REVIEW OF MANIPULATION LASER TECHNOLOGY ON 3-D PULSE SHAPE & POLARIZATION FOR THE CONVENTIONAL PHOTOCATHODE RF GUN AND THE FUTURE Z-POLARIZATION SCHOTTKY EMISSION GUN

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Abstract

We developed an adaptive 3D shaping UV-pulse laser system (based on Ti:S laser) as an ideal light source for yearlong stable generation of a low-emittance electron beam with a charge of 1 nC/bunch. Since 2005, the laser's pulse-energy stability has been kept <1.4% at THG (263 nm) for several months continuously. In addition, to suppress emittance growth due to space charge effect, the 3-D cylindrical shape of the laser pulse is optimized as spatially top-hat (flattop) and temporally a square stacked chirped pulse. We applied a deformable mirror that automatically shapes the spatial profile with a feedback routine, 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. In 2006, we proposed a laser-induced Schottky-effect-gated photocathode gun to realize water bag beam in Luiten's scheme, using Z-polarization of the laser on the cathode. We are applying the hollow laser incidence after a radial polarizer with a convex lens focusing. According to our calculations (NA=0.15), the Z-field of 1 GV/m needs 1.26 MW at peak power for fundamental (790 nm) and 0.316 MW for the SHG (395 nm).

INTRODUCTION

We have been developing a stable and highly effective UV-laser pulse as the light source of a photocathode RF gun [1] that in turn provides a high-brightness electron beam source to achieve future X-ray light sources since 1996 at SPring-8. 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 with 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. Our development of this gun is oriented toward a yearlong stable system for user facility. Since we started to develop the laser test facility in 2001, 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 as the laser light source for the SPring-8 RF gun. Since 2005, the laser's pulse-energy stability has been kept <1.4% at THG (263 nm) for several months continuously. Such improvement reflects an ability to stabilize the laser system in the pumping sources (Q-switched YAG) of the amplifiers with a temperature-controlled base plate in this humidity-controlled clean room that maintained relative humidity at 55%. This system keeps dust particles away from the charged optics and thus avoids burn-out damage by laser.

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. One of the candidates for a reliable 3-D laser pulse shape has been the cylindrical "beer-can" shape (spatially top-hat and temporally square pulse). Over the past seven years at SPring-8's test facility for the photocathode laser light source, several 3-D shaping systems in UV region 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] or the pulse stacker. In its current form, we applied a deformable mirror that automatically shapes the spatial profile with a feedback routine, based on a genetic algorithm, and an UV-pulse stacker consisting of three or four birefringent Alpha-BBO crystal rods for temporal shaping at the same time [7]. In 2006, we have demonstrated a cylindrical 3-D UV-laser pulse with the shaping system described above. 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. The perfect homogeneity of temporal stacking will be automatically optimized with a feedback routine between AOPDF UV-pulse measurement (spectral phase interferometry in UV

region) and high-resolution DAZZLER as a micro pulse shaper. 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 [7] up to now. 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. We found that the last mirror in the vacuum to make normal incidence is an obstacle (wake field and charged-up) for the electron beam. To solve this, we are developing two ways for laser incidence. One is a new hollow laser incidence with a final focusing to suppress asymmetrical wake field effect. The other one is quasi-normal incidence with an angle of 4 degrees without its reflecting mirror in vacuum (The mirror stays out of vacuum chamber).

Recently, another candidate for a reliable 3D-pulse shape was proposed for even lower emittance [8], which is an ellipsoidal with equivalent fluence along the temporal axis. Such uniform 3-D ellipsoidal distributions of charge are one of the ultimate goal in high brightness beam, because of their linear internal force fields. O. J. Luiten simulated a method to actually produce such

bunches, based on photoemission by the femtosecond laser pulses [9].

In 2006, we proposed a laser-induced Schottky-effect-gated photocathode gun to realize water bag beam in Luiten's scheme, using Z-polarization of the laser on the cathode. We are applying the hollow laser incidence after a radial polarizer with a convex lens focusing. According to our calculations (NA=0.15), the Z-field of 1 GV/m needs 1.26 MW at peak power for fundamental (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.

