

# LASER PROFILE SHAPING & EMITTANCE FOR THE PHOTOCATHODE INJECTOR

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## Abstract

Photocathode RF gun can generate high charge and low emittance electron beam, which is the most essential to many research projects. Among the disadvantageous effects to worsen beam emittance in the gun, space charge effect is primary in high charge case. Therefore much endeavour has been made to decrease this effect on LUCX facility (Laser Undulator Compact X-ray source at KEK, Japan). Firstly RF gun is tuned into unbalanced, so that the peak field gradient on the cathode surface is relatively higher than that in the full cell. A laser profile shaper and a series of optical beam line designed for it are employed to convert the driving laser from Gaussian profile into uniform profile. With the uniform driving laser and the unbalanced RF gun, the transverse emittance for 1nC electron bunch has been improved effectively from 5.46πmm.mrad to 3.66πmm.mrad.

## INTRODUCTION

Laser Undulator Compact X-ray source (LUCX) is a test bench for compact high brightness X-ray generator at KEK, which is based on the Compton Scattering. A photo-cathode RF gun with an emittance compensation solenoid is used as the electron source. A chicane composed of 4 dipole magnets allows the laser illuminate on the Cs2Te cathode perpendicularly. Electron beam out of RF gun is accelerated further by a 3-meter constant gradient S-band structure. Figure 1 shows the layout of LUCX facility.

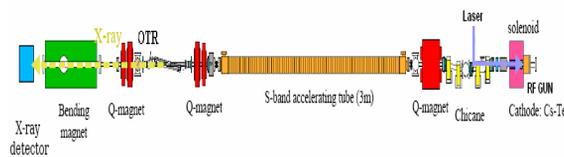


Figure 1: Layout of LUCX facility.

A RF pulse compressor is used to compress 4μs RF pulse into 1μs pulse to increase the peak RF power. In order to enhance the X-ray brightness, it operates at challenged parameters as is shown in table 1. The beam loading effect in the gun cavity and in accelerating tube is so serious that the energy difference among bunches in a train must be considered to compensate. Because only one klystron provides RF power for the gun and accelerating tube, we apply ΔT method [1] to compensate the beam loading effect, which means that laser pulses train injects the gun and electron bunches train injects the accelerating

tube before RF field builds up completely in gun and accelerating tube. RF pulse width is generally 1μs; the injection timing is at about 0.3μs. Therefore field gradient in gun cavity is lower for high charge electron bunch, even though the peak power of input RF pulse is higher. In this case, space charge effect within electron bunch must be considered carefully to release. One recipe we have done is to tune LUCX gun unbalanced, and the field balance  $E_{half\_cell} / E_{full\_cell}$  is 1.3.  $E_{half\_cell}$ ,  $E_{full\_cell}$  are the peak field gradient in half cell and full cell, respectively. The field gradient on the cathode surface is relatively higher when the RF power forwarded into gun is not high enough, which is beneficial to accelerate the bunch much quickly at the beginning stage to release the emittance breakup due to space charge effect. Figure 2 shows the field distribution in LUCX gun [2].

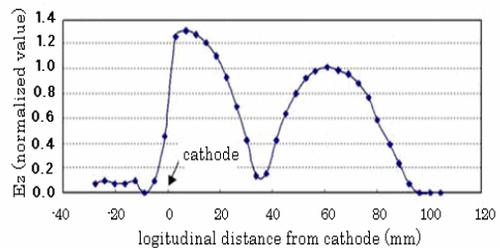


Figure 2 : Field distribution in LUCX gun.

