

Transverse Dynamics of the Azimuthally Inhomogeneous Electron Bunch in a Multilayer Dielectric Cylindrical Waveguide

A M Altmark¹ and A D Kanareykin^{1,2},

¹St. Petersburg Electrotechnical University, St. Petersburg, 5 Prof. Popov St., 197376, St. Petersburg, Russia

²Euclid Techlabs LLC 400 Professional Dr. Ste. 220 Gaithersburg, MD 20879, USA

E-mail: aaltmark@mail.ru

Abstract. In reference [1], a complete analytical solution for Cherenkov wakefields generated by an azimuthally asymmetric annular beam propagating in a coaxial two-channel dielectric structure was presented. A drive bunch generates Cherenkov radiation (wakefield) inside the dielectric loaded waveguide and a second (witness) bunch passing through the structure at an appropriate delay with respect to the drive bunch is accelerated by the wakefield. Use of a ring beam in a multi-layer waveguide can significantly increase the transformer ratio by providing different paths for the ring driver and the accelerated bunch to pass through the structure. The main challenge of this scheme originates in the transverse dynamics of the drive bunch because of its high charge and relatively low energy. To hold the inner dielectric tube inside the waveguide metal (titanium) threads are used. The threads are located inside the drive beam section of the waveguide that leads to the segmentation of the drive beam. In this paper, we study the transverse dynamics of the annular beam with various types of azimuthally asymmetries that depend on the specifics of the beam generation and multilayer waveguide parameters. The different types of beam asymmetry and hybrid mode dependencies are presented using the original BBU-3000 [7] beam dynamics code.

1. Introduction

The efficiency of wakefield acceleration is related to the transformer ratio, defined as the peak energy transfer from the “drive” bunch to “witness” bunch [1, 2]. For traditional accelerating structure [2–4] with collinear drive and witness trajectories and a longitudinally symmetrical charge distribution the transformer ratio does not exceed a value of 2 [2]. In this paper we consider a partial non-collinear scheme of wakefield acceleration in a multilayer cylindrical waveguide [5, 6, 8, 9] (see in figure 1a)).

The coaxial configuration considers the drive bunch is annular and is centred on the axis of a second accelerating channel that carries a witness bunch, figure 1a [1, 8, 9]. This technique allows to separate the driver and witness bunch channels that has been implemented in CLIC design at CERN [10] and previously demonstrated at the Argonne AWA facility [11]. A coaxial two-channel dielectric wakefield structure was examined for use as a high gradient accelerator in [8]. A THz design with mm range aperture potentially can provide GeV/m-level acceleration gradient and high transformer ratio [9]. An experiment is proposed for conduct at FACET (SLAC) to test a mm-scale THz coaxial



structure using its 30 μm short drive bunch. Meanwhile, a cm-scale GHz coaxial structure is currently under study at the Argonne Wakefield Accelerator facility, ANL [9].

Consider a coaxial high transformer ratio design. The driver is a uniform ring of charge that passes through vacuum layer (2), and the witness moves at a distance behind the drive beam in channel (0). The witness delay is chosen to correspond to an accelerating phase of the wakefield. The outer shell (3) improves the dielectric breakdown threshold, which can occur on the metal wall (d). The accelerating field E_z inside channel (0) increases due to the growth of the field in dielectric tube (1). This fact causes the transformer ratio coefficient to exceed 2. The use of a drive bunch with an annular shape is associated with a strong transverse instability, which has been studied in detail in previous publication [1]. The transverse dynamics of a ring beam is much more complex in comparison with the instability of Gaussian bunches [7] because of the azimuthally as well as radial dynamics. We investigated in detail the transverse dynamics of a bunch with an annular shape consisting of several segments. This model of the bunch is chosen from technical considerations of the multilayer dielectric waveguide. The inner dielectric tube (1) is attached with special titanium threads, figure 1b). This segmented bunch passes through the waveguide without interacting with the titanium support elements.