3-D LASER PULSE SHAPING IN UV

The 3D UV-laser pulse shaping system combined with a deformable mirror (transverse: 2D) assisted a genetic algorithms and a chirped pulse stacker (longitudinal: 1D) is shown in Figure 1. Utilizing the long-term stable UV-laser source described above, this system can generate a "beer-can" 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 pulse stacking rods consisting of three birefringent Alpha-BBO crystals in the following.
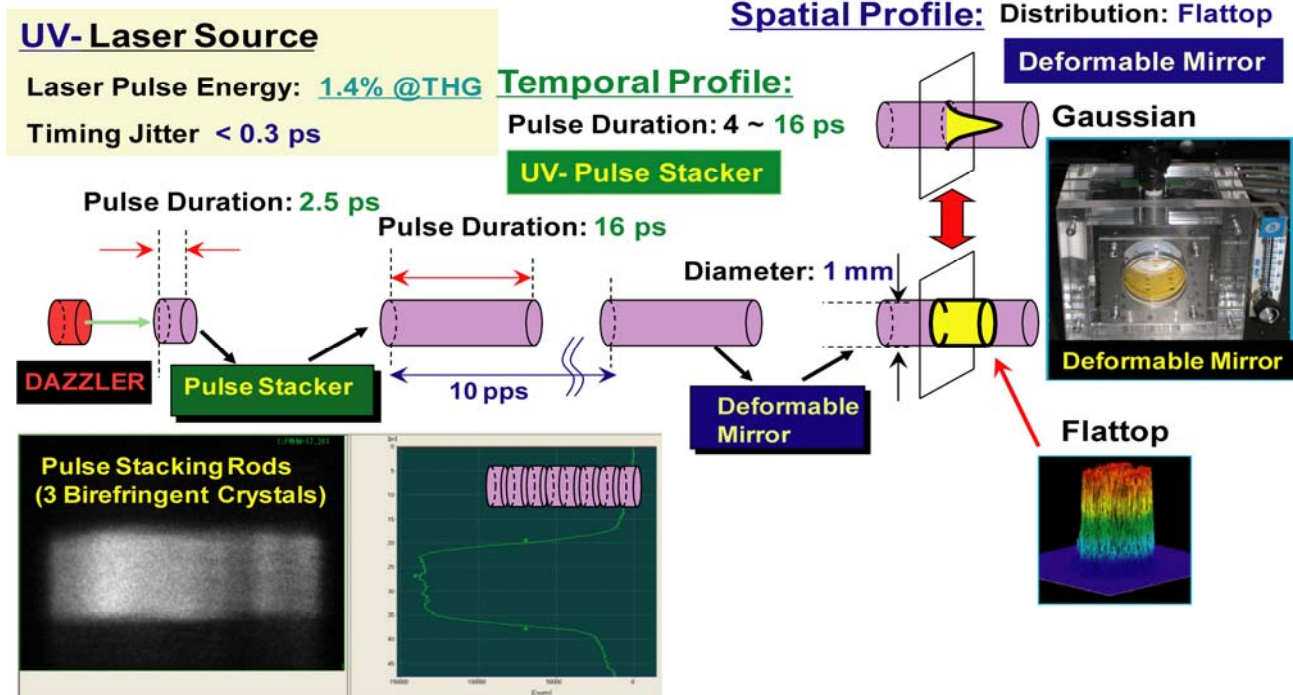

Figure 1: Three-dimensional UV-laser pulse shaping system: the 3D shaping system consists of a deformable mirror (DM) and chirped pulse stacking rods. These two shaping techniques can be optimized independently because there is no interference between them. The schematic drawing of pulse stacking shows 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.

SQUARE TEMPORAL SHAPING (CHIRPED UV-PULSE STACKING)

The chirped pulse stacking rods with fixed optical delays

Avoiding interference due to stacking, the orthogonally polarized chirped pulses are alternatively stacked with the optical delay as long as the micro pulse duration in generating homogeneous electron bunch at the cathode. We call that this method with introducing additional chirp to avoid interference as shown in Figure 2 is "chirped pulse stacking". In 2007, to fix the optical delays between neighbouring micro chirped pulses in the previous 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 incident polarization E_{in} is 45 degrees as shown in Figure 3.
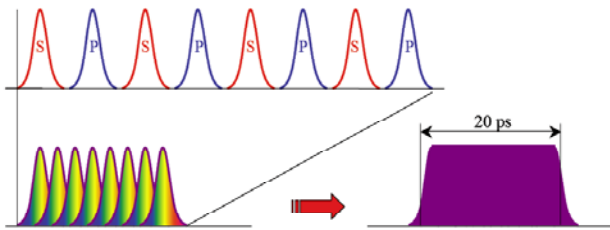