The transverse emittance of electron beam mostly depends on the accelerating process in the beginning stage, during which the beam velocity increases from zero to relativistic velocity. Generally, there are three effects to dilute the beam emittance in photocathode RF gun [3]. They are thermal emittance, space charge effect and RF field effect. Because LUCX gun operates on the conditions of high charge and small injection time, space charge effect is primary among them. We can assume that an electron bunch comprises some beam slices, so the bunch emittance is the sum of all slices emittance in transverse phase space. An ellipse is always employed to indicate the phase space of slice beam. The linear component of the space charge force within slice beam expands beam size and changes beam divergence. According to Liouville's theorem, slice emittance is constant, but the orientation of the slice ellipse rotates in the phase space, and the rotating angle depends on the acceleration process. The different slice ellipses rotate at different angles because of the difference of the space charge effect. Solenoid magnetic field can line-up the orientation of the slice ellipses in transverse phase space, so that the overall transverse emittance of electron beam decreases to a certain degree. The non-linear components of the space charge force in the slice not only change the

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orientation of the slice emittance ellipses, but also distort the slice phase space, so that the slices emittance increases. Comparing with the Gaussian electron beam, the uniform electron beam has smaller non-linear component, so the slices emittance is smaller. The sum of slices emittance becomes smaller after the emittance compensation by solenoid.

Table 1: Operation parameters of LUCX gun

Bunch charge	1nC
Bunch length	10ps
Bunch spacing	2.8ns
Bunch number per train	100 bunch
Train frequency	12.5Hz

The second recipe to release space charge effect in LUCX gun is to convert the driving laser from Gaussian profile into uniform profile. Lots of simulation works prove that the uniform driving laser can improve the beam emittance and some research groups have done some works on shaping of laser profile for their photocathode RF gun. But up to now, there is no enough experimental data to determinate how much percent of emittance improvement could be achieved by this technology. We employ a laser profile shaper to convert the driving laser from Gaussian profile into uniform profile successfully with less than 5% energy loss. A series of emittance measurement have been done with Gaussian and uniform driving laser. The measurement process and results are all presented in this paper.

## LASER SYSTEM AND $\pi$ -SHAPER

### Laser system

Seed laser can provide mode-locked pulse laser. With the SESAM technology, seed laser pulse length can be reduced to 10ps. Wavelength is 1064nm and pulse frequency is 357MHz. One Pockel cell cut out 3-100 laser pulses to be amplified by two stage flash amplifiers. The laser pulse energy after the amplifier can be optimized to 40 $\mu$ J, and pulse length becomes a little bit longer. One sigma of pulse length is about 13ps, which is measured by auto-correction technology. Two stage BBO components convert the laser wavelength to 266nm in the end, pulse energy is about 10 $\mu$ J, which is enough to generate 2nC electron beam per bunch.

### $\pi$ -shaper

A  $\pi$ -shaper [4] (model-262,-VIS) is used to convert the laser profile from Gaussian into uniform. It is an anamorphic variant of a Galilean beam-expanding telescope, with radically varying magnification. It is composed of two lenses which is designed and manufactured carefully according to the Gaussian distribution. The first lens refracts the incident Gaussian beam to produce the desired flattop distribution at the upstream surface of the second lens, and the second lens

collimates the rays to generate a uniform laser beam. Figure 3 shows the principle of  $\pi$ -shaper.

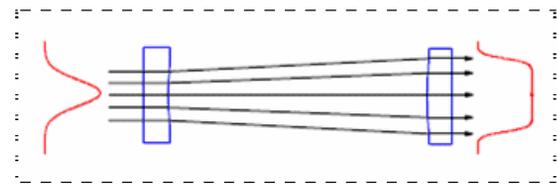


Figure 3: Principle of  $\pi$ -shaper.

### Optical beam for $\pi$ -shaper

Performance of the  $\pi$ -shaper depends on the beam size and beam divergence of the input laser. 4.75mm ( $4\sigma$ ), parallel and Gaussian input laser is required. On these conditions, the output laser is almost transverse uniform, but with a bigger beam size. On the other hand, the overall transverse emittance of electron beam is a function as the laser beam size. On the certain case, there is an optimized beam size, corresponding to the minimized transverse emittance.

