LASER PULSE LENGTH DEPENDENCE OF BEAM EMITTANCE OF PHOTOCATHODE RFGUN

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Abstract

Laser pulse length and laser shape should be optimized to minimize the beam emittance of photo-cathode RF-gun. A 3-D particle tracking simulation predicted the smallest beam emittance could be obtained with the square laser pulse length of about 20 ps. To examine the effect of the laser pulse length to beam emittance, the square laser pulse of 10 and 20 ps was generated with laser pulse stacking of 2.5-ps micro pulses and each beam emittance was measured at the low beam charge of 0.4 nC/pulse. The measured beam emittance was not significantly different each other.

Then beam emittance was measured at the higher beam charge of 1.0 nC/pulse. The minimum beam emittance with 20-ps laser pulse was 2.3 πmmmrad with 0.8mm x 1.0 mm elliptical laser profile. Although we also tried to measure the beam emittance with 10-ps laser pulse, the beam charge of 1.0 nC could not be generated at the same laser spot size due to probably space charge limit. The measured beam emittance for 20-ps laser pulse was smaller than the minimum beam emittance 3.0 πmmmrad for 10-ps laser pulse measured under different laser condition, especially micro pulse of 1.0 ps and laser spot diameter of ø 1.0 mm.

Although we could not compare the laser pulse 10 ps and 20 ps at the equivalent conditions in high charge region, these experimental results would indicate at least the possibility of using long laser pulse about 20 ps to minimize the beam emittance for beam charge around 1.0 nC.

INTRODUCTION

The electron source for several XFEL projects [1-3] requires very low emittance beam as low as 1 πmmmrad. To minimize the beam emittance of a photocathode RF-gun, the laser pulse shape should be optimized three-dimensionally. The transverse shape could be modified with a microlens array [4] or a deformable mirror (DM) [5]. As well as the transverse shape, the longitudinal shape can be also modified with a spatial light modulator [5,6] or pulse stacker described in this paper. Beam emittance of 1.2 πmmmrad for 1 nC/pulse has already realized by J. Yang et. al. with square 9-ps laser pulse [6].

So far, we demonstrated transverse shape optimization and low emittance beam generation of 1.7 πmmmrad at the electron charge of 0.1 nC [5]. The beam emittance at high charge was, however, much larger, because the laser pulse length is too short (5 ps) and the diameter was 1mm (top hat) and therefore the charge density was too high.

In this paper, we tested longer laser pulse of 10-ps and 20-ps square generated with laser pulse stacker to get low emittance in high charge region. Three stages of pulse stacking generated 20-ps pulse from eight micro pulses. The purpose introducing longer laser pulse is to keep the laser beam size small but decrease the charge density. The small beam size contributes to decreasing the initial emittance, and small charge density to the space charge effect. Therefore, long laser pulse is effective especially in high charge region. A 3-D particle tracking simulation predicted smaller beam emittance could be obtained with the laser pulse length of about 20 ps at 1nC/pulse as shown in Fig. 1. It also predicted electron bunch length can keep around 10 ps with both 10 and 20-ps laser pulse length due to bunch length compression in the RF cavity.

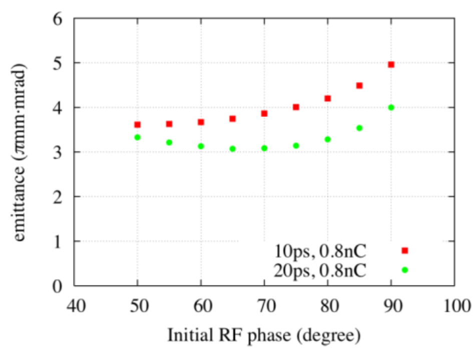

Figure 1: Beam emittance of the photo cathode RF gun for 10 and 20-ps laser square pulse length calculated with a 3-D particle tracking simulation. In the calculation, the laser spot diameter was 1.6 mm (top hat) and the maximum electric field on the cathode was 135 MV/m.

