STUDY OF ENHANCED TRANSFORMER RATIO IN A COAXIAL DIELECTRIC WAKEFIELD ACCELERATOR USING A PROFILED DRIVE BUNCH TRAIN*

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Abstract

A key parameter of wakefield acceleration is the transformer ratio **T**. For a dielectric wakefield accelerator, it has been suggested to use a ramped drive bunch train (RBT), or a multizone dielectric structure to enhance **T**. Here we show the possibility of greatly improving the RBT technique by the use of a numerical algorithm. We study a two-channel 28 GHz structure with two nested Alumina cylindrical shells (CDWA) which is to be excited by a train of four annular bunches having energy 14 MeV and axial RMS size 1mm; the total charge of bunches is 200 nC. For bunch charge and spacing chosen for optimum acceleration gradient, or for optimizing **T** using the standard method, we obtain **T**~3.6. We found that if the charge ratios are 1.0:2.4:3.5:5.0 and the spaces between the bunches are 2.5, 2.5, and 4.5 wakefield periods, then **T**~17. The RBT also can be used successfully in a high gradient THz CDWA structure.

INTRODUCTION

Dielectric wakefield accelerator devices have become an attractive alternative to conventional metallic-structure elements used for electron/positron linear colliders [1]. In dielectric wakefield accelerator (DWA) devices, a high energy drive bunch or train of drive bunches sets up a wakefield via Cherenkov radiation; some of this energy is then transferred to a trailing bunch positioned to receive axial accelerating force. However, other than the possibility to develop high accelerating gradients, an accelerator should have other advantages, such as an attractive transformer ratio. Transformer ratio **(T)** is a measure of the efficacy by which energy provided by a drive bunch is transferred to a bunch that is to be accelerated in a DWA structure. There are two ways to increase the **T**: use a train of drive bunches that have a certain programmed charge and spacing determined by a simple algorithm [2,3] to drive wakefields in a collinear device: (this is termed a “ramped bunch train”[RBT]); or, to separate the drive and witness bunch channels. Our efforts to develop a two-channel wakefield accelerator structure that encloses both channels in one assembly [1] has found that **T**~5-6 can be obtained in the CDWA in which the drive bunch is annular and is centered on the axis of a second accelerating channel that carries a witness bunch (see Fig. 1).

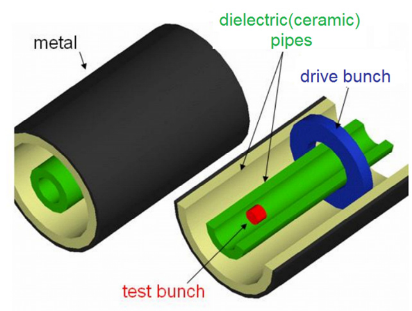

Figure 1: Schematic of the CDWA structure, showing a single annular drive bunch followed by an accelerated witness bunch that moves along the axis.

In the following, we find that it is possible to combine the RBT technique with a multimode two-channel CDWA structure to improve **T**. We can compare our results for the four-bunch train with the **T** for a single bunch having the aggregate charge of all the drive bunches in the RBT. The ratios of bunch charges within the drive bunch train and the spacing between the bunches that optimize the result is specific to the structure being studied, but we find a considerable improvement in **T** can be obtained. In what follows, we shall take bunch parameters modeled on those obtained at the AWA facility (Table 1); this facility

Table 1: Parameters used for CDWA (Alumina)

Design mode	28.09 GHz
External radius of outer coaxial cylinder	14.05 mm
Inner radius of outer coaxial waveguide	13.51 mm
External radius of inner coaxial cylinder	3.175 mm
Accl. channel radius (inner radius of inner coaxial cylinder)	2.0 mm
Relative dielectric constant ε	9.8
Bunch axial RMS dimension $2s$ (Gaussian charge distribution)	2.0 mm
Full bunch length used in PIC simulation	5 mm
Outer drive bunch radius (box charge distribution)	10.34 mm
Inner drive bunch radius	6.34 mm
Bunch energy	14 MeV
Total bunch charge	200 nC
Number of bunches	4

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can provide a single 50nc bunch, but for computational purposes we assume that four 50nc bunches can be provided with arbitrary delays.

ANALYSIS

The computations were done using a PIC code, PIC Solver of the CST Particle Studio being a part of the CST Studio Suite 2010 bundle. Boundary conditions for PIC simulations were: tangential electric fields are zero at metal surface of the waveguide and the input boundary of the unit, and output boundary is open to free space. The code computes fields, and changes in particle energy and position as the bunches move.

