ANALYTICAL AND NUMERICAL INVESTIGATION OF A COAXIAL TWO-CHANNEL DIELECTRIC WAKEFIELD ACCELERATOR*

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Abstract

A new concept for a dielectric wakefield accelerator is proposed that employs a cylindrical multi-zone dielectric structure configured as two concentric dielectric tubes with outer and inner vacuum channels for drive and accelerated bunches. Analytical and numerical computations were carried out for a high-gradient coaxial dielectric accelerator structure (CDS) with its design mode in the THz frequency range.

INTRODUCTION

In conventional linear accelerators, the RF power used to accelerate the beam is derived from high-power RF amplifiers. To achieve multi-TeV energies, high accelerating gradients are necessary to limit the lengths of the two linacs, but the number of amplifiers needed to realize high gradient could become excessive. Thus, alternative two-beam schemes have been proposed [1] wherein RF power is extracted from a low-energy, high current drive beam which is decelerated in power extraction and transfer structures. This power is then directly fed into the structures of the main linac, and used to accelerate the high-energy, low-current main beam. The most active two-beam project now under study is the CLIC concept at CERN [2], where an RF frequency of 12 GHz has been chosen for the fields in the acceleration channel, in the expectation of sustaining a working gradient of 100 MeV/m in a metallic accelerating structure.

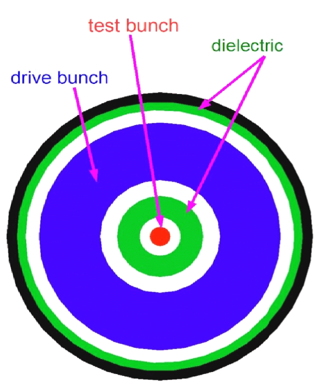

Figure 1: Cross-section of a coaxial dielectric accelerator structure (CDS). Dielectric tubes are green, drive bunch is blue; test bunch is red, and black outer shell is metal.

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In contrast to CLIC, the RF generation mechanism for the structure considered here is by creation of wakefields induced by passage of a charge bunch along a dielectric-lined drive channel. This radiation couples continuously into a parallel acceleration channel, without need for auxiliary coupling elements. Recently a rectangular 5-zone dielectric structure with drive and accelerating channels was investigated [3]. It was shown that a high transformer ratio can be obtained together with a high acceleration gradient. One disadvantage of this structure is that the accompanying transverse deflecting force will probably cause distortion of the accelerated bunch. To partially compensate for this asymmetry, studies have been conducted on a three channel symmetric rectangular DWFA [4]. In this three channel device, one requires two equal drive bunches and one witness bunch. Understanding the merits of increased symmetry for the three channel structure over the two channel structure leads naturally to the concept of a CDS which possesses an even higher degree of symmetry. A diagram for the cross section of the coaxial structure is shown in Fig. 1.

ANALYTICAL RESULTS

When formulating the analytical description of wakefield excitation in a CDS, we neglect entry and exit boundary effects. Therefore effects depending upon the group velocity of excited waves are not considered. The components of electromagnetic wakefield can be obtained by solving inhomogeneous differential equations excited by a moving, relativistic drive charge bunch. The derivation of these equations and their solutions will be published elsewhere.

To have much practical relevance, an accelerating module should show promise for efficient high energy gain of accelerated particles, so that many (but not too many) such modules can be arranged to achieve electron or positron acceleration into the TeV energy range. We take for numerical calculations an annular drive bunch with charge (6 nC) and energy (5 GeV), similar to the SLAC bunch [5]. We ask what test bunch energy could be achieved by using a sequence of 1-m long CDS modules, each with an effective acceleration gradient G = 500 MeV/m and a transformer ratio T ~ 10. Taking a drive bunch energy loss of 50 MeV per module would allow traversal of nearly 100 modules by the drive bunch before energy exhaustion, with an overall energy gain of about 50 GeV by the test bunch. After 10 similar groups of structures each fed by 5 GeV drive bunches (1000 modules altogether) in a total length ~ 1 km, the test beam energy would ideally be 0.5 TeV. The challenge is to devise a module with G = 500 MeV/m and T~10. As shall be shown, this challenge could be met in the single-bunch mode using a mm-scale coaxial dielectric structure.

To obtain such high accelerating gradients it is necessary to use ultrahigh-frequency structures having a small cross-section. At a given frequency of a wake field mode, the necessary cross-section dimensions of the dielectric layers are determined from the dispersion equation. In Table 1 the dimensions of the dielectric shells calculated for an operating frequency of 912 GHz are listed. The symmetric E_{02}-mode is chosen, for which the longitudinal field intensity has a different sign in the drive bunch channel and the accelerating channel. High transformer ratio is ensured by using a much wider drive bunch channel than accelerating channel.

