FEMTOSECOND SINGLE- BUNCH ELECTRON LINEAR ACCELERATOR BASED ON A PHOTOCATHODE RF GUN

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Abstract

A femtosecond single-bunch electron linear accelerator based on a photocathode rf gun was developed in Osaka University for the study of radiation-induced ultrafast physical and chemical reactions. A 32 MeV single electron bunch with bunch length of 98 fs in rms was generated successfully with a magnet bunch compressor, and was used as pump source to study the electron-induced ultrafast reactions or phenomena by pulse radiolysis with a synchronized femtosecond laser (as a probe source). Moreover, in order to improve the time resolution and reduce the synchronized time jitter between the electron beam and the probe light, a new concept of synchronized double-decker electron beams generation in the linac was proposed. The double-decker electron beams were observed in the photocathode rf gun by injecting two laser beams which produced with a picosecond laser. The double electron beams were compressed into femtosecond by rotating the phase-space in magnetic fields.

INTRODUCTION

Ultrashort electron bunches, of the order of 100 fs, are essential to reveal the hidden dynamics of intricate molecular and atomic processes through experimentation such as time-resolved electron diffraction and femto-chemistry [1,2]. Most of electron-induced ultrafast reactions or phenomena were investigated by a time-resolved pump-probe technique (called as pulse radiolysis [3,4]). In the pulse radiolysis, a short electron bunch is used as a pump source. The electron-induced reactions are analyzed generally with a synchronized ultrashort probe light such as femtosecond lasers or radiations. A femtosecond single electron bunch with beam energy of a few tens MeV is very important to be utilized in this technique for observing information of the most basic reaction mechanisms in physics, chemistry and biology (e.g. excitation, ionization, and relaxation of atoms and molecules) on the femtosecond time scale.

However, the synchronized time jitter of a few picoseconds or a few hundreds femtosecond between the electron beam and the analyzing laser light is occurred in the pulse radiolysis due to the accuracy of the mode-locked technique in the laser and the time drift between the electron beam and the laser light. In order to realize the time resolution of pulse radiolysis into femtosecond or attosecond time region, the synchronized time jitter should be reduced. A time jitter compensation technique [3] was developed in Osaka University to improve the time resolution due to the time jitter. In the compensation technique, the time interval between the electron bunch and the laser pulse was measured by a femtosecond streak camera. However, the measured time interval was limited up to 200 fs because of time resolution of the streak camera. To reduce the time jitter between the electron bunch and the analyzing light, a new concept of synchronized double-decker electron beams generation in a photo-injector was proposed. The double electron beams with a time delay between the two beams were generated by injecting two laser beams in laser driven photocathode rf gun. After the rf gun, the beams were accelerated with a booster linear accelerator (linac), and finally compressed into femtosecond by a magnetic compressor. The front of the double bunches will be converted to Cherenkov light as a probe source, while the back is used as a pump electron bunch. The double bunches are generated by one laser. Therefore, no time jitter between the electron beam and the analysis light is caused in the presenting system.

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FEMTOSECOND SINGLE-BUNCH LINAC

The femtosecond single-bunch electron linac was constructed with an S-band (2856MHz) photocathode rf gun, a booster linac and a magnetic bunch compressor, as shown in Fig. 1. A 1.6-cell rf gun with a copper cathode, as the Gun IV type at Brookhaven National Laboratory [5,6], was used in the system. A copper cathode was used in the experiment. At the exit of rf gun, a single solenoid magnet was mounted to compensate the space charge emittance. The cathode magnetic field was measured to be less than 10G at a peak magnetic field of 3kG, resulting in a negligible emittance growth due to the cathode magnetic field.

The rf gun was driven by an all solid-state LD-pumped Nd:YLF picosecond laser. The oscillator was mode-locked with a frequency of 79.3MHz, the 36^{th} sub-harmonic of the 2856MHz accelerating rf, by adjusting the cavity length of the oscillator with a semiconductor saturable absorber mirror (SESAM). The time jitter between the oscillator output and the reference 79.3 MHz rf signal was measured to be <0.5 ps using a phase detector technique. The ultraviolet (UV) light, which was frequency quadrupled to a 262 nm using a pair of nonlinear crystals with the maximum energy of 0.3mJ, was injected on the cathode surface at an incident angle of approximately 2^o along the direction of the electron beam using a prism placed downstream of the gun.

The electron beam produced by the rf gun was accelerated up to 32 MeV with a 2 m long travelling-wave booster linac. The linac was located at a distance of 1.2 m from the cathode surface. The peak rf inputs of the rf gun and the linac were 10 MW and 25 MW, respectively, which was produced by a 35 MW Klystron. The stability of the rf power was 0.1% peak-to-peak. The effective pulse width of the rf was 4 us. The peak on axis electric fields in the rf gun and the linac were approximately 115 and 20 MV/m, respectively. The repetition rate of the operation was 10 Hz in the experiment.

