HIGHER-ORDER EFFECT COMPENSATION IN MAGNETIC COMPRESSOR FOR < 50 FS ELECTRON BUNCH GENERATION

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Abstract

A 98 femtosecond electron beam with energy of 32 MeV has been generated successfully at bunch charge of 0.17 nC in Osaka University by using a rf gun and a magnetic bunch compressor. However, an electron bunch of <50 fs is important for developing pulse radiolysis with time resolution of 100 femtosecond. In order to generate a 50-femtosecond electron bunch, the higher-order effects in the bunch compressor was investigated theoretically. A compensation technique of second order effect was proposed to generate the femtosecond electron bunch by using a nonlinear energy-phase correlation in the booster linac. To reduce third order effect in the bunch compressor, a slit which is installed mid-plane of the compressor was used.

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 <50 fs is important for observing the primary process of radiation chemistry, such as formation of hydrated electrons on the 100-femtosecond time scale. 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 femtosecond electron 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.

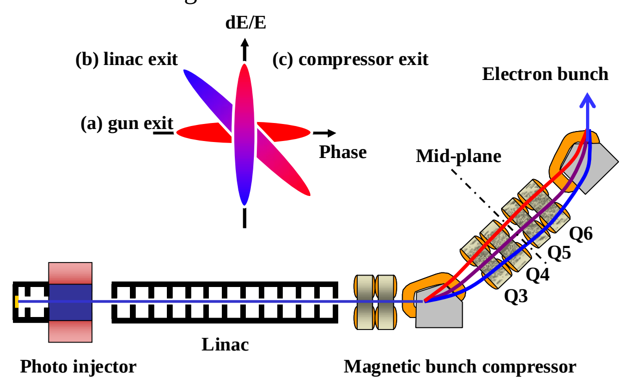

Figure 1: Photocathode femtosecond electron linac and phase space distributions of bunch at the exit of the gun (a), at the exit of the linac (b), and at the exit of the compressor(c).

THEORETICAL DESCRIPTION OF HIGHER-ORDER EFFECTS IN THE BUNCH COMPRESSOR

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

$$z_f \approx z_0 + R_{56}\left(\frac{\Delta E}{E}\right) + T_{566}\left(\frac{\Delta E}{E}\right)^2 + U_{5666}\left(\frac{\Delta E}{E}\right)^3, \qquad (1)$$

where z_f and z_0 are longitudinal positions of electrons at the exit of the compressor and at the exit of the linac, respectively. The bunch head is $z < 0$. R_{56}, T_{566} and U_{5666} are momentum compaction coefficients of the first, second and third-order effects. According to Eq. (1), for the first-order effect, the electrons with high energies are moved backward and electrons with low energies are

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moved forward in the longitudinal direction in the case of a negative value of R_{56}. For the second-order effect, both the low and high-energies electrons are moved backward for a negative value of T_{566}. The third order-effect leads the electrons to move away from the centre of the bunch (z=0). Both the second and third-order effects cause the growth of the bunch length. In the compressor, the coefficients of the second and third-order effects depend on the magnetic fields of four quadrupole magnets (Q3, Q4, Q5 and Q6).

In order to estimate the momentum compaction coefficients of R_{56}, T_{566} and U_{5666}, a simulation of TRANSPORT code [3] was used. We assume that the beam energy is 32 MeV and the compressor fulfils achromaticity (R_{16}=R_{26}=0). The magnetic fields of Q3 and Q4 should be equal to those of Q6 and Q5, respectively, according to the trajectory symmetry around the mid-plane of the compressor. The magnetic field of Q4 should be changed if the magnetic field of Q3 is changed. Figures 2 and 3 show plots of R_{56}, T_{566} and U_{5666} versus the magnetic field of Q3. It indicates the first-order coefficient of R_{56} is constant of -63 mm and the second-order coefficient of T_{566} is equal or less than -550 mm at the magnetic field of 180 G/cm (Q3). If the rms bunch length is 2.0 ps, an appropriate energy spread is 0.95 % for the bunch compression. If the energy-phase correlation in bunch is linear (linear phase-space distribution), the bunch length is increased to be more than 160 fs due to the second-order effect in the compressor. The growth of bunch length due to the third-order effect is 2 fs at U_{5666} = 880 mm (the same condition above). In order to generate a 50-femtosecond electron bunch, the second-order effect in the bunch compressor should be compensated. The third-order effect need to be reduced.

