Minimization of the Single Bunch Energy Spread by Wake Potential

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Abstract

The Osaka University Single Bunch Electron Linear Accelerator has been increased the single bunch charge from 14 nC to 67 nC (4×10^{11} e^-) by means of an injector with three subharmonic-prebunchers. The energy spread of the single bunch depends on the phase angle by which the bunch front leads the crest of the accelerating wave produced by the external rf source. The minimum energy spread is obtained by controlling the phase angle and it depends on the single bunch charge. The energy spread of the single bunch in the range between 0 nC and 16 nC is estimated to be 1 %. The energy spread of the single bunch in the range between 40 nC and 67 nC increases up to 2.5 % with the single bunch charge. The most minimized energy spread is obtained at 33 nC, and it is estimated to be 0.7 %.

Introduction

When a high-current single bunch passes through an rf-structure, wakefields are generated by a bunch-cavity interaction. The wakefields generated by an electron in the single bunch give rise to the forces acting on the successive electrons in the single bunch. The transverse components of the wakefields deflect the electrons and increase the beam emittance, while the longitudinal components change both energies and current distribution of the single bunch itself. It has been reported that the instability due to the transverse components limits the single bunch charge in an S-band structure. As for an L-band structure, the transverse components might be neglected compared with the longitudinal components, since the field strength of the wakefields per unit of the structure is the function of the rf-frequencies as follows:

$$W_L \text{ (longitudinal)} \propto \omega^2$$

$$W_{Td} \text{ (transverse-dipole)} \propto \omega^3$$

$$W_{Tq} \text{ (transverse-quadrapole)} \propto \omega^5$$

The wake potential is defined as the potential experienced by a test particle following the electron for a distance in the single bunch. The net change of the energy of each electron is expressed as the wake potential, that is the single bunch beam-loading, which is obtained by integration of the wakefields while the single bunch travels through the structure and leaves it.

The wakefields experiment has been performed with the single bunch of 16 nC, and the experimental results show that the wake potential is 0.77 - 0.87 MeV / 16 nC for the accelerating structure of Osaka University electron linac. When the single bunch of 67 nC will be accelerated, it is expected that the wake potential will be attained to 3.22 - 3.64 MeV.

Energy Spectrum of the Single Bunch Depending on the RF-Phase

When a single bunch is accelerated by the Osaka University Linac, the phase angle between the single bunch and the accelerating wave can be adjusted by a phase shifter. Figure 1 shows the phase dependence of the energy spectrum for the low-current single bunch of 0.5 nC. With increasing rf-phase, the head of the bunch approaches to the crest of the wave, and the maximum energy increases until the bunch-head reaches the crest. When the bunch-head leads the crest, the maximum energy is kept constant, since some electrons are accelerated by the crest of the accelerating field. When the bunch-tail leads the crest, the maximum energy decreases with the phase. As for the single bunch of 0.5 nC, the current is not so high as to cause the distortion of the accelerating field with wake potential.

The total energy gain of an electron at time, t, can be obtained by adding the external accelerating voltage to the beam-loading voltage, that is the wake potential,

$$E(t) = E_0 \cos(\omega t - \theta) + U_{wl}(t) ,$$

where the second term in right-hand side of the equation is the wake potential, and θ is the phase angle where the single bunch exist. When the high-current single bunch is accelerated, it is expected that the wake potential will be intense enough to change the energy spectrum of the single bunch. Figure 2 shows the dependence of the energy spectrum on the rf-phase for the single bunch of 5 nC. With the increase of rf-phase, the maximum energy increases since the head of the bunch approaches the crest. When the bunch-head leads the crest, the maximum energy decreases by the wake potential. As the bunch-tail approaches the crest, the maximum energy re-increases.

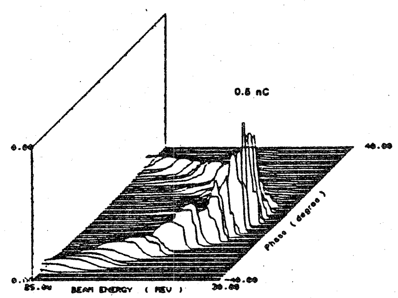

Fig.1 0.5 nC.

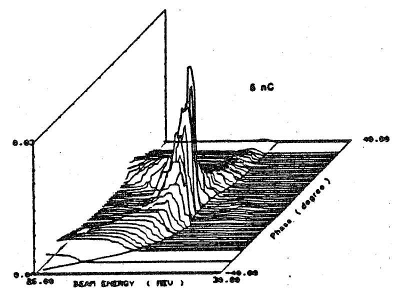

Fig.2 5 nC.

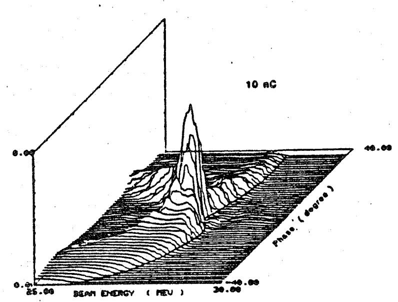

Fig.3 10 nC.

