GENERATION OF DOUBLE-DECKER FEMTOSECOND ELECTRON BEAMS IN A PHOTOINJECTOR

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Abstract

Femtosecond electron beams are practical sources in the pump-probe experiment for studies of ultrafast physical/chemical reactions in materials, in which a femtosecond electron bunch is used as a pump source and a mode-locked ultrashort laser light is used as a probe source. The synchronized time jitter between the electron beam and the laser light limits the time resolution in the experiment. In order to reduce the time jitter, a new concept of synchronized double-decker electron beams generation in a photo-injector was proposed. The double electron beams were observed in a photocathode RF gun by injecting two laser beams which produced with a picosecond laser. The double electron beams were compressed into 380 fs in rms with a phase-space rotation technique in magnetic fields. The beams, which one is used as a pump source and another is used as a probe source, are expected for ultrafast reaction studies on femtosecond scale.

INTRODUCTION

Development of a pump-probe measurement technique in the femtosecond or attosecond scale is important for the study of a dynamic process involving the mechanical motion of electrons and atomic nuclei in physics, chemistry and biology. A pulse radiolysis, which is pumped by an ultrashort electron beam and analyzed by an ultrashort light, is a powerful tool for the observation of ultrafast electron-induced phenomena in materials, such as ionization, excitation, relaxation, electron transformation and so on. The time resolution of the pulse radiolysis has reached to picosecond by using a picosecond electron pulse. In Osaka University, a pulse radiolysis with a time resolution of 800 fs was developed by using a femtosecond electron pulse produced in an L-band linear accelerator, an analysis femtosecond laser light, and the time jitter compensation between the electron pulse and the laser light[1,2].

To improve the time resolution into femtosecond and attosecond, the developments of the three technologies are required: (1) an ultrashort electron bunch, (2) an ultrashort analysis light source, and (3) precise synchronization between the electron pulse and the analysis light. Recently, an ultrashort electron bunch with bunch length of <100fs was generated with a photo-injector in Osaka University [3]. However, the synchronized time jitter between the electron beam and the analysis laser light limits the time resolution in the experiment. In order to reduce the time jitter, 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) up to about 32 MeV with an optimal energy-phase correlation in the bunch for the best compression in magnetic field. Finally, the electron bunches were compressed into femtosecond by transporting it through the magnetic field, which rotates the bunch in the longitudinal phase space distribution. 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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EXPERIMENTAL ARRANGEMENT

The new concept of synchronized double-decker electron beam generation system was shows in Fig. 1(a). A 1.6-cell S-band (2856MHz) RF gun, as the Gun IV type at Brookhaven National Laboratory (BNL) produced by Sumitomo Heavy Industries (SHI)[4,5], was used for the double-decker electron beam generation. The RF gun was composed of two cells: a half cell and a full cell. The length of the half cell was designed to be 0.6 times the full cell length to reduce the beam divergence. The coupling between the waveguide and cavity was located in the full cell. Coupling between the cells was accomplished via the iris of the cavity. The copper cathode used in the system was located on the side of the half cell. A single solenoid magnet was mounted at the exit of the RF gun 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 laser consisted of a laser oscillator, a regenerative amplifier, and a frequency converter. The oscillator was mode-locked with a frequency of 79.3MHz, the 36th 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. After the oscillator, a Pockels cell captured a single oscillator laser pulse to amplify the pulse energy up to about 2 mJ in the regenerative amplifier. The repetition rate of the regenerative amplifier is 30 Hz in the maximum. The amplified pulse was frequency quadrupled to a 262 nm ultraviolet (UV) light with maximum pulse energy of 0.3 mJ using a pair of nonlinear crystals.

The UV light was divided into two by a beam splitter. The time interval of the two pulse 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 by guiding one laser beam into an optical delay. Finally, the UV light 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, as shown in Fig.1(a). The diameter of the beam size at the cathode surface was 1 mm for both the beams. The pulse width of the UV light was measured to be 5 ps in FWHM by a streak camera.

The electron beam produced by the RF gun was accelerated with a 2 m long S-band travelling-wave linear accelerator (linac). The linac was located at a distance of 1.2m from the cathode surface. The energy of the electron bunch was also modulated by adjusted the RF phase for bunch compression, as described below. The operating temperatures of the RF gun and the linac were 32^{o}C and 30^{o}C, respectively. The temperature fluctuation of both the RF gun and the linac were within 0.1^{o}C.

