Generation of THz radiation by sequence of ring beams in multilayer dielectric waveguide

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Abstract. In this paper, we describe a new type of a THz radiation source in a multilayer dielectric waveguide based on the Vavilov-Cerenkov radiation created by a sequence of electron ring beams. We present parameters of the sequence needed for generation of TM\textsubscript{03} mode with frequency of 531.2 GHz in result radiation and results of beam dynamics calculation. Also, we discuss the degree of monochromaticity and spectrum of the THz radiation.

1. Introduction
Recently there have been tendencies related to the development of THz radiation sources, as well as its wide application in various fields of science, such as chemistry, biology, medicine [1]. The main requirements for terahertz radiation are the frequency, amplitude, and the degree of monochromaticity of radiation.

Coherent THz radiation can be created as transition radiation and enhanced by coherent synchrotron radiation (CSR) in storage ring [2]. and emitted by 1GeV energy-electron beam. A THz source based on a radio frequency linear accelerator (linac) [3] and laser-based THz techniques [4] allow to create high power pulses in range 1-10THz. The dielectric waveguide is also used for generation of THz radiation [5]. It is possible to create monochromatic radiation with frequency of TM\textsubscript{0n} mode with use of bunch train. The selection of mode with needed frequency is realized by choosing of distances between bunches. However, the stability of such train depends on strong deflecting HEM (Hybrid Electro Magnetic) modes [6]. The stabilization of deflecting forces is possible with usage of FODO focusing system. However, these methods imply high energy costs.

The bunches with ring form [7] can be stable without focusing system when passing between two dielectric layers in multilayer dielectric waveguide. The aim of this work is to find parameters of bunch parameters as well as beam dynamics calculation to determine the distance of propagation as well as the length of THz packet.

2. Methods
The sequence of ring beams propagates in a multilayer dielectric cylindrical waveguide, which is a dielectric-vacuum-dielectric-metal structure (Figure 1). These beams excite the Vavilov-Cerenkov radiation $E_z$ in the dielectric waveguide behind itself. The parameters of the waveguide (a,b,c) define TM\textsubscript{0n} modes with needed spectrum. The distances between bunches are chosen to excite one of TM\textsubscript{0n} modes.
The length of THz packet depends on transverse instability of beam sequence. So, we calculate dynamics of the sequence to evaluate its propagation distance. In this work we used macroparticle method [6,8] with help of original code “Ring Beam”. The macroparticle method is based on representation of bunch with charge Q as number of N particles with charges Q/N. The field in observation point is superposition of the fields from all forward macroparticles. Each macroparticle is point-charge and create field expressed through Green-function [7]. Last one has analytical expression for multilayer dielectric cylindrical waveguide. The instability arising from the dynamics of ring bunches is due to the presence of HEM modes (Hybrid Electro Magnetic) which form strong transverse field $F_r$ (Lorenz force per unit of charge). The convergence of this macroparticle method is controlled automatically by selecting the optimal time step.

![Diagram](image)

**Figure 1.** Longitudinal (a) and transverse (b) views of vacuum (1), dielectric (2), and metal (3) cylindrical waveguide. The blue arrow shows the direction of bunches propagation.

### 3. Results and discussion

First, we choose parameters of sequence and waveguide presented in Table 1. We get amplitudes and frequencies of TM and HEM modes from analysis of Green function. The sizes of bunches in sequence correspond to vacuum area in waveguide. TM$_{03}$ and TM$_{04}$ are of the greatest interest to THz radiation. In this work we managed to find the distances (0.144 cm) for generating the TM$_{03}$ mode. The amplitude of radiation with TM$_{04}$ mode is damped by longitudinal length of bunches.

![Graph](image)

**Figure 2.** Field $E_z$ (THz radiation based on TM$_{03}$ mode), formed after a sequence of four bunches separated by distance 0.144 cm (parameters a present in Table 1).

Figure 2 is a plot of the resulting field $E_z$, formed after a sequence of four circular bunches propagating from right to left. We have performed the Fourier transform and obtained the resulting
spectrum shown in Figure 3. We have determined the degree of monochromaticity \( m \) as the ratio of TM_{03} mode amplitude to the sum of all the amplitudes:

\[
m = \frac{T_{M_{03}}}{T_{M_{01}} + T_{M_{02}} + T_{M_{03}} + T_{M_{04}}} = 0.64.
\]

![Figure 3. Total radiation spectrum of radiation (parameters a present in table 1).](image)

**Table 1.** Waveguide and bunch parameters for numerical simulation.

| Parameters                      | Value  |
|---------------------------------|--------|
| radius «a» (um)                | 200    |
| radius «b» (um)                | 700    |
| radius «c» (um)                | 900    |
| Frequency mode TM_{01} (GHz)   | 155.4  |
| Frequency mode TM_{02} (GHz)   | 359.2  |
| Frequency mode TM_{03} (GHz)   | 531.2  |
| Frequency mode TM_{04} (GHz)   | 798.3  |
| Frequency mode HEM_{11} (GHz)  | 138.12 |
| Frequency mode HEM_{12} (GHz)  | 222.01 |
| Waveguide length (cm)          | 10     |
| Number of bunches               | 4      |
| beam energy (MeV)              | ~ 75   |
| Distance between bunches (cm)  | 0.144  |
| Dielectric «\varepsilon»       | 3.8    |
| Radius of the ring (um)        | 500    |
| Longitudinal beam size (um)    | 100    |
| Charge (nC)                     | 1      |
| Time step (fs)                 | 1000   |

The start position of sequence is represented in figure 4. Two circles show borders of vacuum area (a and b). Figure 5 shows end of beam dynamics calculation and illustrates that the touching of the bunches of the dielectric tube occurs at 20 cm.
Figure 4. The transverse (a) and longitudinal (b) views of sequence ring bunch start positions.

Figure 5. The transverse (left) and longitudinal (right) views of sequence ring bunch positions at the finish of simulation.

The bunches are shifted in different directions with alternation: the first and third bunch are displaced in the positive direction of the coordinate y, the second and fourth bunches in the negative direction. This circumstance can be explained by the longitudinal distribution of the radial field $F_r$, which in turn determines the wavelength of the THz wave packet. It can be seen from Figure 6 that the radial field values differ in the tails of the bunches. The deflecting field is determined by the spectrum of the HEM modes, which does not coincide with the TM mode spectrum (Table 1). Consequently, the optimization of the distance between the bunches is associated with the TM mode spectrum, but the distribution of the radial field in the bunches remains unoptimized.
4. Conclusion

In the present work we have carried out a study of the process of generation of terahertz radiation by a sequence of ring beams in described multilayer dielectric waveguide. For the resulting radiation, parameters such as frequency and degree of monochromaticity were determined. It was found that this ring generation scheme was more stable, in comparison with the classical scheme using simple Gaussian beams in a dielectric waveguide with a vacuum channel [6] where the train passed 10 cm with FODO system. The train with ring uniform bunches pass 20 cm without FODO. Therefore, this type of generation can be an economically more advantageous solution and therefore it didn’t require the presence of a focusing system.

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Figure 6. Longitudinal distribution of transverse field in sequence of bunches (Table 1). Dotted line shows longitudinal distribution of charge in bunches. The arrows show directions of deflection.