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# SCHEMES FOR ACCELERATION A PART OF ELECTRONS OF DRIVE ELECTRON BUNCHES IN THE DIELECTRIC WAKEFIELD STRUCTURE

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The paper presents several schemes for obtaining the main (witness) bunches from a long sequence of electron bunches, as well as from a part of a single electron bunch in the dielectric wakefield structure. The selected part of the electron bunches passes into the accelerating phase of the wake field due to the difference in the geometric path length between the separated electrons and the excited wakefield.

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## INTRODUCTION

A new method of charged particles acceleration which uses the Cherenkov wakefield excited by electron bunch (EB), or a sequence of EBs in a dielectric structure, is being actively studied theoretically and experimentally [1 - 4].

An accelerator based on this principle is usually a metal waveguide filled with a dielectric inside with a vacuum channel along the axis. In the traditional scheme of wake acceleration, a short EB with a large charge – the driver, during a flight in the vacuum channel of the dielectric structure, excites the mode of the wakefield Cherenkov radiation. Behind of the drive bunch, with a delay of $\sim\lambda_w/2$, where $\lambda_w$ is the wavelength of the excited mode in the waveguide, follows the EB with high energy but a small charge (witness bunch) and accelerates in the excited field. Dielectric waveguide together witness drive and witness bunches was named dielectric wakefield accelerator (DWA). Instead of one bunch with a large charge, to excite the wake field, it is advisable to use a regular sequence of electric bunches, which leads to an increase in the amplitude of the wakefield [5, 6]. However, the creation and accurate injection of a high-energy witness bunch into the accelerating phase of the wakefield is a technically difficult task, which complicates the development of the wakefield acceleration method in dielectric structures. Therefore, to obtain a high-energy witness bunch, it is desirable to have a method that does not require the use of external fields or additional beams and uses part of the electrons of the driver bunch for the next acceleration. That is, it is necessary to create conditions for self-acceleration of a part of electrons in an electron bunch or a part of a train of bunches.

The mechanism of self-acceleration of part of the electrons of a single electron pulse in the resonator structure was proposed in works [7, 8]. Subsequently, works appeared in which the phenomenon of self-acceleration of electrons in resonator structures was studied more detailed [9, 10], and experimental works in which the appearance of accelerated electrons was recorded during the injection of a sequence of relativistic EBs into the plasma and their excitation of wakefields [11]. In last case, nothing was introduced into the plasma except for the driver EBs, and the EBs could create the plasma themselves. That is, the self-acceleration of electrons in the plasma was observed.

In the dielectric structure, the self-acceleration of a small part of electrons from the long sequence of EBs, when they excite the Cherenkov wakefield, was observed in [12]. The sequence had 6000 EBs with an energy of $E \approx 4.5$ MeV. In the experiments, the acceleration of part of the electrons was recorded in the case when the length of each bunch is close to the half-length of the wake wave that is excited in the dielectric structure.

In [13], it was shown that the acceleration of a part of the electrons of each EB of the sequence in the dielectric structure occurs when its length is slightly longer than half the length of the wake wave. In this case, a small part of the electrons from the trailing front of the bunch is accelerated. These electrons fall into the area of simultaneous action of the phase of acceleration and focusing of the wakefield.

Also, in [13], a simple scheme for accelerating a small part of electrons from the long regular sequences of EBs (the bunches are shorter than the half wavelength of the wakefield) in a resonator dielectric structure after the standing wave formation was proposed. The scheme ensures that a part of the electrons enters the accelerating phase of the excited wake field due to the phase shift between the selected part of the electrons of the EBs and the wake wave. The phase shift is created by increasing the geometric path length of the wake wave.

In this paper, the scheme of acceleration of a part of each sequence of EBs in the dielectric structure proposed in [13] is analyzed in more detail. The possibility of creating a phase shift due to the path difference between the wake wave and a part of each EB is considered when the direction of movement of the selected part of the EBs is changed by 90º in the transverse magnetic field. In this case, there is a possibility of reducing the length of the selected bunches.

The paper also proposes a method of accelerating part of the electrons of a separate electron bunch by the wakefield, which is excited by this bunch.

This requires that the wake wave excited in the dielectric waveguide, with the collimator located at the end of the waveguide, is diverted in front of the collimator into an additional waveguide. The additional waveguide is geometrically a chord, and the electrons selected by the collimator move along its arc. The ratio of the chord length to the arc length is equal to the ratio of the group velocity of the wake wave to the electron velocity.