We now turn to the computation of some examples, where we change the drive bunch train to improve **T**. The first example (Fig. 2) shows the axial wakefield trailing a *single* 50nC drive bunch, measured on the axis of the unit (along which the witness bunch moves) and along a line parallel to the axis halfway between the outer and inner radii of the drive bunch annulus. Here and in the next figures axial distance z is counted starting from injection plane of the first bunch. From this we conclude the **T** for this structure is 3.6, calculated as the ratio of maximum accelerating wakefield on the central axis of the structure (see blue curve) to the maximum decelerating wakefield at the drive bunch, z=168 mm, along the centerline behind the drive bunch (see red curve). It is correct to infer **T** from the wakefield behind the annular drive bunch (as shown in Fig. 2) because the transverse profile of the wakefield mode amplitudes is very nearly flat [1] across the radius of the drive bunch channel; this is caused by the large relativistic factor, even for 14MeV. One should observe also that the wakefields are much diminished for z<100 mm: this shows that the superposition of wakefields is limited to a zone behind the drive bunch depending on the length of the structure and the group velocity of the waves set up by the passage of the drive bunch into the structure [4,1].

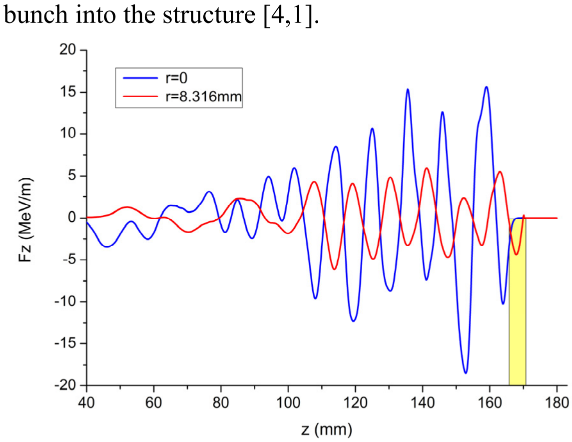

Figure 2a: Axial force from wakefields set up by a single 50nC 14MeV drive bunch in the CDWA structure described in Table I. The head of the drive bunch is located at z=171mm and the bunch travels from left to right.

We now set up a train of drive bunches. Fig. 2b displays the wakefields set up by four equally-charged 50nC drive bunches, spaced apart by the wakefield wavelength of the principal mode (10.66mm). The **T** calculated from the last drive bunch is 3.4, essentially unchanged from the single bunch case. This choice achieves the maximum accelerating gradient 50MeV/m for the witness bunch, which in this example can be located at z=125 mm. This choice of bunch train does not improve **T**.

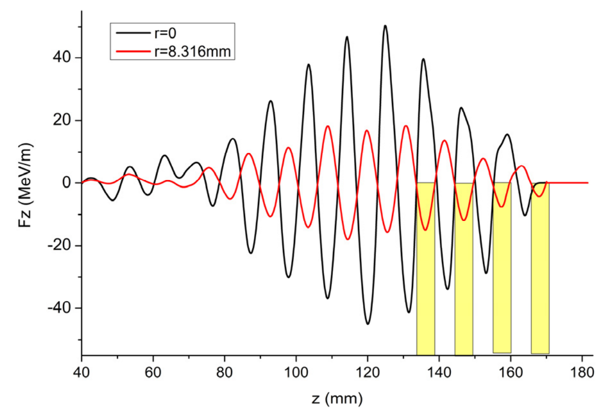

Figure 2b: Axial wakefields set up by four equally charged 50nC, 14MeV drive bunches.

In Fig. 3a, the spacing of the bunches is changed to be one and one-half wakefield periods [5], and we change the distribution of charge among the bunches so that the ratios of bunch charge increases from the first to the last bunch as 1: 3: 5: 7 . In this and the following examples, the total bunch charge for the four drive bunches is fixed at 200nC. The axial wakefield force is reduced, but that is to be expected, as this arrangement no longer provides maximum decelerating force for each bunch. The **T** is now 3.8: thus the suggested algorithm of bunch charge ramping and spacing is not generally helpful, most likely because of the multimode behaviour of the wakefields excited by this choice of drive bunches.

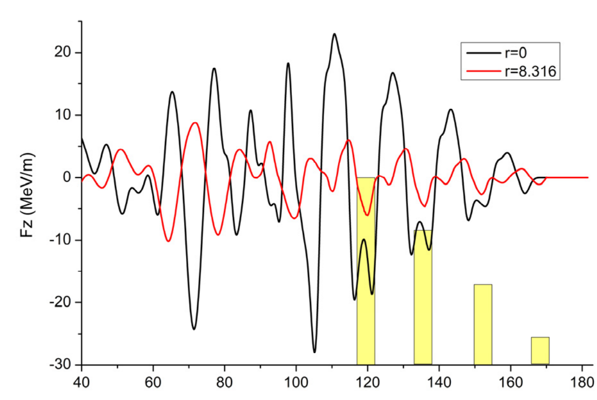

Figure 3a: Axial wakefields excited by a ramped bunch charge of drive bunches spaced by 1.5 wakefield wavelengths.