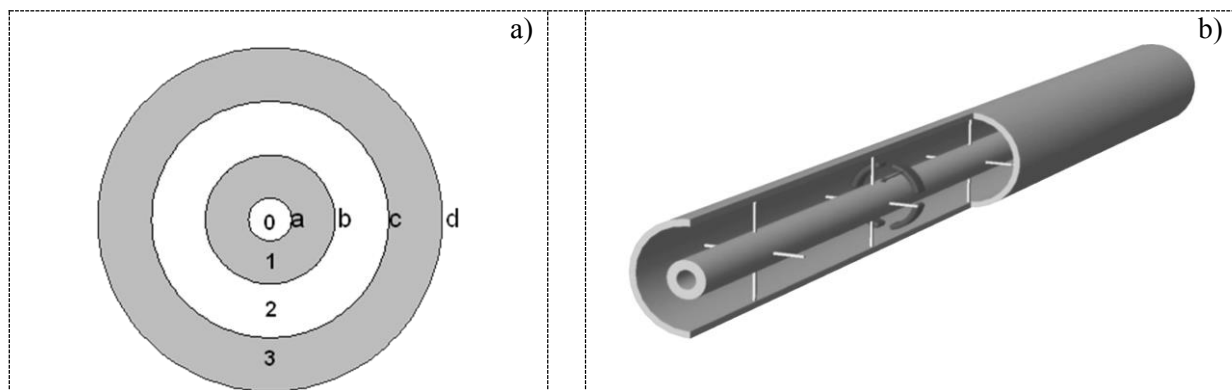


Figure 1. Cylindrical dielectric waveguide: a) cross-section. Radial layers are indicated by numbers (0,2 vacuum and 1,3 dielectric) and boundaries between layers with lower case letters. b) azimuthally segmented bunch passing through the cylindrical multilayer dielectric waveguide with threads

Figure 2 shows the transverse structure of the TM_{01} mode. It can be seen that the field E_z in dielectric tube 1 increases and the field in the vacuum channel 0 has a maximum value that provides efficient transfer of energy to witness bunch. Figure 3 shows the wakefield E_z (superposition of TM modes) behind the Gaussian bunch in channel 0 and vacuum layer 2. One can see the increase of the transformer ratio up to 3.5 value.

It should be noted that the field enhancement occurs only for the TM modes. The wakefield generated by a Gaussian bunch in layer 2 contains, in addition to TM modes, unwanted parasitic axially asymmetric hybrid electromagnetic (HEM) modes. This fact leads to the absence of the effect of increasing field. Therefore, transformer ratio is possible only for bunch with a ring charge distribution because the wakefield is mostly determined by TM - modes.

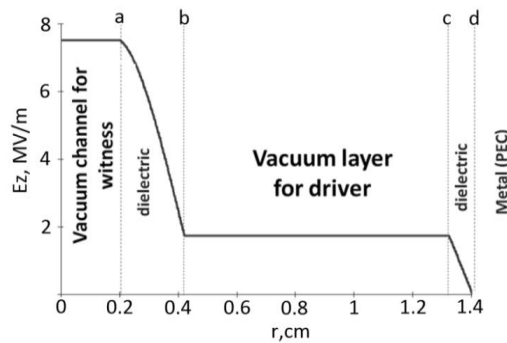


Figure 2. Radial structure of the TM_{01} mode

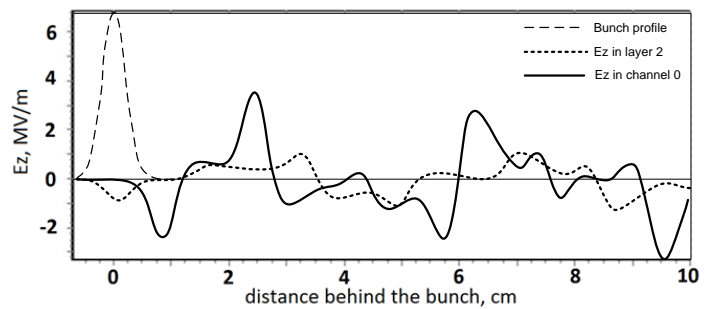


Figure 3. Wakefield in vacuum channel 0 and vacuum layer 2 for bunch #3 in Table 2 in the waveguide from Table 1.

2. HEM-mode structure

We showed in the previously published work [1] that the vacuum layer 2, through which the drive bunch is passing, can be divided into two areas: the area of the internal dielectric tube and the area of the outer dielectric layer. The radial displacement of the particles depends on the area of their passage through vacuum layer 2. This structure of the radial force is caused by the superposition of asymmetric *HEM* modes which can be divided into three types: positive, negative and alternating. The radial structure of each type of event is displayed in Figures 4-5. The sign of the radial force F_r of the alternating *HEM* mode depends on the particle position in vacuum layer 2 (figure 4). The position of a particle does not influence the sign of the positive and negative *HEM* modes (figure 5). In other words, the positive and negative modes are associated with deflection towards the outer and inner dielectric layers respectively.