LASER PULSE STACKING

Pulse stacker is composed of sets of half-wave plates and polarizing beam splitter cubes. The fully s-polarised pulse laser is rotated to 45 degrees polarised pulse with a half-wave plate. It is divided into an s-polarized pulse and p-polarised one with a polarizing beam splitter. The p-polarized pulse is delayed with an optical delay line and then combined with the s-polarized pulse after another polarized beam splitter. Finally, as shown in Fig. 2, the laser pulse of 2.5 ps was stacked with optical delay at each stage to generate longer square pulse. With three stages, we can obtain 20-ps square pulse.

The polarizing beam splitter cubes used in the first and second stage is optical contact type (produced by Showa Optronics) considering the high power density of the UV laser. The polarizing beam splitter used in the third stage is bonded with optical cement, because the power density

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is lower at the stage. The diagram of the optical system is shown in Fig. 3.

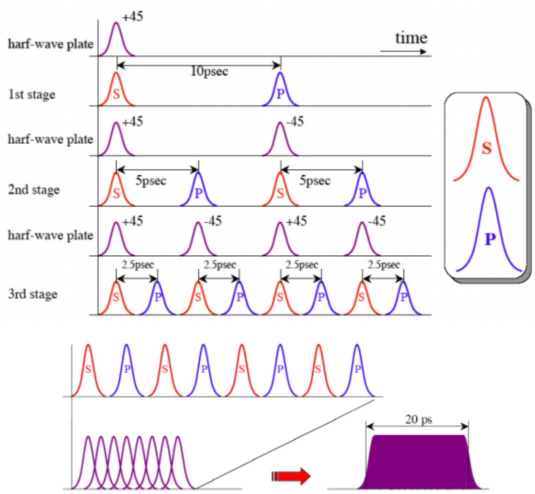

Figure 2: Timing chart of pulse stacking

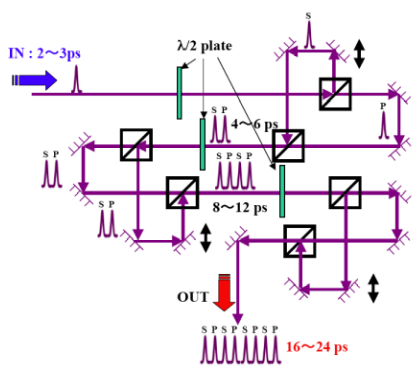

Figure 3: Optical system of laser pulse stacker (three stages)

PULSE LENGTH CONTROL

Finding the origins of optical delay lines

To generate long pulse without any timing gap or overlap, origins of the optical delay lines must determined with a precision less than 1 ps. The origin is defined here as the position of micrometer in the delay line such that the s-polarization and p-polarization pulses reach the cathode at the same time. The way that determines the origin is as follows. The energy of the electron pulse was measured for two laser pulses divided by each stage of the pulse stacker. The energy of the electron beam is measured as beam position on a profile monitor after a bending magnet downstream the RF-gun cavity. To eliminate the positioning jitter and short time drift, the beam positions were measured for 5000 times. The micrometer for p-polarized pulse was tuned as these two electron beam pulses come to the same position on the profile monitor after 3-5 times iterations. The timing precision of the origin was about 0.5 ps estimated from the position jitter distribution.

Setting of optical delay lines

After setting the origins of three micrometers, the position of these micrometers are determined by simple calculation. For example, if the pulse length is 20 ps, the micrometer positions are set as follows,

Position for 1st stage: origin - 1.5mm
Position for 2nd stage: origin - 0.75mm
Position for 3rd stage: origin - 0.375mm.

