Study on Bunch Compression by Use of the Wake Fields

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Abstract

In order to compress an electron bunch effectively using the path difference in the magnetic field, a linear energy variation with time in the bunch is required. We numerically derived such bunch shapes giving linear energy variations, by taking account of the wake field excited in the accelerating structure by the electron beam, in addition to the accelerating field driven by an external RF power source. We conducted experiments to produce a short bunch by the method. By tuning the injection system of a L-band linac, the shape of an electron bunch was made similar to an ideal one and then it was compressed in an achromatic beam transport system. The electron bunch compressed by the method became shorter than that obtained with the standard adjustment of the injection system for obtaining the electron beam with a narrow energy spread.

1 Introduction

The 38 MeV, L-band linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University, can accelerate a single bunch beam with charge up to 73 nC, or 4.5×10^{11} electrons in a bunch, using a three-stage sub-harmonic buncher (SHB) system [1]. The charge in a bunch is one of the highest intensities accelerated with linacs and the number of electrons is larger than that required for linear colliders. The wake field induced in the accelerating structure by such a high intensity electron beam is a serious problem for next generation accelerators. It is an impediment to accelerating electrons in the structure and efforts are being made toward reducing or eliminating it. We, on the contrary, are investigating positive uses of the wake field. One application is to produce an electron beam with a small energy spread [2,3] and another is to produce a short bunch [4]. In order to compress a bunch longitudinally, an energy variation with time is first given to electrons in a bunch, and then the bunch is led to a uniform magnetic field. The bunch becomes short due to the pass difference with energy in the magnetic field. This method is called magnetic compression. If the energy of electrons in a bunch linearly varies with time, a very short bunch could be produced by the magnetic compression method.

We are studying to produce an extremely short bunch by magnetic compression using the wake field induced by the bunch is superposed upon the sinusoidal RF field in the accelerating structure. In this paper, we report derivation of such an ideal temporal shape for magnetic compression and experimental results of producing a short bunch by the method.

2 Optimum Bunch Shape

For the SLAC type disk-loaded structure with the RF frequency of 2.856 GHz, the longitudinal wake function for the time range from 0 to 20 ps may be described by the expression [5]

$$\omega(\tau) = A \cdot \exp\left\{-(\tau/B)^n\right\}, \tag{1}$$

where τ is the temporal distance, A = 226 V/pC/m, B = 6.13 ps, and n = 0.605. Frequency dependence of these parameters is given by

$$A \propto \omega^2, B \propto \omega^{-1}. \tag{2}$$

For the L-band linac with f_{RF} = 1.3 GHz, these parameters are calculated as A = 46.8 V/pC/m and B = 13.5 ps over the range from 0 to 50 ps. The longitudinal wake function for the entire accelerating

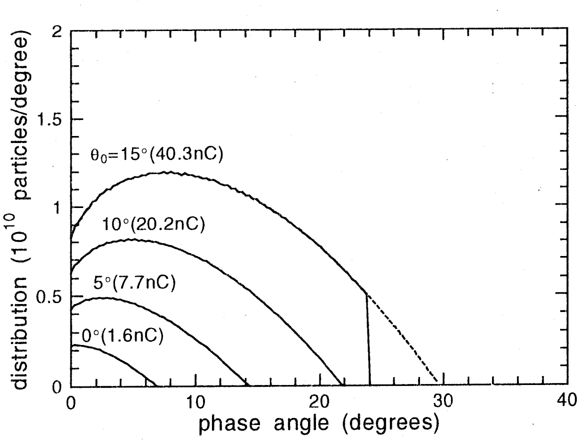

Fig. 1 Optimum charge distributions for K=-0.05 MV/degree. θ_0 is the phase angle of the bunch head measured from the crest of the wave. The values in the brackets are total charge. The dashed lines indicate the region where the parameters of the wake functions are not available.

