Longitudinal Wake Field Characteristics of the KEK Positron Generator Linac

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Abstract

The effect of a longitudinal wake field on a high current multi-bunched beam was investigated at the primary electron section of the KEK positron generator linac. The energy spectrum of multi-bunches due to the beam loading was compared with a numerical analysis by the computer code *TBCI*.

I. INTRODUCTION

For the purpose of attaining a large luminosity in a future e^+e^- linear collider, it is necessary to operate the accelerator in the multi-bunch mode. While this enhances the efficiency of the accelerating structure without a large increase in the RF power, it causes many problems regarding beam dynamics. When a bunched beam traverses an accelerating structure, it excites electromagnetic fields (called wake fields [1]). Transversally, the wake field kicks any trailing particles, and then brings about a cumulative beam breakup. On the other hand, a longitudinal wake field extracts energy from the accelerating field, leading to a variation in the beam energies. Although the problems related to the single-bunch phenomena have been studied by several people [2], there have so far been few investigations on the multi-bunch phenomena of highly intense bunched beams.

The positron generator linac at KEK [3] has a high intensity primary electron beam, which is bunched and accelerated to 250 MeV by an RF field. The beam is split into 5-6 bunches with the electric charge of a few nano Coulomb, respectively. A series of experimental studies on the wake field characteristics of the KEK positron generator linac has been carried out [4]. In this paper we discuss the longitudinal wake field characteristics of the high-intensity, multi-bunched beam. The energy spectrum of such a multi-bunched beam is measured at the energy analyzing station and compared with numerical analysis by using the computer code *TBCI*.

II. EXPERIMENTAL SETUP

The primary electron section of the KEK positron generator linac comprises the following components: An electron gun emits an intense electron beam of 150 keV with a peak current of 10 A and a pulse width of 4.2 ns. A sub-harmonic buncher with a modulation frequency of 119 MHz and a following drift space longitudinally compresses the beam to a 2 ns pulse with a peak current of 15 A. A prebuncher and a buncher operating at 2856 MHz then split the beam into several bunches. In traveling through a subsequent regular accelerating section, the average energy of the bunches reaches about 250 MeV. The accelerating section is 22 m long and has the same operation frequency to the bunchers. At the end of the primary electron section there is an energy analyzing station, which includes collimeters, a bending magnet, beam profile monitors, a wall current monitor, a slit and a bunch monitor of the stripline type. In measurements of the energy spectrum, the energy resolution is set to 0.15 % by using a slit width of 1 mm. The measured energy spectrum indicated a bunch structure due to a transient beam loading effect. Several peaks in the measured energy spectrum could be identified with bunches by using a bunch monitor.

III. RESULTS AND DISCUSSIONS

The measurement of a high-current multi-bunched beam at the above-mentioned energy analyzing station gave the energy spectrum shown in Fig.1.

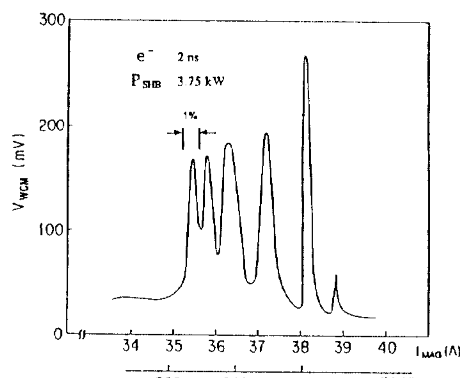

Figure 1. Energy spectrum measured at the energy analyzing station.

There are several peaks in the spectrum which correspond to bunches. The bunch-to-bunch energy difference, which should be attributed to the longitudinal wake field, was estimated by a numerical analysis according to the following. The energy gains and charges of bunches were determined from Fig.1 and are listed in Table 1.

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Table 1. List of bunch characteristics

Bunch	Energy Gains (MeV)	Charges (nC)
1	255.2	1
2	251.1	6
3	245.3	7
4	239.4	9
5	236.2	4
6	233.9	4

Before starting a numerical analysis, we present the basis of energy extraction by a multi-bunched beam[5]. Suppose that an accelerating structure of length L is fully filled with RF power. If the attenuation of the field is negligible, or if the structure has a constant gradient, the energy gain of a test particle from the accelerating field is

$$\Delta E|_{\text{acc}} = e\mathcal{E}_0 L \ , \tag{1}$$

where $\mathcal{E}_0$ is the field gradient. In order to clarify the properties of the longitudinal wake field, we first concentrate on the wake field excited in the fundamental accelerating mode. The fundamental wake field excited by a short bunch of charge, q, is

$$\mathcal{E}_{\text{wake}} = -2kq \ , \tag{2}$$

where k is the loss factor per length of the fundamental mode. If the charge distribution is symmetric about the bunch center, the energy loss of a single bunch by the wake field is given by

$$\Delta E|_{\text{single}} = -ekqL \ . \tag{3}$$

We next consider the energy loss by the wake field, which advanced bunches excite. Since the group velocity of the fundamental mode is a few percent of the speed of light, we neglect the propagation of the fundamental wake field, compared to the structure length. The energy loss of the n-th bunch by the excited field of proceeding bunches is then given by

$$\Delta E|_{\text{multi},n} = -2eL \sum_{m=1}^{n-1} kq_m \ , \tag{4}$$

where q_m is the charge of the m-th bunch. Since the loss factor is a function of the bunch length, σ_z[6], it can assume different bunch-to-bunch values if each bunch possesses its own length, respectively. After all the total energy gain of the n-th bunch is given by

$$\Delta V_n/L = \mathcal{E}_0 - kq_n - 2\sum_{m=1}^{n-1} kq_m \ . \tag{5}$$

Here, we have used the abbreviated notation $V \equiv E/e$.

