Acceleration of a High-Current Single Bunch in a Linear Accelerator

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1 Introduction

The energies realistically attainable by an electron-positron storage ring are limited to several hundreds GeV by both the external RF power and the power loss imposed by synchrotron radiation. In the linear accelerator, particles are accelerated without losing energies due to synchrotron radiation. A linear collider seems to be one of the feasible accelerators to reach particle energies on the order of 1 x 1 TeV in an electron-positron colliding beam-machine. The linear collider consists of two linear accelerators facing each other, one for single bunch of electrons and the other for single bunch of positrons. The two linear accelerators are triggered at the same time, and both of the two sing e bunches are brought into head-on collision at the interaction point in the same manner as in an electron-positron storage ring. In the linear collider, however, the particles are accelerated to high energies after passing through a half way length of the collider, and they are thrown away after collision. The total length of the linear collider is given by the ratio of a center-of-mass energy and an average accelerating gradient in the linear accelerator. If the gradient of 100 MV/m is realized through the overall length of the linear accelerator, the half way length of the linear collider will be 10 km long. In order to make linear collider feasible, a number of ploblems associated with minimizing the cost of constructing and operating such a very large beam-machine have to be solved.

In addition to the fiscal problems, there are two other problems which to be solved from an entirely new angle. One is related to the generation of high-current single bunch. It includes the new method to increase the number of particles in a single bunch. A quasi-relativistic electron beam from an electron gun should be injected into one bucket of the accelerating fields, in opposition to the longitudinal defocusing due to the space-charge effect. The other is associated with physics of accelerating high-current single bunch. The longitudinal and transverse wakefields generated by a bunch-cavity interaction limit the number of particles in a single bunch which can be accelerated in the linear collider.

2 Linear Collider Injector

2.1 Bunch Parameters

The parameters of the bunch are determined by the conditions at the interacion point where two single bunches collide after passing through each of the final focusing system. The number of particles contained in a single bunch is basically determined by the luminosity. The luminosity for linear collider is given by

$$L = \frac{N_b f_r}{4\pi \sigma_x \sigma_y} P(D_x, D_y) \quad , \tag{2.1}$$

where N_b is the number of paricles per single bunch, f_r is the repetition rate, σ_x and σ_y are the transverse bunch dimensions at the interaction point, and $P(D_x,D_y)$ is a luminosity enhancement factor. If the bunch parameters[1] are given as $\sqrt{\sigma_x \sigma_y} = 0.5\ \mu m$, $\sqrt{\beta_x \beta_y} = 0.5$ cm, then $P(D_x,D_y) = 1.3$. When the machine is operated at the repetition rate of 400 Hz, the number of particles in the single bunch should be 1×10^{11} (16 nC). Assuming that the bunch-length σ_z is equal to 1 mm, the peak current of the bunched beam is estimated to be about 5 kA.

2.2 Generation of High-Current Single Bunch

A high-current single bunch is generated by a linear collider injector. A pulsed beam is generated by an electron gun, and it is injected into a prebuncher. For the purpose of generating a single bunch, all the electrons contained in the pulsed beam should be injected into one of the rf-buckets produced in the prebuncher. If all the electrons are not injected into one of the rf-buckets but the electrons are distributed into several rf-buckets, a single bunch with several satellite-bunches will be produced. The pulse width of the beam should be less than the acceptance angle of the prebuncher. Assuming that the acceptance is 240°, the pulse width of the beam should be less than 230 ps for S-band, and 510 ps for L-band linear accelerator. The peak current of the beam should be 140 A for the beam of 230 ps, and should be 60 A for the beam of 510 ps, in order to obtain the single bunch of particles with $N_b = 1.0 \times 10^{11}$ (16 nC). It is difficult to generate these high-current beams with the pulse length on the order of subnano-second. However, the pulsed electron beam can be produced without difficulty by a conventional thermionic triode gun, if the pulse width is on the order of nanosecond. In order to generate a high-current single bunch, the beam bunching by means of the velocity modulation with a subharmonic prebuncher (SHPB) is indispensable.

2.3 Subharmonic Prebuncher System

When a prebuncher is excited by a subharmonic frequencies, the rf-bucket is enlarged in the phase-space and the pulse width of the beam required to produce a single bunch can be made longer. In addition, the number of electrons injected into the rf-bucket is increased, and then the increase in the single bunch charge is realized.

The single bunch electron linear accelerators have been developed through two generations. The subharmonic prebuncher excited by the 6th subharmonic frequencies was applied to the single bunch electron linear accelerators in early stage of their development. Table 2.1 shows the specification of these single bunch linear accelerators of the 1st generation.

