PULSE RADIOLYSIS USING DOUBLE-DECKER FEMTOSECOND ELECTRON BEAM FROM A PHOTOCATHODE RF GUN

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Abstract

Double-decker pulse radiolysis (DDPR), which utilized double-decker electron beams, was investigated for a new pulse radiolysis with a high time resolution. The double-decker electron beams were generated by injecting two UV lights to a photocathode radio-frequency (RF) gun. In the pulse radiolysis, one electron beam was used for a pump beam; the other, a conversion to a probe light. Finally, the first DDPR was demonstrated successfully, resulting in an observation of solvated electrons in water with a 10-90% rise time of 8.6 ps.

INTRODUCTION

Pulse radiolysis, which utilizes a pump electron beam and a probe light, is a powerful tool that can be used for the observation of ultrafast radiation-induced phenomena involving the mechanical motion of electrons and atomic nuclei in reaction mechanisms that are studied in physics, chemistry, and biology. Pulse radiolysis with a high time resolution, which will be developed in the future also, would give a more comprehensive understanding of ultrafast phenomena for not only monitoring but also controlling the radiation-induced phenomena. However, the time resolution of the pulse radiolysis is limited by the pulse widths of the electron beam (pump source) and the probe light, the velocity difference of the both due to a refractive index of a sample, and the synchronized time jitter between the both [1].

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 [2]. In the linac, a picosecond electron beam was generated using a photocathode RF gun and a driving laser of Nd:YLF picosecond UV laser. The picosecond electron beam was accelerated up to 32 MeV by a booster linac with an optimal energy-phase correlation for compression. Finally, the electron bunch was successfully compressed into femtoseconds, e.g., 98 fs in rms at 0.2 nC [2]. As the result, a combination of the femtosecond electron beam and a femtosecond laser realized pulse radiolysis with femtosecond time resolution, e. g., ≈230 fs due to the pulse widths of the both. For improving the synchronized time jitter between a pump beam and probe light, double-decker electron beams, which are used for a pump beam and probe light, were generated by two UV lights of the driving laser [3]. Double-decker pulse radiolysis (DDPR) based on the beams would improve the synchronized time jitter because RF synchronization between a pump electron beam and a probe laser is not required.

In this paper, the double-decker pulse radiolysis (DDPR), which utilized double-decker electron beams, was investigated for a new pulse radiolysis with a high time resolution. The double-decker electron beams were generated by two UV lights and the photocathode RF gun for the pump beam and probe light in the pulse radiolysis measurement.

EXPERIMENTAL ARRANGEMENT

Figure 1 shows the DDPR including a laser injection system, the photocathode RF gun linac, and a pulse radiolysis system from the upstream. In the laser injection system, Nd:YLF picosecond laser was used as a driving laser for the photocathode. The output of the picosecond laser was 200 μJ/pulse of UV (262 nm) at 10 Hz. The pulse width of the UV light was measured to be 5 ps in FWHM using a femtosecond streak camera. The UV light was separated by a beam splitter (BS) for the generation of the double-decker electron beams. The temporal separation of the two UV lights was adjusted by an optical delay (OD1). The interval of the two lights was set to 4.2 ns, which corresponded to 12 periods of S-band RF (2.856 GHz, 1 period: 0.35 ns) because of a similar condition of an accelerating field in the RF gun. Furthermore, the spatial separation was also adjusted by mirrors with actuators. The two UV lights were directed to the photocathode RF gun linac. The linac consisted of a 1.6-cell S-band RF gun with a copper cathode, a 2 m-long traveling-wave linac, and a magnetic bunch compressor, of which details are discussed in references [2]. In order to generate the double-decker electron beams, the two UV lights were injected onto the photocathode. The incident angle of the lights was ≈68° along the direction of the electron beam for an increase in a beam charge. The UV lights on the cathode were arranged almost horizontally because the double-decker electron beams were rotated azimuthally due to a longitudinal magnetic field of a solenoid magnet at the gun exit. The double-decker electron beams were accelerated in the gun and the linac using a 35-MW klystron. The beam energy at the gun exit was ≈4 MeV at a laser injection phase of 30° according to a measurement using a dipole section and screen. In the linac, the electron beams were accelerated up to 32.7 MeV. The total beam charge of 1.4 nC was generated by the UV light of 200 μJ/pulse at a laser injection phase of 30°. In the experiment, the linac phase was set to 85° for minimum energy spread of the beams from a viewpoint of transportation. The beams travelled through the magnetic bunch compressor for the pulse radiolysis system. The pulse widths of the double-decker beams were estimated to be ≈1 ps in rms according to the linac phase condition