Table I: Parameters for coaxial DWFA module

Frequency of the E_{02} design mode	912.5GHz
External radius of outer dielectric shell	1060.5 μm
Inner radius of outer dielectric shell	1047.5 μm
External radius of inner dielectric shell	89.5 μm
Inner radius of inner dielectric shell	50.0 μm
Permittivity of dielectric shells ε	5.7
R.m.s. bunch length σ_z	34.6 μm
Outer drive bunch radius	718.5 μm
Inner drive bunch radius	418.5 μm
Bunch energy	5 GeV
Bunch charge	6 nC

In Fig. 2, radial profiles of the longitudinal electric field amplitudes of the dominant E_{0m} modes of the wake field are shown. The radial dependence of E_z is uniform inside the vacuum spaces and steps up in the dielectric layers. The ratio of the field amplitude in the accelerating channel to the field amplitude in the drive bunch channel for the E_{02}-mode is equal to 32.5. For phase synchronism with a 5 GeV drive bunch, the frequencies of the first six modes in ascending order are 611.3 GHz (E_{01}), 912.5 GHz (E_{02}), 2417.8 GHz (E_{03}), 4018.6 GHz (E_{04}), 5393.7 GHz (E_{05}), 5665.2 GHz (E_{06}). Only the first three of these modes have appreciable field strength in the accelerating channel; the amplitudes of the E_{01} and the E_{02} modes at the structure axis are ~ 350 MV/m.

In Fig. 3 the axial profiles of composite longitudinal and the transverse forces acting on a test electron, moving at a distance 25 μm from the axis of the accelerating channel are shown. The maximum of the accelerating gradient of 587.6 MeV/m is located at about 306 μm behind the drive bunch center. The transformer ratio at this maximum is 7.7.

The transverse force at the maximum of the accelerating field is equal to zero. If the center of a test

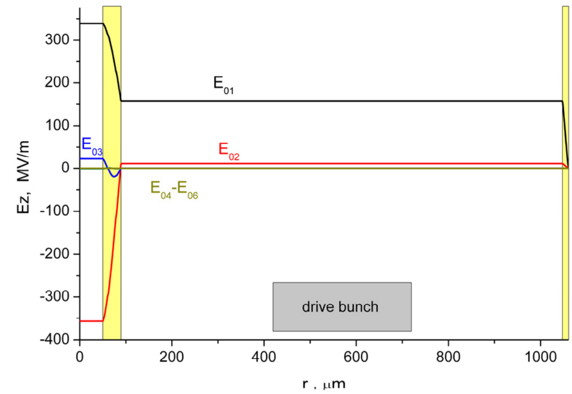

Figure 2: Transverse profiles $E_z(r)$ for the first six TM-modes, with the E_{02} operating mode. Locations of the two dielectric shells are highlighted in yellow.

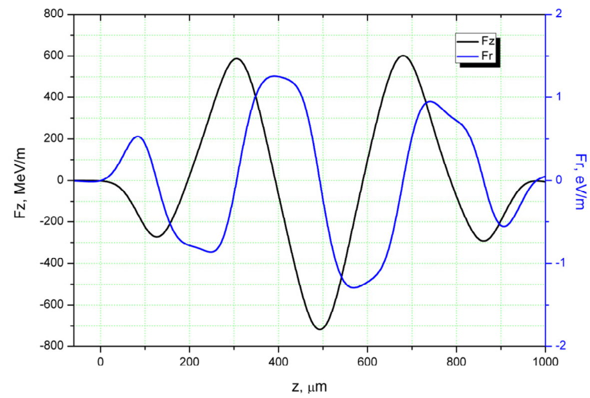

Figure 3: Axial profiles of composite longitudinal force (black line) and the composite transverse force (blue line), the latter at the distance of 25 μm from center of the accelerating channel. The drive bunch moves from right to left and its center is located at z = 0.

bunch is placed at the maximum of this accelerating field, the transverse force will be focusing for the bunch head and defocusing for the bunch tail, leading to slight pinching of the bunch. As follows from Fig. 3, it is desirable to place a witness bunch a little ahead of the maximum of the accelerating field, because the radial force there is focusing. But, even if a witness bunch is positioned at exactly the maximum of the accelerating field, the radial forces there do not appear dangerous for short accelerating modules: e.g., if we take a module length of 1 m (see above), a test electron located 34.6 μm behind the maximum of the accelerating field (same r.m.s. length as the drive bunch) and at distance 25 μm from an axis, will deflect only 0.85 μm in the transverse direction.

PIC SIMULATIONS RESULTS

For simulations, the PIC Solver of the Microwave Studio code was used. A ring cathode placed at the input end of the structure was the electron source for the annular drive bunch. For boundary conditions, the vanishing of the tangential component of electric field at all boundary surfaces was taken, except for the output end where an open boundary condition was assumed.