	Year	Energy	Charge	SHPB System
EG&G	1969	30 MeV	1.5 nC	6th SHPB (216 MHz)
SLAC*	1971	19 GeV	0.2 nC	(Bunch Chopper*)
ANL	1971	20 MeV	7.0 – 12.0 nC	6th SHPB (216 MHz)
Univ. of Tokyo	1977	35 MeV	1.0 – 1.5 nC	6th SHPB (476 MHz)
ISIR-Osaka Univ.	1978	38 MeV	7.0 – 14.0 nC	6th SHPB (216 MHz)

Table 2.1 Single bunch electron linear accelerators of the 1st generation.

Exciting the SHPB by lower frequency, the single bunch of higher current can be obtained. On the other hand, a longer drift distance is required to bunch the beam electrons, and the space-charge defocusing of high-current beam should be taken into consideration. Therefore, it is desirable to bunch the beam with a couple of subharmonic prebunchers rather than with a single subharmonic prebuncher alone. There exist three single bunch electron linear accelerators, which belong to the 2nd generation with subharmonic multi-prebunchers system. Table 2.2 shows the specification of these linear accelerators.

	Year	Energy	Charge	SHPB System
SLC - Inj.	1983	35 MeV	8 nC	18th SHPB + 18th SHPB
ANL	1983	20 MeV	25 nC	12th SHPB with Double Gap
ISIR-Osaka Univ.	1984	38 MeV	67 nC	12th SHPB x 2 + 6th SHPB

Table 2.2 Single bunch electron linear accelerators of the 2nd generation.

The SLC injector produces a single bunch of 0.5×10^{11} particles (8 nC) by means of the two subharmonic prebunchers excited by the frequenies of 178.5 MHz which are 16th subharmonic frequencies of 2856 MHz. The single bunch is accelerated by a 3 m long accelerating waveguide up to 50 MeV. The properties of the single bunch has been studied extensively utilizing the first 100 m of the SLAC linac.

The ANL and ISIR-Osaka Univ. single-bunch linear accelerators are L-band machines. They possess the advantage of accelerating a high-current single bunch, which is higher than that of any S-band single bunch electron linear accelerators. ANL linac consists of a 12th subharmonic prebuncher with double gaps to obtain a short drift distance between an electron gun and a prebuncher. The single bunch of picosecond (25 to 36) duration and up to 40 nC in charge, with dE/E = 1.0 % at FWHM over the energy range of 4 to 22 MeV are available to the beam window.

The ISIR-Osaka Univ. linac produced a single bunch with a 6th subharmonic prebuncher during past 5 years. In order to increase a single bunch charge, a 6th subharmonic prebuncher is replaced with three subharmonic prebunchers (two 12th subharmonic prebunchers and a 6th subharmonic prebuncher). The maximum single bunch charge is, therefore, increased from 14 nC to 67 nC (4.0×10^{11} particles). The energy spread, dE/E, of the single bunch depends on the charge, and it is in the range between 0.7 and 2.5 % at FWHM. Fig. 2.1 shows the block diagram of the subharmonic prebuncher system of ISIR-Osaka Univ. single bunch electron linac.

2.4 Simulation of Subharmonic-Bunching

In order to design a subharmonic prebunching system, it is highly required to calculate the beam bunching considering the space-charge effect of the high-current pulsed beam. The longitudinal space-charge defocusing forces present in a high-current beam of uniform radial charge-density inside a cylindrical conducting tube can be calculated by the disk-model. The force acting on the i-th disk due to the j-th disk is basically calculated by the distance between two disks. As the energy of