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[2]. Finally, the double-decker electron beams were used in the pulse radiolysis system. The front electron beam of the double-decker beams was converted to a probe light by Cherenkov radiation in the air. The path length for Cherenkov radiation was set to 280 mm for enough intensity of the light, which depends on the path length [4]. The probe light travelled through an optical delay (OD2) in order to measure a time-resolved transient absorption in a sample. The back electron beam, which was used as a pump electron beam, reached the sample at a delay of 4.2 ns with respect to the front beam. The probe light was injected to the sample after travelling through a long path. The spatial distance between the paths for Cherenkov radiation and the pump beam was set to ≈5 mm in the vertical direction to avoid the beam for the probe light traveling through mediums, e. g., mirrors and the sample as shown in Fig. 1 (a). The intensity of the probe light, which decreased due to a transient absorption in the sample caused by the back beam, was monitored by a silicon avalanche photodiode (APD, S2382, Hamamatsu Photonics K. K.) through an optical fiber. The APD was driven by a bias voltage of 60 V. The waveforms from the APD were measured by an oscilloscope (6100A, LeCroy Co.). Shutters (S) controlled the generation of the front/back electron beams for the probe/pump sources individually.

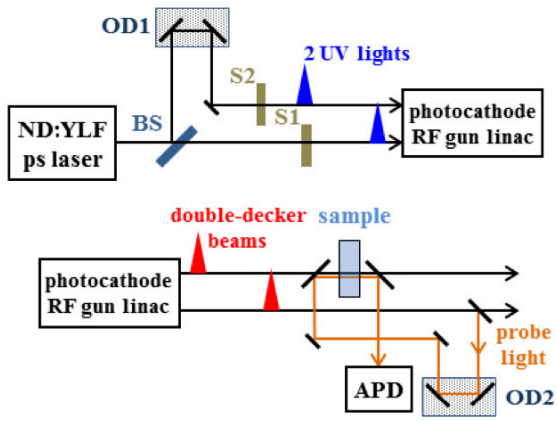

Figure 1: Laser injection system (top) and pulse radiolysis system (bottom) in DDPR. BS denotes a beam splitter; S, a shutter; OD, an optical delay.

RESULTS AND DISCUSSIONS

Generation of Double-decker Electron Beams

Figure 2 shows the spatial and temporal separations of the double-decker electron beams. Figure 2 (a) shows the spatial separation at the sample position measured by a screen. The distance between the beams was adjusted to ≈5 mm because of the geometry of the sample and conversion to the probe light with Cherenkov radiation. The spatial distances between the double-decker electron beams at the gun exit and the linac exit were 7.8 and 6.6 mm, respectively. The distance was not constant because the beams travelled through magnets and RF cavities, which focused or defocused the beams. The back (top)/front (bottom) electron beams were used for the pump/probe sources. Figure 2 (b) shows the temporal separation measured by a current-transformer (CT) at the gun exit. In adjusting the temporal separation, the energies of the beams at the linac exit were set to the same by the optical delay (OD1) in the laser injection system. The beam energies were measured by a bending magnet and screen. The interval of the double-decker electron beams was measured to be 4.2 ns. The electron bunch charges were 0.74 (front) and 0.62 (back) nC according to the CT sensitivity of 0.35 nC/V peak-to-peak.

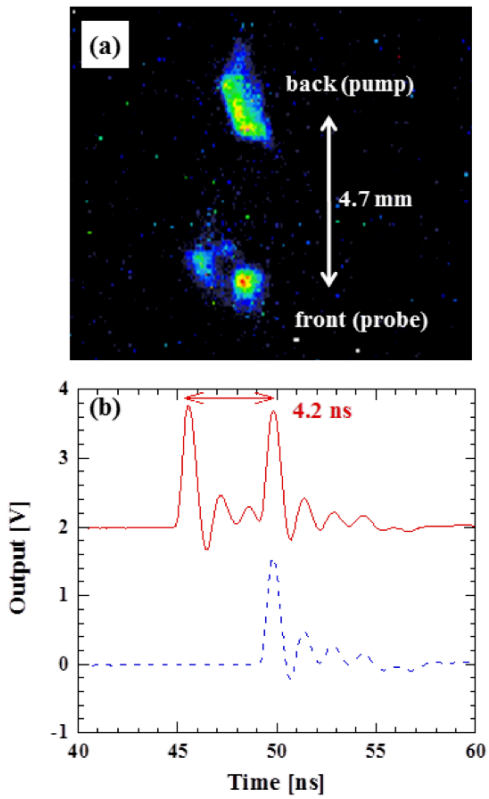

Figure 2: (a) Spatial separation of the double-decker electron beams at the sample position. The back (top)/front (bottom) electron beams were used for the pump/probe sources. (b) Temporal separation at the gun exit with only offsets adjusted for comparison. Waveforms for cases using the two UV lights (solid line) and using one UV light for the back beam (dotted line) are shown.