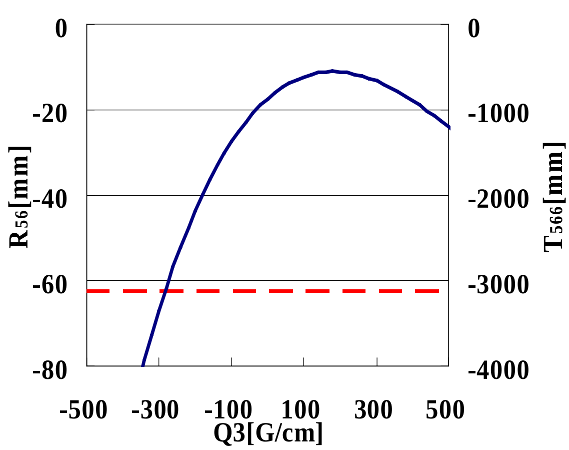

Figure 2: Plots of R_{56} (dashed line) and T_{566} (solid line) versus magnetic field of Q3.

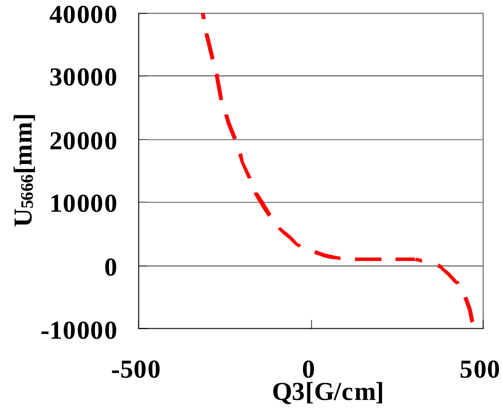

Figure 3: Plots of U_{5666} (dashed line) versus magnetic field of Q3.

COMPENSATION OF HIGHER ORDER EFFECTS IN MAGNETIC FIELD

Compensation of Second Order Effect

In order to compensate the second-order effect, the energy-phase correlation in phase space at the exit of the linac 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

$$E_0 \approx E_i + eV_l \cos(\varphi_l + k_s z) \ , \qquad (2)$$

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 $z < 0$, k_s is the RF wave number. The energy gain is maximum at φ_l = 90°. The bunch head will be accelerated more than the tail at 90° < φ_l <180 °. The relative energy spread in bunch thus becomes

$$\frac{\Delta E}{E} \approx -\frac{eV_l k_s \sin\varphi_l}{E_0} z - \frac{eV_l k_s^2 \cos\varphi_l}{2E_0} z^2 + \frac{eV_l k_s^3 \cos\varphi_l}{6E_0} z^3 , \qquad (3)$$

where the first and second order coefficients are negative. The third order coefficient is positive. The rms bunch length is assumed to be 2.0 ps and the RF compression in the linac is negligible.

The phase space distribution at the compressor exit thus can be expressed to second order by inserting Eq. (3) into Eq. (1)

$$\begin{aligned} z_f &\approx A z_0 + B z_0^2 \\ A &= 1 + \frac{-eV_l k_s \sin\varphi_l}{E_0} R_{56} \\ B &= \frac{-eV_l k_s^2 \cos\varphi_l}{2E_0} R_{56} + \left(\frac{-eV_l k_s \sin\varphi_l}{2E_0}\right)^2 T_{566} \end{aligned} \ . \qquad (4)$$

To compensate the second-order effect the coefficient,

$$B = \frac{-eV_l k_s^2 \cos\varphi_l}{2E_0} R_{56} + \left(\frac{-eV_l k_s \sin\varphi_l}{2E_0}\right)^2 T_{566} = 0 \ . \qquad (5)$$

Figure 4 shows the phase space distributions at the exit of the compressor in the cases of nonlinear energy-phase correlation input and linear correlation input. The second-order effect was compensated by using the nonlinear energy-phase correlation. The accelerating RF phase was 107°. The coefficients, R_{56}, T_{566} and U_{5666}, were -63 mm, -550 mm and 880 mm, respectively. The data indicates that the second-order effect was compensated because the electrons at both higher and lower energies were almost compressed comparing with the case of the linear energy-phase input.