Therefore, at the end of the additional waveguide, it is not difficult to ensure that the selected electrons enter the accelerating phase of the wake wave for further acceleration.

## 1. SCHEME FOR THE ACCELERATION OF A SMALL PART OF THE ELECTRONS OF A LONG SEQUENCE OF BUNCHES

### 1.1. INCREASE OF GEOMETRIC WAVEGUIDE LENGTH

The main task in the proposed acceleration schemes is to create a phase shift of the wake wave relative to the selected part of the EB. The phase shift of the electromagnetic wave in the section of the waveguide is defined as

$$\Delta\varphi = \frac{2\pi l}{\lambda_0}\sqrt{\varepsilon\mu - (\lambda_0 / \lambda_{cr})^2}\ . \qquad (1)$$

From eq. (1) follows the phase shift of the wake wave $\Delta\varphi$ can be changed by changing the geometric length of the waveguide $l$, the value of the dielectric $\varepsilon$ or magnetic permeability $\mu$ of the dielectric or the critical wavelength $\lambda_{cr}$ by changing the dimensions of the waveguide ( $\lambda_0$ is the wavelength in free space).

The scheme for the acceleration of a small part of the electrons of a long sequence of EB, with an increase in the geometric length of the path of the wake wave relative to the electron bunches, is shown in Fig. 1.

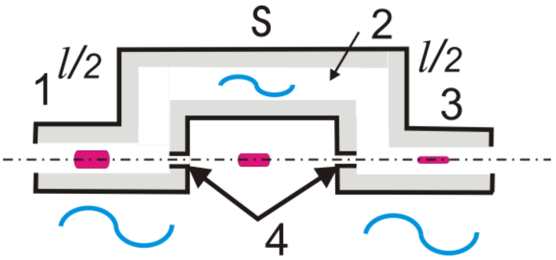


*Fig. 1. Scheme of acceleration of a part of electrons of a sequence of electron bunches: 1 – the waveguide in which the wake wave is excited (extractor); 2 – the phase shift node of the wake wave relative to the EB; 3 – the waveguide in which the shifted electrons gain its energy (main linac); 4 – collimators, $l/2$ and $s$ are lengths of waveguides of the phase shift node*

Next, EBs enter the collimator of the phase shift node of the wake wave relative to EBs 4. The wake wave enters the phase shift node and takes an additional path in it. EBs continue to move straight but lose most of the electrons that fall on parts of the collimator and the walls of the waveguide. Behind the shift node is waveguide 3. In waveguide 3, the separated electrons form a new sequence of EBs. The bunches of this sequence have a smaller radius and charge, but the length of the bunches at the exit from the shear node remains unchanged. In the waveguide 3 bunches enter the accelerating phase of the wakefield and increase their energy.

The output of waveguide 3 is closed with a titanium foil, "transparent" for relativistic EBs. The total length of all waveguides, including waveguides of the phase shift node, is a multiple of half the length of the wake wave in the waveguide. This makes it possible to establish the resonator mode of operation of the accelerator with the formation of a standing wave.

The length of the waveguides of the phase shift node is $2\cdot l/2+s$, but the additional path of the wake wave relative to the selected electrons is $l$.

In order for the electrons separated by the collimator to enter the accelerating phase of the wake wave after passing through the phase shift node, the difference in the path that the wake wave and the selected electrons $l$ should be equal $l = n\lambda_w/2$ (where *n* is an odd integer).

For example, consider an accelerator made of a waveguide of the round cross-section with a quartz dielectric tube. The inner and outer diameters of the dielectric tube are 1 cm and b = 1.4565 cm, respectively. For the electron energy of the beam of 4.5 MeV [14] the resonance frequency of $E_{01}$ mode of a wake wave equal to 8.415 GHz. The wavelength of the wake wave in the waveguide is $\lambda_w = 3.56$ cm. The path of the wake wave in the phase shift node will be 1.78 cm larger than the path of the separated electrons.

Acceleration of the separated electrons of a bunch occurs due to the field accumulated by previous bunches during the formation of a standing wave in the resonator structure. Acceleration of the selected electrons does not occur before the formation of a standing wave. For the accelerator used in our experiments [11] the standing wave establishment time is on average 0.1 μs, which corresponds to 300 bunches.

