ELECTRON BUNCH GENERATION FEMTOSECOND PHOTOCATHODE RF GUN

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Abstract

A femtosecond electron bunch is essential for the observation of ultrafast reactions and phenomena in materials. 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 was changed by space-charge effect and RF compression in the RF gun. Emittance of the femtosecond electron bunch was also varied by space-charge effect. Bunch charge generated in the RF gun was studied theoretically based on Schottky effect.

フェムト秒フォトカソード RF 電子銃による 電子ビーム発生

1. Introduction

Femtosecond electron bunches on the order of 100 fs or less 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 based on 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 [1]. A femtosecond electron bunch has been used in pulse radiolysis in order to study the kinetics of solvated electrons with time resolution of femtoseconds [2].

However, femtosecond electron bunch of several MeVs generated by a photocathode RF gun can be also essential in UED, pulse radiolysis, and FELs in order to observe ultrafast reactions and phenomena on the order of <100 fs. In order to generate a femtosecond electron bunch, femtosecond ultra-violet (UV) light was projected onto the photocathode RF gun. Bunch length at a linac entrance was measured with a phase-scan technique [3]. Emittance at the linac exit was measured with a quadrupole-scan technique.

2. 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), i.e., 56 fs in root-mean-square (rms). 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

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RF gun at an incident angle of approximately 2° along the electron beam direction, where the spot size was reduced to 2 mm in diameter by an aperture. The maximum of the bunch charge was 100 pC with 15 μJ of UV. The beam energy at the gun exit was 4.2 MeV.

In bunch charge measurement, a current transformer (CT), 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° with respect to the electron beam. The electron beam profile on the screen was acquired by a CCD camera (CCD1) with a background subtraction process. The emittance was analyzed with the dependence of the beam size on the inverse of the quadrupole focal length with least-squares fitting. Finally, rms bunch length at the linac entrance was measured by a phase-scan technique [3], 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 linac can give small/large energy modulation to short/long electron bunches. The bunch length was analyzed with the dependence of the correlated energy spread on the accelerating phase in the linac with least-squares fitting.

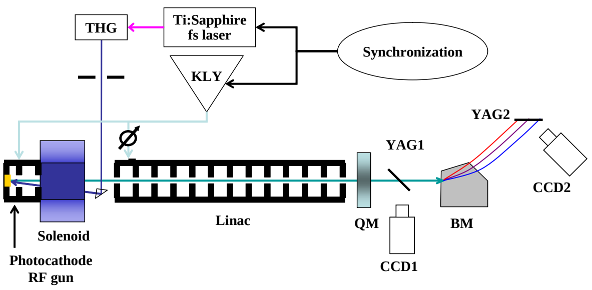

Figure 1: Schematic diagram of a femtosecond electron source.

3. Introduction

3.1 Bunch charge

Figure 2 shows the bunch charge as a function of the injection phase of the femtosecond UV light. The laser energy was varied from 3 to 20 μJ/pulse. The laser spot diameter was 2 mm at the cathode surface. The solenoid was fixed at 1.75 kG, which was optimal for emittance compensation. In this paper, the bunch charge due to space-charge and Schottky effects was studied theoretically at once. The bunch charge generated in the RF gun has been expressed with Schottky effect. Based on the Schottky effect, i. e., field emission due to effective electric field on the cathode surface, the bunch charge can be described with accelerating and decelerating field due to RF and space-charge effect. In the data, QE of the order on 1.0×10^{-5} was obtained.

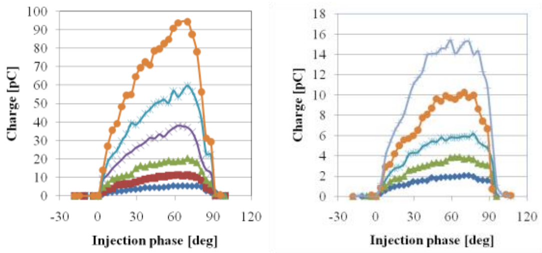

Figure 2: Bunch charge as a function of injection phase of the femtosecond UV light. In the left figure, the UV spot size and power were 2 mm ϕ and ranging from 1 to 15 μJ/pulse. In the right figure, the UV spot size and power were 2 mm ϕ and ranging from 0.5 to 4 μJ/pulse.

3.2 Beam emittance

In the measurement of the emittance, a standard quadrupole-scan technique was used with the quadrupole magnet (QM) and the screen (YAG1). Figure 3 shows the emittance at the linac exit as a function of the magnetic field of the solenoid set at the gun exit. In the data, the bunch charge was a constant of 50 pC/pulse with 16 μJ/pulse of UV. The laser spot diameter was 2 mm on the cathode surface. The laser injection phase was set to 25° relative to the zero crossing of the RF field for the reduction of RF emittance. The correlated energy spread of the electron bunch was minimized at each data by changing the accelerating phase in the linac. The beam emittance depends on linear and non-linear space-charge effects, the RF emittance and thermal emittance. In order to compensate the linear space-charge effect, the magnetic field of the solenoid was varied. The error bar in the data represents the error of the least-squares fitting obtained by the quadrupole scan technique. The best compensation minimized the emittance to 1.2 πmm-mrad at the solenoid field of 1.75 kG. Figure 4 shows the dependence of the emittance on space-charge. The emittance also depends on space-charge effect. 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.

