is focused. We conducted a feasibility study of this laser-induced Schottky effect on the photocathode with a comparison between radial and azimuth polarization shown in Fig. 8. In this experiment, the linear polarization of the incidence laser switches only from vertical to horizontal direction. In this method, we can check the Z-field effect separately from the multi-photon process. Comparing the photo-emission process with these polarizations, we demonstrate the feasibility of this new conceptual photocathode.

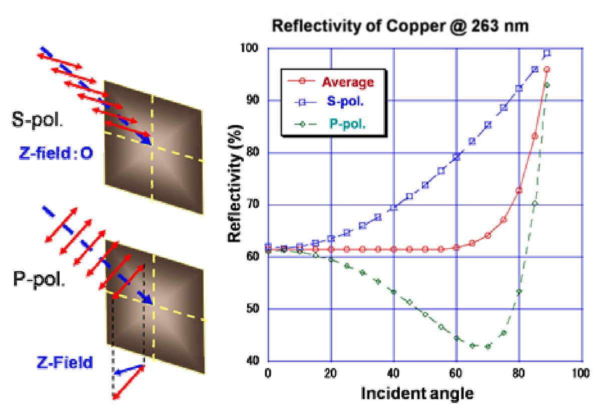

Figure 7: Incident angle dependency of reflectivity (Cu)

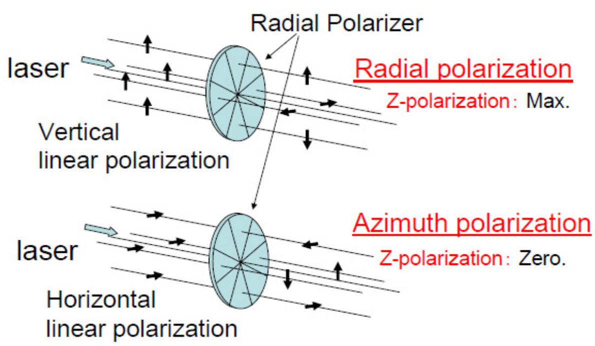

Figure 8: Concept of feasibility test for Schottky effect due to Z-polarization at focus point with the comparison of Z-fields between radial and azimuth polarization

SUMMARY

At present, if the oscillator is stable without mode-locking failure, the overall laser system can remain stable during yearlong operation with the energy stability described in this paper. We reviewed a short pulse (5~20 ps) laser beam subjected to 3D cylindrical "beer-can" shaping (both temporal (1D) and spatial (2D)) as an ideal UV light source for the generation of yearlong stable low-emittance electron beams with a high charge. In its current form, it comprises a deformable mirror that automatically shapes the spatial UV laser profile with a feedback routine, which is 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 "beer-can" 3D-shaped laser pulse, so far we have obtained a minimum horizontal normalized emittance of 1.4 π mm mrad. This high-brightness electron source has maintained its emittance at levels which are almost sufficiently low for meeting the X-ray FEL requirements during a yearlong continuous operation. However, the vertical emittance was around 1.5 times greater than the horizontal emittance. It was found that the last mirror in the vacuum chamber which generates the normal incidence presents an obstacle (wake field and charged-up by dark current) for the electron beam. In order to solve this problem, we developed two methods for generating laser incidence. One method involves the generation of a new hollow laser incidence with a final focusing to suppress the asymmetrical wake field effect, and the other method involves a quasi-normal incidence with an angle of 4 degrees without the reflecting mirror in vacuum (the mirror is located outside the vacuum chamber).

Our next laser shaping goal is the generation of a uniform 3D ellipsoidal distribution. In 2006, we proposed a laser-induced Schottky-effect-gated photocathode gun for realizing water bag beams in Luiten's scheme by using the Z-polarization of the laser on the cathode [7]. We apply the hollow laser incidence with a convex lens focusing after passing the laser through a radial polarizer. According to our calculations (NA=0.15), a Z-field of 1 GV/m needs 1.26 MW at peak power for the fundamental wavelength (790 nm) and 0.316 MW for the SHG (395 nm) [10]. This concept of laser-induced Schottky emission can be applied to photocathode RF and DC guns. In the first feasibility test run, we prepared a radial polarizer (8-way segmented half-waveplate) for SHG (395 nm) or THG (263 nm) to generate the radial and azimuthal polarizations. The metal cathode candidates are platinum, gold, silver, and copper. Comparing the photo-emission process with these polarizations, we demonstrate the feasibility of this new conceptual photocathode.

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