Wakefield acceleration in multilayer dielectric waveguide with usage of ring beam

A Altmark¹, N Lesiv² and K Mukhamedgaliev³

¹Physics Department, St.-Petersburg State electrotechnical University, 5 prof. Popov str., St. Petersburg 197376, Russian Federation
², ³Faculty of Electronics, St.-Petersburg State electrotechnical University, 5 prof. Popov str., St. Petersburg 197376, Russian Federation

²E-mail: nikita.lesiv@gmail.com

Abstract. In this paper, we simulated the process of wakefield acceleration of electron Gaussian bunch by electron ring beam. The beam dynamics of ring uniform is discussed in detail. Calculation results show that wakefield accelerating scheme is more effective compared to the scheme with one-layer dielectric waveguide excited by gaussian bunch.

1. Introduction
In the last decade, the wakefield acceleration of charged particles has become widespread since this method allows to reach high values of the accelerating field gradient in short distances. The main principle of wakefield acceleration is to create a large accelerating field \( E_z \) by high charge beam (driver) and placing an accelerated low charge beam (witness beam) in the required phase of \( E_z \).

Recently, the dielectric waveguides with different geometries are used as wakefield structures [1] due to the high accelerating field can be created. The efficiency of wakefield acceleration is defined by transformer ratio of energy \( R \) [2] between driver and witness. There are two ways to increase of \( R \): usage of bunch train [2, 3] and multilayer structures [4, 5]. The latter ones consist of different vacuum areas for driver and witness divided by dielectric layer. Cylindrical geometry of the waveguides was considered in paper [4] where authors proposed an analytical expression for a multilayer structure and presented annular beam dynamics made in CST Particle Studio. The possibility of wakefield acceleration in a two-channel rectangular dielectric structure was considered in [5]. Analytical calculations were carried out, as well as experimental studies. In present work, we propose the calculation of the dynamics made by macroparticle method which is based on analytical expression for Green-function. This approach allows to calculate the dynamics more precisely, since the field calculations include many modes. The use of the PIC code for accurate calculations is associated with mesh nodes increasing what causes a sharp growth of calculation time. We chose a cylindrical structure over rectangular one due to the high value of \( E_z \) on waveguide axis.

It should be noted that acceleration process depends on propagation length of driver. Last one defined by transverse beam dynamics. We present numerical results of beam dynamics calculation of driver with ring uniform. At the end we compare propagation of ring beam in multilayer dielectric waveguide with usual scheme of wakefield acceleration used one-layer dielectric waveguide.

2. Methods
The multilayer waveguide (figure 1) consists of two dielectric layers (1 and 3) and two vacuum areas (0 and 2). The ring beam (driver beam) propagates in area 2 and his energy has low value (10-
50 MeV. The acceleration of a Gaussian bunch results from the fact that the ring beam excites the Vavilov-Cherenkov $E_z$ radiation in a dielectric waveguide. Second accelerating beam with gaussian uniform is placed in vacuum channel 0 with delay, which is selected according to maximal value of wakefield behind the driver. It is possible to transfer energy from the ring bunch to the gaussian one. Figure 1 shows field created by ring beam in vacuum areas 0 and 2. We can see that the value of wakefield in the area 0 greater than in the area 2. This fact explains that the transformer ratio (relation of maximal accelerating field to maximal decelerating field inside driver) in greater than 2 like in classical collinear scheme [2]. Figure 2 illustrates transformer ratio enhancement in multilayer waveguide (figure 1) when driver bunch creates accelerating field $E_z$ in area 0. Maximal value of $E_z$ field in central vacuum channel is stronger than in area 2.

The wakefield consist two types of modes: $\text{TM}_{0n}$ modes which form accelerating field and $\text{HEM}_{mn}$ modes which form deflecting field. Transverse instability of the ring beam defined by asymmetric $\text{HEM}_{1n}$ modes [6]. The strongest $\text{HEM}_{1n}$ modes called as dipole modes ($\text{HEM}_{1n}$).

The value of energy gain by witness depend on distance passed in waveguide. This value limits by transverse beam dynamics of ring beam. Our purpose is to find maximal propagation length of ring beam. Numerical simulation must be stopped when ring beam touches dielectric.

In this study, the macroparticle method is used to simulate the beam dynamics of wakefield acceleration of an electron bunch [7]. We used original code “Ring Beam” based on knowledge of Green function for multilayer dielectric waveguide. According to this code, the beam is represented as number of charged macroparticles. The charge of each macroparticle is equal to the charge of the bunch, referred to the number of macroparticles, and the mass is equal to the mass of the electron. The field created by the bunch is calculated as the sum of the fields of all the macroparticles. This numerical model allows to simulate the motion of real electron bunch.

