MITIGATION OF THE SPACE CHARGE EFFECT FOR IMPROVING THE PERFORMANCE OF THz-CUR SOURCE*

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Abstract

A THz Coherent Undulator Radiation (THz-CUR) source has been developed at the Institute of Advanced Energy, Kyoto University. A photocathode RF gun and a chicane bunch compressor are used for generating short-bunch electron beams. In the previous study, it was found that the space charge effect was strongly degraded the beam quality such as the bunch length and energy spread at the high bunch charge condition, around 160 pC. This beam degradation resulted in the reduction of the highest frequency and the maximum intensity of THz-CUR. To mitigate the space charge effect for improving the performance of THz-CUR source, we have investigated the dependence of the electron beam quality on the parameters of laser (pulse width and transverse size) by using a numerical simulation code GPT.

INTRODUCTION

A photocathode RF gun used as electron source in a compact accelerator system at Kyoto University can provide an electron beam with high charge by injecting a UV laser with the wavelength of 266 nm to a cathode. The pulse duration of laser pulses was measured as 5.8 ± 0.2 ps-FWHM with Gaussian distribution [1]. The laser size of 0.5 mm-rms was measured at the equivalent position with the cathode surface. An electron bunch with the beam energy of 4.6 MeV is compressed by a bunch compressor chicane before passing through a planar undulator to generate an intense quasi-monochromatic THz Coherent Undulator Radiation (THz-CUR). At present, the frequency of THz-CUR can be tuned in the range of 0.16 - 0.65 THz with the bunch charge of 60 pC but with 160 pC bunch charge, the THz-CUR at 0.65 THz cannot be generated [2]. Because it was observed that the properties of the electron beam, such as the bunch length, were affected by space charge force when the bunch charge increased. The bunch length had duration of 1.11 ps-FWHM at 60 pC charge and increased to 1.36 ps-FWHM at the bunch charge of 160 pC, from GPT simulation [3].

An aim of this study is to find the way to mitigate the space charge effect. We need to study what the laser distribution is significant for bunch compression and impacts to obtain the short bunch length. In this paper, the dependence of the electron beam quality on the operation condition such as the laser injection phase, solenoid current and parameters of laser (laser pulse width and laser size) have been investigated. The results of bunch length dependence on the transverse size and pulse width of the laser induced photoelectrons from the photocathode RF gun are presented. The bunch length can be shortened by transverse truncated-Gaussian laser distributions and more better by increasing longitudinal laser pulse width. This improvement will enhance the radiated power of CUR.

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SPACE CHARGE EFFECT

An analytical model of the Gaussian beam to express the charge density referring to space charge force can be written as following equation [4]

$$\rho = \frac{Q}{(2\pi)^{3/2}\sigma_x^2 Erf\left(r/\sqrt{2}\sigma_x\right)^2 \sigma_z} e^{-((x^2+y^2)/2\sigma_x^2)-(z^2/2\sigma_z^2)} \quad (1)$$

where Q is the total charge, Erf is an error function, r is the beam radius, σ_x and σ_z are the rms beam sizes in transverse and longitudinal direction. This equation clearly shows that the charge density depends on the bunch charge (in both planes) which can be controlled by the injection laser in a photocathode RF gun.

Figure 1 shows the comparison of particle distribution at the chicane entrance between turn off and turn on space charge effect from GPT simulation [4] with the present laser distribution of our THz-CUR source. Actually, the solenoid focusing can be used especially for the compensation of the linear space charge force but cannot for the nonlinear space charge force on the cathode surface. However, the degradation of electron beam quality due to the non linear space charge force can be mitigated with the manipulation of laser distribution.

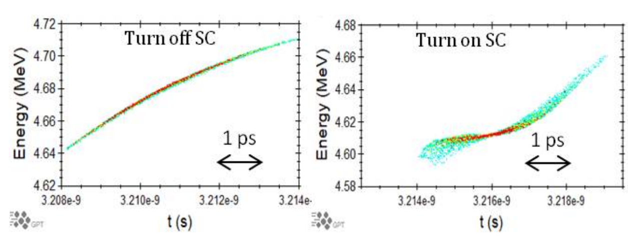

Figure 1: Longitudinal distribution at the chicane entrance turn off and turn on space charge at 60 pC charge.

The longitudinal phase space with the present distribution of a drive laser at the chicane entrance is optimized with RF phase and solenoid field to get the suitable energy chirp for compression process. Figure 2 shows the longitudinal phase space distribution given by GPT simulation in different bunch charge conditions at the chicane entrance. The laser injection phase and the solenoid field have been set to get the suitable energy chirp for the following compression process. In the following, we will manipulate the distribution of the laser profile to mitigate the space charge effect to obtain an effective compression of the bunch length.

