EXPERIMENTAL INVESTIGATIONS OF MULTI-BUNCH INSTABILITY BY A TRANSVERSE WAKE FIELD

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Abstract

A multi-bunch instability due to a transverse wake field relevant to future linear colliders was investigated at the primary electron section of the KEK positron generator linac. A transverse shift of the last bunch was observed by changing a transverse offset of the beam position at the entrance of the first accelerating cavity.

Introduction

Future linear colliders[1] will require multi-bunch operation for the attainment of large luminosity. Under multi-bunch operation, it is essential to overcome any beam instability induced by a transverse wake field, since it may result in both emittance growth and blow-up of the spot size at the collision point.[2] The problems related to the transverse wake field and its effects on a high-intensity, single-bunch electron beam have been already resolved both theoretically and experimentally by several researchers.[3] The multi-bunch instability, however, has so far been treated only theoretically;[4] results suggest several possible methods to reduce this instability. Only a few experimental studies[5] have taken place concerning high-intensity, multi-bunch electron beams; especially, no experiments have been reported on the multi-bunch instability caused by a transverse wake field (except for BBU[6] or pulse-shortening effects for a very long train of bunches, where only the beam loss was observed). We first observed a multi-bunch instability for a few bunches at the primary electron section of the KEK positron generator linac.

Experimental

The layout of the KEK positron generator linac[7] is shown in Fig. 1. It involves a 250-MeV primary electron section, starting from a 150-keV, high-intensity electron gun with a peak emission current of 10 A and a pulse width of 4.2 ns. The electron beam is longitudinally compressed to a 2-ns pulse with a peak current of about 15 A by a Sub-Harmonic Buncher(SHB) with a modulation frequency of 119 MHz and a subsequent drift space of about 3 m. It is then split into several bunches in a bunching section operating at 2856 MHz, and accelerated to 250 MeV in a regular accelerating section at the same frequency. Fig. 1 also shows parts of the focusing system related to the experiment: the steering coils and quadrupole magnets that are arranged so as to produce a betatron wavelength of about 40 m. An energy-analyzing station[8] in front of the positron conversion target comprises collimators, an energy-analyzing magnet, beam-profile monitors, a current monitor, a slit, and a bunch monitor of the strip-line type.[9] The measured energy spectrum of the beam indicated several peaks, which have been identified as being bunches using a bunch monitor. The electric charge on each bunch amounted to several nano-Coulomb; the total energy spread was about 9 %.

In order to observe at PRM-A how the transverse position of the beam moves, we changed the transverse (vertical) offset of the beam position at the entrance of the first accelerating cavity by flowing a current in a steering coil, ST-1(see Fig. 1) . A photograph of a typical case is shown in Fig. 2; the bunch structure appears and the last bunch (right-most side) moves very sensitively to the vertical offset at the entrance of the accelerating cavity. In Fig. 3, the transverse displacement of the last bunch is plotted as a function of the offset at the first accelerating cavity, which was measured at the profile monitor, PRM-1, immediately after steering coil, ST-1. It shows an almost linear dependence, which is reasonable from a theoretical point of view.

Several tests and analyses were performed to confirm that the observed effect is due to a transverse wake field. First, the beam trajectory for two typical cases in which the effect seems to appear, was checked. The result showed normal behavior of betatron oscillations (Fig. 4). The transverse beam positions at PRM-A with SHB both ON and OFF was then compared. No effects were observed when SHB was OFF (Fig. 5a). Since SHB being ON and OFF corresponded to five- and twelve-bunch operations with almost the same total charge, the same average energy, and the same total energy spread, we could verify in this way that the observed effects depend on the electric charge per bunch, and that the effects are not caused by different possible orbits due to momentum differences. A semi-long beam with a peak current of 2.3 A and a pulse width of 40 ns was accelerated in order to determine whether the effects appear when the electric charge per bunch is smaller (the total electric charge was almost twice that of the 2-ns beam). No transverse blow-up was observed (Fig. 5b), verifying that the electric charge per bunch is essential for the effects. Finally, the z-dependence (here, z is again the length of the accelerator) of the effects was investigated . By changing the beam offset, at the second accelerating section (see Fig. 1), not at the first, reduced z by maintaining almost the same offset, we found that the effects became smaller (Fig. 5c). The reduction ratio of the transverse offset was about 3.5, obtained by applying a large initial offset, so as to produce the same transverse effect.

