TRANSVERSE BUNCH DYNAMICS IN RECTANGULAR DIELECTRIC LOADED WAKEFIELD ACCELERATOR*

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Abstract

Beam breakup (BBU) effects resulting from parasitic wakefields provide a potentially serious limitation to the performance of dielectric structure based accelerators. We report here on comprehensive numerical studies of transverse bunch dynamics in a rectangular dielectric loaded accelerating structure. The numerical part of this research is based on a particle-Green's function beam dynamics code (BBU-3000) that we are developing. The code allows rapid, efficient simulation of beam breakup effects in advanced linear accelerators. It is shown that the LSE modes make its main contribution to the transverse deflecting force causing beam breakup in rectangular DLA structures. Results of test simulations are presented.

INTRODUCTION

A new method of wakefield acceleration of charged particles using bunches passing through the dielectric waveguide structure, is currently the subject of intense experimental and theoretical studies [1-5].

Techniques based on the Dielectric Wakefield accelerator concept are some of the most promising to date in terms of their potential to provide high gradient accelerating structures for future generation linear colliders [2-4]. High-current electron bunches in accelerator structure generate electromagnetic fields with the amplitude of the longitudinal electric field component up to 100 MV/m at GHz frequency range [2-4] and up to ~ GV/m at THz [5], which is used to accelerate the subsequent low-current bunch. The accelerated structure is a dielectric loaded waveguide with an axial vacuum channel, Fig.1. A high charge, electron drive beam propagating through the waveguide vacuum channel generates electromagnetic Cherenkov radiation (wakefields) which is used to accelerate a less intense beam following the leading bunch at an appropriate distance.

The dynamics of the beam in structure-based wakefield accelerators leads to beam stability issues not ordinarily found in other machines [6]. In particular, the high current drive beam in an efficient wakefield accelerator loses a large fraction of its energy in the decelerator structure, resulting in physical emittance growth, increased energy spread, and the possibility of head-tail instability for an off axis beam, all of which can lead to severe reduction of beam intensity. Beam breakup effects resulting from parasitic wakefields provide a potentially serious limitation to the performance of dielectric structure based wakefield accelerators as well [6,13].

The purpose of this work is research on beam dynamic simulations in rectangular waveguide (Fig. 1), providing a number of technological and constructive advantages in comparison with a traditional for DLA cylindrical waveguide. We have implemented software for rapid, efficient simulation of beam breakup effects in this type of DLA structures [13].

WAKEFIELD IN RECTANGULAR WAVEGUIDE

Transverse deflecting force in a rectangular DLA structure is a vector sum of F_x and F_y components, which can be expressed as:

$$F_x = E_x - \beta H_y \, , \; F_y = E_y + \beta H_x \qquad (1)$$

Knowing longitudinal field component E_z one can find F_x and F_y using Panofsky-Wenzel theorem:

$$\int F_x dz = \frac{1}{k}\frac{\partial E_z}{\partial x} \, , \quad \int F_y dz = \frac{1}{k}\frac{\partial E_z}{\partial y} \qquad (2)$$

where k is a wave number, E_z – longitudinal component of electric field.

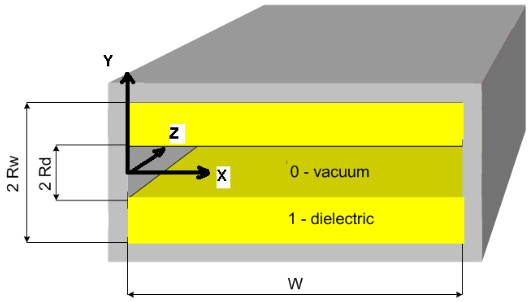

Figure 1.Rectangular Dielectric Loaded Accelerating structure with axial vacuum channel: $R_d = 0.5cm$, $R_w = 1cm$, $\varepsilon = 10$, $W = 2.3\,cm$

The complete $\vec{E}$ wakefield can be expressed in terms of *LSM* (Longitudinal Section Magnetic) and *LSE*

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*Work supported by Ministry of Education and Science of the Russian Federation, the program "Scientific and scientific-pedagogical personnel of innovative Russia" and the Russian Foundation for Basic Research (09-02-00921)
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(Longitudinal Section Electric) modes, and each type of these modes consists of even and odd components correspondingly, where this wave classification is based on eigenfunctions symmetry relatively to the y coordinate [7-9].