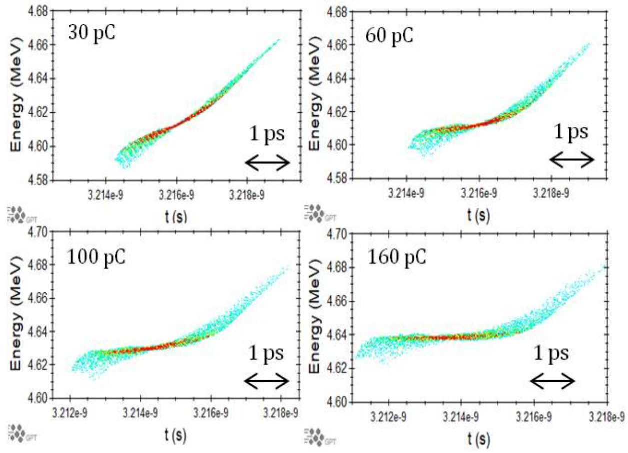

Figure 2: Energy-time phase space with space charge effect with the bunch charge of 30 pC, 60 pC, 100 pC, and 160 pC.

WAY TO REDUCE THE BUNCH LENGTH

Bunch compression with negative R_{56} Chicane

In general, the first order momentum compaction R_{56} has to match with the bunch's energy chirp h by $R_{56} = -1/h$. The energy chirp is defined by the slope of energy spread (dE) over electron position (dt), $h = dE/cdt$. Our chicane bunch compressor was designed to compress a bunch with negative linear longitudinal dispersion ($R_{56} < 0$) and positive energy chirp ($h > 0$). The energy chirp of this machine is mainly induced by the dependence of the acceleration efficiency on the electron generation timing on the cathode.

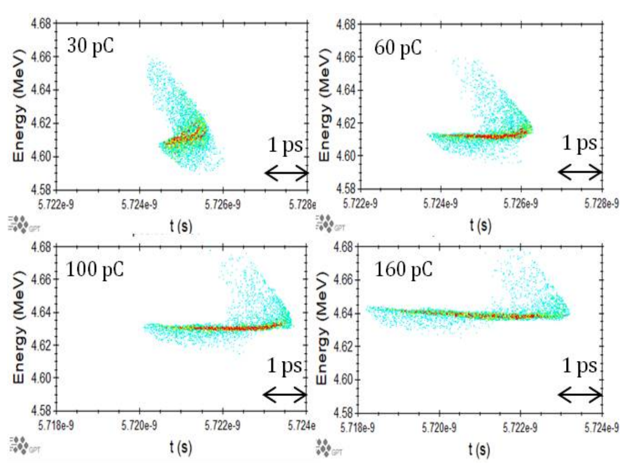

Figure 3: Longitudinal phase space after bunch compression chicane with Gaussian distribution at different bunch charge.

According to the optimization of machine condition for bunch compression at the bunch charge of 160 pC, the RF phase would be 20 and 10.5 degrees and the solenoid fields are 0.182 and 0.103 Tesla in cases of turn off and turn on the space charge effect, respectively. But it was obviously found that the particle distributions as shown in Fig. 3 are not completely rotated after passing through the chicane magnet when the bunch charge increases.

Mitigation of space charge effect

To intentionally restrain the space charge effect, the drive laser pulse of uniform in transverse and longitudinal direction at the photocathode is required to be a potential way for producing the short electron bunch length [ref]. The parameters of the laser distributions illuminating the cathode which are examined in this study are listed in Table 1. We have investigated the difference of transverse laser distribution between Gaussian, truncated-Gaussian, and uniform profile with longitudinally Gaussian distribution. Figure 4 shows the transverse truncated-Gaussian profile, which can be modified by clipping the drive laser of Gaussian profile with an aperture.

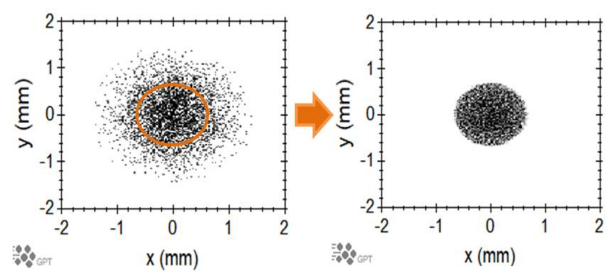

Figure 4: Transverse laser size (left) Gaussian and (right) truncated-Gaussian profile with 160 pC charge.

Table 1: Distributions of the Laser Illuminating the Cathode

Transverse laser size of 0.5 mm-rms	Laser pulse width-FWHM
Gaussian	5.8 ps and 10 ps
Truncated-Gaussian	5.8 ps
Uniform	5.8 ps

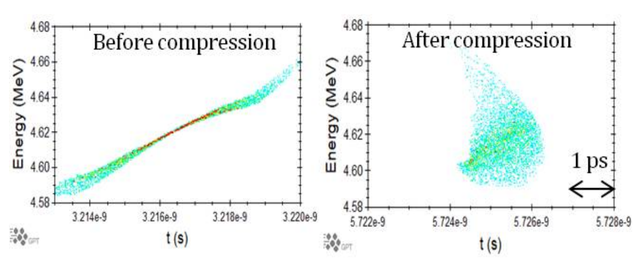

Figure 5: Longitudinal particle distributions of the beam at (left) the entrance and (right) the exit of the chicane magnet with 160 pC charge in case of truncated-Gaussian laser.

