SIMULATION STUDY ON ATTOSECOND ELECTRON BUNCH GENERATION

Koichi Kan#, Takafumi Kondoh, Jinfeng Yang, Yoichi Yoshida, The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka, 567-0047, Japan

Abstract

Pulse radiolysis, a stroboscopic method with an ultrashort electron bunch and an ultrashort light, is essential for the observation of ultrafast reactions. The time resolution of pulse radiolysis depends on the electron bunch length. In Osaka University, a 98-fs electron bunch was generated by using a photocathode electron linac for a development of femtosecond pulse radiolysis. Furthermore, a subfemtosecond/attosecond pulse radiolysis is proposed to study the ionization and thermalization processes in subfemtosecond/attosecond time region. In order to realize such a high time resolution, the possibility of attosecond electron bunch generation based on the photocathode RF gun linac and a magnetic bunch compressor was studied. In the simulation, the bunch length growths due to charge, transverse and longitudinal emittance were investigated.

INTRODUCTION

Pulse radiolysis, which is a pump-probe measurement based on an ultrashort electron beam and an ultrashort light, is a powerful tool for the observation of ultrafast phenomena involving the mechanical motion of electrons and atomic nuclei in physics, chemistry and biology [1]. The time resolution of pulse radiolysis depends on the electron bunch length, the probe light pulse width, and the timing jitter between the electron bunch and the probe light. A 98-fs electron beam was generated in last year by using a photocathode electron linac for the development of a femtosecond pulse radiolysis [2]. However, an electron bunch of subfemtosecond/attosecond is important for observing the ultrafast primary process of radiation chemistry, such as ionization and thermalization processes in attosecond time region.

In this paper, we report theoretical descriptions of beam dynamics in the photocathode RF gun linac and the magnetic bunch compressor. A compensation technique of higher order effects on the bunch was proposed by using the nonlinear energy-phase correlation produced in the linac by adjusting the accelerating RF phase.

PHOTOCATHODE LINAC AND MAGNETIC BUNCH COMPRESSOR

Figure 1 shows the ultrashort electron bunch generation system. A 1.6-cell S-band (2856MHz) RF gun was used in the system. A copper cathode used in the system was located in the half cell. A single solenoid magnet was mounted at the exit of the RF gun to compensate the space charge emittance of the electron beam. The RF gun was driven by an Nd:YLF picosecond laser. The laser 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. The output of UV (266 nm) light with maximum pulse energy of 0.3 mJ was injected on the cathode surface.

The electron beam produced by the RF gun was accelerated by a 2 m long S-band travelling-wave linac with an optimal energy-phase correlation in the bunch for the bunch compression, in which the head electrons of the bunch have more energy than the bunch tail. A magnetic bunch compressor, which was constructed with two 45°-bending magnets and four quadrupole magnets as shown in Figure 1, compresses the correlated electron bunch into femtosecond by rotating the phase space distribution of the bunch in a magnetic field.

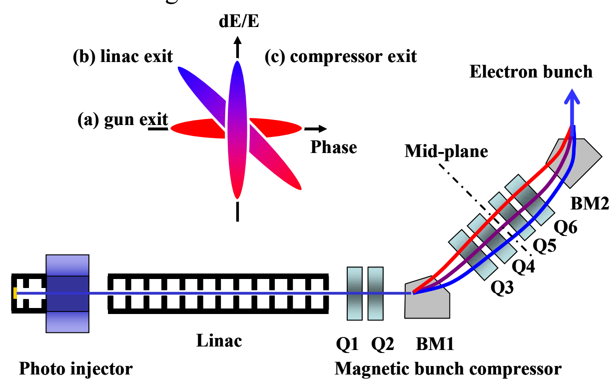

Fig. 1. Photocathode femtosecond electron linac and phase space distributions of bunch at the exit of the gun (a), at the exit of the linac (b), and at the exit of the compressor(c).