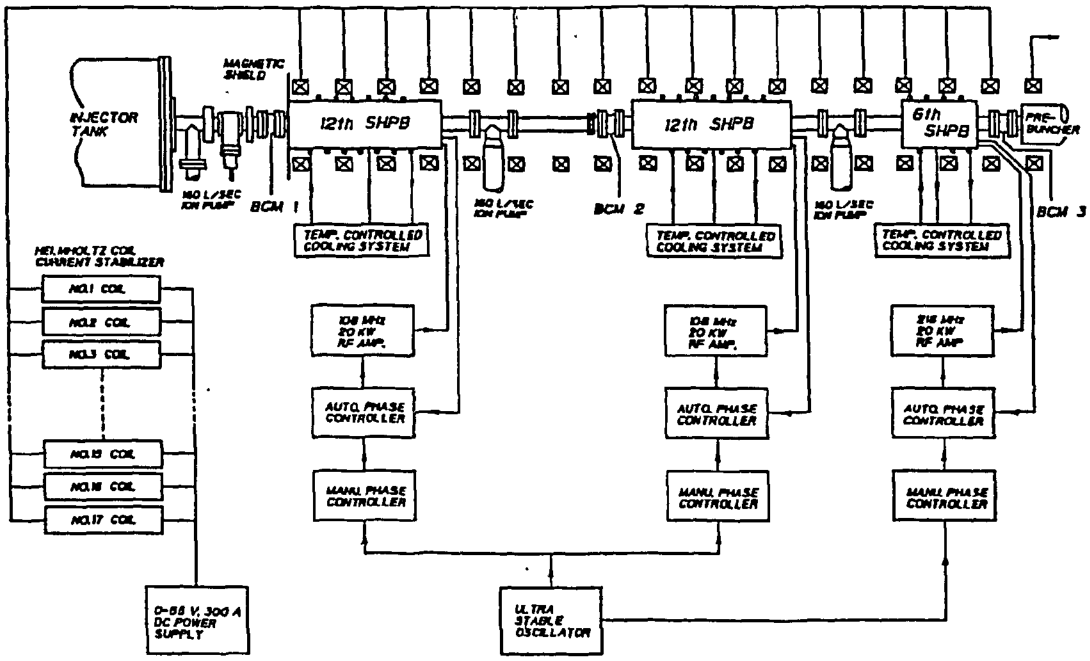

Fig. 2.1. Block diagram of the subharmonic prebuncher system of ISIR-Osaka Univ. single bunch electron linear accelerator.

electron beam is about 100 keV, the relativistic correction of the distance is required. In the conventional disk-model, however, the force on a disk is corrected by the total energy of electron in the disk, and then the force on the i-th disk due to the j-th disk differs from the force on the j-th disk due to the i-th disk. In the modified disk-model developed to design the new subharmonic prebuncher system for ISIR-Osaka Univ. linac, the forces are corrected by the average γ of the two disks to conserve the total energy of disks during the space-charge defocusing.

It is assumed that the initial beam pulse from an electron gun is a Gaussian shaped beam with the following beam parameters: the pulse width σ_t = 4.5 ns, the peak current I_p = 15 A and the initial beam energy E_0 = 100 keV. The beam is divided by 73 infinitely thin disks of equal charge. The program calculates both the longitudinal positions and the energies of the disks by the following equations.

$$\frac{d\gamma_i}{dz} = \frac{2 e Q_i}{\epsilon_0 m_0 c^2 \pi r^2} \sum_{\substack{j=1 \\ j \neq i}}^{N} \sum_{n=1}^{\infty} \frac{[J_1(j_{0n}\frac{r}{a})]^2}{[j_{0n} J_1(j_{0n})]^2} e^{-\left|\frac{j_{0n}}{a}\frac{(\gamma_i+\gamma_j)}{2}\beta_0(\theta_i-\theta_j)\frac{\lambda}{2\pi}\right|} + \frac{e E_{rf}}{m_0 c^2} \sin\theta_i \quad (2.2)$$

$$\frac{d\theta_i}{dz} = \frac{2\pi}{\lambda}\left(\frac{1}{\beta_0} - \frac{\gamma_i}{\sqrt{\gamma_i^2 - 1}}\right) . \quad (2.3)$$

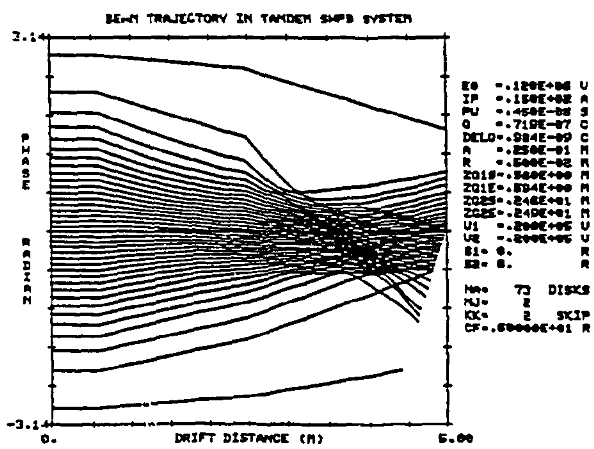

Fig.2.2-a. Beam trajectory in a tandem subharmonic prebuncher system (12th SHPB + 12th SHPB). The number of electrons, N_b is 4.5×10^{11}.

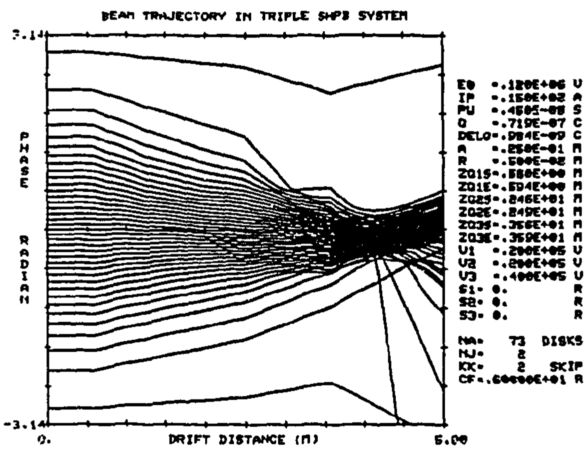

Fig.2.2-b. Beam trajectory in a triple subharmonic prebuncher system (12th SHPB + 12th SHPB + 6th SHPB). The number of electrons, N_b is 4.5×10^{11}.