The stacked laser pulse was finally checked by the beam energy distribution on the profile monitor with illuminating all eight micro pulses. The energy distribution of the beam is shown in Fig. 4. At an optimum phase (85 degree), the beam focuses on the profile monitor. When RF phase is 44 degree, the energy dispersion was made purposely larger to evaluate stacking pulse structure. The uniformity is not ideal but there are not any gaps and strong hot spot in the distribution. Therefore, the eight micro pulses are thought to be stacked properly. The incomplete uniformity mainly comes from the insufficient flatness of energy among the laser micro pulses.

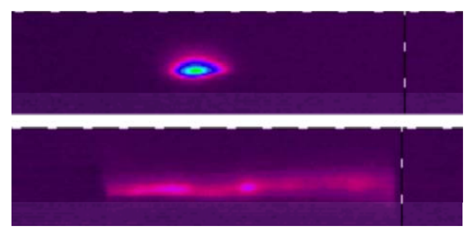

Figure 4: The energy distribution on the profile monitor for the 20-ps laser square pulse at different RF phase. Top: RF phase at 85 degree (3.52 MeV @center), Bottom: RF phase at 44 deg (3.29MeV @center)

The information of the pulse length of the micro pulse can be also obtained from this measurement. When the micro pulse was around 1.5 - 2.0 ps, five strong spots were observed on the profile monitor as shown in Fig. 5. These spots come from overlapping on the edges of two micro pulses. Not all energy spots are seen on the profile monitor, because of small screen. The number of the spot was found to be totally seven when the RF phase was moved.

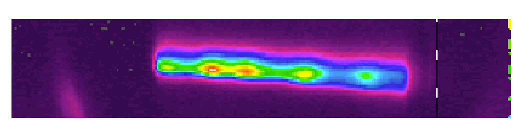

Figure 5: The energy distribution on the profile monitor for the 20-ps laser pulse, when the micro pulse is around 1.5 -2.0 ps.

Simulation results of the energy distribution for micro pulse lengths of 1.5 ps and 2.5 ps are shown in Fig. 6.

There are seven spots for the case of 1.5 ps, while there is not any strong spot for the case of 2.5 ps.

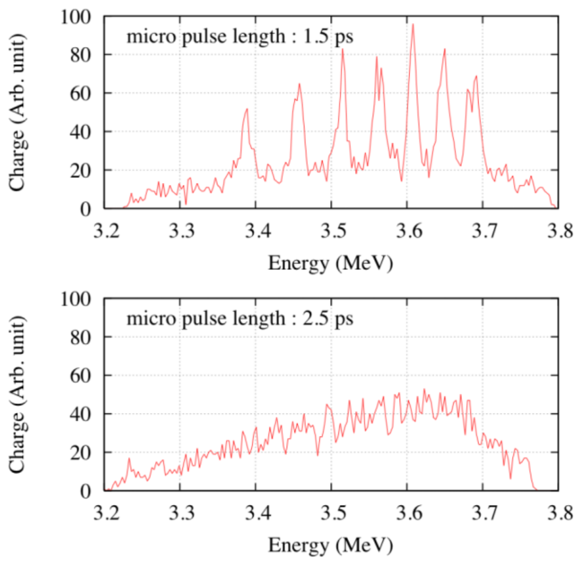

Figure 6: Simulated of the energy distribution for micro pulse length of 1.5 ps (Top) and 2.5 ps (Bottom).

BEAM EXPERIMENTS

Laser distribution and electron beam charge

The laser pulse energy of eight (20 ps) and four (10 ps) micro pulses was tuned by the angle of half-wave plates to get the beam charge of 0.4 nC and energy flatness. The results are shown in Fig. 7.