The magnetic bunch compressor, as shown in Fig. 1, was constructed with two 45^{o}-bending magnets and four quadrupole magnets (two pairs), which provides the necessary path length dependence on energy. The picosecond electron bunch, which was produced in the linac with an energy-phase correlation, was compressed into femtosecond by rotating the bunch in the longitudinal phase space distribution. In order to obtain a short bunch length, all magnets were carefully installed with the minimum lattice error to reduce the aberrations in the phase space distribution. The inside two quadrupole magnets had equal magnetic fields, while the outside quadrupole magnets had equal magnetic fields. The dispersion function is symmetric on the mid-plane of the compressor. However, during the compression, higher-order momentum dispersion, especially the second-order dispersion, causes a nonlinear deformation of the longitudinal phase space, which increases the final bunch length. To reduce the nonlinear effects, we used the curvature of the rf waveform in the linac. By re-phasing the linac away from the zero-crossing of the rf (i.e. away from the linear slope), a nonlinear energy correlation along the bunch length can be introduced. The correlation can offset the effects of the nonlinear path length in the magnetic compression by optimizing the magnetic fields of four quadrupole magnets.

The compressed bunch length was obtained by measuring Cherenkov radiation emitted from the electron bunch in air at the compressor exit with a femtosecond streak camera (HAMAMATSU, FESCA-200, C6138). The optical measurement system to guide the Cherenkov radiation to the streak camera, as shown in Fig. 1, consisted of a thin Al mirror and two convex lenses with focal length of 20 cm. Its optical pass length was about 2 m. An optical band pass filter (BPF), which is centered at

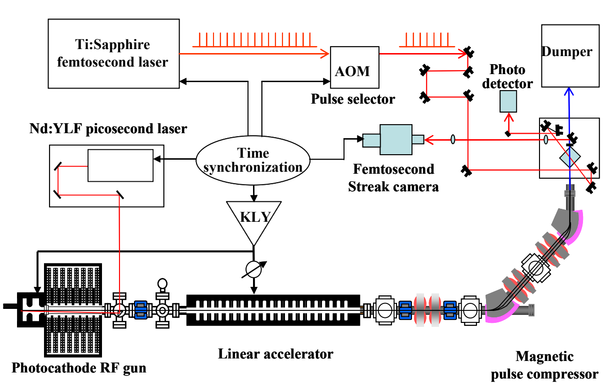

Figure 1: Femtosecond single-bunch electron linac in Osaka University.

480 nm and has a band width of 11 nm in FWHM, was used to reduce the radiation pulse broadening due to optical dispersion. A 15 um-wide slit in the streak camera was used in the measurement to avoid the pulse broadening due to space charge effect in the camera. The time resolution of the streak camera under the measurement time region of 20 ps was 183 fs in FWHM and 78 fs in rms.

Figure 2 gives a plot of the rms compressed bunch length versus the bunch charge. The bunch lengths were measured under the constant linac phase of 94 ^{o}, but the four quadrupole magnetic fields were optimized to obtain the minimum bunch length at each charge. The minimum bunch length was obtained to 98 fs in rms at bunch charge of 0.17nC.

The dependence of the bunch length (σ_z) versus the bunch charge may be described as

$$\sigma_z = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}\,, \qquad (1)$$

where σ_1 versus the bunch charge may be described as represents the increase of bunch length caused by the longitudinal emittance growth in the rf gun due to the space-charge effect, σ_2 is the increase of bunch length due to the space charge effect during the compression, and σ_3 is the bunch length increase which is independent on the bunch charge. According to the analytical model [7]

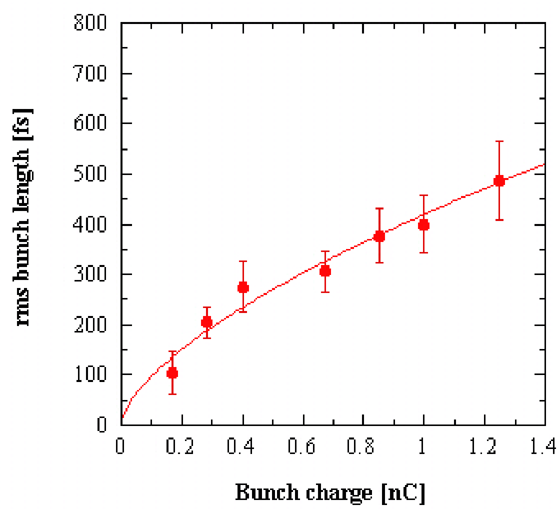

Figure 2: Bunch length vs. bunch charge.

which the longitudinal emittance in the rf gun due to the space-charge effect is linearly dependant on the bunch charge (Q), we can write $\sigma_1 \propto \sqrt{Q}$. The bunch length increase due to the space charge effect during the compression may be described as $\sigma_2 \propto Q$. Then, we can rewrite Eq.1 as

$$\sigma_z = \sqrt{aQ + bQ^2 + \sigma_3^2}\,, \qquad (2)$$

where a and b are parameters which are independent on the bunch charge. By fitting the data in Fig.2, we obtained that a=(1.2+/-0.2)x10^5, b=(5.5+/-0.4)x10^4 and σ_3=2+/-1fs. The data indicated that, if Q>1nC, the increase of bunch length is dominated by the space charge effect in the bunch compression. The increase of bunch length at Q<1nC is occurred with the longitudinal emittance growth due to the space charge effect in the rf gun. The increase of bunch length, which is independent on the bunch charge, is negligible.