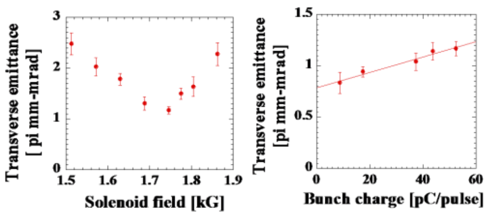

Figure 3: Emittance at the linac exit as a function of magnetic field of the solenoid (left). The laser injection phase and the bunch charge were 25° and 50 pC/pulse,

respectively. Emittance as a function of bunch charge (right).

3.3 Bunch length measurement

In the measurement of the bunch length, a phase-scan technique [3] was used with the 45°-bending magnet (BM) and the screen (YAG2), as shown in Fig. 1. The correlated rms energy spread was decided by the rms beam size on the screen, which was located at 0.7 m downstream of the bending magnet. According to the reference [3], the energy spread can be expressed as,

$$\sigma_{dE}^2 = \sigma_{11}\left(\frac{2\pi}{360}V_l\sin(\phi_0)\right)^2 - 2\sigma_{12}\left(\frac{2\pi}{360}V_l\sin(\phi_0)\right) + \sigma_{22} \qquad (1)$$

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.

The bunch length at the gun exit depends on space-charge effect and the acceleration phase in the RF gun. Figure 4 shows the rms bunch length as a function of the bunch charge. The bunch charge was varied by the driving laser power of the regenerative amplifier. The laser spot diameter on the cathode was ranging from 0.5 to 2 mm. In the data, the laser injection phase was 25°. RF compression overwhelming the longitudinal space-charge effect in the RF gun was observed at low charge, e. g., 200 fs in rms at 8 pC with the laser spot diameter of 2 mm. At zero-charge, the bunch length corresponds to the laser pulse width of 200 fs. At high charge, the bunch length increased due to space-charge effect, e. g., 400 fs in rms at 70 pC. The bunch length also increased with the smaller laser spot size due to space-charge effect at the cathode surface. However, with the low bunch charge can decrease the bunch length. The bunch length due to space-charge effect increased linearly with the bunch charge at a rate of 3.4 fs/pC with the laser spot diameter of 2 mm. Figure 5 shows the longtitudinal emittance as a function of the bunch charge. The longitudinal emittance due to space-charge effect increased linearly with the bunch charge at a rate of 0.03 deg-keV/pC.

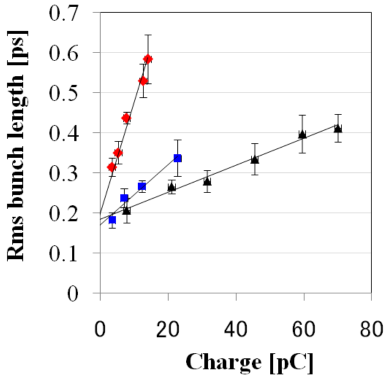

Figure 4: Rms bunch length as a function of bunch charge. The red, blue and black plots indicate the laser spot diameter on the cathode of 0.5, 1, 2 mm, respectively.

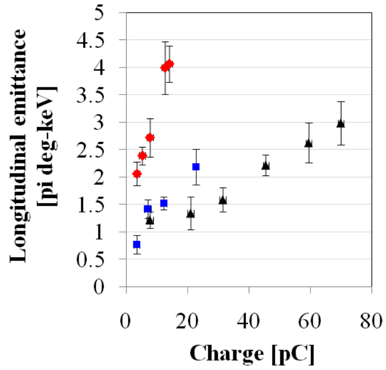

Figure 5: Longitudinal emittance as a function of bunch charge. The red, blue and black plots indicate the laser spot diameter on the cathode of 0.5, 1, 2 mm, respectively.

4. Conclusion

The femtosecond electron source based on the photocathode RF gun and the femtosecond laser was investigated experimentally. The bunch length at the linac entrance was measured with a phase-scan technique. In the condition of the laser injection phase of 25°, the RF compression overwhelming the longitudinal space-charge effect in the RF gun was observed at low charge, e. g., 200 fs in rms at 8 pC with the laser spot diameter on the cathode of 2 mm. A low longitudinal emittance of 1 deg-keV was also obtained. In order to generate an electron bunch of <100 fs and sub-femtosecond, the femtosecond electron bunch would be compressed with a magnetic bunch compressor, which can compensate the second-order effect. Furthermore, the optimization of the laser spot size and the bunch charge generate a short-bunch and low-emittance electron beam which can supress the increase in compressed bunch length and the aberration in the compression. The compressed bunch would be investigated by the analysis of Coherent Transition Radiation (CTR) with a Michelson interferometer.

References

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[3] D. H. Dowell et al., SLAC Report No. SLAC-PUB-9541, revised 2002.