![Figure 1. Dielectric waveguide.](image-url)
Figure 2. The field created by the ring beam in the vacuum cavity and the vacuum channel (the pink line is the field inside the central vacuum channel, the red line is the field inside the vacuum layer where the annular flare is flying).

3. Results and Discussion
The simulation was carried out with the following parameters of the bunches and waveguide (table 1, table 2). The propagation of beam is directed from left to right. From figures 3, 4 we can see that transverse and longitudinal views of ring beam at the end of simulation. The macroparticles in tail of ring beam experience maximal value of deflecting field and touch inner dielectric tube 1. So, the maximal propagation distance for offset 0.03 cm is 42 cm.

| Parameters of the ring bunch | Parameter value | Parameters of gaussian bunch | Parameter value |
|------------------------------|-----------------|-----------------------------|----------------|
| Charge                       | 100 nC          | Charge                      | 100 nC         |
| Longitudinal length          | 0.4 cm          | Longitudinal length         | 0.4 cm         |
| Radius of the ring           | 0.8 cm          | Radius of the ring          | --------       |
| Energy                       | 15 MeV          | Energy                      | 15 MeV         |
| Number of macroparticles     | 1600            | Number of macroparticles    | 1600           |
| Offset                       | 0.03 cm         | Offset                      | 0.03 cm        |

| Multilayer waveguide         | Parameter value | One-layer waveguide         | Parameter value |
|------------------------------|-----------------|-----------------------------|----------------|
| a                            | 0.2 cm          | a                           | 0.5 cm         |
| b                            | 0.6 cm          | b                           | --------       |
| c                            | 1 cm            | c                           | --------       |
| d                            | 1.4 cm          | d                           | 1.317 cm       |
| The dielectric constant      | 3.75            | The dielectric constant     | 3.75           |
| Frequency of TM mode          | 6.23            | Frequency of TM mode        | 6.23           |
Figure 3. The transverse view of the waveguide and the bunch at the end of the simulation.

The transverse dynamics show that the particles in the ring move in the radial direction both towards the dielectric tube 1 and toward the dielectric layer 3. The direction of the greatest displacement is determined by the direction of the offset and the field structure of the dipole HEM mode. The stability of the annular beam is explained by the fact that the electrons in the beam are between two dielectrics, which attracts particles to its sides.

For comparison, we choose simple one-layer waveguide (table 1) which parameters was selected to make frequency of the first TM mode like in multilayer waveguide. The parameters of the Gaussian driver bunch (charge, longitudinal length, offset) are the same as the ring beam. It is seen from the figure 5, which shows the dynamics calculation results of Gaussian beam, that the acceleration process stop at the distance 24 cm when the bunch touches the dielectric wall.

Figure 4. The longitudinal view of the ring beam.

Figure 5. The longitudinal view gaussian bunch
4. Conclusion
The analysis of beam dynamics calculation of two schemes show that ring beam propagate farther than gaussian one in twice. Despite of difficult uniform of ring beam his stability is determined by influence of two dielectric layer. The high stability of ring beam and high value of transformer ratio in multilayer waveguide make this method of wakefield acceleration is perspective for future research. It should be noted that the calculations presented in this article correspond to 0.03 cm offset. Therefore, one of the ways to increase the propagation length of the ring beam is to place center of ring beam more accurately relative to the axis of the waveguide. This way allows to nonlinearly increase the propagation length.

Acknowledgments
The work was supported by the Ministry of Education and Science of the Russian Federation (project 3.6522.2017).

References
[1] Conde M, Gai W, Konecny R, Power J et al 1998 AIP Conf. Proc. 472 626
[2] Kanareykin A, Gai W et al 2003 Proc. PAC’03 1894
[3] Power J, Gai W, Kanareykin A and Sun X 2001 Proc. PAC’01 114.
[4] Sotnikov G, Marshall T, and Hirshfield J 2009 Phys. Rev. ST-Accel. Beams 12
[5] Sotnikov G and Marshall C 2011 Phys. Rev. ST-Accel. Beams 14 031302
[6] Sheinman I, Kanareykin A and Sotnikov G 2012 RUPAC, MOPPA010 266-268
[7] Altmark A M and Kanareykin A D 2012 J. Phys.: Conf. Ser. 357 012001