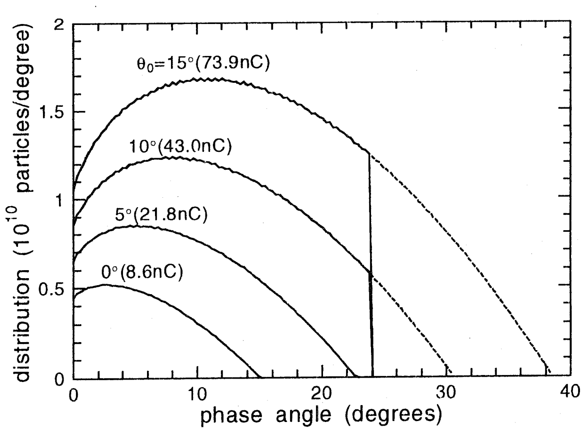

Fig. 2 Optimum charge distributions for K=-0.1 MV/degree. θ_0 is the phase angle of the bunch head measured from the crest of the wave. Values in the brackets are total charge. The dashed lines indicate the region where the parameters of the wake functions are not available.

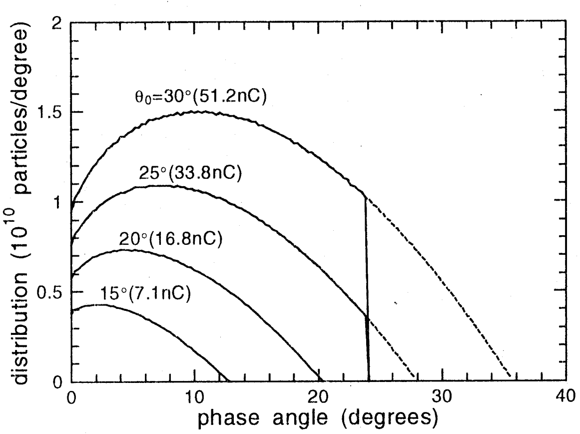

Fig. 3 Optimum charge distributions for K=0.05 MV/degree. θ_0 is the phase angle of the bunch head measured from the crest of the wave. Values in the brackets are total charge. The dashed lines indicate the region where the parameters of the wake functions are not available.

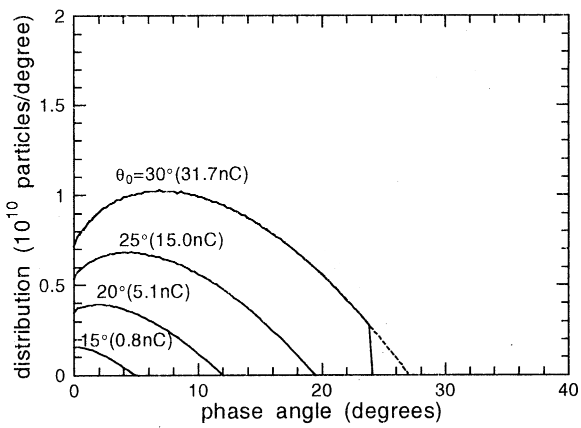

Fig. 4 Optimum charge distributions for K=0.1 MV/degree. θ_0 is the phase angle of the bunch head measured from the crest of the wave. Values in the brackets are total charge. The dashed lines indicate the region where the parameters of the wake functions are not available.

structure of the length L is given by $W_L=\alpha(\tau)\times L$. The energy gain of an electron in the accelerating structure without the wake field is given by $\Delta W = eV(\phi) = eV_0\cos(\phi) = eE_0L\cos(\phi)$, where e is the electron charge, V is the effective voltage, E_0 is the maximum accelerating field in the structure generated only by an external RF power source, and ϕ is the phase angle measured from the crest of the traveling wave. On the other hand, the energy gain including the wake field is given by

$$V(\phi) = V_0\cos(\phi) - \int_0^{\theta_0-\phi} f(\theta)W_L(\theta_0-\phi-\theta)d\theta\,, \qquad (3)$$

where $f(\tau)$ is the charge distribution of a bunch and θ_0 is the phase angle of the bunch head measured from the crest.