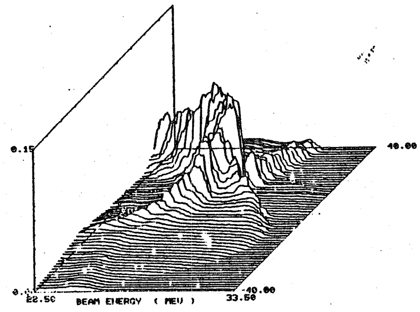

Fig.4 45 nC.

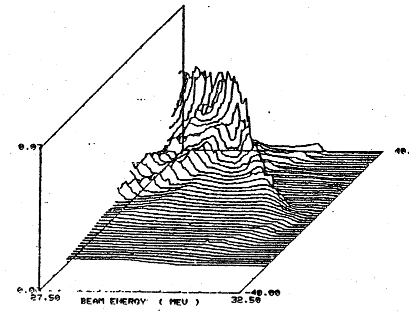

Fig.5 55 nC.

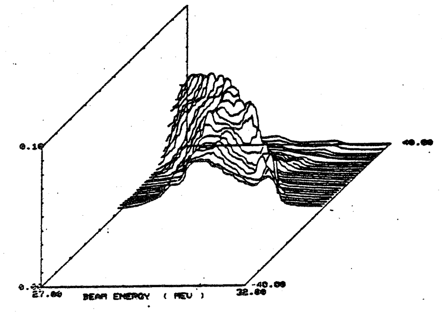

Fig.6 67 nC.

Figure 3 to 6 show the dependence of the energy spectrum on the rf-phase for the single bunch of 10 nC, 45 nC, 55 nC, and 67 nC respectively. The maximum energy for the single bunch decreases with incresing the single bunch charge. It shows that the wake potential increases in proportional to the bunch charge. Figure 5 shows that the value of the wake potential reaches into 3.25 MeV at 55 nC (0.91 MeV / 16 nC) of the single bunch charge. The beam-loading of the single bunch reaches into 10 % of the external accelerating energy.

Minimization of the Energy Spread

When a high-current single bunch is accelerated by a linear accelerator, the net accelerating field has a deep dent produced by the wake potential. With increasing charge, the energy spread is also increased. The minimum energy spread can be obtained, when the single bunch is accelerated at the positive phase angle where the negative going slope of the accelerating voltage waveform can be made to cancel with the positive going slope of the wake potential. The effect of the cancel depends on the shape of the wake potential which is determined not only by the single bunch charge but by the shape of the single bunch.

Figure 7 shows the minimum energy spread which can be obtained by controlling the phase angle to accelerate the single bunch. As for the single bunches accelerated by the Osaka Univ. machine, the energy spread is observed to be 1.0 % for the single bunch charge of 0 - 16 nC. It seems that the increase in the energy spread by the wake potential is canceled by the phase-control. In the region between 16 - 40 nC, the decrease in the energy spread is effective by the cancel of the negative going slope with the wake potential. The minimum spread is observed to be 0.7 % at the single bunch charge of 33 nC. When the single bunch of high-current greater than 40 nC is accelerated, the energy spread increases with the single bunch charge. It seems to be reasonable to consider that the increase of the single bunch charge gives rise to increase the going slope of the wake potential, and it exceeds the slope of the external accelerating voltage. If the energy spread of the single bunch greater than 33 nC is to be minimized, the higher gradient of external accelerating voltage or the longer length of the single bunch should be required for the Osaka University electron linac.

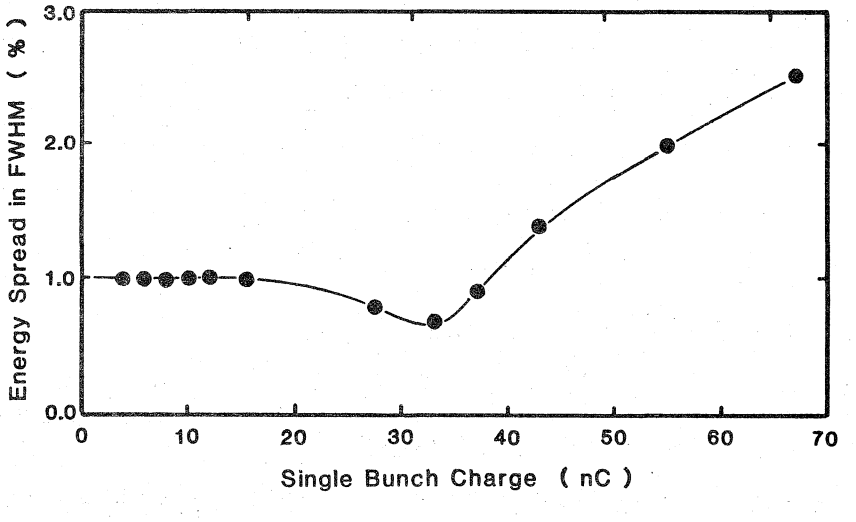

Fig.7 Minimum energy spreads for single bunch charge.