Figure 2: Principle of chirped-pulse stacking (8 pulses: three birefringent crystal rods): Avoiding interference, the orthogonally polarized chirped pulses are alternatively stacked with the optical delays in each birefringent crystal as long as the micro pulse duration in generating homogeneous electron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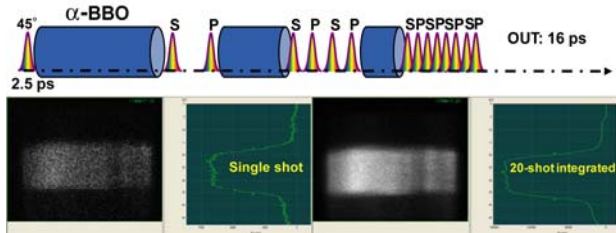

Figure 3: UV-laser pulse stacking rods: The angle of rotation of each crystal against incident polarization is 45 degrees. The drawings are shown in the case of three birefringent α-BBO crystal rods. This pulse stacking kit is commercially available (http://www.luminex.co.jp/) under license from SPring8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

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 order to realize this temporal delay, the linearly polarized 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 Figure 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.

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.
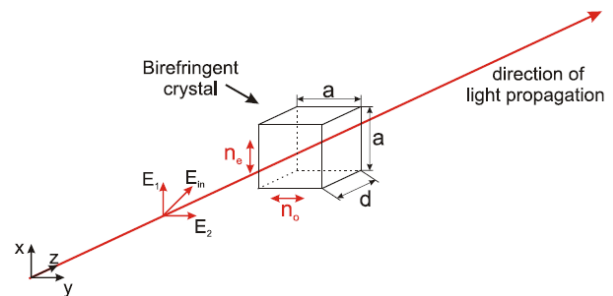

Figure 4: The optical delay in a birefringent crystal

Homogeneous connection at the cathode

To generate a long pulse without any timing gap or overlap, the optical delays in each birefringent crystal as long as the micro pulse duration in generating homogeneous electron bunch at the cathode. It should be taken into account stretching factor due to the total amount of GDD during transport through transparent optics. We checked the homogeneity of electron bunch with measurement of electron energy spectra. 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. Introducing second dispersion with DAZZLER, micro chirped pulse duration is optimized to make the electron beam profile at the dispersion section homogeneous (lower right in Figure 5).
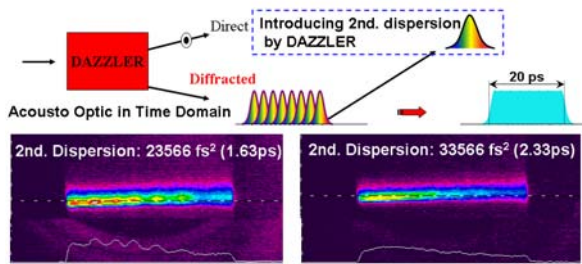
Figure 5: Generating homogeneous electron bunch: we optimized GDDs to roughly stretch the micro pulses with DAZZLER (HR-800, FASTLITE) and then additionally micro pulse shape for fine tuning with the depth and position of the dip in the spectra and the higher order dispersions up to the 4th.

THE FUTURE Z-POLARIZATION SCHOTTKY EMISSION GUN WITH HOLLOW LASER INCIDENCE

We propose a laser-induced Schottky-effect-gated photocathode gun using Z-polarization of the laser source [7]. Radial polarized laser propagation modes exist theoretically and were recently generated practically. Focusing a radial polarized beam on the photocathode, the Z-polarization of the laser is generated at the focus point. The generated Z-polarization field can exceed an electrical field of 1 GV/m easily with fundamental wavelength from compact femtosecond Ti:Sa laser systems. According to our calculations (NA=0.15 60-% hollow ratio, inside-out Gaussian beam), the Z-field of 1 GV/m needs 1.3 MW at peak power for the fundamental (790 nm) and 0.32 MW for the second harmonic generation (SHG). In the field of 1 GV/m, the work function of copper cathode reduces ~2 eV [7]. This Schottky effect can be used as a gate of the photo-emission process as shown in Figure 6.
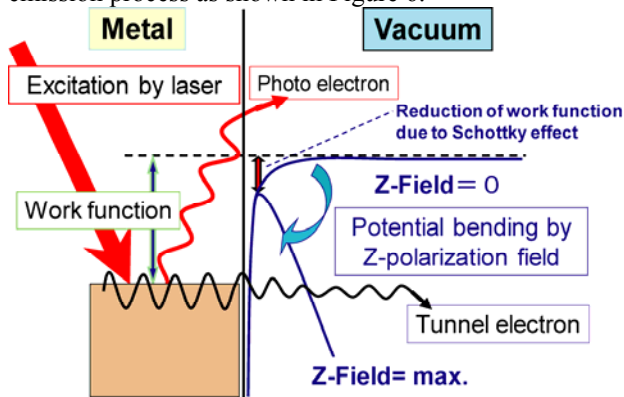