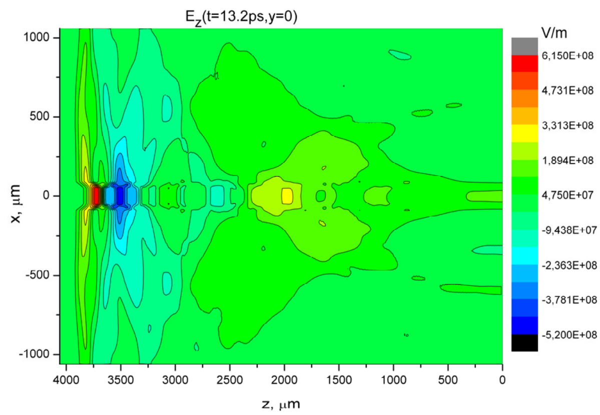

Figure 4: Map of axial wakefield in CDS at time t = 13.2 ps after injection. Drive bunch is at the far left.

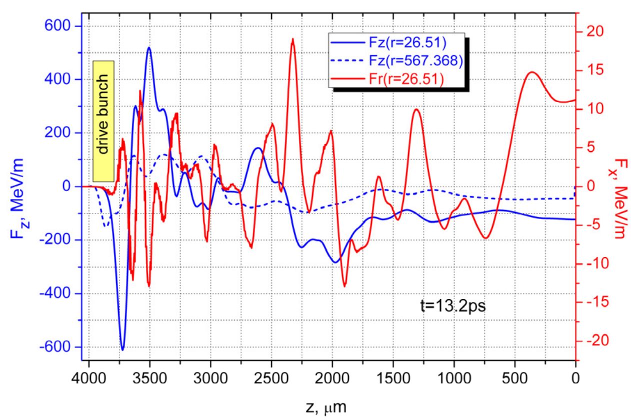

Figure 5: Axial (blue solid line) and transverse (red line) forces acting upon accelerated electrons versus z, the latter at r = 26.5 μm. Dashed blue line shows the force acting upon electrons at the center of the drive channel, at r = 567.4 μm. Time of observation is t = 13.2 ps.

In Fig. 4, a contour map of the axial electric field in the x-z plane (y=0) of the coaxial structure at t = 13.2 ps is shown. The bunch head is approximately at a distance of 3967 μm from the entrance to the structure. One can see the Cherenkov cones of the radiation at the forward front of wake fields in the inner dielectric tube. The wake field in the accelerating channel at short distances from the drive bunch is very strong. With increasing distance behind the drive bunch the field energized in the structure becomes more and more irregular. This irregular character of the wake field is caused by interference between Cherenkov radiation, the quenching wave, and transition radiation [6]. The excited field has considerable amplitude only for small distances behind the drive bunch. This conclusion is confirmed by results of the numerical computations presented in Figs. 4-5. Behind the drive bunch there is only one strong maximum of the accelerating field. The accelerated bunch would be positioned at the center of the intense blue stripe at z = 3500 μm.

1D profiles of longitudinal forces acting upon electrons along the centers of the accelerating and the drive channels are shown as blue lines in Fig. 5. The accelerating gradient has a maximum of 520 MeV/m, located at z = 3500 μm, i.e, displaced 380 μm from the center of the drive bunch. The position and the value of the first maximum of the accelerating field show good agreement between the analytical results of the previous section and the results of the PIC simulation. However, as Fig.4 and Fig. 5 show, the validity of the analytical results presented in the previous section is limited here to a region extending roughly from the drive bunch to the first maximum of the accelerating field. From the data of Fig. 5 it is possible to calculate a transformer ratio $T \sim 6$.

One important feature found by the PIC simulation is that in the vicinity of the accelerating field maximum the transverse force (red line in Fig. 5) is focusing: the transverse force is negative while the displacement from the axis is positive, thereby providing a stabilizing force for the radial motion of a witness particle. This is a distinct improvement in comparison with the case of the rectangular dielectric structure [3]. A restoring transverse force ~ 12.5 MeV/m on a typical 5 GeV witness electron at z = 3500 μm gives a betatron period of stable oscillation of ~ 0.92 m. Further studies have shown that the peak of this focusing transverse force tracks the motion of the longitudinal force accelerating peak as the drive bunch moves along the channel, and this occurs even when the dimensions of the structure are altered in important ways. It appears to be caused by the quenching wave disturbance that originates at the input end of the structure. The second feature shown in the PIC simulation results is the strong influence of the quenching wave at distances beyond one period of the accelerating field, a result that is absent in the analytical formulation. PIC studies also show the motion of the drive bunch to be exceptionally stable, probably due to a flat $E_z(r)$ profile.

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