STABILITY OF ELECTRON ORBITS IN THE STRONG WAKE FIELDS GENERATED BY A TRAIN OF FSEC BUNCHES*

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Abstract

A tall, dielectric-lined rectangular wake field microstructure is being analyzed as a possible stageable element of an advanced linear wake field accelerator, to be driven by a train of fsec microbunches. These microbunches would be chopped out of a longer bunch using a powerful CO_2 laser and formed into a rectangular-profile bunch using a quadrupole. The fsec bunches set up a periodic wake field in the microstructure that can be built up to 600 MV/m, for example, using ten 3-fsec bunches each containing 2 pC of charge. Results are described from computations of test particle electron orbits in the longitudinal and transverse wake fields excited by these fsec bunches. It is found that test electrons in drive bunches will be well confined within the structure for a travel distance of ~10 cm and test electrons located in an accelerated bunch will have stable motion for at least 50 cm.

INTRODUCTION

Acceleration of electrons in wake fields set up by a series of driving bunches in a dielectric structure has shown promise as a linear accelerator in which large gradients might be possible [1,2]. Such wake fields are interesting because they do not require power injected into the structure from an external source, but rather use fields set up by bunches obtained from a conventional rf linac. Recently, we have studied the use of tall, planar dielectric wake field structures having micron-scale dimensions [3]. Such structures are capable of precision manufacture using microcircuit technologies, and have the capability of achieving very high field gradients: indeed, a series of ten, 3-fsec 1-pC charge bunches has recently been shown to set up a wake field of ~500 MeV/m in a structure 18.8×150 μm in cross section [4]. The bunches are 10 μm wide, and dielectric slabs a few μm thick line the structure. Planar dielectric structures offer the attraction of improving the stability of the bunch motion and the amount of charge carried compared with a cylindrical structure of comparable size, and the small transverse dimension permits a large wakefield to be developed.

The bunches could be obtained initially from a 500 MeV rf linac-type source, and are processed using a LACARA accelerator "chopper" [3], or possibly an IFEL [5] used as a "pre-buncher", so as to obtain a sequence of bunches a few fsec in duration. A TW CO_2 laser is used as a "modulator" [3] of the original psec, nC bunch provided by the linac to form such a sequence of short bunches, each having charge in the pC range. These *drive* bunches, the energy of which can be recycled, would in practice be followed by an *accelerated bunch* which is situated in the accelerating component of E_z which follows the drive bunch train. In this way fields comparable with those achieved in laser plasma wake field accelerators can be set up, yet the energy is obtained largely from the rf linac source rather than the laser. We have found that it is possible to distort the original circular cross section of the input bunches into a rectangular profile, using a quadrupole, and that the rectangular profile is maintained for several centimeters of travel [4].

Transverse fields set up by the bunch have been calculated, and an estimate has been made of how far a drive bunch might travel without additional focusing [6] (several cm). Also, studies have been made of fields in 3D using the PIC code KARAT. The E_z component of wake field was found to be rather uniform in cross section. In the structure under study, the wake fields are dominated by two modes having nearly the same periodicity (about 21 μm in the chosen geometry). In this paper, we study the motion of *test particles* which are situated initially in a grid of loci at the location of any drive or accelerated bunch (see Fig. 1). Our findings show that adequate stability of the drive bunches can be obtained by choosing a tall structure (300 μm), and that a certain group of test particles can be accelerated for a distance of ~1/2 m or more without external focusing, maintaining a nearly stable profile and gaining energy of 300 MeV in that distance.

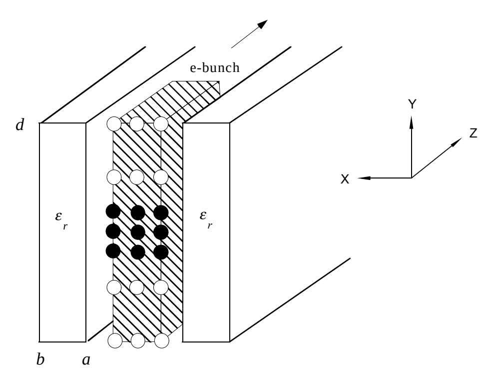

Figure 1: Schematic slab bunch within a planar wake field structure. Circles stand for test particles in the (decelerated) drive bunch while dots stand for test particles in the accelerated bunch.

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NUMERICAL PROCEDURE AND MODEL

A complete theory for excitation of wake fields in 3D planar dielectric-lined waveguides, similar in structure to a theory for cylindrical waveguides [7], has been formulated [6]. Park wrote a code [8] based on his theory [6] to calculate distributions of wake field forces excited by a train of rigid electron bunches moving at a constant velocity. In this paper, the code is used to calculate dynamics for test particles by adding a routine solving the Lorentz force equations, in which the wake field forces are as in Ref. 6.