The typical result of the calculation is shown in Fig. 2.2. The figure shows that the disks tends to exchange energy and to reduce their approach velocity as they close to each other. The disks existed in the angle within 180° are stably bunched into a smaller bunch than is otherwise predicted by the conventional disk model.

3 Wakefields Generated by a High-Current Single Bunch

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.

If a unit point charge passes through an rf-structure, the wake potential $W(\tau)$ is defined as the potential experienced by a test particle following a distance $c\tau$ behind the unit charge. The amplitude of the wake potential depends on the frequency for a resonant mode in the rf-structure. The scaling with frequency for the longitudinal wake and the transverse wake per unit of structure are given by

$$W_L(\text{longitudinal}) \approx \omega^2 \tag{3.1}$$

$$W_{Td}(\text{transverse-dipole}) \approx \omega^3 \quad (3.2)$$

$$W_{Tq}(\text{transverse-quadrapole}) \approx \omega^5 \quad (3.3)$$

It has been reported that the instability due to the transverse components limits the single bunch charge in an S-band structure at SLC. The luminosity is, therefore, limited by the transverse wakefields. As for an L-band structure, the transverse components might be neglected, while the longitudinal components is dominant, since both the dipole and the quadrupole transverse wake potentials clearly decrease with the rf-frequency .

3.1 Longitudinal Wake Fields

The longitudinal wake potential with an accuracy less than a few percent for the short range less than 30 ps is analytically expressed by

$$W(\tau) = A\left[\exp -(\tau/B)^n\right] \quad (3.3)$$

where A = 226 V/pC/m, B = 6.13 ps and n = 0.605 for SLC structure 2). As A and B are roughly proportional to ω^2 and ω^{-1} respectively, the wake potential for L-band structure is obtained by scalling the frequency ω. The longitudinal wake potential for L-band structure can be calculated by putting A = 46.8 V/pC/m, B = 13.5 ps and n = 0.605. The longitudinal wake potentials per unit length for a point charge of 1 pC are shown in Fig. 3.1, both for S-band and for L-band structures.

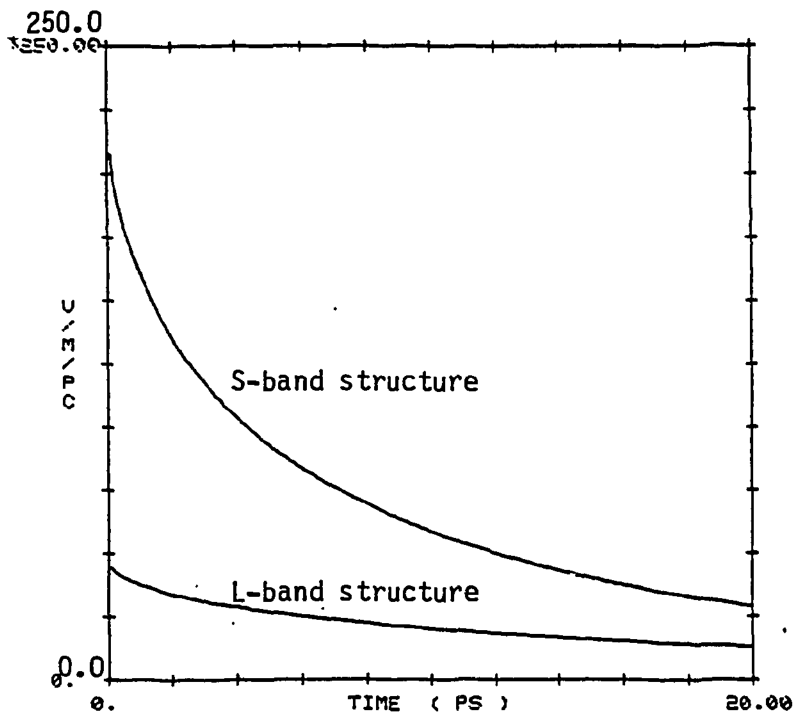

Fig. 3.1. The longitudinal wake potentials per unit length for a point charge of 1 pC.

The wake potential $U_b(t)$ for a single bunch can be obtained by the integration of the wakefields while the single bunch travels through the structure and leaves it.

$$U_b(t) = \int_{-\infty}^{t} W(t-\tau)\, I(\tau)\, d\tau$$

$$= \int_{0}^{\infty} W(\tau)\, I(t-\tau)\, d\tau \quad , \qquad (3.4)$$

where $I(\tau)$ is a current distribution of a single bunch.