Discussion

The results are summarized as follows:

(1) The observed shift of the beam position at the output of the accelerator is proportional to the offset at the entrance of the accelerating cavity (Fig. 3).

(2) The observed effects depend on the electric charge per bunch, not on the total electric charge (Fig. 5a,b).

(3) The dependence of the effects on the length of the accelerator is sufficiently strong (Fig. 5c).

In order to quantitatively explain the results, we tried to make a very rough estimation by applying, for instance, a two-particle model by Wilson to our case. Wilson's formula[3] is

$$\frac{X_f}{X_i} \cong \frac{eN\beta W_d z}{8\pi V_0},$$

where X_f and X_i are the offsets at the entrance and output of the accelerating cavity, respectively; N the number of particles; β the betatron wavelength; W_d the dipole wake field at the separation between the model particles; z the length of accelerating sections; and V_0 the average energy. If we take eN=10 nC, β=40 m, $W_d \cong 10^{15}$ V/C/m^2, z=24 m, and eV_0=120 MeV,

$$\frac{X_f}{X_i} \cong 3,$$

which is roughly consistent with the experimental value of about 1 (Fig. 3). Here, the value obtained at SLAC[2] for a dipole wake field was assumed. The difference may be attributed, for instance, to the fact that it is of the cavity type; KEK's is a quasi-constant gradient type, while SLAC's is a constant-impedance type. As a result, the above (1) and (2) were verified semi-quantitatively. The z-dependence (above (3)) was also checked by using the same formula, where it is linear in z. In our experiment, the ratio of z in the two cases is about 22 m/16 m $\cong$ 1.4. Taking into account the energy dependence, this factor is reduced to about 1.7, which still seems to be too small to explain the experimental value (about 3.5).

The discrepancy may be explained by the multi-particle model by Suzuki.[10] According to his theory, the transverse shift in a multi-bunch scheme is proportional to z^{n-1}, where n is the bunch number. In our case, it gives about $(1.4)^{5-1} \cong 3.8$; after taking into account the energy dependence again, the ratio of the transverse shift becomes about 4.6. This value agrees roughly with the observation of about 3.5. In this connection, we will continue to analyze the observed data based on Suzuki's model as well as numerical simulations.

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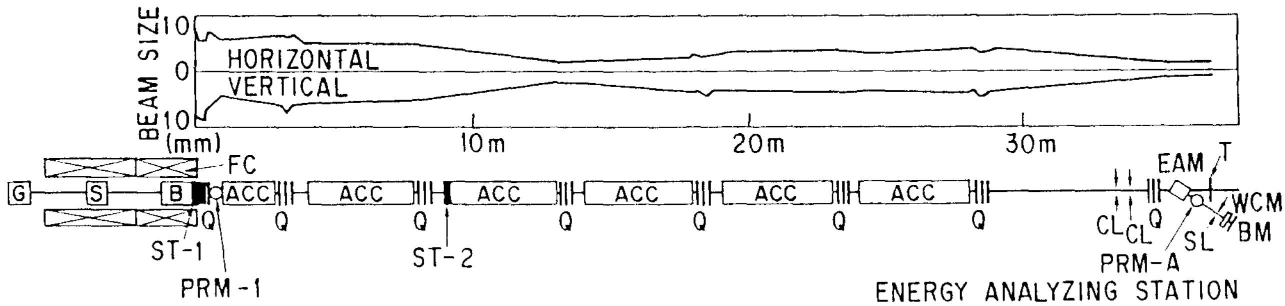

Fig. 1. Layout of the primary electron section of the KEK positron generator linac. The calculated beam size is also shown (see also Ref. 9). G is an electron gun; S, SHB; B, a prebuncher and a buncher; ACC, accelerating cavities; FC, focusing solenoids; Q, quadrupole magnets; ST, steering coils; EAM, an energy-analyzing magnet; PRM, profile monitors; CL, collimators; SL, a slit; WCM, a wall current monitor; BM, a bunch monitor; and T, a positron production target.

