ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP012

SMITH-PURCELL RADIATION EMITTED BY PICO-SECOND ELECTRON BUNCHES FROM A 30 KeV PHOTO-ELECTRON GUN

M. R. Asakawa*, S. Yamaguchi
Department of Pure and Applied Physics, Kansai University, Osaka, Japan

Abstract

A compact radiation source based on the combination of Smith-Purcell radiation and the coherent radiation emitted by the short electron beam is being developed. A photo-electron gun driven by 100 fs laser generated short pulse electron beam with a charge of 300 pC at the space-charge limitation operation. To evaluate the pulsewidth of the photo-electron beam, we developed a method based on the envelope equation. In this method, the pulsewidth was evaluated by the comparison of the measured beam radius and calculated beam radius. The result showed that while the pulsewidth increased with the beam charge, it remained shorter than 3.3 ps even at the maximum charge operation. With this electron beam, experiments to generate Smith-Purcell radiation was performed. Nonlinear dependence of the radiation energy on the charge was observed and this result indicated the occurrence of the collective radiation process.

PULSEWIDTH LENGTHENING OF PHOTO-ELECTRON BEAM

The electron gun consists of a cathode electrode held at -30 keV and a grounded anode electrode. The photo-emission surface of tungsten, 19 mm in diameter, was irradiated by a frequency-tripled Ti:sapphire laser. The pulsewidth of the laser pulse was measured to be 92 fs. The incident angle was set to be 60 degree to the normal and the ellipsoidal laser spot had an area of 1.5×3 mm^2. The irradiation energy onto the cathode was varied from 20 to 260 μJ. Further irradiance led to the unfavorable plasma formation which caused to short-circuit. The spacing between the electrodes were 10 mm. The anode electrode was a metallic disk, 14 mm in diameter, 2 mm in thickness, and had a pinhole with a diameter of 2 mm at the center. The electron passed through this pinhole moved forward to a phosphor screen located at 83 mm from the pinhole. The beam diameter was estimated from the fluorescent image and the beam charge was also measured at the phosphor screen. The pressure of the electron gun was maintained below 5×10^{-7} Pa for all experiments [1].

By irradiating a 220 μJ laser pulse, the photo-electron gun reached to the space-charge limitation [2] and electron beam with a charge of 300 pC emerged from the cathode electrode. Roughly estimated current density at the cathode surface exceeded to 20kA/cm^2, which is 700 times as dense as Child-Langmuir limitation current density. Figure 1 shows the dependence of the beam diameter on the beam charge at the phosphor plate. The maximum charge of the electron beam which passed through the pinhole was measured to be 11.6 pC when the electron gun reached at the space charge limitation operation. It is seen that the diameter increased with the beam charge up to the charge of 4 pC and remained almost constant for larger charge. This result indicates that the electron beam with the charge greater than 5 pC may increase its pulsewidth to relax the repulsive self-field.

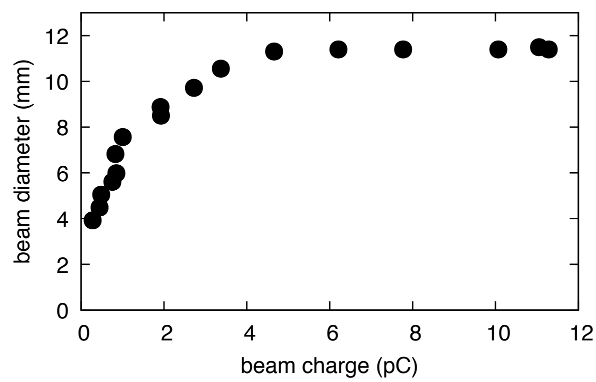

Figure 1: Dependence of the beam diameter on the beam charge.