Using the expression for the wakefields generated by a point charge in rectangular waveguide, one can write the transverse fields as:

$$Fx=\sum_{n=1}^{N_x}\sum_{m=1}^{Ny}\left(Fxo_{n,m}^{LSM}\sin\left(Kzo_{n,m}^{LSM}\zeta\right)+Fxe_{n,m}^{LSM}\sin\left(Kze_{n,m}^{LSM}\zeta\right)\right)+\ldots$$
$$\ldots+\sum_{n=1}^{N_x}\sum_{m=1}^{Ny}\left(Fxo_{n,m}^{LSE}\sin\left(Kzo_{n,m}^{LSE}\zeta\right)+Fxe_{n,m}^{LSE}\sin\left(Kze_{n,m}^{LSE}\zeta\right)\right)$$

$$Fy=\sum_{n=1}^{N_x}\sum_{m=1}^{Ny}\left(Fyo_{n,m}^{LSM}\sin\left(Kzo_{n,m}^{LSM}\zeta\right)+Fye_{n,m}^{LSM}\sin\left(Kze_{n,m}^{LSM}\zeta\right)\right)+\ldots$$
$$\ldots+\sum_{n=1}^{N_x}\sum_{m=1}^{Ny}\left(Fyo_{n,m}^{LSE}\sin\left(Kzo_{n,m}^{LSE}\zeta\right)+Fye_{n,m}^{LSE}\sin\left(Kze_{n,m}^{LSE}\zeta\right)\right) \tag{3}$$

where $Kzo_{n,m}^{LSM}$, $Kze_{n,m}^{LSM}$ - longitudinal wavenumbers of odd and even LSM- modes, $Kzo_{n,m}^{LSE}$, $Kze_{n,m}^{LSE}$ - longitudinal wavenumbers of odd and even LSE-modes, $Fxo_{n,m}^{LSM}$, $Fxe_{n,m}^{LSM}$, $Fxo_{n,m}^{LSE}$, $Fxe_{n,m}^{LSE}$, $Fyo_{n,m}^{LSM}$, $Fye_{n,m}^{LSM}$, $Fyo_{n,m}^{LSE}$, $Fye_{n,m}^{LSE}$ - coefficients depending on the coordinates of the bunch and observation point, the bunch charge and wave numbers, ζ -distance behind the bunch.

With this study, we present the beam breakup simulation results for the rectangular DLA structure with the parameters of Fig.1:

We assume that transverse coordinates x and y of the bunch and the observation point are equal each other. Fig. 2 shows dependence of the transverse field on the transverse coordinates x and y. With the bunch trajectory offset increasing along the y-axis, Fig.2a, one can see that all types of the modes including the parasitic ones are excited, and the odd LSE modes will prevail in its contribution to the transverse deflecting field. If the bunch offset increasing off the waveguide center along of the x axis, the deflecting force will be represented only by odd LSM and even LSE-modes. As seen from Fig.2b Maximum of transverse field is reached when offset on x is equal to w/4 value.

In this work we present numerical simulations of the transverse dynamics of the bunch with parameters [10-11]: Q=100nC, $\sigma_z = 0.4\,cm$, $\sigma_x = 0.3\,cm$, $\sigma_y = 0.01\,cm$, $\sigma_x = 0.3\,cm$, $offset_y = 0.08\,cm$, $W = 15\,MeV$ moving along the waveguide with the parameters Fig.1.

The numerical part of this research is based on a particle-Green's function beam breakup code we are developing that allows rapid, efficient simulation of beam breakup effects in cylindrical DLA structures [13]. The new capabilities of BBU-3000 emphasize features important for more accurate treatment of BBU in rectangular dielectric based accelerators [7-9,12].