The dielectric structure is shown in Fig. 1, with the beam channel width $2a$ = 15 μm, the dielectric thickness b-a = 1.9 μm, and the dielectric (channel) height $2d$ = 300 μm, and the relative dielectric constant ε_r = 3. The rigid drive bunches are 10 μm wide, 300 μm high, and 1 μm (3 fsec) long, each containing 2 pC of charge. The initial velocity of test particles is assumed to be the same as that of drive bunch, which has a relativistic energy factor of $\gamma = 1000$ (510.5 MeV). The self-field effect and the reaction on the drive bunch are neglected. The test particles in the drive bunch are initially uniformly distributed within a 10×300−μm rectangle while the test particles in the accelerated bunch are located within a 10×40−μm rectangle. In simulations, 861 computational particles are used to calculate the interaction between wake fields and test particles.

The place of injection of the accelerated bunches can be optimized. At a place behind the last drive bunch appropriate for acceleration, the transverse wake fields are small while the axial field is large. Since the axial slippage between the wake fields and accelerated particles is quite small, one can estimate what wake field peaks are potentially good for acceleration using only the initial field distributions. Therefore, we first find the possible positions and then do dynamic simulations one by one to obtain the best one favoring stable motion.

MOTION OF DRIVE BUNCH

Coherence of wake fields from different drive bunches requires a fixed bunch spacing. The first dive bunch is set at z = 1200 μm and the 10th drive bunch is at 1009.2 μm, with a spacing of 21.2 μm. The stability of the 10th drive bunch is examined by initially setting test particles at z = 1009.2 μm, where the axial wake field force on the axis is –210.2 MeV/m, excited by first 9 drive bunches.

Fig. 2a shows the dependence of F_x on y at z = 1009.2 μm for x = 0, 1, 3, 5 μm (F_x is anti-symmetric with respect to x). It is seen that the magnitude of F_x increases nearly linearly with x, and F_x is focusing or defocusing, depending on y. F_x is focusing around y = -95, -25, 25, and 95 μm while defocusing around y = -135, -60, 0, 60, and 135 μm. Fig. 2b shows the distributions of the test particles at z = 1009.2 μm, 4 cm, 7 cm, and 10 cm under the influence of the wake fields. The four x-direction focusing locations can be easily identified from the z = 4-cm distribution. Because of a strong defocusing force in the region of 115 μm < |y| < 150 μm (two y-ends), particles there get lost to walls (see the z = 10-cm distribution). Fig. 2c shows the dependence of average relativistic energy factor and percentage of surviving particles upon axial distance. All the particles go ~2 cm without hitting any walls, and finally more than 70% arrive at z = 10 cm. The particles are decelerated from <γ> = 1000 (510.5 MeV) to 955.2 (487.6 MeV).

Simulations show that 94% of the test particles at the second drive bunch survive traveling 10 cm while 77% at the fifth and 73% at the eighth.

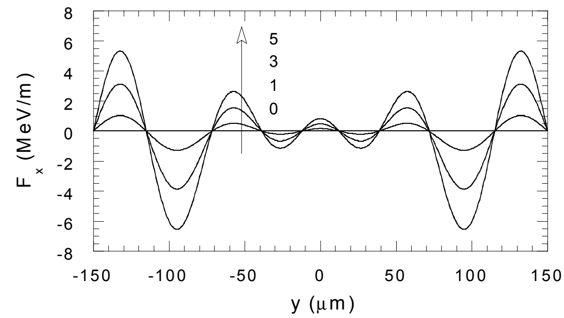

Figure 2a: Dependence of F_x on y for x = 0, 1, 3, and 5 μm. F_x is focusing when F_x < 0, while F_x is defocusing when F_x > 0.

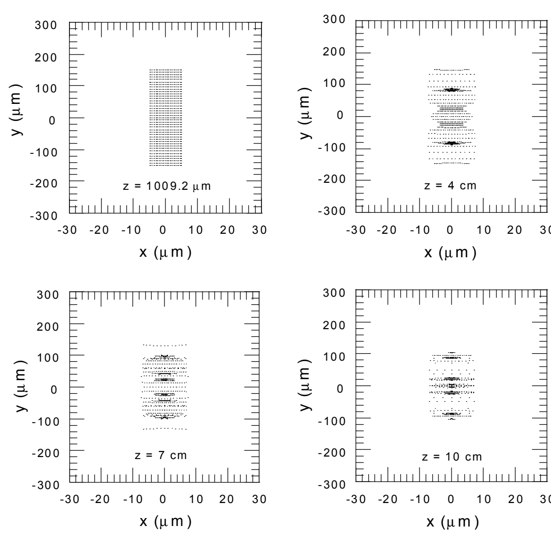

Figure 2b: Drive bunch test particle distributions at z = 1009.2 μm, 4 cm, 7 cm, and 10 cm.