To estimate the pulsewidth of the beam charge from the dependence of the beam radius on the beam charge shown in Figure 1, we developed a method based on the envelope equation [3]

$$\frac{d^2r}{dz^2} - \frac{K}{r} - \frac{\epsilon}{r^3} = 0, \tag{1}$$

where r denotes the radius of the electron beam moving along $z-$axis with a perviance K and an emittance ϵ. The emittance ϵ of the photo-electron beam emerged from a metallic cathode with a work function ϕ by irradiation of photons with a energy of $h\nu$ is given by

$$\epsilon = \gamma \beta \pi r \sqrt{\frac{2(h\nu - \phi)}{3mc}}, \tag{2}$$

where γ and β are the Lorentz factor and the normalized velocity of the electron beam, respectively. In our case, $\phi = 4.5$ eV and $h\nu = 4.66$ eV. The perviance K for the electron beam with an initial radius r_0, an initial current density j_0 at the pinhole and a normalized pulsewidth τ is defined as

$$K = \alpha(\tau) \frac{e j_0 r_0}{2\varepsilon_0 m (\gamma\beta c)^3}, \tag{3}$$

Here $\alpha(\tau)$ is the ratio of the transverse electric field produced by a short-pulse electron beam with a pulsewidth T to that produced by a DC electron beam, and the normalized pulsewidth τ is defined as

$$\tau = \frac{c\beta T}{r} \tag{4}$$

* asakawa@kansai-u.ac.jp

39th Free Electron Laser Conf. FEL2019, Hamburg, Germany JACoW Publishing
ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP012

Different from the DC electron beam, the short-pulse electron beam produce the electric field not only on its cylindrical side-surface but also on its both base surfaces. According to Gauss' low, thus, the transverse electric field of the short-pulse beam is weaker than that of DC beam. Parameter $\alpha(\tau)$ is introduced to take account this effect. From numerical calculations of the electric fields produced by the cylindrically distributed charges whose τ (= height/radius) range from 10^{-3} to 1, we obtain an empirical formula

$$\alpha(\tau) = 0.78\tau^{0.59}. \tag{5}$$

A particle in cell type numerical simulation stated that the pulsewidth of the electron beam lengthened significantly near the cathode electrode and remained constant after the beam passed through the pinhole. With the assumption that the pulsewidth remained unchanged during the propagation in the 83 mm-long field free drift space, the initial current density j_0 is evaluated by a charge Q measured at the phosphor plate and a pulsewidth T which functions as a calculation parameter

$$j_0 = \frac{Q}{\pi r_0^2 T}. \tag{6}$$

Here the pinhole radius r_0 = 1 mm. The estimation of the pulsewidth was carried out in the following steps.

- measure the beam charge Q_{exp} and beam radius r_{exp} at the phosphor plate.
- by using eq. (1), calculate radii r_{cal} of beams after the propagation through the 83 mm-long drift space with a charge of Q_{exp} and various pulsewidth T.
- find the best T with which r_{cal} agrees well with r_{exp}.

Figure 2 shows the dependence of the estimated pulsewidth on the beam charge. It is seen that the pulsewidth increases rapidly as the charge exceeds 5 pC and, even with the maximum charge, the pulsewidth remains less than 3.3 ps. Corresponding longitudinal spatial length of the electron beam is $0.33c \times 3.3\text{ps} = 0.327$ mm, here 0.33 is the normalized velocity of 30 kV electron. The photo-electron beam was short enough to excite the coherent millimeter-wave.

GENERATION OF COHERENT SMITH-PURCELL RADIATION USING SHORT-PULSE ELECTRON BEAM

The electron beam whose longitudinal length is shorter than the radiation wavelength can generate coherent radiation. We performed the experiment to generate the coherent Smith-Purcell radiation with the photo-electron beam. A metallic grating with a period of 2 mm was assembled just behind the pinhole so that the electron beam may graze the grating surface. Experimental setup is shown in Figure 3 and details of the grating are listed in table 1. With this grating, the resonance wavelength of the Smith-Purcell radiation is to be 4.1 mm for an observation angle of 10 degree

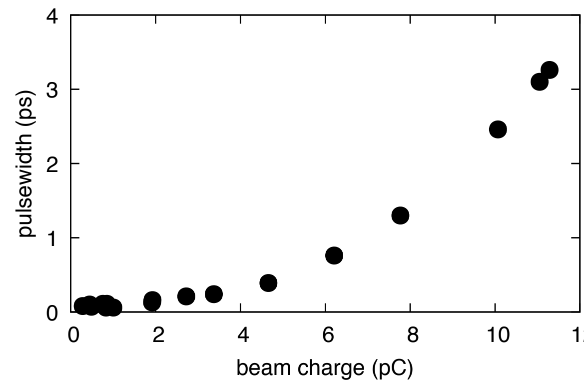

Figure 2: Dependence of the pulsewidth on the beam charge.

and is 12 times longer than the longitudinal beam length of the electron beam at the maximum charge. The radiation was outcoupled through a single-crystalline quartz window into the air and the radiation energy was measured using a bolometer. In this case, the movable phosphor plate served as a charge collector to measure the charge of the beam which had passed through the grating.