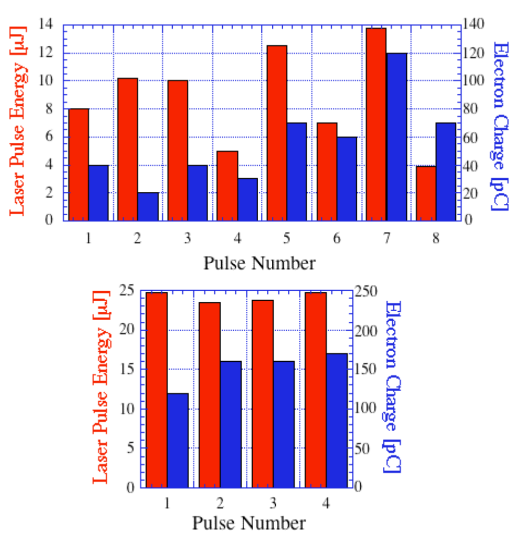

Figure 7: The laser pulse energy and electron beam charge of micro pulse for 20-ps (Top), and 10-ps pulse structure (Bottom).

The 20-ps pulse was generated with pulse stacker of three stages, and 10 ps with first two stages. The energy flatness for 20 ps is worse than 10 ps. The polarizing beam splitter of the third stage could not divide the two pulses ideally because it is bonded with optical cement and the energy loss of p-polarization pulse is larger at higher intensity.

There is a difference in total pulse energy to get the same charge of 0.4 nC; 70.4 μJ for 20 ps and 96.6 μJ for 10 ps. This is due to both of the Schottky effect and space charge limit. These effects is not theoretically calculated but can be understand from the facts that four micro pulses in 10-ps pulse individually generate increasing charge of 0.12, 0.16, 0.16, 0.17 nC, but generate only 0.4 nC with all four pulse at the same time.

Setup of Beam emittance measurements

The electron beam generated from the RF gun was accelerated to 26 MeV with a 3m-long accelerating structure. The beam emittance was measured with quad scan downstream the accelerating structure [7].

When we operate quad scan to measure the beam emittance, the beam size must be measured at the resolution of the order of 10 μm. To realize the fine resolution, we adopted a profile monitor with a thin screen and high resolution CCD camera. The screen is an alumina fluorescence sheet (Desmarquest AF995) with the thickness of 0.05 mm. The CCD camera is 1.3-mega pixels camera (SONY XCD-SX910). It has a 1/2-inch CCD chip with 1280(H) x 960 (V) pixels, and each pixel size is 4.65 x 4.65 μm^2. To get a large depth of field, we used a telecentric lens of 1/4 magnification. The estimated resolution of the image is about 20-30 μm. Only center quadrupole magnet of the triplet quadruple magnet was used to focus the beam on the screen with quad scan. The setup of the quad scan measurement is shown in Fig. 8.

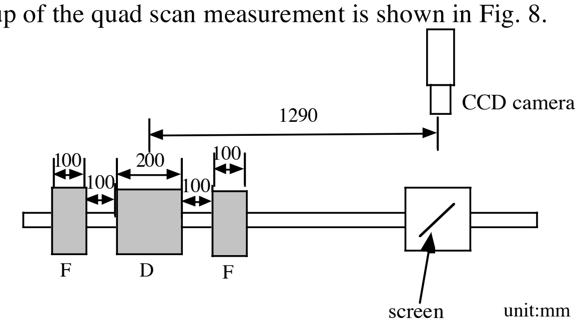

Figure 8: Setup of quad-scan measurement.

The emittance measurement was automatically executed in about 5 minutes if the measurement points were less than 15. The automatic measurement system was programmed with Labview 7.1 and Vision developing module (National Instruments Co.).

Beam emittance measurements

Beam emittance for 10 and 20-ps laser pulse was measured in low charge region of 0.4 nC/pulse. The current of solenoid coils were optimized to get minimum beam emittance. The laser shape was elliptical (0.8 mm (H) x 1.0 mm (V)). In this experiment, the optimization of DM could not executed because the CCD of laser profiler was damaged. The results of the quad scan are shown in Fig. 9. The emittance of both beam were almost same, 3.2 πmmmrad for 20 ps and 3.3 πmmmrad for 10 ps.

