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Emittance measurement & optimization for the photocathode RF gun with laser profile shaping

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Abstract The Laser Undulator Compact X-ray source (LUCX) is a test bench for a compact high brightness X-ray generator, based on inverse Compton Scattering at KEK, which requires high intensity multi-bunch trains with low transverse emittance. A photocathode RF gun with emittance compensation solenoid is used as an electron source. Much endeavor has been made to increase the beam intensity in the multi-bunch trains. The cavity of the RF gun is tuned into an unbalanced field in order to reduce space charge effects, so that the field gradient on the cathode surface is relatively higher when the forward RF power into gun cavity is not high enough. A laser profile shaper is employed to convert the driving laser profile from Gaussian into uniform. In this research we seek to find the optimized operational conditions for the decrease of the transverse emittance. With the uniform driving laser and the unbalanced RF gun, the RMS transverse emittance of a 1 nC bunch has been improved effectively from 5.46 πmm·mrad to 3.66 πmm·mrad.

Key words laser shaping, space charge effect, emittance, photocathode RF gun

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1 Introduction

The laser Undulator Compact X-ray source (LUCX) is a test bench for the compact high brightness X-ray generator at KEK, based on inverse Compton Scattering. In order to increase the X-ray brightness, it is essential to generate an electron beam with high charge, multi bunch, low emittance and small focusing beam size. The LUCX facility operates at challenging conditions; the operational parameters are listed in Table 1. A photo-cathode RF gun with an emittance compensation solenoid is used as an electron source. A chicane composed of 4 dipole magnets allows the laser to illuminate the surface of Cs2Te cathode perpendicularly. The electron beam from the RF gun is accelerated further by a 3-meter constant gradient S-band accelerator. Fig. 1 shows the layout of the LUCX facility.

Table 1. Operation parameters of the LUCX gun.

bunch charge	1 nC
bunch length (FWHM)	10 ps
bunch spacing	2.8 ns
bunch number per train	100 bunch
train frequency	12.5 Hz

In case of a multi-bunch train of an electron beam, the wake field excited by the anterior bunches in the gun cavity and in accelerating tube decelerates the posterior bunches. This is called a longitudinal beam

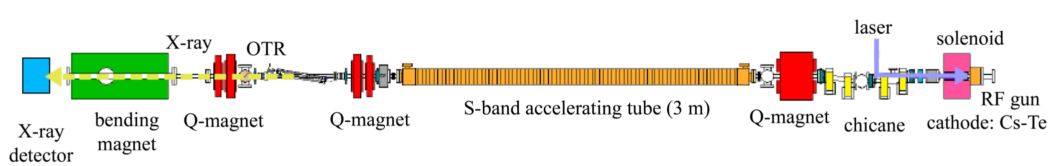

Fig. 1. Layout of LUCX facility.

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loading effect, which is very serious for a bunch train of high charge. Energy differences among bunches of the train must be compensated. Because a single klystron drives the gun and the accelerator through the RF divider and coupler, we have no other choice but to apply the ΔT method [1] to compensate the longitudinal beam loading effect. Because the bunch train is injected into the accelerating structure before the RF field builds up completely, the field gradient acting on the electron bunch is much lower than that after the RF field has built up. Space charge effects within an electron bunch must be considered carefully. We transform the driving laser profile from Gaussian into uniform shape in order to decrease the non-linear components of the space charge force. Some simulation works have demonstrated that a uniform driving laser improves the beam emittance. However, there is not enough experimental data available to evaluate how much emittance improvement could be achieved by this technology up to now. We install a laser profile shaper in the laser system to convert the driving laser from Gaussian profile into uniform profile successfully. The emittance measurement has been done with Gaussian and uniform driving lasers. We describe in this paper the optimization of the beam emittance and present our results.

