FEMTOSECOND ELECTRON BUNCH GENERATION USING PHOTOCATHODE RF GUN

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Abstract

A femtosecond electron bunch is essential for the observation of ultrafast phenomena. In order to improve the time resolution of pulse radiolysis and ultrafast electron diffraction (UED), that involve the use of an ultrashort electron bunch and ultrashort light, a femtosecond photocathode RF gun was investigated experimentally. The bunch length due to space-charge and RF effects in the gun was measured. Emittance of the femtosecond electron bunch was also measured.

INTRODUCTION

Femtosecond electron bunches on the order of 100 fs or less [1] can be used in accelerator physics applications such as free electron lasers (FELs) and laser-compton X-ray. Such electron bunches are also key elements in the study of ultrafast reactions and phenomena in time-resolved pump-probe experiments involving the application of techniques such as ultrafast electron diffraction (UED) and pulse radiolysis. The time resolutions in UED and pulse radiolysis depend on the electron bunch length. In UED, an electron bunch is used as a probe source and ultrafast phenomena, such as laser-induced phase transients, are monitored using electron diffraction patterns. Pulse radiolysis also involves the use of an electron bunch and a laser; this technique is a powerful tool that can be used for the observation of ultrafast radiation-induced phenomena involving the mechanical motions of electrons and atomic nuclei in reaction mechanisms that are studied in physics, chemistry, and biology. At Osaka University, a photocathode-based linear accelerator (linac) and a magnetic bunch compressor were constructed for femtosecond pulse radiolysis involving a femtosecond electron bunch. A picosecond electron bunch with a transverse emittance of approximately 4 mm-mrad was generated using a photocathode RF (radio frequency) gun by projecting a Nd:YLF picosecond laser onto a copper cathode. The electron bunch was accelerated up to 32 MeV by the booster linear accelerator with an optimal energy-phase correlation in the bunch (the acceleration of the bunch head was greater than that of the bunch tail) for compression of the bunch. Finally, the electron bunch was successfully compressed into femtoseconds, e.g., 98 fs in rms at 0.2 nC [2]. A femtosecond electron bunch has been used in pulse radiolysis in order to study the solvated electrons with time resolution of femtoseconds [3].

However, compressed bunch length with the picosecond photocathode RF gun and the magnetic bunch compressor is limited to ≈ 100 fs because of longitudinal emittance and the bunch length before the compression [4]. In order to obtain the bunch length of tens of femtoseconds or a few femtoseconds, a combination of femtosecond photocathode RF gun and the magnetic bunch compressor is essential because even the initial bunch length before the compression increases the compressed bunch length of the order on a few femtoseconds because of the higher-order effects such as T_{556} [5]. In order to obtain a femtosecond electron bunch in the RF gun, femtosecond ultra-violet (UV) light was projected onto the cathode. Bunch length at a gun exit was measured with a phase-scan technique [6]. Emittance at the linac exit was measured with a quadrupole-scan technique.

EXPERIMENTAL ARRANGEMENT

Figure 1 shows the experimental arrangement. A 1.6-cell S-band (2856 MHz) RF gun with a copper cathode and a Ti:Sapphire femtosecond laser was used to produce a femtosecond electron bunch. In the laser system, the mode-locked Ti:Sapphire oscillator (Tsunami, produced by Spectra-Physics Co.) was driven with an output of 800 mW at 79.3 MHz, the 36th sub-harmonic of the 2856 MHz accelerating RF. The outputs of the oscillator laser were amplified up to 0.8 mJ/pulse synchronized with a 35 MW klystron in a regenerative amplifier (Spitfire, produced by Spectra-Physics Co.). The regenerative amplifier was driven at 10 Hz and the laser pulse width is <130 fs in full-width-half-maximum (FWHM). The amplified pulse was converted to femtosecond UV light (266 nm) by the THG of nonlinear optics (TPH-Tripler, produced by Minioptic technology Co.). The maximum power of the UV was 140 μJ/pulse. The femtosecond UV light was injected into the RF gun at an incident angle of approximately 2^{o} along the electron beam direction, where the spot size was varied with an aperture and a lens. The beam energy at the gun exit was 4.2 MeV.

In bunch charge measurement, a current transformer, which was calibrated with a picoammeter, set at the gun exit was used. The femtosecond electron bunch produced by the RF gun was accelerated up to 27 MeV by a 2 m long S-band travelling-wave linac. Transverse emittance at the linac exit was measured with a standard quadrupole scan technique, in which the beam size on a YAG screen (YAG1, 100 μm-thick, produced by Ohyo Koken Kogyo Co.) was varied by a quadrupole magnet (QM). The screen was mounted at 45^{o} with respect to the electron

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beam. The electron beam profile on the screen with a background subtraction process. Rms bunch length at the gun exit was measured by a phase-scan technique [6], in which correlated rms energy spread of the electron bunch was measured. A YAG screen (YAG2) was set at 0.7 m downstream of a bending magnet (BM). The electron beam profile on the screen was acquired by a CCD camera (CCD2). The bunch length was analyzed with the dependence of the energy spread on the accelerating phase in the linac with least-squares fitting.