The bunch compression was also simulated by PARMELA code [4]. Figure 5 shows the phase space distribution at the compressor exit after optimization of φ_l and the magnetic fields of four quadrupole magnets. The optimal value of φ_l was obtained to be 105°, which is agree with the theoretic description. The rms bunch length was 78 fs with a charge of 0.1 nC. The optimal RF phase of φ_l changed for the different input bunch length for the compressor. However, the third-order effect was remained in the simulation as shown in Fig. 5.

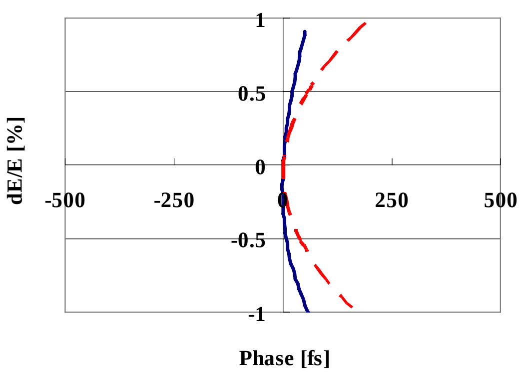

Figure 4: Phase space distribution after compression for linear phase-energy input (dashed line) and nonlinear phase-energy input (solid line).

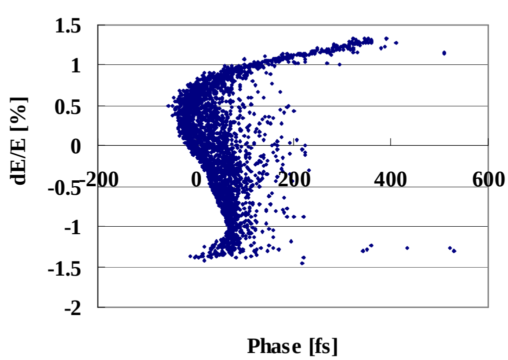

Figure 5: Compensation of second order effect in PARMELA simulation.

Reduction of Third Order Effect

The growth of bunch length due to the third-order effect is dependent on the energy-spread of the bunch. The third-order effect can be reduced by energy selection. To select the electron energy, a slit mounted at the mid-plane of compressor was considered. The shorter bunch length of electron beams can be obtained with a narrow slit. Figure 6 shows the phase space distribution at the exit of compressor with the slit width of 6.0 mm. Comparing with Fig. 4, the electrons with higher and lower energy were removed. The rms bunch length was obtained to be 48 fs. The bunch charge was 83 pC.

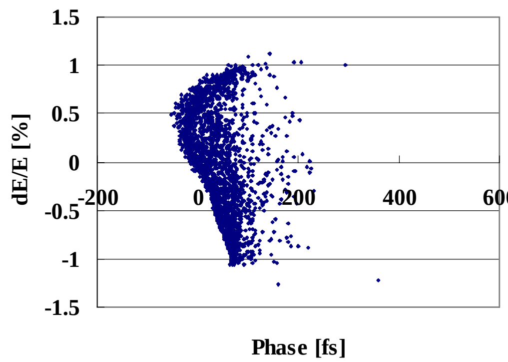

Figure 6: Reduction of third order effect by the slit.

CONCLUSIONS

In summary, the higher-order effects in the magnetic bunch compressor were investigated theoretically. A compensation technique of the high-order effects was proposed with optimizing the accelerating RF phase in the linac. In the simulation, a 78 fs electron bunch was observed by compensating the second-order effect in the compressor. The bunch length was shortened to be 48 fs by using a slit to reduce the third-order effect. According to this simulation, an electron bunch of < 50 fs will be realized and pulse radiolysis with femtosecond time resolution will be developed.

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