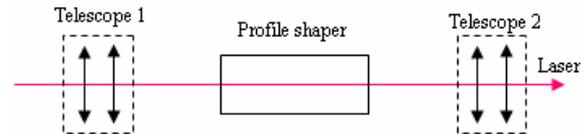
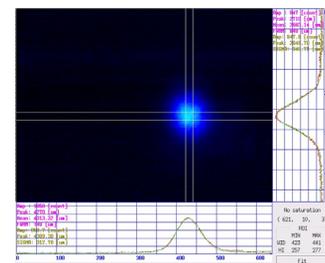
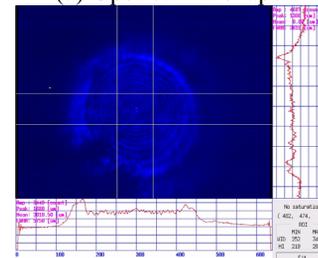


Figure 4: Optical beam line for  $\pi$ -shaper.

Two well designed telescopes are installed near  $\pi$ -shaper as Figure 4 shows. One is at upstream of  $\pi$ -shaper, which can be used to adjust the beam size and divergence of the input laser; another is at downstream of  $\pi$ -shaper to adjust the beam size of output laser easily. Figure 5 shows that the laser profile before and after this shaper. We can find that the transverse distribution of laser improves greatly.



(a) Upstream  $\pi$ -shaper



(b) Downstream  $\pi$ -shaper

Figure 5: Beam size VS K value.

## EMITTANCE MEASUREMENT

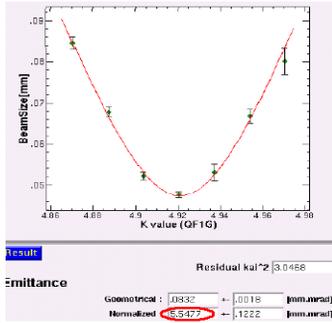


Figure 6: Beam size VS K value.

We measured the electron beam emittance with the Q-scan method at the downstream of the accelerator tube by one Quadruple magnet and one OTR screen as Figure 1 shows. By changing current of the quadruple magnet and recording the electron beam size, the relationship between beam size and K value can be defined. By this relation curve, we can calculate normalized transverse emittance as Figure 6 shows.

### Gaussian laser case

At first, RF phases in gun and in the accelerator tube are optimized to the minimized energy spread. At

optimized RF phases, fixing laser beam size on the cathode, we scan solenoid current and calculate beam emittance, and then we can get the relation curve between the transverse emittance and the solenoid current shown as Figure 7. From the result, we get the minimum emittance at the fixed beam size. We change the laser beam size on the cathode and scan the solenoid current as above described. We can get the relation curve between minimum normalized emittance and the laser beam size as Figure 8 shows.

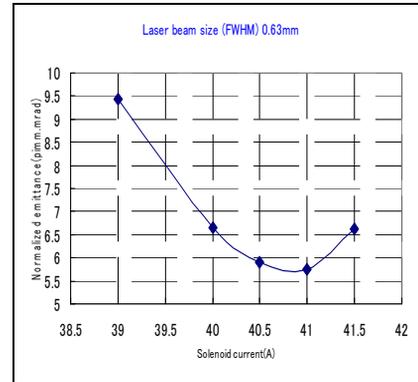


Figure 7: Normalized emittance VS solenoid current.