In order to obtain the linear energy variation with the phase angle in the bunch, the gradient of the effective voltage with respect to the phase angle should be constant as $\mathrm{d}V(\phi)/\mathrm{d}\phi = K$, where K is a constant coefficient for the voltage variation with the phase angle. By differentiating Eq. (4) with respect to ϕ and replacing $\theta_0-\phi$ with x, we obtain the integral equation for the optimum bunch shape as

$$f(x) = \frac{1}{W_L(0)}\left[K + V_0\sin(\theta_0-x) - \int_0^x f(\theta)\frac{\partial}{\partial x}W_L(x-\theta)d\theta\right] \qquad (4)$$

The integral equation was solved numerically and we obtain the bunch shape $f(x)$. The bunch shape for K = 0 has been investigated by Loew and Wang, which results in the minimum energy spread [6]. We studied the bunch shape for $K \neq 0$.

The optimum bunch shapes calculated for K=-0.05, -0.1, 0.05, and 0.1 MV/degree are shown in Fig. 1, 2, 3, and 4, respectively.

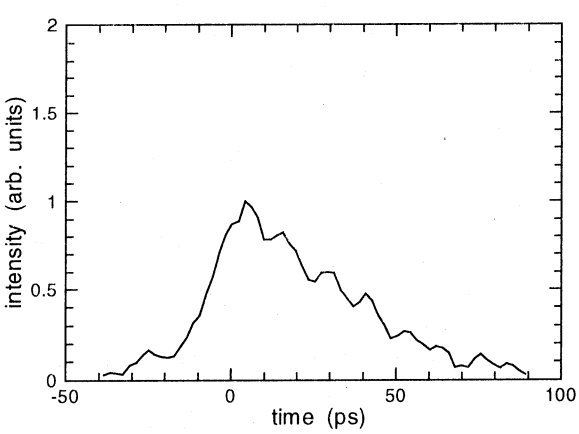

Fig. 5 Temporal profile of the bunch reproducing the optimum shape experimentally. It was obtained by measuring optical transition radiation with a streak camera.

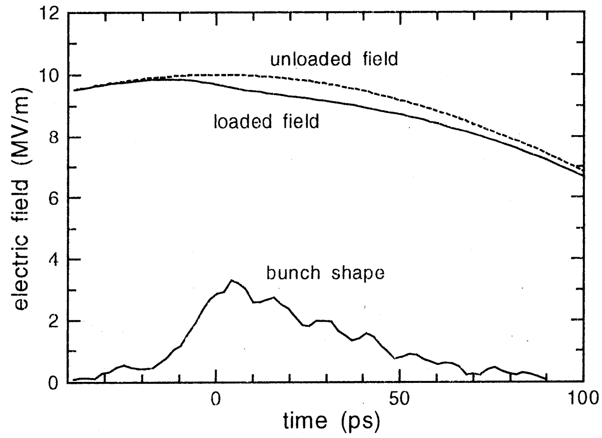

Fig. 6 Electric fields in the accelerating structure. The dashed line shows the field driven only by an external RF power source, denoted by unloaded field, and the solid line shows the field including the wake field, denoted by loaded field, which was calculated using the measured bunch shape as below.

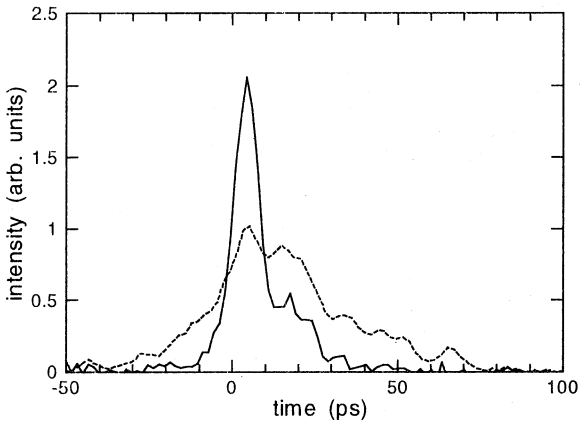

Fig. 7 Temporal Profiles of the bunch measured at the end of the straight line using Cerenkov radiation in air. The dashed and the solid lines show the bunch profile before and after magnetic compression, respectively. The bunch was compressed from 38 to 9 ps.

Since K is negative in the first two cases, the electron energy decreases linearly with the phase angle. In the last two cases with positive K values, on the other hand, the electron energy increases linearly. By comparing Figs. 1 and 3, or Figs. 2 and 4, it may be seen that higher charge is necessary to produce the optimum bunch shape for a negative K value than for a positive value. Since these bunches have a sharp-cut head, it is difficult to realize these bunch shapes precisely without using a high-speed chopper. Nevertheless, we attempted to produce such a bunch shape by adjusting the injection system of the L-band linac comprising three sub-harmonic bunchers in addition to a pre-buncher and a buncher.