DOUBLE-DECKER ELECTRON BEAM ACCELERATOR

To generate synchronized double-decker beams in the linac system, the incident UV light pulse was divided into two pulses (beams) by a beam splitter. One was guided into an optical delay to produce a time delay between the two pulses. The time interval of the two pulses should be the integral multiple of 350ps, because the rf gun is operated by 2856MHz (1period=350ps) rf. The time delay was adjusted to 1.4ns in the experiment. Finally, the double UV light beams were injected on the cathode surface at an incident angle of approximately 2^o along the direction of the electron beam using the prism placed downstream of the gun. The diameter of the beam size at the cathode surface was 1 mm for both the beams.

Figure 3 shows the profiles of the double-decker electron beams at the exits of the rf gun, the linac and the bunch compressor. The beam profiles at the exit of the bunch compressor were measured in air. The double-decker electron beams were successfully generated by the rf gun and accelerated by the linac. The spot sizes of the two beams downstream of the linac were about 1 mm in diameter. The distance between the centers of the two beams was 2.6 mm. In the measurement, the solenoid magnetic field was fixed to 1.75 kG for the best space-charge induced emittance compensation as described below, resulting in the increase of the beam size and the distance between the two beams at the exits of the rf gun. The increase of the beam size of both the beams after the bunch compression was due to scattering of the electrons with the 20 um-thick titanium vacuum window downstream of the compressor.

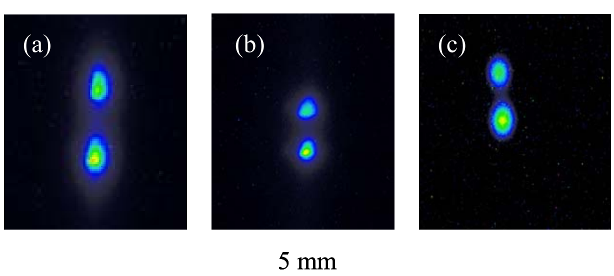

Figure 3: Double-decker electron beam profiles at exits of the rf gun (a), the linac (b) and the bunch compressor (c).

The electron charge and time interval between two beams were measured by a beam current transformer downstream of the linac. Figure 4 gives the outputs of the current transformer. The solid line represents the output of the double-decker bunches, while the dashed line is the output of the back electron bunch only without the front bunch by shutting the front laser beam. The back signal of the outputs with time of >2 ns in Fig. 4 was a noise caused by the impedance mismatch in the current transformer. The data shows that the time interval of the double-decker electron bunches was 1.4 ns, which is equal to four periods of the accelerating 2856 MHz rf. It indicates that the two electron beams were generated in the rf gun and accelerated in the linac with a same rf phase. The charge of the front bunch (down-beam) was measured to be 0.65 nC and 0.47 nC for the back bunch (up-beam). The different charge of the two bunches was due to the power difference between the double laser beams produced in the beam splitter.

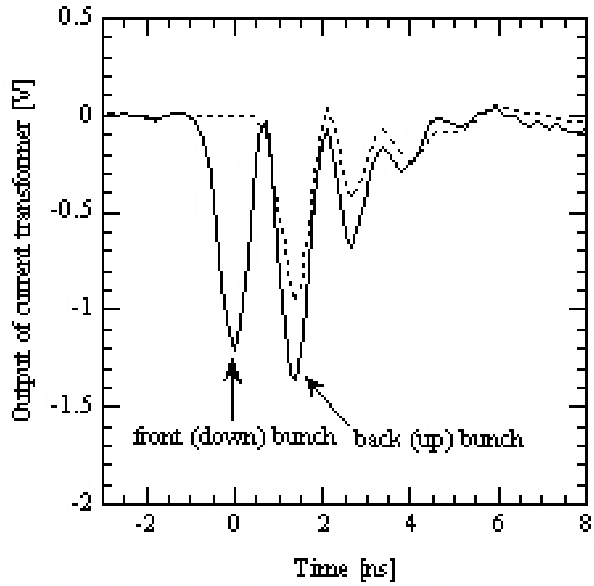

Figure 4: Outputs of the current transformer.

The normalized transverse emittance of both the beams downstream of the linac was obtained to 2.5+/-0.6 mm-mrad for the up beam and 3.6+/-0.7 mm-mrad for the down beam. The minimum relative energy spread was 0.1+/-0.03% for the two beams. The compressed bunch length was obtained to 430+/-25 fs for the up bunch and 510+/-20 fs for the down bunch. The different emittance and different bunch length of the double beams were almost caused by the different bunch charge. However, the space-charge emittance compensation may not be optimal at the down beam, because the electron charge of the down beam is larger than that of the up beam.

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