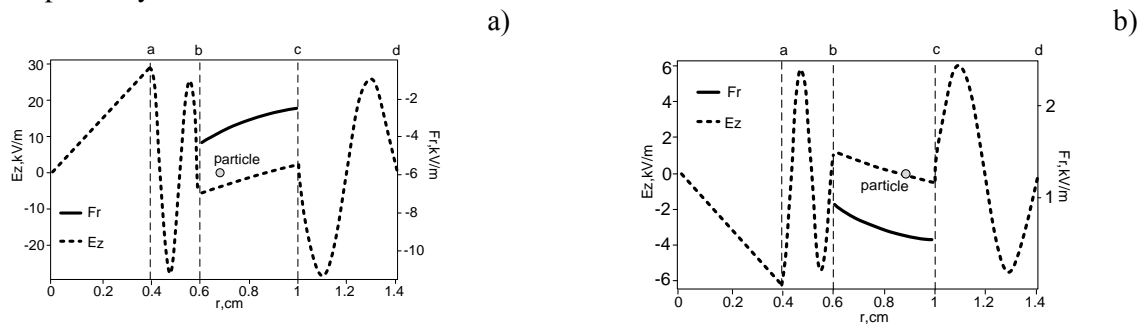


Figure 4. Radial structure of alternative *HEM*-mode (Table 1): a) particle near inner dielectric tube causes a negative sign; b) particle near outer dielectric layer causes a positive sign.

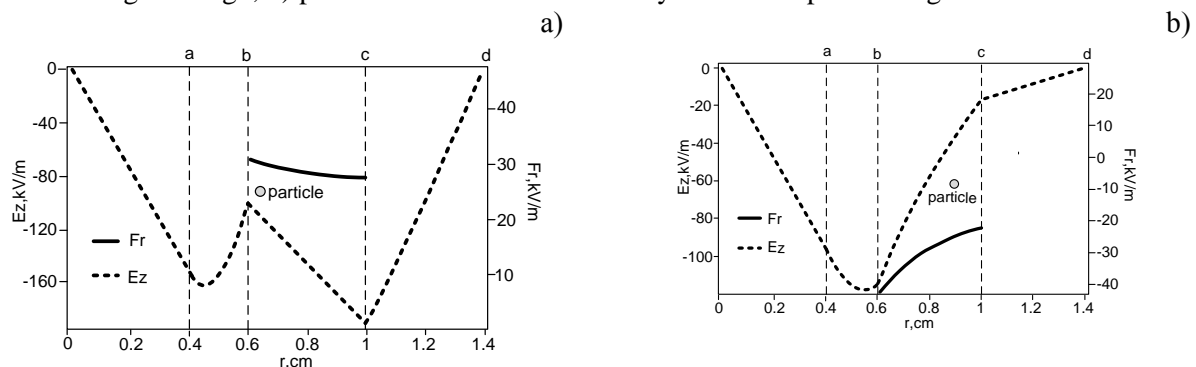


Figure 5. Radial structure of positive (a) and negative (b) *HEM*-modes (Table 1).

3. Beam dynamics modelling

With the in-house code BBU-3000 [7] we studied the dynamics of bunches, which consist of three and four azimuthally segments (Table 1). This code is developed for beam dynamics calculation in dielectric waveguides. The transverse dynamics of these bunches evolves quite rapidly despite the zero offset (transverse position of bunch center). The main contribution to the deflection forces comes from *HEM*-modes, the order of which is equal to coefficient of azimuthal filling N (the number of segments in the bunch). Fig.6 shows the quadruple *HEM* modes ($v=4$) and Fig.7 corresponds to *HEM* modes with the order $v=3$. We can see that the particles in tail of the bunch are displaced along angular coordinate to the centers of the segments and increase radial dynamics. The radial displacement is explained by location of the majority of particles in vacuum layer 2. The present results show that radial positions of particles close to area of inner dielectric tube.