SIMPLE MODEL FOR ULTRASHORT ELECTRON BUNCH GENERATION

Introduction of Simple Model for Attosecond Electron Bunch Generation

In order to generate an attosecond electron bunch, theoretical study of the bunch length growth is essential. To simplify bunch length growth due to 2nd-order effect and longitudinal emittance, an equation was proposed as,

$$\sigma_z^f \approx \sigma_z^{2nd-order} + \sigma_z^{\varepsilon}, \quad (1)$$

where σ_z^f, $\sigma_z^{\text{2nd-order}}$ and σ_z^{ez} are the final compressed bunch length, the bunch length growth due to 2nd-order effect and the bunch length growth due to longitudinal emittance. In this model, the bunch length growth in compressor was obtained. For an exact solution, bunch length growths due to the coherent synchrotron radiation (CSR) effect, the space-charge effect and the transverse

 1-4244-0917-9/07/$25.00

emittance should be considered. However, in this model, these effects are not considered.

The bunch length growth due to the 2nd-order effect, $\sigma_z^{2nd\text{-}order}$, is caused by fringing fields of the magnets in the bunch compressor. Finally, the compressed bunch length is determined by the longitudinal emittance at linac exit, if the longitudinal emittance is preserved. The longitudinal emittance decides the distribution of phase space and the bunch length.

Bunch Length Growth due to 2nd Order Effect

In bunch compression, fringing fields of the magnets cause higher order disadvantageous effects on the bunch length. The transformation in the bunch compressor with higher order effects can be expressed by

$$z_f \approx z_0 + R_{56}\left(\frac{\Delta E}{E}\right) + T_{566}\left(\frac{\Delta E}{E}\right)^2 \qquad (2)$$

where z_f and z_0 are longitudinal positions of electrons at compressor exit and linac exit, respectively. The bunch head is $z < 0$. R_{56}, and T_{566} are momentum compaction coefficients of the first and second-order effects.

In order to estimate the momentum compaction coefficients of R_{56} and T_{566} TRANSPORT code [3] was used. With beam energy of 35 MeV, first-order coefficient of R_{56} was constant of -63 mm and the second-order coefficient of T_{566} was equal or less than -550 mm [4]. When T_{566} is equal to -550 mm, bunch length growth due to 2nd-order effect is minimized and the magnetic fields of Q3 and Q4 are 180 G/cm and -60 G/cm, respectively.

In order to minimize the bunch length, the energy-phase correlation in phase space at the linac exit was estimated. To simplify energy modulation, we assume that no energy-phase correlation is occurred in the RF gun. The beam energy at the gun exit is E_i = 4 MeV. The electron energy at the linac exit (after acceleration) can be expressed by

$$E_0 \approx E_i + eV_l \cos(\varphi_l + k_s z_0) \qquad (3)$$

where V_l =31 MV is the electric field in the linac, φ_l is the accelerating RF phase, z is the longitudinal position from the bunch center, in which the bunch head is $z_0 < 0$, k_s is the RF wave number. The energy gain is maximum at φ_l = 90°.

With expansion of Eq. (3), we can obtain

$$\frac{\Delta E}{E} \approx -\frac{eV_l k_s \sin\varphi_l}{E_0} z_0 - \frac{eV_l k_s^2 \cos\varphi_l}{2E_0} z_0^2, \qquad (4)$$

$$\frac{\Delta E}{E} \equiv a z_0 + b z_0^2$$

where a and b are simplified coefficients of first and second term. By inserting Eq (4) into Eq (2), an equation of final electron position, z_f, expressed by

$$z_f \approx \left(1 + aR_{56}\right) z_0 + \left(T_{566} a^2 + R_{56} b\right) z_0^2. \qquad (5)$$