For a Gaussian bunch, Eq. (3.4) can be written in the form

$$U_b(t) = \frac{A\,c\,e\,N_b}{\sqrt{2\pi}\,\sigma_z} \exp\left[-\left(\frac{t-t'}{B}\right)^n\right] \exp\left[-t'^2 c^2 / 2\sigma_z^2\right] dt'. \qquad (3.5)$$

The wake potential $U_b(t)$ of a single bunch of particles with $N_b = 1.0 \times 10^{11}$ are shown in Fig. 3.2 (a-d) and Fig. 3.3 (a-d) for several values of the bunch length σ_z. These results show that the wake potential for L-band structure is smaller than the potential for S-band structure. It seems that the L-band structure is sutable for accelerating a high-current single bunch.

The total energy loss ΔU is expressed in terms of the wake potential $U_b(t)$ and the current distribution $I(t)$,

$$\Delta U = \int_{-\infty}^{\infty} U_b(t)\, I(t)\, dt \quad . \qquad (3.6)$$

The energy left behind in the rf-structure by the single bunch is equal to the total energy loss of the single bunch. Thus, the loss parameter k is given by

$$k = \frac{\int_{-\infty}^{\infty} V_b(t)\, I(t)\, dt}{q^2} \quad , \qquad (3.7)$$

where q is the single bunch charge. The loss parameter k for several values of the bunch length σ_z are shown in Table 3.1.

Bunch Length	Loss parameter k (MeV/m/1x10^{11}particles)	
σ_z (mm)	S-band structure	L-band structure
0.5	1.209	0.291
1.0	0.976	0.253
2.0	0.728	0.207
4.0	0.492	0.157

Table 3.1 The loss parameter k for several values of the bunch length σ_z.

3.2 Energy Spread of the Single Bunch

When a single bunch is accelerated by a linear accelerator, the total energy gain of an electron at time, t, can be obtained by adding the wake potential to the external accelerating voltage,

$$E(t) = E_0 \cos(\omega t - \theta) + U_b(t) , \tag{3.8}$$

where θ is the phase-angle between the single bunch and the accelerating voltage. With increase of bunch charge, the wake potential $U_b(t)$ increases from the small fraction of the accelerating voltage to the value which is large enough to distort the net accelerating voltage. Figures 3.4 (a-e) show the

S-band (2856 MHz)

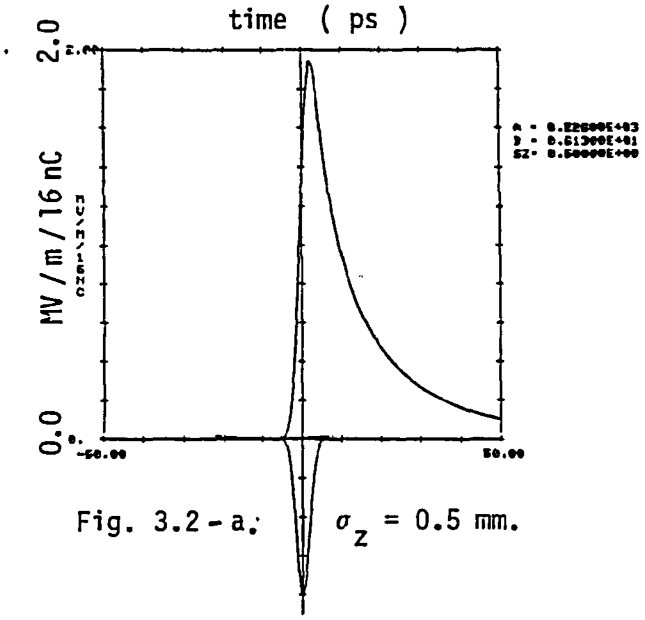

Fig. 3.2 - a. σ_z = 0.5 mm.

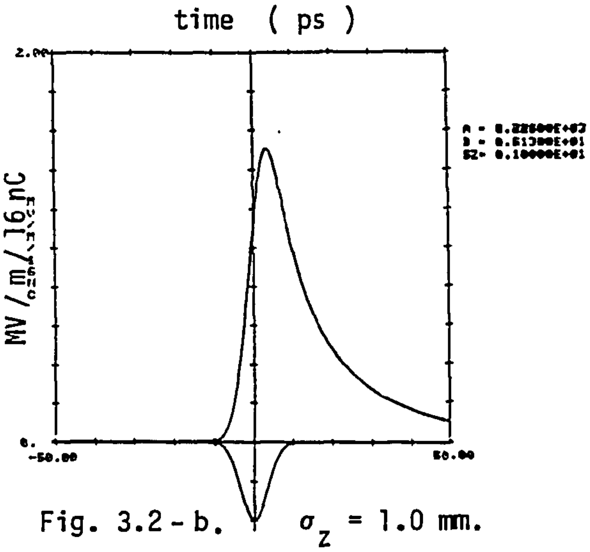

Fig. 3.2 - b. σ_z = 1.0 mm.