Figure 6: The principle of laser-induced Schottky-effect-gated photocathode gun: The question is if the femtosecond temporal response of cathode is available. According this temporal response issue, we will start feasibility tests with several metal cathode candidates.

We investigated with a plane-field emitter assisted by laser radiation field. We have indirect evidence of such a laser field effect through comparison between normal and oblique incidences to the cathode. It is well known that the oblique incidence obtains higher QE than normal incidence. It cannot be explained only with Brewster's angle. However, we have to think about multi-photon absorption 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 Figure 7. It indicates that the laser field can assist the Schottky effect on the cathode.
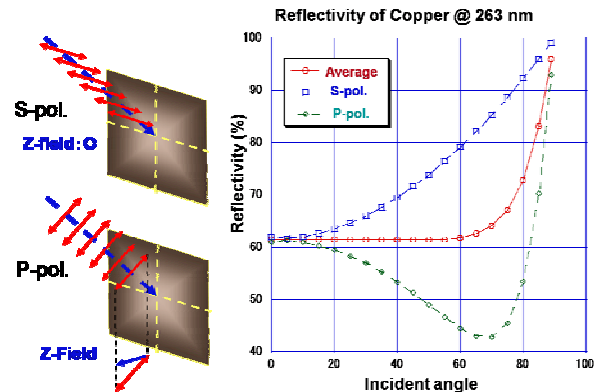

Figure 7: Incident angle dependence of reflectivity (Cu)

Up to now, we have only discussed focusing radial polarization to maximize the Z-field on the photocathode. On the other hand, focusing an azimuth polarized beam makes Z-polarization zero. We conducted a feasibility study of this laser-induced Schottky-effect on the photocathode with the comparison between radial and azimuth polarization. In this experiment, the linear polarization of the incidence laser switches only from vertical to horizontal. In this method, we can check just the Z-field effect separated from the multi-photon process. Comparing the photo-emission process with these polarizations, we make clear the feasibility of this new concept of photocathode.

SUMMARY

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. We reviewed a 3-D cylindrical "beer-can" shaping (both temporal (1D) and spatial (2D)) short pulse (5~20 ps) laser beam as an ideal UV-light source for yearlong stable generation of a low-emittance electron beam with a high charge. In its current form, 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.

For our next laser shaping goal is uniform 3-D ellipsoidal distribution. In 2006, we proposed a laser-induced Schottky-effect-gated photocathode gun to realize water bag beam in Luiten's scheme, using Z-polarization of the laser on the cathode [7]. We are applying the hollow laser incidence after a radial polarizer with a convex lens focusing. According to our calculations (NA=0.15), the Z-field of 1 GV/m needs 1.26 MW at peak power for fundamental (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 make clear the feasibility of this new concept of photocathode.

REFERENCES

[1] T. Taniuchi et al., Proc. of FEL'96, 1996, p. 137.

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

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

[4] J. Rivers, "SCSS X-FEL Conceptual Design Report", RIKEN, May 2005.

[5] H. Tomizawa et al., Proc. of EPAC02, 2002, p. 1819.

[6] H. Tomizawa et al., Proc. FEL05, 2005, p. 138.

[7] H. Tomizawa et al., Proc. FEL07, 2007, p. 298.

[8] C. Limborg-Deprey et al., NIMA 557, 2006, p. 106.

[9] O. J. Luiten et al., Phys. Rev. Lett. 93, 2004, p. 094802.

[10] H. Tomizawa et al., Proc. of FEL07, 2007, p. 382.

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