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 μs. 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. A high-power phase shifter installed in a 30 MW RF line, as shown in Fig. 1, was used to adjust the RF phase of the linac for energy modulation.

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. The details are described in ref. [3].

RESULTS AND DISCUSSIONS

Figure 1(b) shows the beam profiles of the double electron bunches 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 profiles show that the double electron beams were generated in the rf gun and accelerated in the linac with same distance between two beam, which was called double-decker beam. However, the operation of the bunch compressor may be not optimal, resulting in the distance increase between the two beams at the exit of the compressor.

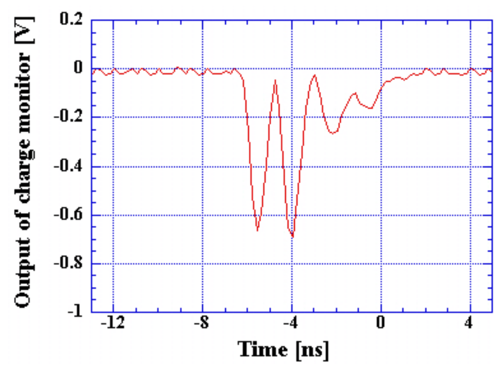

Figure 2: Output of charge monitor downstream of the linac.

Figure 2 gives the signal output of a charge monitor downstream of the linac. The time interval of the double electron bunches was about 1.4 ns. The charge of the front bunch (down-beam) was 0.62 nC and 0.55 nC for the back bunch (up-beam). The different charge was almost caused with the different energies of the double laser beams, which were produced in the beam splitter.

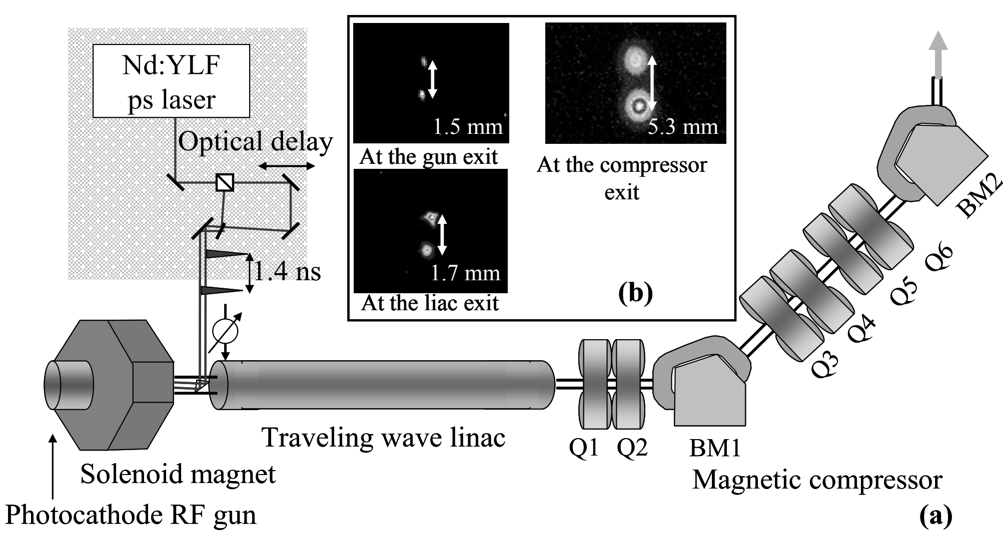

Figure 1: Generation system of double-decker electron beams using a photocathode rf gun.

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We also measured the energy spread of the double beams downstream of the linac by using the first 45°-bending magnet and a 30 μm-thick screen which was made of sintered Al_2O_3 doped with Cr and mounted on the midplane of the compressor. The distance from the exit of the bending magnet to the screen was 0.74 m. A quadrupole magnet, installed at the exit of the linac and upstream of the bending magnet, was used to reduce the energy spread growth due to the dispersion function. The resolution of the relative energy spread in the measurement was 0.01% in rms. Figure 3 shows the dependences of the relative rms energy spread on the linac phase. The rf phase in the rf gun was fixed to 30° off zero-crossing rf phase to produce a low-emittance beam. The data shows that the minimum relative energy spread was observed at the linac phase of 86°, 0.08% for the up-beam and 1.2% for the down-beam. The maximum beam energy was 31.8 MeV after the linac.