We next determine if there is some other choice of drive bunch charges and spacings that will improve **T**, but yet result in a potentially sizeable wakefield amplitude. To obtain improved transformer ratio we proceed from the following, which is strictly proved for the collinear single-mode device: wakefields with maximum transformer ratio are generated by drive bunches whose particles lose the same energy [5]. From this statement it follows that for a train of point bunches with repetition period equal to a half wavelength (or one and a half wavelengths), to obtain the maximum transformer ratio the bunch charge should rise from head to tail in the train as the ratios of odd integer numbers. For the Gaussian longitudinal density of a bunch the charge of the n*th* bunch should change according to the relation [5]: $Q_n = Q_1[1+T(n-1)]$, where Q_1 is the charge of the first bunch, and **T** is the transformer ratio of a single bunch. In the case of a multimode device, such a simple formula does not exist, therefore to obtain desirable locations of bunches and values of their charges it is necessary to run simulations, the number of which is equal to the number of bunches in the train. First, a calculation with one bunch is carried out, a location of the maximum of an accelerating field in the drive bunch channel is determined, and at this location the second bunch is placed and a new calculation of structure excitation is performed. At the location of the second bunch, the superposition is such that the field there becomes decelerating. Then, each subsequent drive bunch is to be located at the maximum of the accelerating field from the prior bunches, and the charge of the n*th* bunch is set according to the formula: $Q_n = Q_1[1+T_{n-1}]$, where T_{n-1} is the transformer ratio after the (n-1)*st* bunch. An answer to the goal of improved transformer ratio is provided by the result shown in Fig. 3b. In this example the computation is run out to a greater distance, 201mm to the front edge of the first drive bunch. The spaces between the bunches are respectively, approximately 2.5, 2.5, and 4.5 wakefields periods, and the charge ratios are 1.0, 2.4, 3.5, and 5.0; again, maintaining the constant total drive bunch charge at 200nC. The **T** from the last bunch is 17, a factor of 5 times as large as the **T** for the simple 4-bunch train of equal charges spaced by one wakefield period. Notice the peak wakefield amplitude following the fourth drive bunch is only 28MeV/m, down from 50MeV/m in Figs. 3,4. This prescription for the drive bunch charge and spacing was obtained by striving for uniform drive bunch deceleration, which means that this arrangement should extract more energy from the entire drive bunch train than that, e.g., shown in Figs. 2b or 3a. This example establishes that a considerable enhancement of **T** is possible in the multimode CDWA system using a flexible RBT method. The four drive bunches in the example of Fig. 3b each experience nearly the same decelerating force (~1.5 MeV/m).

We performed [6] a series of computations in which the ratio of the last bunch charge to the first bunch charge Q_4/Q_1 was varied, while the other parameters of the bunch train, including total charge, were fixed. We found that as this charge ratio increases from 5 to 10, **T** decreases from ~18 to 6, while the gradient increases from ~29 to 39MeV/m.

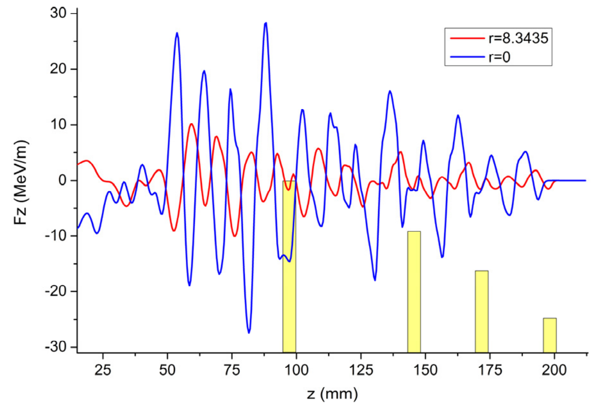

Figure 3b: In this example the bunch charges and spacings vary so as to enhance **T**.

More detailed information [6] about the energy distribution of all particles in the homogeneous bunch train (HBT) case of Fig. 2b and the RBT case of Fig. 3b reveals that the average energy loss of all particles is 2.36 MeV in the former case, whereas the average energy loss for the RBT is 0.76 MeV. Therefore, the travel distance of the RBT train should be greater by 3.1 times. The accelerating gradient for the RBT case is smaller, by a factor ~1.8, than acceleration gradient for the HBT case. From these numbers we find that the energy gain of a test bunch in the RBT case will be greater by a factor 1.7 than the corresponding energy gain for the HBT.

We have studied [6] the applicability of the ramped drive bunch train with four drive bunches to a high gradient THz CDWA structure and find that the RBT technique can be successfully applied to small THz collider –type structures.

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