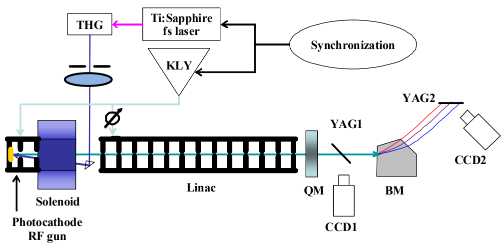

Figure 1: Schematic diagram of femtosecond electron gun measurement.

RESULT AND DISCUSSION

Bunch Charge

Figure 2 shows the bunch charge as a function of the laser injection phase. The laser energy was varied from 3 to 40 µJ/pulse with a constant laser spot size of 2 mm in diameter. The maximum bunch charge with a UV of 40 µJ was 160 pC. In this paper, the bunch charge due to space-charge and Schottky effects was studied theoretically at once. Based on the cathode surface field due to accelerating RF and decelerating field of space-charge, the bunch charge, Q, can be expressed as,

$$Q = e\frac{W_l}{h\nu}A\left(h\nu - h\nu_0 + \sqrt{\beta\left(E_0\sin(\phi_0) - \frac{Q}{2\pi\varepsilon_0\sigma_x^2}\right)}\right)^2 \quad (1)$$

where W_l is laser power, $h\nu$ is photon energy, $h\nu_0$ is work function, β is field enhancement factor, σ_x is laser spot radius, E_0 is peak RF field, and A is a constant.

The bunch charge was simulated by a numerical solution, in which the varying bunch charge balanced the left and right part in Eq. (1). The photon energy and work function were 4.7 and 4.3 eV, respectively. With field enhancement factor of 16, RF field of 90 MV/m, laser spot radius of 1 mm, and, a constant, A, of 6×10^{-6} (eV)$^{-2}$, the line was obtained by least-squares fitting. According to the parameter, QE at zero-charge and zero-field was estimated to 7×10^{-7} and the decelerating field at a charge of 160 pC was estimated to 3 MV/m, which corresponded to hundredths of the peak RF field. QE of the order on 1×10^{-5} was measured at laser injection phase of 30^{o}.

Beam Emittance

In the measurement of the emittance, a standard quadrupole-scan technique was used with the quadrupole magnet (QM) and the screen (YAG1), as shown in Fig. 1. Figure 3 (left) shows the emittance at the linac exit as a function of the solenoid field. The bunch charge was a

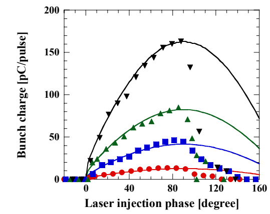

Figure 2: Bunch charge as a function of laser injection phase. The plots indicate laser power of 3, 10, 20, and, 40 µJ/pulse from the lower. The lines are simulation results according to Eq. (1)

constant of 50 pC/pulse with the spot size of 2 mm on thecathode surface. The laser injection phase was set to 25^{o} relative to the zero crossing of the RF field for the reduction of RF emittance. The energy spread of the electron bunch was minimized by the accelerating phase in the linac. The beam emittance depends on linear and non-linear space-charge effects, the RF emittance, and the thermal emittance. The error bar in the data represents the error of the least-squares fitting obtained by the quadrupole scan technique. The solenoid field of 1.75 kG compensated the transverse emittance to 1.2 mm-mrad. In the previous study of picosecond RF gun, emittance of ≈ 3.5 mm-mrad was obtained [2]. The decrease in emittance of femtosecond RF gun would be caused by the RF emittance due to the bunch length. Figure 3 (right) shows the emittance as a function of the bunch charge. The solenoid field was fixed to 1.75 kG. The increase in emittance due to space-charge effect was obtained as a rate of 0.008 mm-mrad/pC. The thermal emittance was obtained as 0.8 mm-mrad at zero-charge with a laser spot size of 2 mm in diameter on the cathode. The thermal emittance of 0.1 mm-mrad would be obtained by optimizing the laser spot size to ≈ 0.2 mm and decreasing the bunch charge.

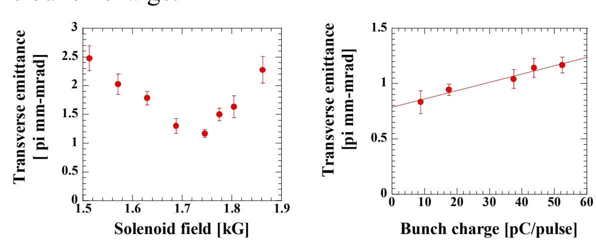

Figure 3: (left) Emittance at the linac exit as a function of solenoid field. (right) Emittance as a function of bunch charge.