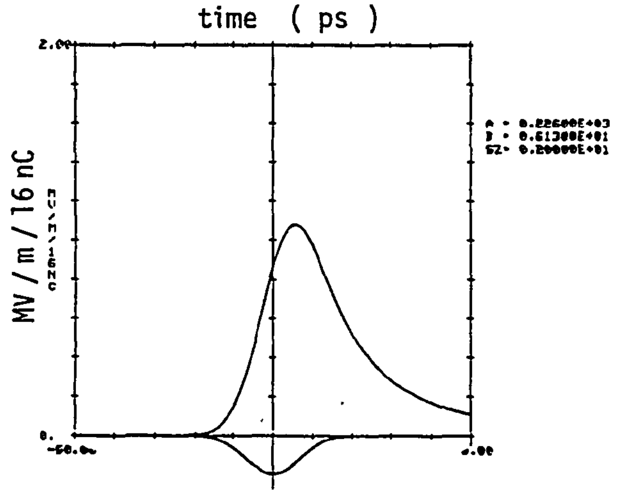

Fig. 3.2 - c. σ_z = 2.0 mm.

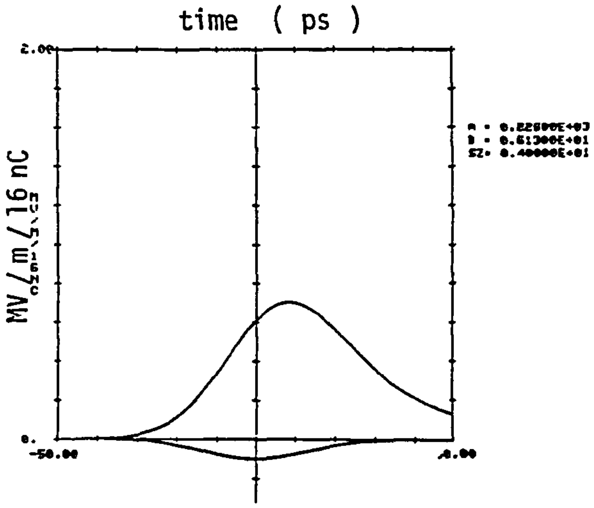

Fig. 3.2 - d. σ_z = 4.0 mm.

Fig. 3.2 - a, b, c & d. The wake potential $U_b(t)$ of a single bunch of particles with $N_b = 1.0 \times 10^{11}$ for an S-band structure.

L-band (1300 MHz)

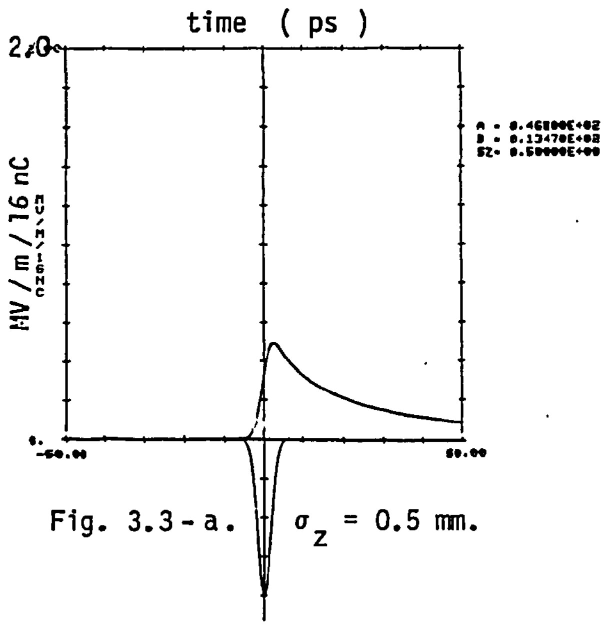

Fig. 3.3 - a. σ_z = 0.5 mm.

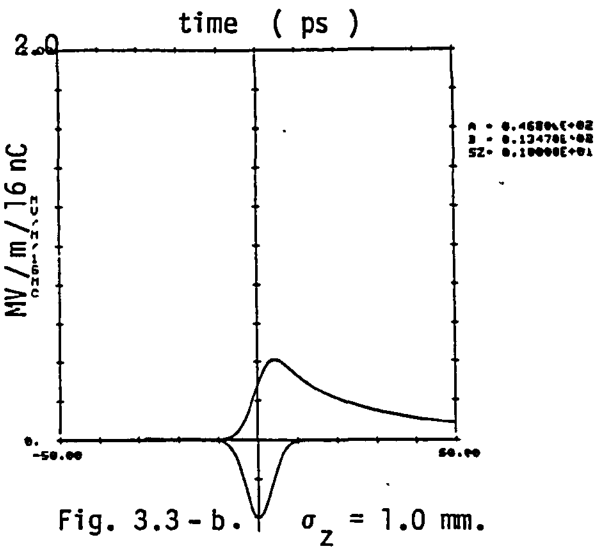

Fig. 3.3 - b. σ_z = 1.0 mm.