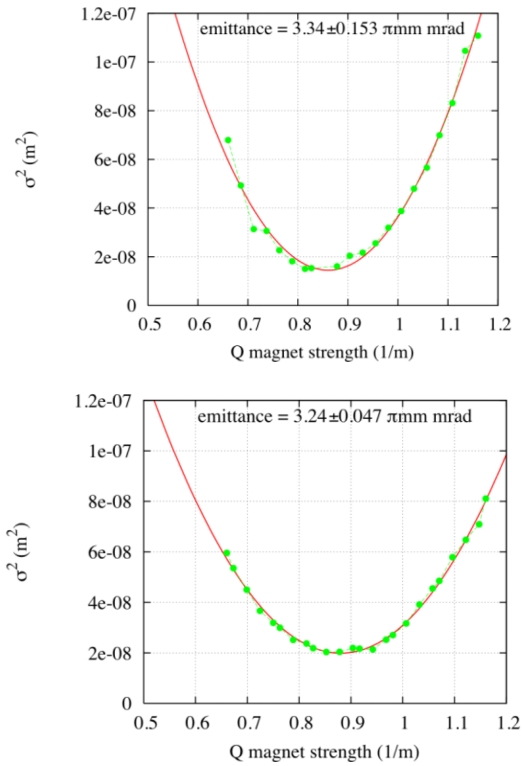

Figure 9: Measured beam emittance for 10-ps and 20-ps laser pulse at the beam charge of 0.4 nC/pulse.

Next, the beam emittance was measured in case of high current beam. The beam current of 1.0 nC was generated for 20-ps pulse but only 0.6 nC beam current could be generated for 10-ps pulse at the same laser spot size, though the laser power was high enough. It may be due to space charge limit. After further optimizing parameters such as solenoid current, RF phase and half-wave plates, the measured minimum emittance of the beam for 20-ps laser pulse was 2.3 πmmmrad as shown in Fig.10.

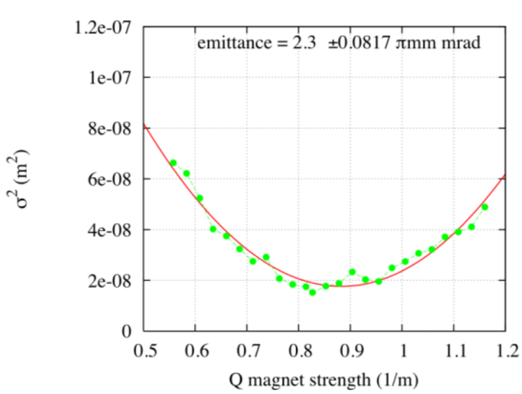

Figure 10: Measured beam emittance for 20-ps laser pulse at the beam charge of 1.0 nC/pulse.

DISCUSSION

Long laser pulse of 20 ps generated with a pulse stacker was tested, and low emittance beam of 2.3 πmmmrad was generated successfully without optimization of laser transverse profile with DM. No large difference was found between 10 ps and 20 ps in the low charge region. It is very important that the beam current for 10 ps could not reach 0.7 nC if the laser beam size was small even if the laser pulse energy was increased high. This effect may limit the initial emittance of the beam in high charge region. Long laser pulse of 20 ps is thought to have an advantage in generating high charge with small initial beam size.

Of course, the pulse charge of 1nC could be generated if the laser spot size was large enough. However, the measured beam emittance for 20-ps laser pulse was smaller than the minimum beam emittance 3.0 πmmmrad for 10-ps laser pulse at 1.0 nC/pulse measured under different conditions of micro pulse length at 1 ps and laser profile modified with DM to a flat circle of ø1.0 mm [8].

The possibility of 20-ps laser pulse to get low emittance has been confirmed by these results. Next, the splitter cube of the third stage in pulse stacker will be exchanged to that bonded with optical contact. Then micro laser pulses should be tuned to get flat longitudinal distribution of electron beam. Further experiments to pursue smaller beam emittance will be planed with simultaneous transverse and longitudinal laser profile optimization.

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