In the bunch compression for the first-order, φ_l need to be 107° because appropriate rotation in phase-space require $a = -1/R_{56}$. With first term to be 0 the bunch length depends on second-term decided by second-order effect and nonlinear energy modulation in the linac. Furthermore, for tails of the distribution, an electron position, z_0, can be replaced to bunch length, σ_z^i. The bunch length growth due to 2nd-order effect can be expressed as

$$\sigma_z^{2ndOrder} \approx \left|T_{566} a^2 - R_{56} b\right| \sigma_z^{i\,2}, \qquad (6)$$

where the initial bunch length, σ_z^i, is a bunch length at the linac exit. Eq. (6) means the bunch length growth due to 2nd-order effect is a function of the square of initial bunch length, σ_z^i. In order to minimize the bunch length growth due to 2nd-order effect, the bunch length at the linac exit should be shortened.

Longitudinal Emittance Induced Bunch Length

The compressed bunch length also depends on longitudinal emittance, ε_z, because longitudinal emittance decides the distribution in z-direction phase-space. When a bunch is compressed, the distribution is rotated as shown in Fig. 1 (c). Longitudinal emittance is an area of the distribution. A bunch with lower longitudinal emittance is compressed to shorter bunch. To simplify this problem, we assume the distribution is ellipse completely. If the longitudinal emittance is preserved before and after compression because of no acceleration, with Eq. (4) and initial bunch length, σ_z^i, the energy spread, dE/E, is expressed by

$$\frac{\Delta E}{E} = a\sigma_z^0, \qquad (7)$$

where a is simplified coefficient in Eq. (4). In this model, when an electron beam has an appropriate energy spread, the energy spread is decided by bunch length.

When the phase-space distribution is rotated to minimize bunch length, the longitudinal emittance induced bunch length, σ_z^{ez}, is expressed by

$$\sigma_z^{ez} = \frac{\varepsilon_z}{\Delta E} = \frac{\varepsilon_z}{a\sigma_z^0}. \qquad (8)$$

The longitudinal emittance induced bunch length, σ_z^{ez}, is inversely proportional to initial bunch length, σ_z^i. In order to minimize the compressed bunch length, a bunch length at linac exit should be lengthened.

Results of Simple Model

Fig. 2 shows the dependence of the final compressed bunch length, σ_z^f, on the initial bunch length at the linac exit, σ_z^i. For a short initial bunch length, compressed bunch length depends on the longitudinal emittance. For a long initial bunch length, the compressed bunch length is decided by the higher order effect in the bunch compressor. For example, when the initial bunch length at linac exit is 2 ps (in the present system), the limit of compressed bunch length is decided by higher-order effect in the compressor to be 60 fs. In order to generate an attosecond electron bunch, the initial electron bunch with bunch length of 100 fs and longitudinal emittance of lower than 0.01 deg-keV is required as shown in Fig. 2.

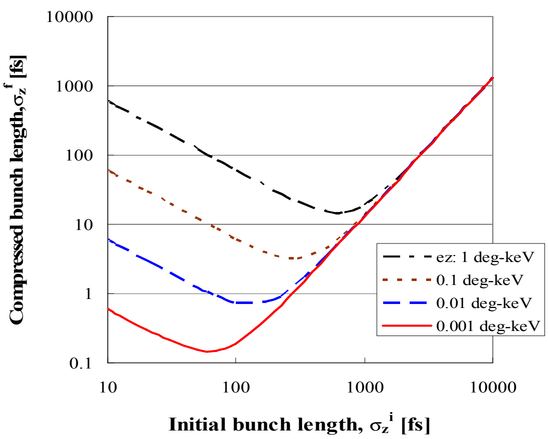

Fig. 2. Dependence of final compressed bunch length, σ_z^f, on initial bunch length at linac exit, σ_z^i, and longitudinal emittance, ε_z.