2 Driving laser and π-shaper

The driving laser system is composed of a seed laser, a flash-pumped amplifier, a frequency converter and a transport system [2]. The seed laser comes from a passive mode-locked oscillator. The pulse length σ_t is 4.2 ps and the wavelength is 1064 nm at 357 MHz pulse frequency. A Pockels cell selects laser pulses to amplify through two stage flash amplifiers at a 12.5 Hz repetition frequency. A single laser pulse energy can be amplified up to 40 μJ. The pulse length becomes a little bit longer, with a FWHM of about 13 ps. A pair of nonlinear crystals converts the laser wavelength to 266 nm with a maximum pulse energy of 10 μJ. The 266 nm laser pulses are transported over a length of 13 meters from the laser room to the RF gun tunnel and injected into the Cs_2Te cathode by a mirror in vacuum, which is located 0.9 meter downstream of the cathode.

Fig. 2. Principle of the π-shaper.

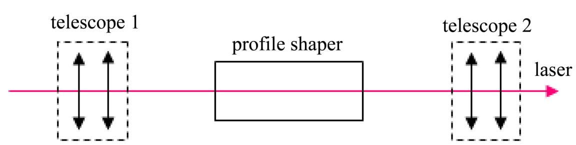

Fig. 3. Telescopes for the π-shaper.

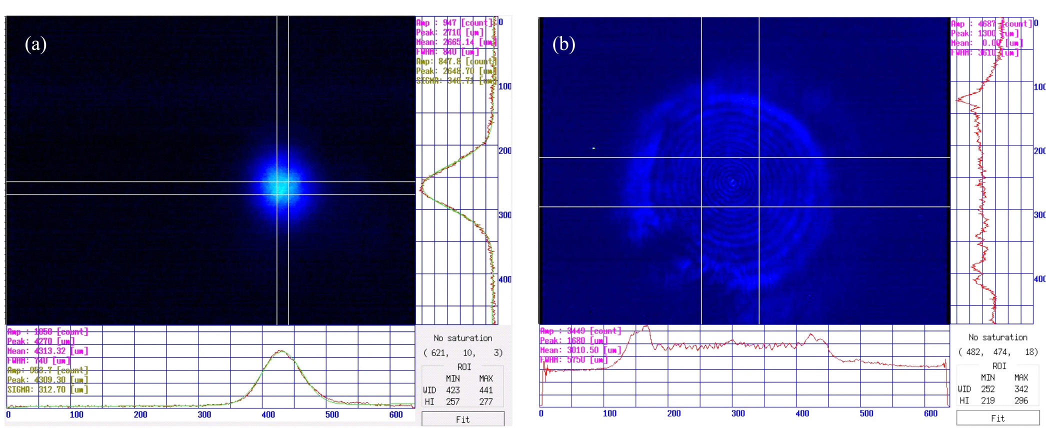

Fig. 4. Laser profile. (a) Input laser profile; (b) Output laser profile.

A π-shaper [3] (model-262,-VIS) is inserted into the transport system to transform the laser profile from Gaussian into uniform. It is an anamorphic variant of a Galilean beam-expanding telescope, with radically varying magnification. Through the shaper, laser energy distribution over the transverse cross section is redistributed without energy loss. Fig. 2 shows the principle of the π-shaper. The π-shaper requires the input laser beam at the following conditions: 4.75 mm (4σ), parallel and Gaussian profile. Therefore one telescope is installed upstream to adjust the beam size and the divergence of the input laser to satisfy the requirements. Another telescope is installed downstream of the shaper to change the laser beam size on the cathode surface for emittance optimization. Fig. 3 shows the setup of the two telescopes. Fig. 4 shows the input laser profile and the output laser profile. The transverse distribution of the laser improves greatly with less than 5% energy loss.

3 Emittance measurement and optimizing

The transverse emittance was measured downstream of the accelerator by a standard quadrupole-scan technique. The beam size was measured on an OTR screen downstream of a pair of quadrupole magnets which were varied so that the beam passed through a waist at the screen. The distance between the OTR screen and the second quadrupole magnet is 0.6 meter. The electron beam image on the screen was recorded by a CCD camera. The beam size at each quadrupole setting was measured by averaging 5 different images. The image of the background is subtracted from each image of the beam profile captured from the screen. The images were analyzed off line and the rms beam size was obtained. Finally, the RMS transverse emittance was obtained by a least-squares fitting of the beam size as a function of the inverse of the quadrupole focal length [4]. The interface of the emittance measurement is shown in Fig. 5. The RF gun generates an electron bunch with around 1 nC, which is in the space charge regime. The space charge dominates the effects diluting the beam intensity in phase space. The transverse emittance growth due to the linear space charge effect can be compensated by the solenoid compensation technology [5].