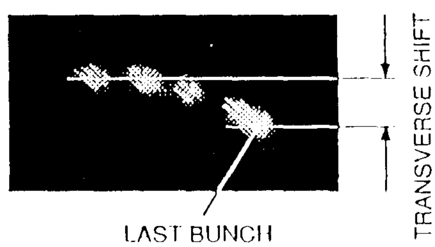

Fig. 2. Transverse(vertical) shift of the last bunch observed at the profile monitor PRM-A at the energy-analyzing station.

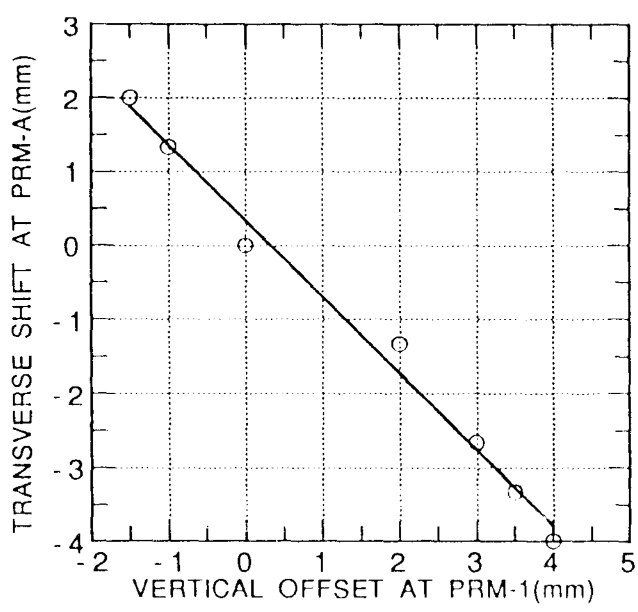

Fig. 3. Transverse shift at the end of the accelerator as a function of the initial offset. The solid line shows a least-squares fit.

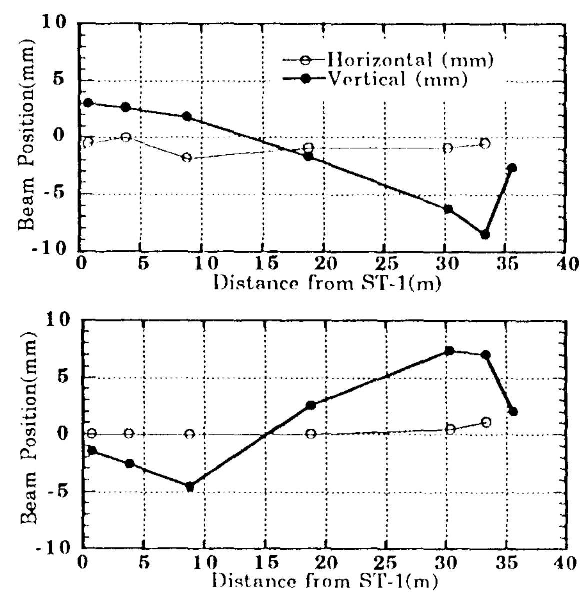

Fig. 4. Beam trajectory for two typical cases in which the effect seems to appear.

(a)

(b)

(c)

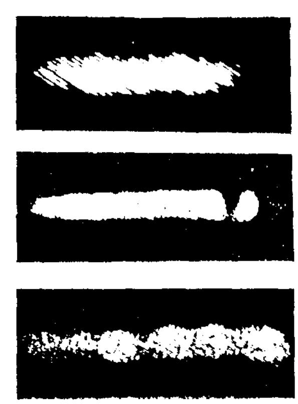

Fig. 5. No transverse blow-up was observed (a) with SHB OFF, and (b) with a semi-long pulse beam. The effect is smaller when the length of accelerator is diminished (c).