We now compare the experimental result with a numerical analysis. We evaluate the longitudinal wake field by means of the *TBCI*-code. Although the structure of the KEK positron generator linac is a quasi-constant gradient, the evaluation was performed by assuming a constant impedance structure. Figure 2 shows the calculated longitudinal wake field excited by a bunch of length 7.5 mm, which is a probable bunch length of the KEK positron generator linac.

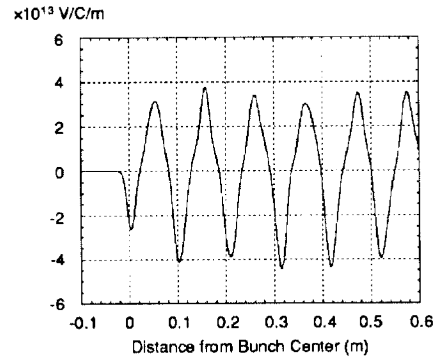

Figure 2. The longitudinal wake field of the KEK positron generator linac excited by a bunch 7.5 mm long.

In order to obtain a loss factor of constant gradient structure, we calculated the corresponding wake fields of a constant impedance structure using various apertures and then average them.

Assuming that all of the bunches have the same bunch length (7.5 mm), we obtained the energy spectrum shown in Fig.3(b).

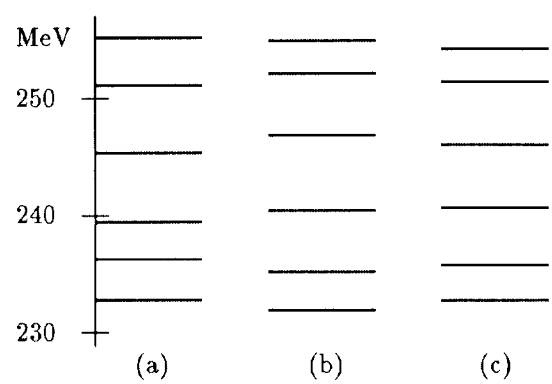

Figure 3. (a) Energy spectrum measured. (b) Energy spectrum computed not including higher modes. (c) Energy spectrum computed with higher modes.

To improve the numerical estimation, we include the higher modes of longitudinal wake field. To this end, we computed the loss factors at the positions of the trailing bunches, which are listed in Table 2. Note that the loss factors at the following bunches are almost double the single bunch loss factor, as expected. The difference is ascribed to the higher modes of the longitudinal wake field. Using the modified loss factors, the energy spectrum (c) in Fig.3 is computed.

Table 2. Loss factors evaluated at the bunch positions

Bunch	Loss Factor $(\times 10^{13}\ \mathrm{V/C/m})$
1	1.8
2	3.4
3	3.3
4	3.6
5	3.5
6	3.2

In the previous argument, we assumed that all of the bunch lengths to be equal to 7.5 mm. For the purpose of investigating the effect of changes in the bunch length, we calculated the wake fields of various bunch lengths. The single bunch loss factor changes as shown in Fig.4 when shortening the bunch.

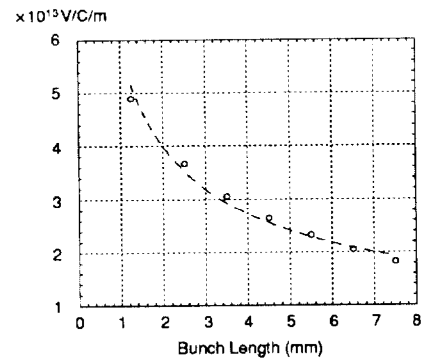

Figure 4. Dependence of the longitudinal wake field of the KEK positron generator linac on the bunch length.

In the short range, the diffraction model [6] implies that the loss factor varies as $\sigma^{-1/2}$. Although this model is not applicable to the present bunch lengths, the loss factor still varies as $\sigma^{-1/2}$. As a result, the amount of the loss factor can change bunch-to-bunch due to the difference in the bunch length.

Furthermore, as the bunch length becomes shorter, more of the higher modes are excited. For example, the wake field of a bunch with a length of 2.5 mm has the shape shown in Fig.5.

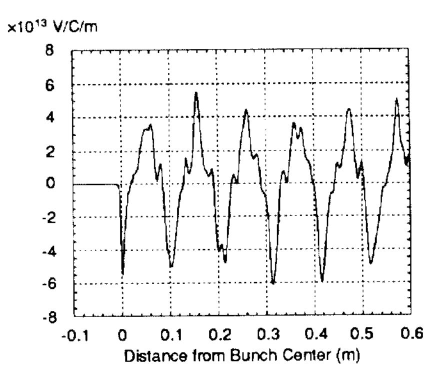

Figure 5. The longitudinal wake field of the KEK positron generator linac excited by a bunch of 2.5 mm long.

Comparing Fig.5 with Fig.2, one is easily convinced that the higher modes of the wake field by the short bunch are more excited than that by a long bunch. The loss factors of the trailing bunch are largely influenced by these higher modes.

Table 3. Loss factors of bunch with length 2.5mm

Bunch	Loss Factor $(\times 10^{13}\ \mathrm{V/C/m})$
1	3.7
2	4.8
3	4.1
4	5.8
5	5.1
6	4.0

The loss factors for the trailing particles remarkably depart from the double type which appear during single beam loading.

The measured energy spectrum can be partly explained by a numerical analysis. To obtain a better agreement between the experimental and numerical investigations, we need to obtain the precise information concerning the bunch length. This implies that keeping the energy of bunches in high precision requires us to closely control the bunch lengths of the multi-bunched beam.

V. RFERENCES

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