Bunch Length Measurement

In the measurement of the bunch length at the gun exit, a phase-scan technique [6] was used with the 45^{o}-bending magnet (BM) and the screen (YAG2) located at 0.7m downstream of the BM, as shown in Fig. 1.The linac can give small/large energy modulation to short/long electron bunches. The correlated rms energy spread was measured by the dependence of energy spread on the accelerating phase in the linac. According to the reference [6], the energy spread can be expressed as,

$$\sigma_{dE}^2 = \sigma_{11}\left(\frac{2\pi}{360}V_l\sin(\phi_0)\right)^2 - 2\sigma_{12}\left(\frac{2\pi}{360}V_l\sin(\phi_0)\right) + \sigma_{22} \quad (2)$$

where σ_{dE} is the energy spread, V_l is the accelerating voltage in the linac. The coefficients of σ_{11}, σ_{12} and σ_{22} are the fitting parameters. The coefficient of σ_{11} corresponds to the square of the bunch length, which change the variation of the energy spread due to the accelerating phase in the linac. The longitudinal emittance, which is important for the compressed bunch length, was also analyzed with the Eq (2).

The bunch length at the gun exit depends on space-charge effect and the acceleration phase in the RF gun. Figure 4 (left) shows the rms bunch length as a function of the bunch charge. The laser spot size on the cathode was ranging from 0.5 to 2 mm. The laser injection phase was fixed to 25°. The RF field balancing the longitudinal space-charge effect was observed at low charge. At the zero-charge, the bunch length was estimated to be the laser pulse width of ≈ 200 fs. Even if the laser spot size was decreased to 1 mm, the bunch length was maintained by a low charge, e. g., 180 fs at 4 pC. The bunch length due to space-charge effect increased linearly with the bunch charge at a rate ranging from 3.4 to 25 fs/pC. Figure 4 (right) shows the longitudinal emittance as a function of the bunch charge. The longitudinal emittance, which is important parameter for a bunch compression, was also decreased at a low charge. The longitudinal emittance increased at a rate ranging from 0.03 to 0.22 deg-keV/pC. The longitudinal emittance of 0.9 deg-keV was obtained with a laser spot size of 1 mm and a charge of 4 pC.

Figure 5 (left) shows the bunch length as a function of the laser injection phase. The bunch charge was ranging from 17 to 100 pC due to a constant laser power of 36 μJ/pulse. The laser spot size was 2 mm. The bunch compression due to the lower injection phase was observed because the RF slope along the longitudinal direction became stronger close to zero-cross. Figure 5 (right) shows the longitudinal emittance as a function of the laser injection phase. The longitudinal emittance was also decreased at a low injection phase. The decrease ratio in bunch length and longitudinal emittance at the phase of 25° and 3° was tens percents due to the RF slope and the low charge. The bunch length and the longitudinal emittance were 150 fs and 0.7 deg-keV at the phase of 3°, respectively. However, because of varying bunch charge and the accelerating phase slippage in the RF gun, the bunch length and the longitudinal emittance would be complicated.

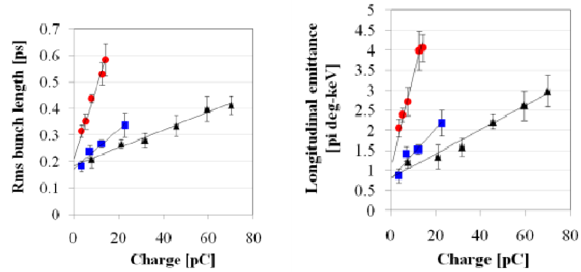

Figure 4: (left) Rms bunch length as a function of bunch charge. (right) Longitudinal emittance as a function of bunch charge. The dots, triangles, and rectangles indicate the laser spot size on the cathode of 0.5, 1, and 2 mm, respectively.

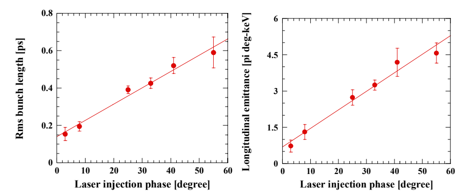

Figure 5: (left) Rms bunch length as a function of laser injection phase. (right) Longitudinal emittance as a function of laser injection phase. The bunch charge was ranging from 17 to 100 pC due to a constant laser power of 36 μJ/pulse.

CONCLUSIONS

The femtosecond photocathode RF gun was investigated experimentally. The beam of longitudinal parameters at the femtosecond RF gun exit were measured by a phase-scan technique, resulting in the bunch length of 180 fs and the longitudinal emittance of 0.9 deg-keV at a laser spot size of 1 mm in diameter and a bunch charge of 4 pC. The bunch length at zero-charge of ≈ 200 fs corresponded to the laser pulse width. The thermal emittance of 0.8 mm-mrad was obtained at a laser spot size of 2 mm, i. e., 1 mm in radius. According to the previous simulation [5], bunch length of a few femtoseconds with a bunch compression at an initial bunch length before the compression of 200 fs, a longitudinal emittance of 0.1 deg-keV and a transverse emittance of 0.1 mm-mrad. With the femtosecond RF gun and a new bunch compressor, which can compensate the second-order effect perfectly with sextupole magnets, the compressed bunch length would be tens of fs. In order to realize the bunch length of less than 10 fs, optimization of the laser spot size and the bunch charge would be essential for the thermal emittance of 0.1 mm-mrad, which reduce the longitudinal aberration increasing the compressed bunch length. The compressed bunch length will be measured by analysis of Coherent Cherenkov Radiation (CCR) or Coherent Transition Radiation (CTR).

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