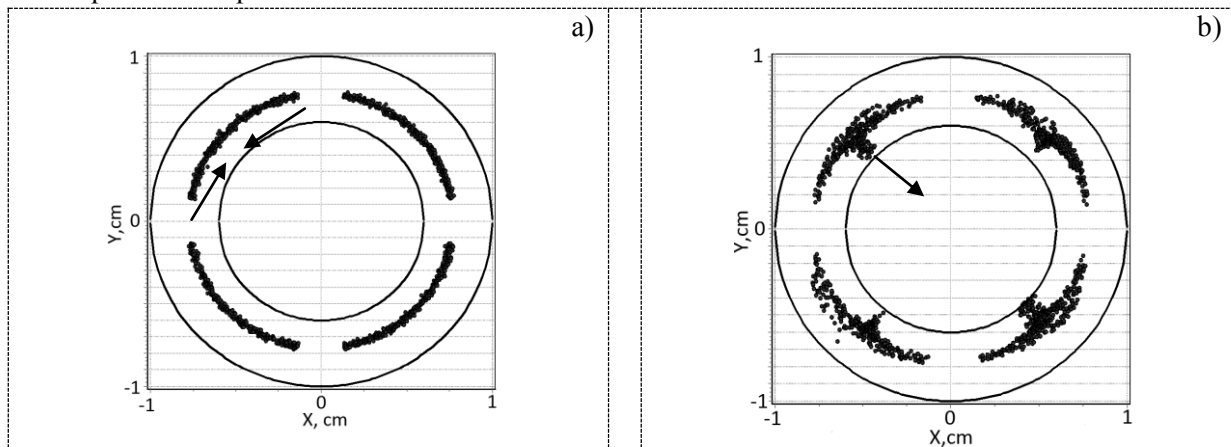


Figure 6. Results of dynamics calculation of azimuthally inhomogeneous ($N=4$) bunch #1 from Table 2 and waveguide from Table 1: a) initial particle positions; b) after propagating for 36 cm.

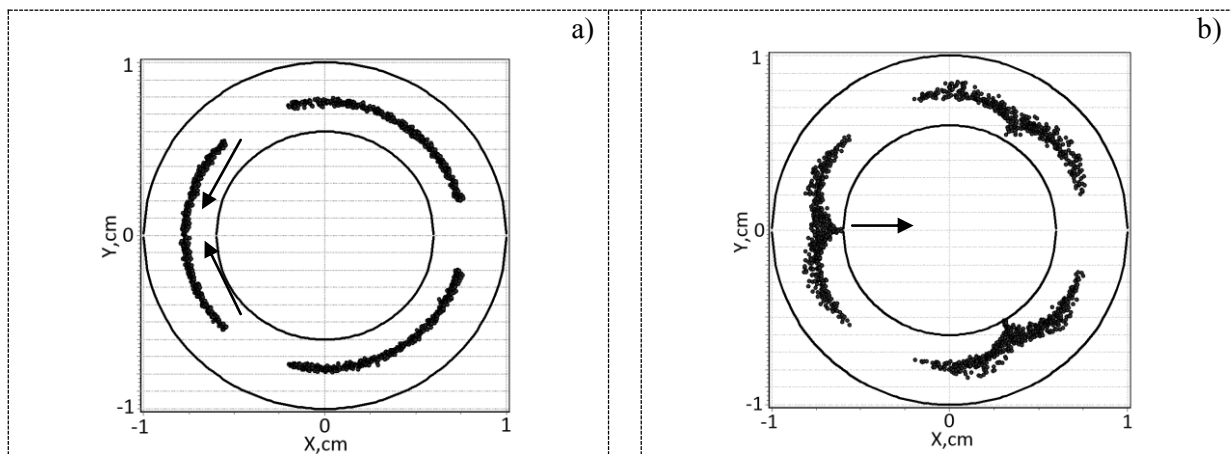


Figure 7. Results of dynamics calculation of azimuthally inhomogeneous ($N=3$) bunch #2 from Table 2 and waveguide from Table 1: a) initial particle distribution; b) after propagating for 34 cm.

Table 1. Parameters of the coaxial waveguide used in the transverse beam dynamics analysis.

#	a, cm	b, cm	c, cm	d, cm	ϵ_1	ϵ_2	f, GHz (TM ₀₂)
1	0.2	0.60	1.00	1.40	4.72	4.72	13.84

Table 2. Parameters of the annular drive beams used in the transverse beam dynamics analysis

#	beam type	N	Q , nC	σ_z , cm	σ_r , cm	offset, cm	radius, cm	W , MeV
1	asymmetrical annular beam	4	100	0.2	0.01	0	0.8	150
2	asymmetrical annular beam	3	100	0.2	0.01	0	0.8	150
3	Transverse point bunch with Gaussian longitudinal profile	-	10	0.2	0	0.8	-	15

4. Conclusions

A multilayer concentric annular dielectric wakefield device can be used to develop a transformer ratio greater than 2. We have modified the BBU-3000 code to investigate beam breakup effects from the annular electron drive beam in this device. The effects of azimuthal beam inhomogeneity originating from support structures for the inner dielectric tube were specifically studied.

- BBU effects from azimuthally inhomogeneous beams are a critical issue for dielectric based accelerator development.
- The number of segments in the annular bunch defines the highest order of the *HEM*-modes contributing to the deflecting force.
- Azimuthal displacement of particles results also in radial forces.
- There are three types of *HEM*- modes that are defined by the bunch position.

References

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