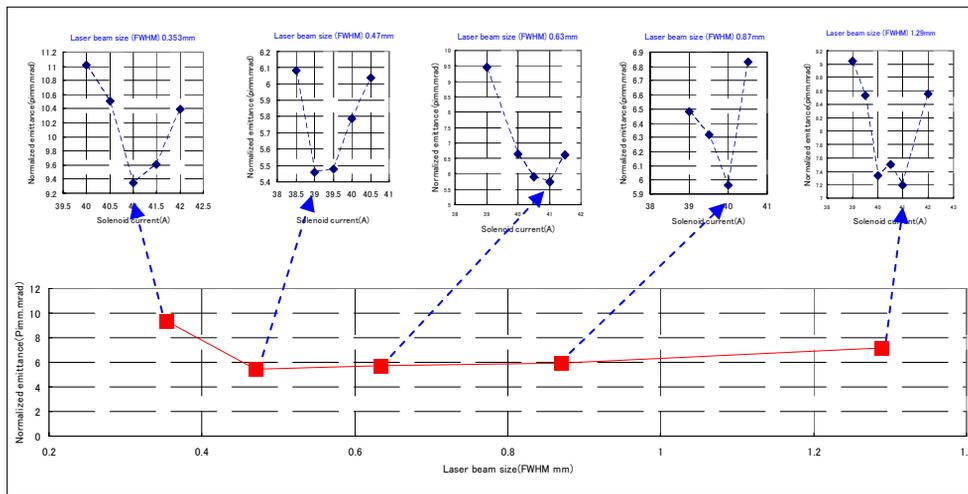


Figure 8: Minimum normalized emittance VS laser beam size (1nC Gaussian laser, above curves show the electron beam emittance at the different laser beam size 0.353mm, 0.47mm, 0.63mm, 0.87mm, 1.29mm).

### Uniform laser case

The profile shaper and attached optical beam line are inserted into the laser system to shape the laser profile from Gaussian into uniform. By the telescope downstream the shaper, laser beam size on the cathode can be adjusted. By the same procedure as to the Gaussian laser, we can get the curve between minimum normalized emittance and the laser beam size to the uniform laser shown in Figure 9. Electron beam emittance improves from  $5.46\pi\text{mm.mrad}$  (Gaussian laser) to  $3.66\pi\text{mm.mrad}$ .

Figure 10 shows the simulation result by ASTRA [5] code and experimental result for uniform profile laser, which matches each other well. The difference between them comes from the alignment error possibly, because the emittance is measured at downstream of the accelerator tube. There are some alignment errors between laser position on cathode and electro-centre of RF field in gun cavity, between electro-centre of RF field in gun cavity and the magnetic-centre of solenoid magnet, and between the trajectory of electron beam and the electro-centre of RF field in accelerator tube. Simulation doesn't take account of the alignment errors.

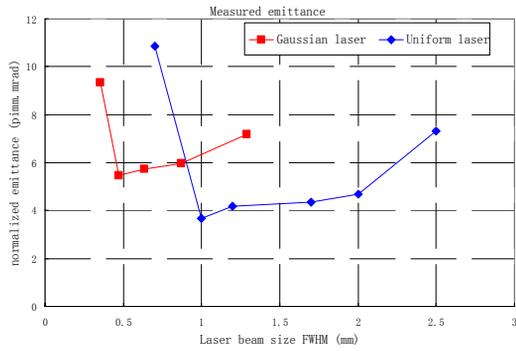


Figure 9: Minimum normalized emittance VS laser beam size (Gaussian laser and uniform laser)

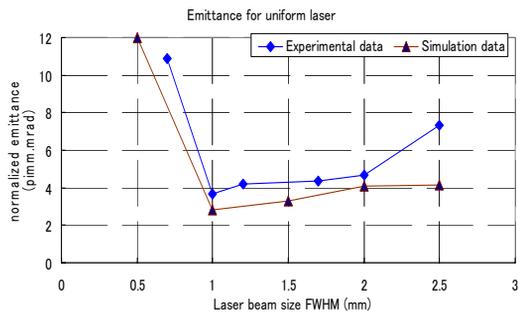


Figure 10: Minimum normalized emittance VS laser beam size for uniform laser (experimental and simulation results)

## CONCLUSIONS

We set up an optical system to shape the Gaussian profile laser into the uniform profile laser in order to decrease the space charge effect for the high charge electron beam in the photocathode injector. By Quadruple magnet and OTR screen, we measured electron beam emittance precisely and systematically. The uniform distribution of laser can improve the beam emittance from  $5.46\pi\text{mm.mrad}$  (Gaussian laser) to  $3.66\pi\text{mm.mrad}$  for 1nC electron bunch. The experimental results match the simulation results well.

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