### 1.2. ACCELERATION OF SELECTED ELECTRONS BY THE WAKEFIELD

As it was shown in works [12, 14], in the case when the length of the EBs is slightly longer than half the length of the wake wave, a small part of the electrons located at the bunch front can be accelerated. The amplitude of the wakefield in this case is less than in the case when the length of the bunch slightly less than half the length of the wake wave. Therefore, in our example, we will consider the injection into the accelerator of the drive EBs with a length slightly less than half the length of the wake wave.

Fig. 2,a shows the location of the EB relative to the wake wave for drive bunches in the extractor.

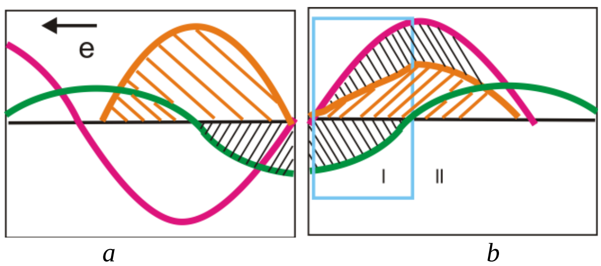


*Fig. 2. a – the location of the EB relative to the wake wave in the wakefield extractor; b – the location of the separated electrons relative to the wake wave after the phase shift node in the main linac. Red sinusoid is longitudinal component of the wakefield; green sinusoid – transverse component of the wakefield; the region I shows the area of the wake field where the part of separated electrons are accelerated and focused, dashed brown area shows bunch current distribution*

Fig. 2,b shows the location of the separated electrons relative to the wake wave with a phase shift of $\lambda_w/2$. An important conclusion is that there is the wakefield phase where electrons can be accelerated and, at the same time, focused. In Fig. 2,b this is a region I. Electrons that fall into region II with the defocusing phase of the transverse component of the field are quickly pushed to the surface of the dielectric and fall out of acceleration. Thus, the length of the selected EBs at the output of waveguide 3 is reduced by approximately two times, compared to the length of the driver bunches.

### 1.3. SCHEME WITH TURNING OF ELECTRON BUNCHES IN MAGNETIC FIELD

A more perfect scheme for accelerating a part of electrons from a long sequence of electron bunches in a resonator system with a dielectric structure is a scheme with the separation of a part of electrons when the bunches turn in a transverse magnetic field, Fig. 3.

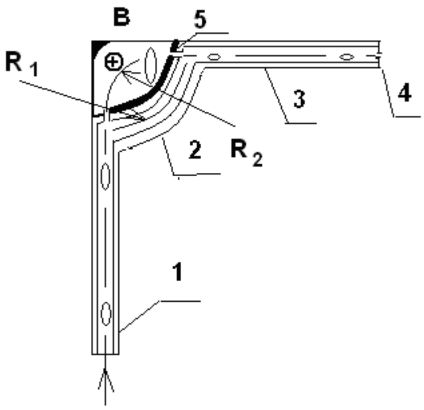


*Fig. 3. Scheme of the acceleration of the part of electrons from the EB sequences with the possibility of reducing their length: 1 – waveguide in which the wakefield is excited (extractor); 2 – waveguide section for delaying the wake wave; 3 – waveguide for accelerating the selected electrons (main linac); 4 – metal foil for creating a resonator mode of operation; 5 – a collimator*

The proposed scheme is calculated in such a way that only the most high-energy part of the EBs electrons, separated by the collimator, enters the second part of the structure (main linac).

At the turning radius of the beam, $R_2 = 6$ cm, the magnitude of the magnetic field $B = 0.2771\,\text{T}$ (electron energy $E_b = 4.5\,\text{MeV}$). The length of the path taken by electrons moving from the first part of the structure to the second is $\ell_b = 9.42$ cm.

For an accelerator with the parameters adopted in the previous paragraph (the wavelength is $\lambda_w = 3.56$ cm) the path of the wake wave should be half the length of the wake wave in the waveguide than the path of the separated electrons. That is, the path length of the wake wave should be $\ell_b + \lambda_w/2 = 11.2$ cm. Accordingly, the radius of rotation of the waveguide is $R_1 = 7.13$ cm. By choosing the location of the collimator relative to the EB, the length of the selected EBs can be reduced.

The location of the selected electrons relative to the wake wave is identical to that shown in Fig. 2, therefore, when reducing the length of the selected EBs, the phase shift should be made not by $\lambda_w/2$, but by $\lambda_w/4$. This will make it possible to reduce the load on the wake wave and increase the efficiency of the acceleration of the selected EBs. At the same time, the turning radius of the waveguide decreases to $R_1 = 6.57$ cm. As in the previous case, the acceleration of a part of the EBs electrons can begin only when the standing wave mode is established in the accelerator.