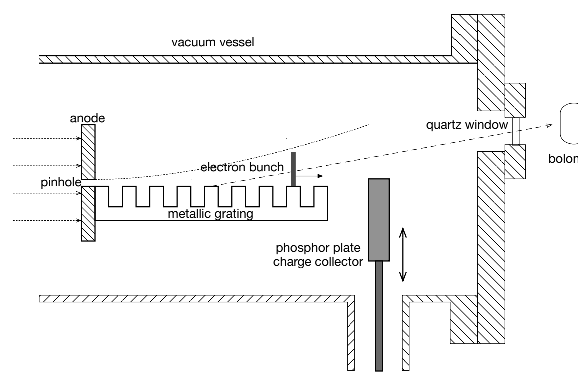

Figure 3: Experimental setup.

Table 1: Grating Parameters

period	2 mm
depth	4 mm
number of periods	20
width	5 mm

Figure 4 shows the dependence of the radiation energy on the beam charge. Due to the increase in the beam radius during the propagation along the grating surface, the half of the electron beam was scraped off, so the maximum charge was limited to 7.9 pC in this experiment. The radiation energy was proportional to 1.6th power of the charge. This nonlinear dependence is the evidence of the collective behavior of the short electron beam [4].

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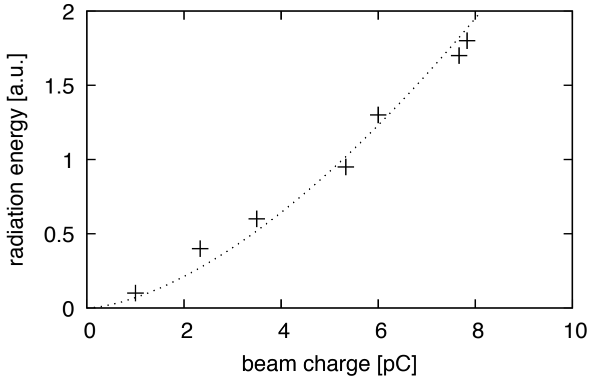

Figure 4: Dependence of the radiation energy on the beam charge. Dashed line indicates $\propto Q^{1.6}$ curve.

In an ideal situation, however, quadratic dependency should be observed. First the weaker dependency observed in the experiment may be linked to the increase in the longitudinal length of the electron beam with the beam charge. Radiation field produced by a pack of N electrons lying in the longitudinal length of $c\beta T$ is approximately expressed as

$$NE_0\left[1-\frac{1}{6}\left(\frac{\pi c\beta T}{\lambda}\right)^3\right], \tag{7}$$

where E_0 is the radiation field produced by single electron and λ is the wavelength of the radiation. In the experiments $\pi c\beta T/\lambda$ is 1/4 at most, thus the second term involving the pulsewidth lengthening effect is negligible. The other cause that should be consider may be the fact that number of electrons contributing to produce Smith-Purcell radiation is not proportional to the beam charge. Because the surface wave from which Smith-Purcell radiation originates is evanescent, only the electrons moving vicinity of the grating surface contribute to excite the surface wave. The damping length of the surface wave $\frac{1}{\alpha}$ is related to the wavenumber of the surface wave k, the wavenumber of the grating κ and the plasma frequency of the electron beam ω_p as [4, 5]

$$\alpha^2 = (k+\kappa)^2 - \frac{\omega^2}{c^2} + \frac{\omega_p^2}{c^2}. \tag{8}$$

For this experiment, $\frac{1}{\alpha} \approx 0.4$ mm. Only electrons within 0.4 mm from the grating surface, thus, contribute to the radiation process. As shown in Figure 1, the beam diameter rapidly increased from 4 mm to 11 mm as the charge increase from 0.1 pC to 4 pC. Thus the cross-sectional charge density was not proportional to the charge and rather remained constant for low charge range. We attribute the weaker dependency to this effect.

Further experiments are now under way. A terahertz time-domain spectroscopy system had been installed to measure the time-trace of the electric field of the radiation. Also combined metallic slit arrays are being developed to demonstrate the efficient outcoupling of the energy of the evanescent surface wave [6].

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