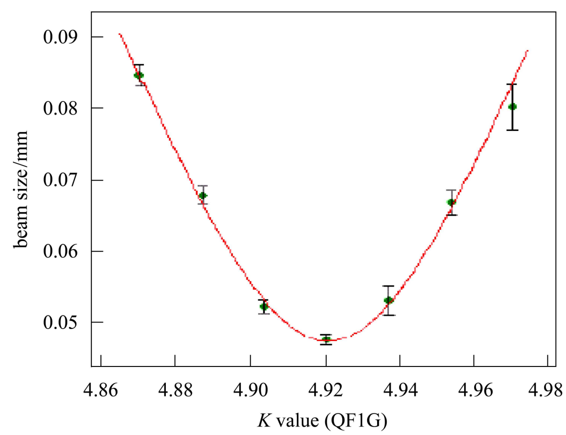

Fig. 5. Interface of the emittance measurement.

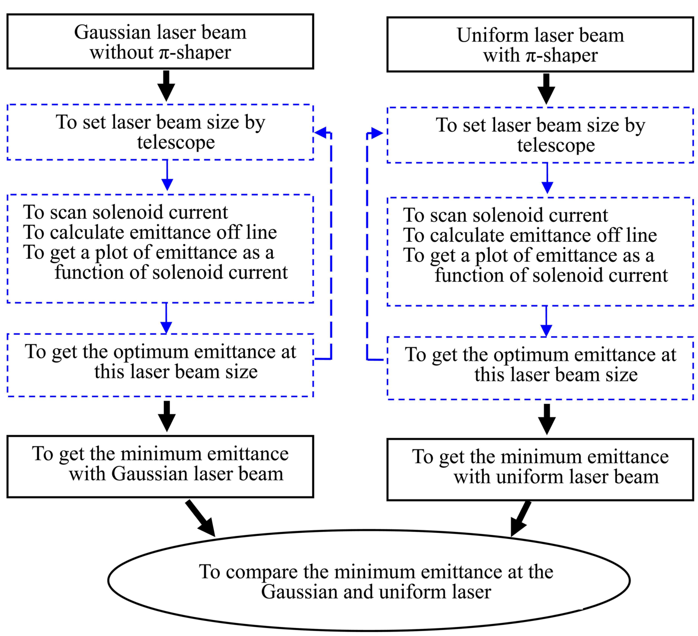

Fig. 6. Optimizing process of the beam emittance.

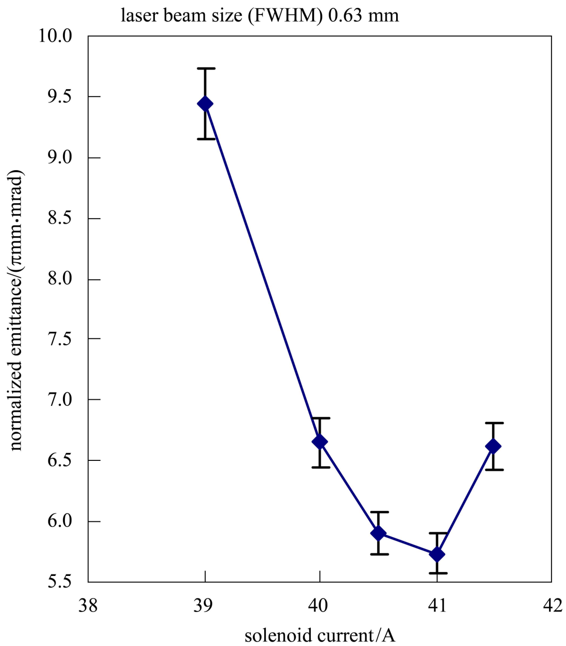

Fig. 7. Normalized emittance vs solenoid current.