3 Bunch Compression Experiments

The L-band linac is comprised of a 100 kV electron gun, the SHB system, a prebuncher, a buncher and a 3 m accelerating structure. The gun has a cathode with an area of 3 cm^2 (EIMAC YU-156). The SHB system is composed of two 12th and one 6th SHBs in order to produce an intense single bunch beam. The main accelerating structure is a quasi-constant gradient type with the accelerating frequency of 1.3 GHz. The typical bunch length is 20-30 ps and the maximum energy is 38 MeV.

Experiments to compress the bunch were conducted in an achromatic beam transport system from the linac room to an experimental room. First, we made the bunch shape close to the optimum one by adjusting phases and amplitudes of RF in the injection system. We observed the temporal profile of the bunch by measuring optical transition radiation with a streak camera, emitted from a stainless steal plate in the downstream straight beam line. The measured temporal profile of the bunch is shown in Fig. 5. The calculated accelerating fields with and without the wake field, which are denoted by loaded field and unloaded field, respectively, are shown in Fig. 6, together with the bunch shape used for calculation of the wake field.

The temporal profile of the bunch was measured, using Cerenkov radiation in air, at the end of the straight beam line before compression and at the experimental room after compression. Fig. 7 shows the measured bunch profiles before and after compression plotted with the broken and the solid lines, respectively. In this experiment, the electron bunch was compressed from 38.4 ± 3.5 down to 9.7 ± 0.7 ps as shown in Fig. 7, and the charge in the bunch decreased from 30 down to 20 nC. Then the peak current increased from 0.78 to 2 kA. On the other hand, using the bunch shape obtained by the ordinary adjustment of the linac for making the energy spectrum sharp, the bunch length was compressed to 11.6 ± 1.3 ps and the peak current was 1.7 kA. We could produce a shorter bunch with a higher peak current using magnetic compression by taking the wake field into account.

4 Conclusion

We numerically derived bunch shapes, which give linear energy variations with time in the bunch by taking the wake field into account. The injection system of the linac was adjusted, so that shape of the electron bunch became similar to the optimum one, and then the bunch was compressed in achromatic beam transport system. We were able to produce a shorter electron bunch with a higher peak current by the method taking the wake field into account.

Acknowledgement

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References

[1] S. Okuda, S. Suemine, T. Yamamoto, G. Isoyama, "Improvement of Pulse Characteristics for Injection and the Increase of the Beam Intensity in the ISIR Single-Bunch Electron Linac", Proc. 23rd Linear Accelerator Meeting in Japan, Tsukuba, Japan, September 16-18 (1998) 169.

[2] R. Kato, H. Kobayashi, Y. Iwase, Y. Nakajima, G. Kondo, S. Suemine, G. Isoyama, "Wake Field and Energy Spectra of the ISIR L-Band Linac", Proc. 21st Linear Accelerator Meeting in Japan, Tokyo, Japan, September 30 - October 2 (1996) 114.

[3] R. Kato, G. Isoyama, "Conceptual Design of Two Stage Alpha Magnets with an RF Chopper for Producing a Short Electron Bunch with a High Current and the Narrow Energy Spectrum", Proc. 21st Linear Accelerator Meeting in Japan, Tokyo, Japan, September 30 - October 2 (1996) 111.

[4] H. Kobayashi, R. Kato, G. Isoyama, "Study on the Bunch Compression by use of the Wake Field", Proc. 22nd Linear Accelerator Meeting in Japan, Sendai, Japan, September 9-11 (1997) 84.

[5] P. B. Wilson, "High Energy Electron Linacs: Application to Storage Ring RF Systems and Linear Colliders", SLAC-PUB-2884, February (1982) Chap. 10.

[6] G. A. Loew, J. W. Wang, "Minimizing the Energy Spread within a Single Bunch by Shaping Its Charge Distribution", IEEE Trans. on Nucl. Sci., NS-32, No. 5, October (1985) 3228.