The transverse emittance was measured downstream of the linac and upstream of the bunch compresor with a standard quadrupole scan technique. Figure 4 gives the plot of the normalized rms transverse emittance versus the solenoid magnetic field. The rf phase in the rf gun was fixed to 30° and 86° in the linac. The lowest emittance was obtained at the solenoid magnetic field of 1.75 kG, 2.5 mm-mrad for the up-beam and 3.6 for the down-beam. However, the different emittance of the double bunches was almost caused by the different bunch charge. The space-charge emittance compensation was not optimal at the down-beam. In the quadrupole scan measurement, both the beams were about 0.9 mm away from the center axis of the quadrupole magnet. It results the emittance increase in the measurement. The emittance of the beam should be lower than the measured data in Fig. 4.

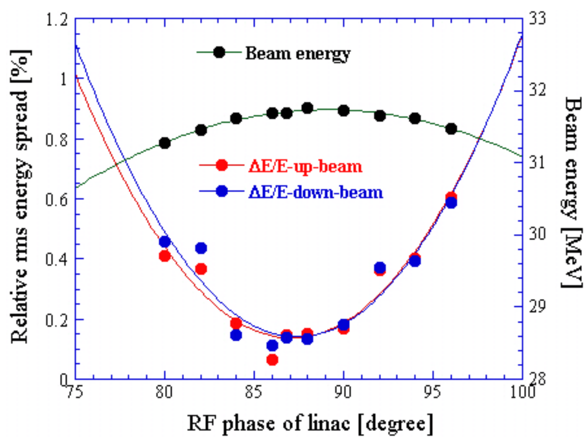

Figure 3: The relative energy spread of the beams as a function of the linac phase.

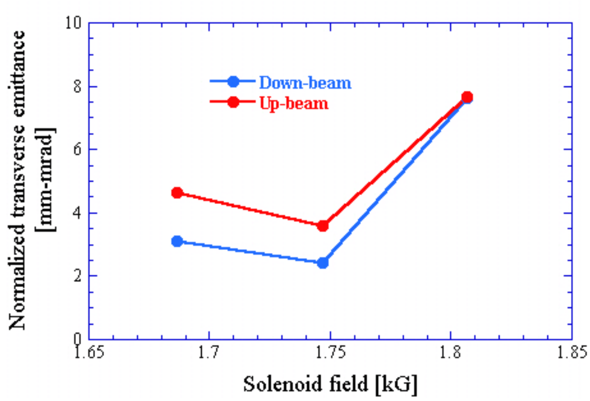

Figure 4: The normalized emittance of the beams as a function of the linac phase

Figure 5 gives a temporal distribution of the front bunch (i.e. up-beam) measured by the streak camera. The details of the measurement were described in ref. [3]. In the measurement, the linac was re-phased at 94° off crest of the rf waveform, which was the optimum phase for the shortest bunch length. The rf phase of the gun was fixed at 30°. The rms bunch length was obtained to be 380 fs by fitting the bunch shape to a Gaussian distribution.

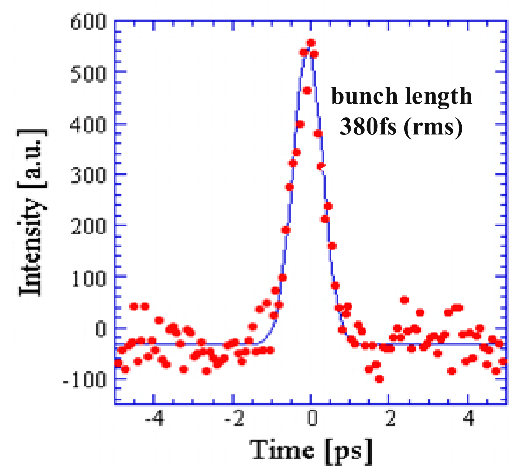

Figure 5: The temporal distribution of the front bunch (up-beam) measured by the streak camera.

CONCLUSIONS

A new concept of synchronized double-decker electron beams generation in a photo-injector was proposed. The double-decker electron beams with time interval of 1.4 ns were observed in the photocathode RF gun by injecting two laser beams which produced with a picosecond laser. The relative energy spread of the double beams downstream of the linac was measured as a function of the linac phase. The normalized emittance of the double beams was obtained at different solenoid field. The double electron beams were compressed into 380 fs in rms with a phase-space rotation technique in magnetic fields. The beams, which one is used as a pump source and another is used as a probe source, are expected for ultrafast reaction studies on femtosecond scale.

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