However, the non-linear component of the space charge force distorts the beam ellipse distribution in phase space, and it is impossible to compensate the emittance growth due to the non-linear space charge effects by this technology. Compared with the Gaussian driving laser, the uniform laser produces an electron bunch with a smaller non-linear component of the space charge force, which means a lower emittance. Within the electron bunch with constant charge, the space charge force is related to the electron beam size. When optimizing the electron beam by the solenoid compensation technology, one should optimize the solenoid current for the electron beam at different beam sizes respectively. The emittance optimizing process is shown in Fig. 6. The RF phases in the gun and the accelerator are set to 28° and 84° respectively, which corresponds to the minimum energy spread downstream of the accelerator. All measurements are for the electron bunch of 1 nC charge.

We take the Gaussian laser case as an example to explain the process. The first step is to set the driving laser profile to Gaussian without the π-shaper. The second step is to set the laser beam size to a reasonable value. The third step is to scan the solenoid current and measure the beam emittance. In this way we get a plot of the emittance as a function of the solenoid current as shown in Fig. 7. The optimum emittance for this particular beam size can be found. The next step is to set the laser beam size to a different value and repeat the above process again and again. Finally we get by this procedure a plot of the optimum emittance as a function of the laser beam size (Fig. 8), from which the minimum emittance for the Gaussian laser case can be obtained. By the same procedure, we get the minimum emittance for the uniform laser case as shown in Fig. 9.

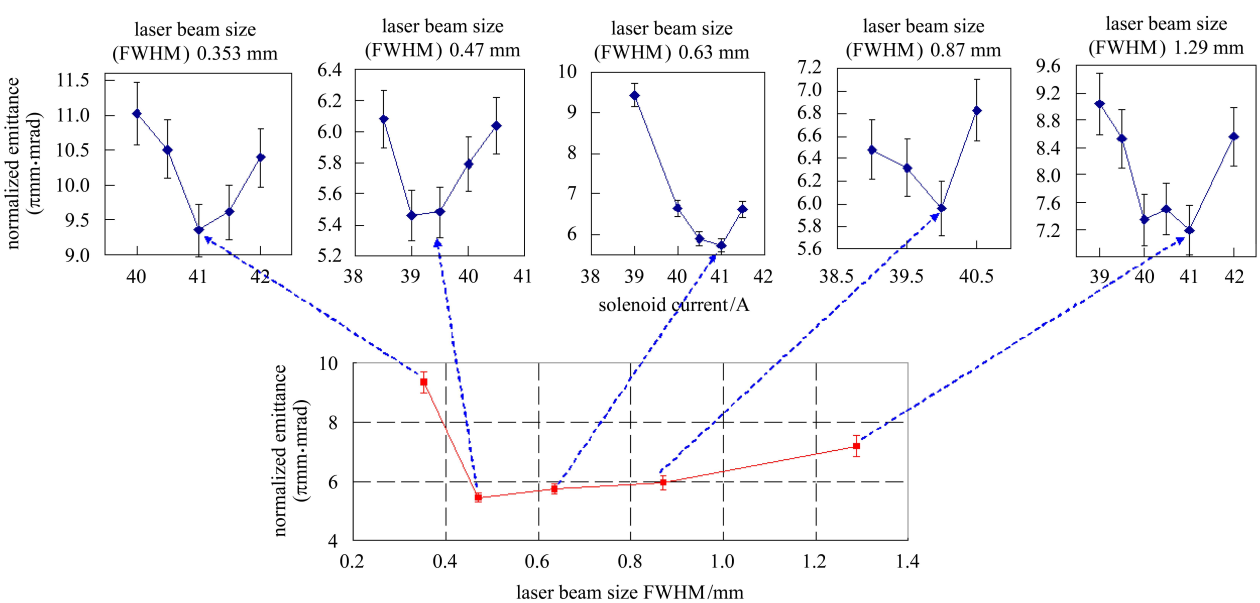

Fig. 8. Emittance compensation results of the solenoid with driving laser beam sizes (FWHM) of 0.353 mm, 0.47 mm, 0.63 mm, 0.87 mm and 1.29 mm, respectively. The lower part is a plot of the optimum emittances as a function of beam size. A minimum emittance of 5.46 mm·mrad is achieved.