Figure 5 shows the longitudinal phase space in case of truncated-Gaussian profile. The results of compressed bunch length are summarized in Table 2. If we focus on only the shape of the transverse laser distribution, it clearly shows that the bunch length with the truncated-Gaussian laser transverse is the best compression. The simulation result of bunch length decreases from 1.36 ps to 0.88 ps with the bunch charge of 160 pC. But the uniform spatial distribution was compressed to only 1.07 ps-FWHM. It is interesting to note that, the transverse space charge force for truncated-Gaussian laser distribution may be more linear and smaller than uniform transverse profile [5].

Table 2: Compressed Bunch Length with 160 pC Charge

Laser pulse width	Transverse laser size 0.5 mm-rms	Electron bunch length-FWHM
5.8 ps-FWHM	Gaussian	1.36 ps
5.8 ps-FWHM	Truncated-Gaussian	0.88 ps
5.8 ps-FWHM	Uniform	1.07 ps
10 ps-FWHM	Gaussian	0.69 ps
10 ps-FWHM	Truncated-Gaussian	0.43 ps

When we increase the longitudinal pulse width from 5.8 ps to 10 ps-FHWM with Gaussian distribution, we can compress the electron bunch from 1.36 ps to 0.69 ps and 0.43 ps for Gaussian and Truncated-Gaussian, respectively. In case of no space charge effect with the present laser distribution of Gaussian distribution used in THz-CUR source, the length of electron bunch is compressed to 0.21 ps-FWHM, which could be the minimum bunch length available in this source.

RADIATED POWER OF THz-CUR

The improvement of performance of the THz-CUR source can be confirmed from the calculation of radiated power. The radiation peak power can be expressed by dividing the radiation energy with the radiation pulse width, $N_u\lambda_r/c$. The energy spectral for CUR is given by [6]

$$\frac{d^2W}{d\omega d\varphi} = \frac{Q^2 N_u^2 \gamma^2}{2\pi}\eta\frac{K^2}{(1+K^2+\gamma^2\theta^2)^2}\times JJ^2\left\{\frac{sin\left[N_u\pi(\frac{\omega}{\omega_r}-1)\right]}{N_u\pi(\frac{\omega}{\omega_r}-1)}\right\}^2 B(\omega)^2 \quad (2)$$

where Q is bunch charge, N_u is the number of undulator periods, K is the undulator parameter, JJ is the Bessel function, and $B(\omega)$ is the bunch form factor.

For radiated power generated from our source, it can be calculated from the 4.6 MeV electron beam and the peak undulator field of 0.43 Tesla with 10 periods. Figure 6 shows the results of relative radiated power with a quasi-monochromatic spectrum. It was obviously found that the radiated power at the first harmonic (0.17 THz) increases 21 % for truncated-Gaussian, 14 % for uniform transverse profile, and 25 % and 30 % for 10 ps longitudinal laser distribution with transverse laser of Gaussian and truncated-Gaussian distribution, respectively. All cases were compared with the power result calculated from the bunch length of laser pulse width of 5.8 ps and Gaussian transverse profile. It is well known that the bunch length has an impact on the radiation properties in the generation of coherent undulator radiation.

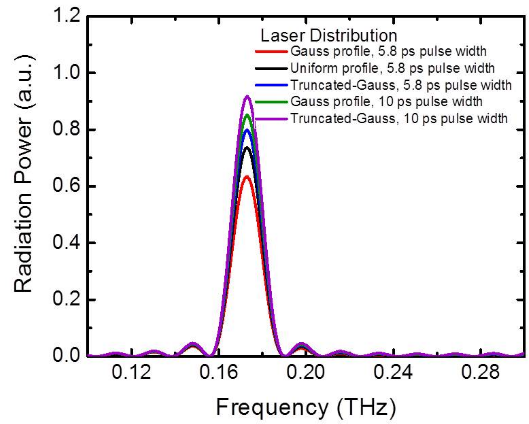

Figure 6: Radiated power with bunch charge of 160 pC as a function of frequency with the 4.6 MeV electron energy.

CONCLUSIONS

In this study, we investigated the bunch length as a function of the parameters of laser (pulse width and transverse size) by using a numerical simulation code GPT for mitigating the space charge effect. By controlling the transverse laser profile on the photocathode from Gaussian to truncated-Gaussian and uniform distributions, it was found that the best bunch compression can be obtained by truncated-Gaussian distribution. In addition, increasing in longitudinal pulse width of the laser can be an effective way to mitigate the space charge effect to achieve the shorter length of electron bunch. We will examine the truncated-Gaussian distribution in transverse direction as well as enlarge the laser pulse duration (longitudinal direction) to generate higher the radiated power of THz-CUR in experimentally.

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