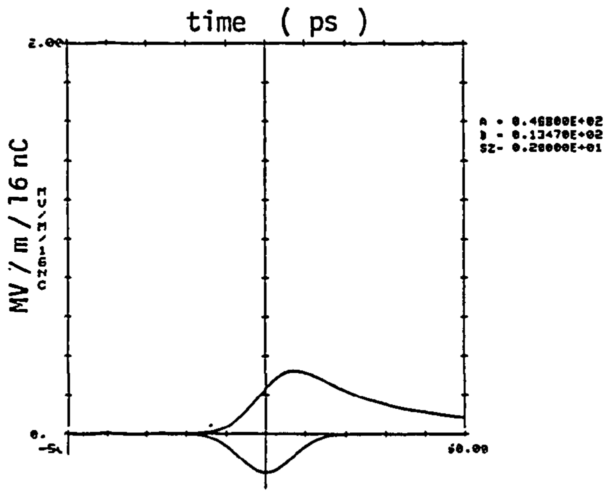

Fig. 3.3 - c. σ_z = 2.0 mm.

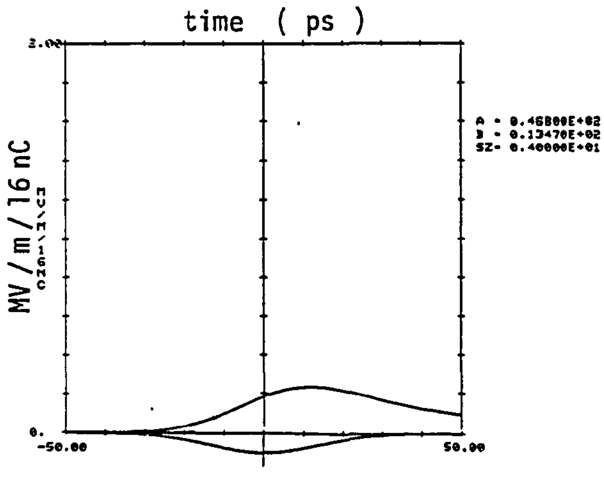

Fig. 3.3 - d. σ_z = 4.0 mm.

Fig. 3.3 - a, b, c & d. The wake potential $U_b(t)$ of a single bunch of particles with $N_b = 1.0 \times 10^{11}$ for an L-band structure.

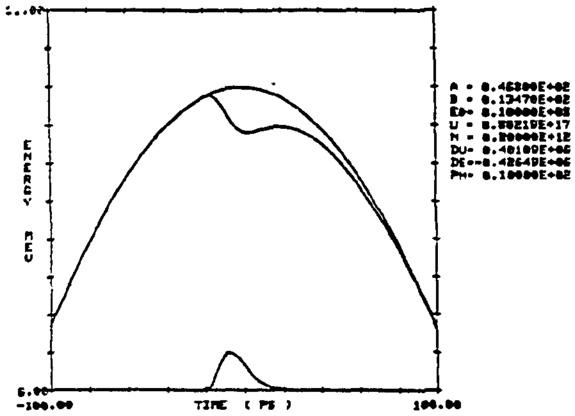

Fig. 3.4 - a. Phase $\theta = 3.45°$.

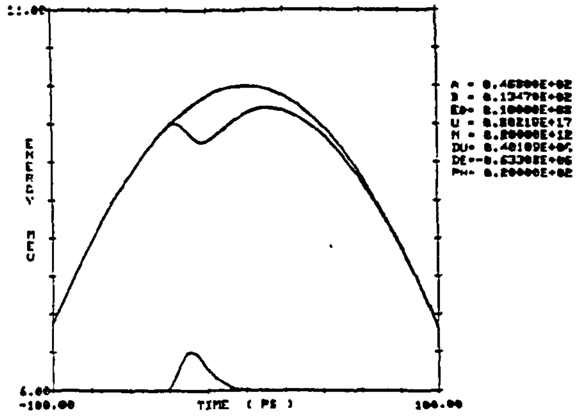

Fig. 3.4 - b. Phase $\theta = 13.45°$.