Gaussian driving laser

Figure 7 is the plot of the beam transverse emittance versus the solenoid current for a bunch charge of 1 nC. The beam size (FWHM) of the Gaussian driving laser on the cathode is 0.63 mm. The optimum emittance is 5.72 mm·mrad. The error bar in the data represents the error of the least-squares fit from which the emittance is determined in the quadrupole-scan technique.

Figure 8 shows the emittance compensation results of the solenoid with driving laser beam sizes (FWHM) of 0.353 mm, 0.47 mm, 0.63 mm, 0.87 mm, 1.29 mm, respectively. The lower part of Fig. 8 shows the optimum emittance as a function of the beam size. The minimum emittance 5.46 mm·mrad is achieved with a laser beam size of 0.47 mm and a solenoid current of 39 A.

Uniform driving laser

Figure 9 is a plot of the optimum emittance as a function of the beam size. The curve with squares is for the Gaussian laser and the curve with rhombuses is for the uniform laser. A minimum emittance of 3.66 mm·mrad is achieved for the uniform laser with a laser beam size of 1.0 mm.

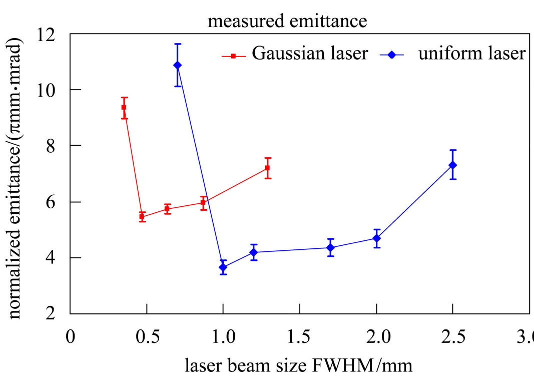

Fig. 9. Optimum normalized emittance vs laser beam size for the Gaussian and the uniform laser.

Figure 10 shows the simulation results obtained with the code ASTRA [6] and the experimental results for a uniform driving laser, which match each other to a reasonable degree. The difference originates possibly from the alignment error, because the emittance is measured at downstream of the accelerator tube. There are some alignment errors, including the error between the electric center of the RF field in the gun cavity and the trajectory of the electron beam, the error between the magnetic center of the solenoid magnet and the trajectory of the electron beam, and the error between electric center of the RF field in the accelerator tube and the trajectory of the electron beam. We tried to align all beam-line devices in the installation, but it is difficult to evaluate the actual alignment errors. The simulation doesn't take account of these alignment errors.

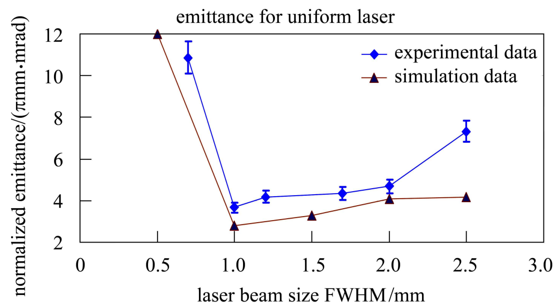

Fig. 10. Experimental and simulation results of the normalized optimum emittance VS laser beam size for the uniform laser. The curve with rhombuses shows the experimental results and the curve with triangles shows the simulation results by ASTRA.

4 Conclusions

We installed a π-shaper and set up an optical system to shape the Gaussian profile laser into a uniform profile laser in order to decrease the space charge effect for the high charge electron beam in the photo-cathode injector. By quadruple magnet and an OTR screen we measured the electron beam emittance precisely and systematically. The uniform distribution of the laser can improve the beam emittance from 5.46 mm·mrad (Gaussian laser) to 3.66 mm·mrad for the 1 nC electron bunch. The experimental results match the simulation results well.

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