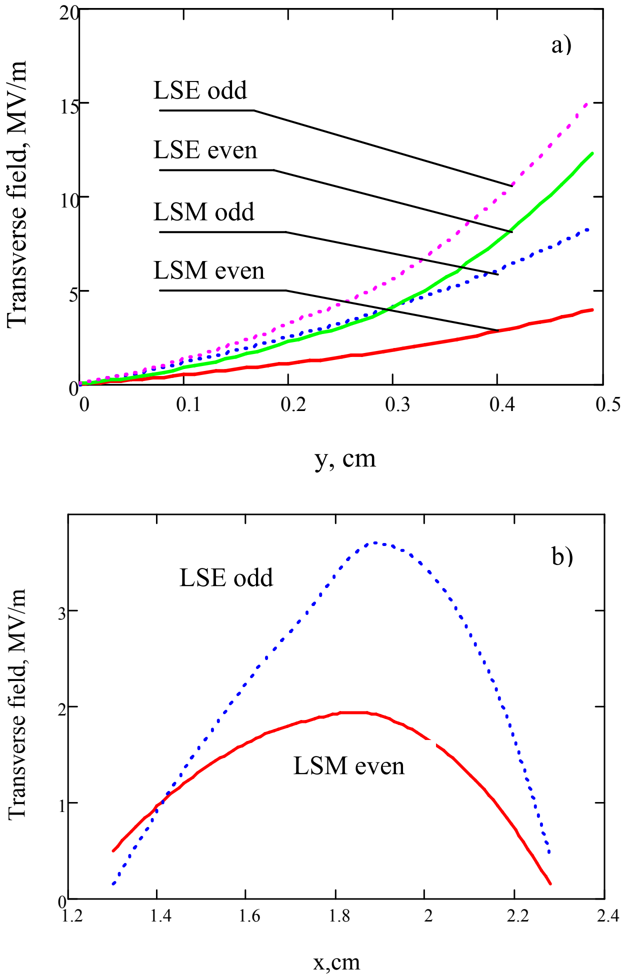

Figure 2.Transverse field as function of a) offset along y ax (with 0 offset along x ax) b) offset along x ax (with 0 offset along y ax.

For a bunch propagating in the rectangular waveguide the particles which are placed in tail of bunch experience the strongest deflecting force. Our simulations showed that the bunch with significant offset of 3mm propagated only 4 cm in the waveguide (Fig.3a) before it touched the dielectric wall, Fig.3. The cross-section of the waveguide at the X-Y plane clearly shows that the particles located around the center of bunch experience main deflecting force, Fig.3b.

At the same time, decreasing offset to 800 um would elongate the structure length up to 10 cm only. Presented test simulations show that the focusing is critical for the rectangular DLA structure the same way as it is required for the cylindrical DLAs that has been studied previously [6,13], and one have to design an external FODO channel for the control of the beam in the presence of strong transverse wakefields.

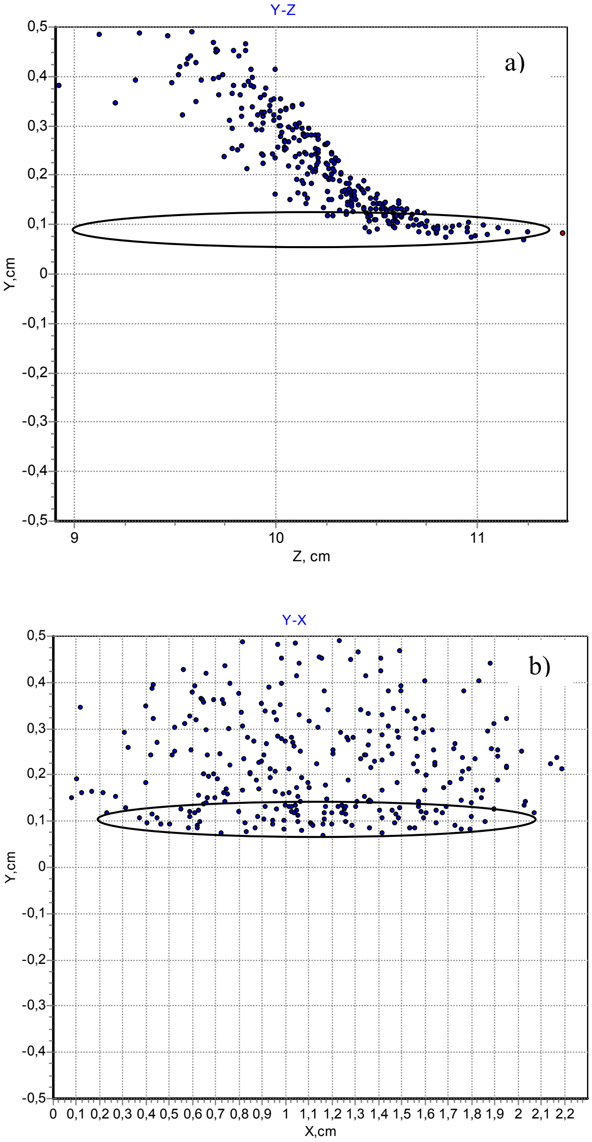

Fig.3.Results of beam dynamics simulations for the parameters of Fig.1 (solid line show initial borders of bunch) a) Y-Z plane b) Y-X plane

CONCLUSION

The software effort is based on development of the BBU-3000 code upgrade. A number of new features have been incorporated including a rectangular dielectric based structure capabilities.

We have used the new code to model the dielectric structure BBU for the test rectangular structure and AWA electron beam parameters. The results of the simulations show that the main contribution to the transverse deflecting field is made by odd LSE-modes. It was found that the maximum of transverse field is reached at offset value on x equal quarter of the structure half-width that critically impact transverse beam stability. The structure for the tested parameters (Fig.1) can be 4-10 cm long with no focusing applied. Furthermore, the usefulness of a linearly tapered quad channel in controlling beam breakup is confirmed.

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