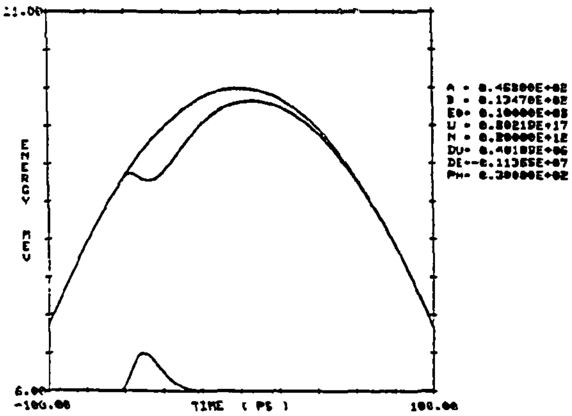

Fig. 3.4 - c. Phase $\theta = 23.45°$.

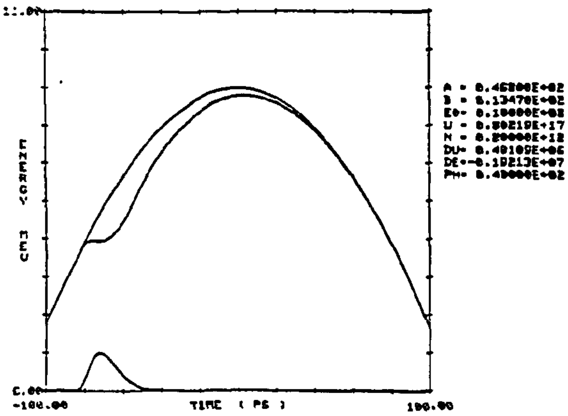

Fig. 3.4 - d. Phase $\theta = 34.45°$.

Fig. 3.4 - a, b, c & d. Results of calculation of the net accelerating voltage in the ISIR - Osaka Univ. L-band structure for several values of the phase angle, θ, where the single bunch is accelerated. The number of particles, $N_b = 2.0 \times 10^{11}$ (32 nC).

results of calculation of the net accelerating voltage in the ISIR-Osaka Univ. structure for several values of the phase-angle where the single bunch is accelerated. The bunch shape obtained from the experiment is fitted in the gamma function.

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.

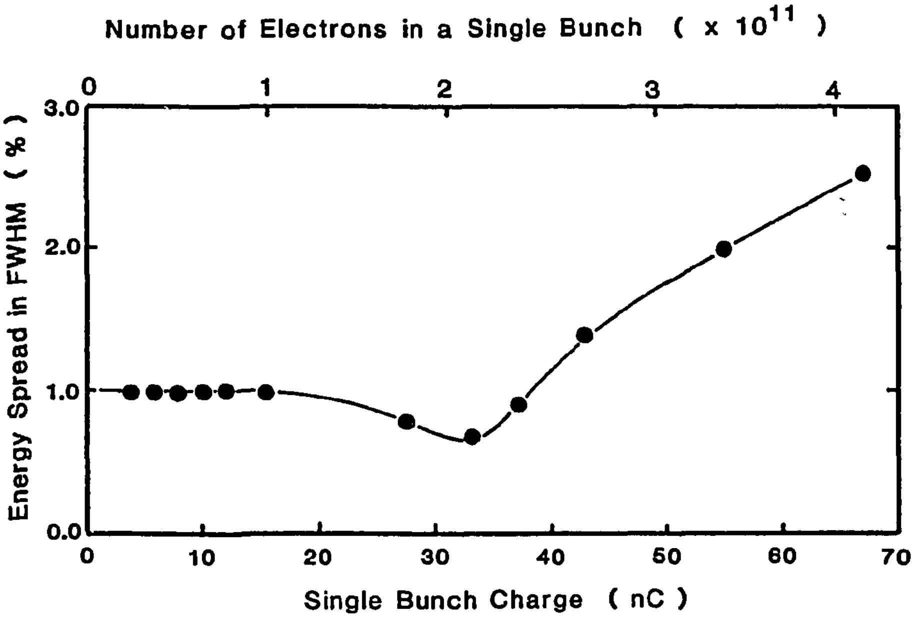

Fig. 3.5. The minimum energy spread which can be obtained by controlling the phase-angle, θ, where the single bunch is accelerated by the ISIR - Osaka Univ. L-band single bunch electron linear accelerator.

Figure 3.5 shows the minimum energy spread which can be obtained by controlling the phase-angle to accelerate the single bunch by the ISIR-Osaka Univ. single bunch electron linear accelerator. The energy spread is observed to be 1.0 % for the single bunch charge in the range 0 - 16 nC, in spite of the increase in spread with the increase of the bunch charge. It seems that the increase in the energy spread due to the wake potential is cancelled by the phase-controll. For the bunch charge within the region 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 that the increase in the single bunch charge gives rise to the increase of 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 bunch-length is required.

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