SIMULATION RESULTS OF SUBFEMTOSECOND ELCTRON BUNCH GENERATION

The bunch compression was also simulated by PARMELA code [5]. The beam energy was 35 MeV. In order to compensate the higher-order effect and satisfy symmetry of beam trajectory, two sextupole magnets were set at the after BM1 and before BM2. The transverse and longitudinal space-charge effect mesh was set to 0.1 rms of respective size. The transverse emittance growth in the compressor was minimized by envelope matching, in which the twiss-parameters in the x and y directions were scanned. The magnetic fields of sextupole magnets and twiss-parameters in z direction were also scanned for compensation of higher-order effect and an appropriate phase-space rotation due to R_{56} at the condition of a constant bunch length.

Fig. 3 shows the dependence of compressed bunch length on initial transverse and longitudinal emittance. The initial rms bunch length and the bunch charge were 100 fs and 1 fC, respectively. The compressed bunch length not only depends on the longitudinal emittance, but also depends on the transverse emittance. The compressed bunch length is a function of the square root of transverse emittance. Even if the transverse emittance growth is minimized by envelop matching, the momentum in x-direction causes the path differences of the electrons. The path differences increase the longitudinal emittance at the compressor exit. In order to generate an attosecond electron bunch, transverse emittance of 0.05 mm-mrad is required for the initial beam with bunch length of 100 fs and longitudinal emittance of 0.001 deg-keV.

Fig. 4 shows the dependence of compressed bunch length on the bunch charge. In the low transverse emittance and the high charge region, the space charge effect increases the bunch length. For the high transverse emittance beam, the bunch length is increased slightly due to the space-charge effect.

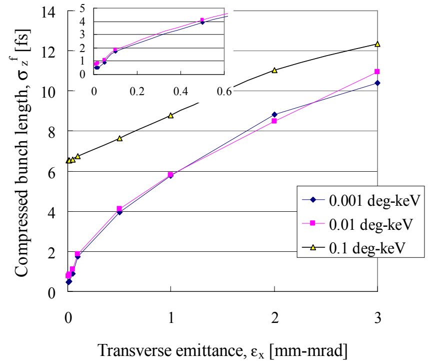

Fig. 3. Dependence of compressed bunch length, σ_z^f, on transverse emittance, ε_x, and longitudinal emittance, ε_z.

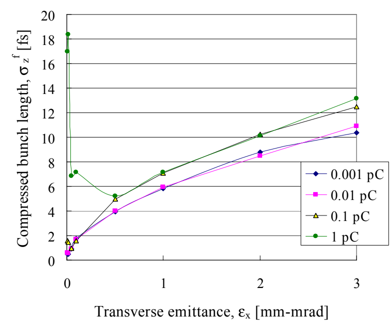

Fig. 4. Dependence of compressed bunch length, σ_z^f, on transverse emittance, ε_x, and bunch charge.

CONCLUSIONS

In summary, the possibility of attosecond electron bunch generation was studied. In the simulation, the bunch length growth due to the bunch charge, the transverse and longitudinal emittance was investigated. A beam with the transverse emittance of 0.05 mm-mrad and longitudinal emittance of 0.001 deg-keV is required to generate attosecond electron bunch at a charge of 1 fC. Now, a new photocathode electron gun is being developed to generate a low-emittance femtosecond beam with emittance of 0.1 mm-mrad and bunch length of 100 fs in Osaka University. However, there is a remained problem of how to generate a 0.05 mm-mrad beam. The bunch length growth due to CSR effect needs to be studied.

ACKNOWLEDGEMENTS

We thank Ryoichi Hajima (JAEA) and Atushi Ogata(ISIR) for much support and discussion.

REFERENCES

[1] H. Kobayashi et al., Inter. J. Radiat. Appli. Instrum., C, Vol. 34, Issue 4, 1989, Pages 447.
[2] J. Yang et al., Nucl. Instr. and Meth., A 556, 52-56 (2006).
[3] Karl L. Brown, SLAC Report-75 June (1982)
[4] K. Kan et al., Proc. of EPAC2006, (2006) 2502.
[5] Lloyd Young et al., Proceedings of PAC2003, 3521 (2003)