First Double-decker Pulse Radiolysis

Figure 3 shows the first DDPR measurement. A water sample with a thickness of 10 mm was used. Figure 3 (a) shows the photodiode outputs (peak to peak) as a function of the optical delay (OD2) in the pulse radiolysis system with a band-pass filter (BPF) of 800±20 nm. Each data corresponds to the conditions of the shutters (S1, S2); i.e., *LB*, *L*, and *B* denotes the front/back electron beams of On/On, On/Off; and Off/On, respectively. The BPF was

set upstream of the optical fiber in order to select spectral information. Only when the probe light goes through the sample after the pump beam, a light absorption due to the solvated electrons generated by the pump beam occurs. As the result, the plot for *LB* decreased at a time of ≈0 ps because of the light absorption. The intensity for *B*, which corresponded to Cherenkov radiation by the pump beam in the sample, could not be ignored because of the intensity for *L*. In evaluation of the transient absorption according to the Lambert-Beer law, an optical density, *O.D.*, was estimated as $\mathrm{O.D.} = Log(I_0/I) = Log(L/(LB-B))$, where I_0 denotes the intensity of the probe light without the pump beam; *I*, that with the pump beam. The terms (*LB*, *L*, and *B*) denote the photodiode outputs for the shutter conditions mentioned above. Figure 3 (b) shows the transient absorption due to the solvated electrons according to the equation and Fig. 3 (a). The optical density increased at a time of ≈0 ps as expected in Fig. 3 (a). Thus, first DDPR was demonstrated with an optical density change of 0.043, although the 10-90% rise time was obtained as 8.6 ps, which was caused almost by the sample thickness.

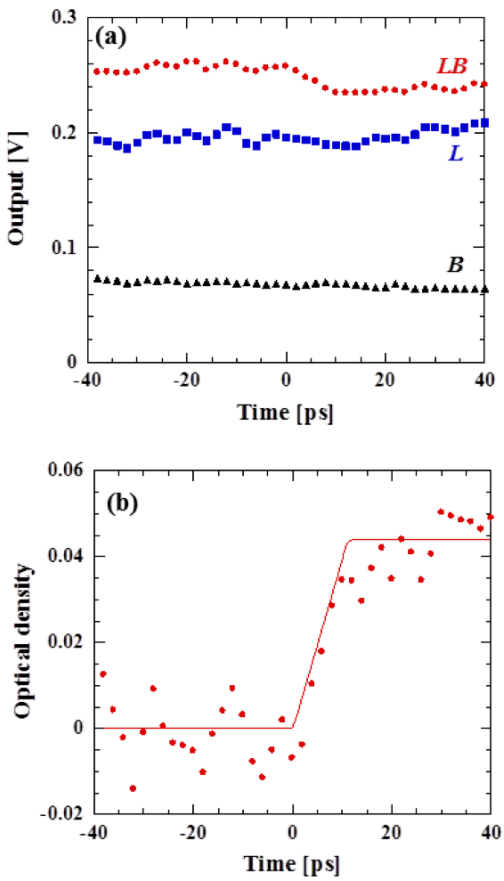

Figure 3: (a) Photodiode outputs as a function of the optical delay in the pulse radiolysis system with a BPF of 800 nm. (b) Transient absorption due to the solvated electrons. Solid line denotes simulation result using least-squares fitting.

CONCLUSIONS

Double-decker pulse radiolysis (DDPR), which utilized double-decker electron beams, was demonstrated, resulting in DDPR with the 10-90% rise time of 8.6 ps. DDPR also indicated a feasibility of a spectrum measurement. In the future, the time resolution in DDPR will be improved by the optimizations of the double-decker electron beams and pulse radiolysis system, e. g., femtosecond double-decker beams, Cherenkov radiator, reference measurement, and EVS. Besides improving the time resolution, another application to a pulse radiolysis in THz-range would be expected.

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