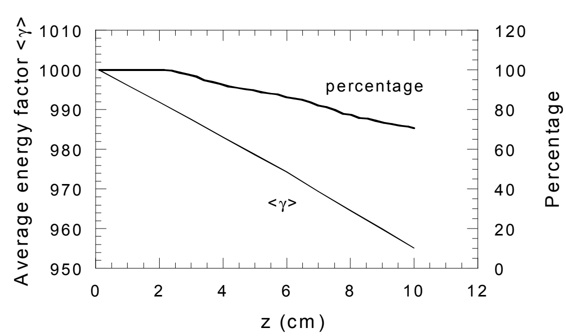

Figure 2c: Dependence of average energy factor and percentage of surviving particles on axial distance.

MOTION OF ACCELERATED BUNCH

The accelerated bunch comes from a different source than the drive bunch. The stability of accelerated particles depends on positions in the wake field and the size of the region the particles take up. Simulations show that the test particles in the accelerated bunch following a train of 10 drive bunches should to be situated at z = 60.5 μm, where the transverse wake field forces are small and focusing in a rectangular region of $|x| < 5$ μm and $|y| < 20$ μm while the axial wake field force on the axis reaches its peak, 618.1 MeV/m, as shown in Fig.3a. F_x and F_y are focusing when less than zero, since they are plotted at $x > 0$ and $y > 0$ respectively.

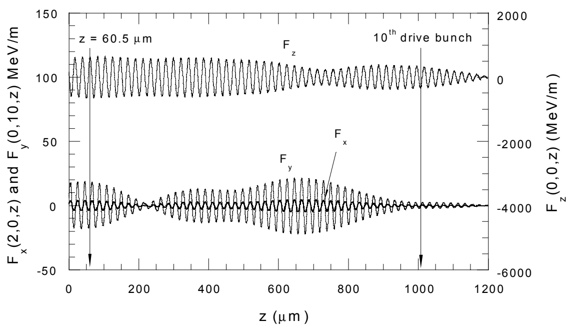

Figure 3a: Dependence of wake field forces $F_x(2,0,z)$, $F_y(0,10,z)$, and $F_z(0,0,z)$ on axial distance z, excited by 10 drive bunches. The stability of the accelerated bunch is examined by setting test particles at z = 60. 5 μm.

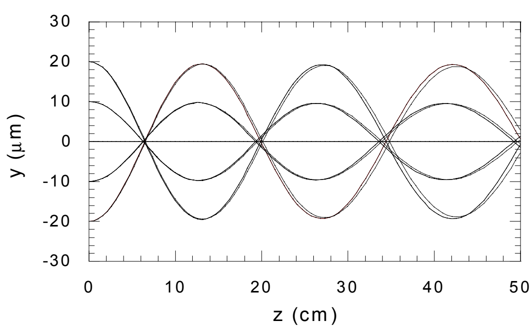

Figure 3b: Orbits on the y-z plane for 15 sampled accelerated particles.

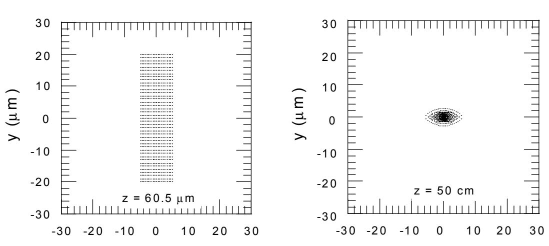

Figure 3c: Test particle distributions on the x-y planes at z = 60.5 μm where 861 electrons are initially distributed and at 50 cm where they are all well focused again.

Simulations show that during the course of acceleration, the particles experience focusing and defocusing alternatively, and they are well confined within a rectangular region of $|x| < 7.5$ μm and $|y| < 20$ μm. Fig. 3b shows the orbits on the y-z plane for 15 sampled accelerated particles. Fig. 3c shows the initial distribution (z = 60.5 μm) and final distribution (z = 50 cm).

It is found that the bunch of particles is accelerated from $\langle\gamma\rangle = 1000$ (510.5 MeV) to 1589.1 (811.5 MeV) in a 50-cm distance.

DISCUSSION

In the analysis, the electron bunch is assumed to be cold. A rough estimation of effect of finite emittance can be made as follows. Suppose we take a 500 MeV electron beam with a radius of 50 μm and a normalized emittance of 1 mm-mrad as an example. The maximum normalized transverse velocity is 2×10^{-5} and the maximum transverse displacement caused by the emittance is 7.5 μm after a 37.5-cm travel. From this it follows that the emittance effect is not so important for a 10-cm interaction between decelerated test particles and the wake fields. For accelerated test particles, the emittance effect will be reduced because both F_x and F_y are nearly linearly focusing forces in the whole region the particles take up. Of course, a more sophisticated code is needed to better understand emittance effect on the stability.

We have also studied a 1-pC bunch 150 μm tall (half the height and charge as the example) inside the same structure, and find nearly the same acceleration gradient and similar stability behavior.

We have shown that both drive and accelerated bunches can enjoy comparatively stable motion whilst traversing many centimeters through the structure, permitting a very large gradient to be exploited for particle acceleration.

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