It is possible to design a cascade scheme for the acceleration of part of the electrons of the EBs, Fig. 4.

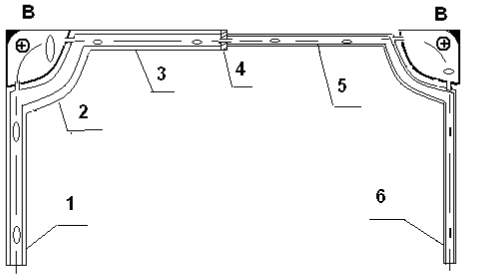


*Fig. 4. Scheme of two cascade accelerator of the part of electron bunches: 1 – a waveguide in which the wake field is excited (extractor); 2 – a segment of the waveguide for delaying the wake wave; 3 – a waveguide for accelerating the separated electrons (1st linac); 4 – a titanium foil for creating a resonator mode of operation; 5 – a waveguide for exciting the wake wave in the second stage; 6 – a waveguide for accelerating electrons in the second cascade (2nd linac)*

Such a scheme will make it possible to obtain a new sequence of EBs with higher energy and shorter length of bunches. When the length of the bunches is reduced, the second stage is to be calculated for a higher frequency. Under the condition that the length of the bunches is close to half the length of the wake wave.

## 2. SCHEME FOR ACCELERATION OF A PART OF THE ELECTRONS OF A SINGLE ELECTRON BUNCH

Consider the possibility of acceleration of a fraction of electrons of a single EB by the wakefield, which is excited by the same bunch in the dielectric structure. This requires that the separated electrons fall into the wakefield, which was previously excited by the bunch in which these electrons were located. It is necessary that the selected electrons, which move at a speed close to the speed of light, and the excited wake wave, which moves at the group speed, "meet" again.

To accelerate part of the electrons of a single electron bunch, you can use the accelerator scheme, which is shown in Fig. 5. The wake wave, which is excited by the electron bunch in the first waveguide 1, cannot exit through the collimator 4 and moves through the additional waveguide 3 to the entrance to the second part of the accelerator. At the same time, the electrons separated from the bunch also get here, moving along a large arc of the central angle, the chord of which is the waveguide 3.

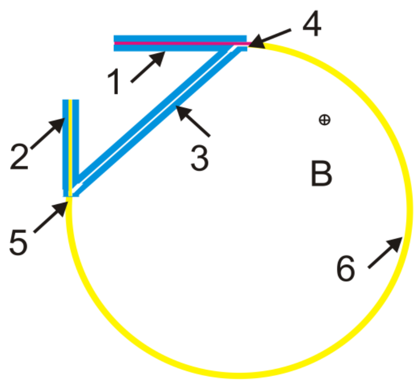


*Fig. 5. Scheme of acceleration of a part of electrons of a single electron bunch by the wakefield, which is excited by the same bunch. Here 1 is a dielectric structure in which the wakefield is excited; 2 is a dielectric structure in which "cut out" electrons by the collimator are accelerated; 3 is a waveguide for the wake wave; 4 and 5 are collimators; 6 is trajectory of selected electrons*

Based on the fact that the time of movement of selected electrons along an arc trajectory of length $L$ with speed $v_e$ and the time of movement of the energy of the wake wave (wave packet) moving with group speed and passing the path $\ell$ are the same, it is possible to write:

$$\frac{L}{v_e} = \frac{\ell}{v_g}. \qquad (2)$$

In the case of partial filling of a waveguide of the round cross-section with a quartz dielectric at $a = 1$ cm, $b = 1.46$ cm, which is located in a metal waveguide, the length of the wake wave in the waveguide is $\lambda_w \approx 3.56$ cm, the group velocity $v_g = 0.338c$. Accordingly, at $v_e = 0.995c$, and $\ell / L = 0.3398$, to ensure such a ratio of the path of the wake wave to the path of electrons, the central angle should be 260.43º. When the radius of rotation of electrons in a magnetic field is 21 cm the length of waveguide *3* is $\ell = 32.43$ cm, and the length of the electron trajectory is $L = 95.45$ cm. To ensure the wave phase shift by $\lambda_w / 2$, we take the length $\ell = 34.22$ cm the value of the magnetic induction should be $B = 0.079$ T.

In waveguide *3*, it is possible to use a dielectric with a lower dielectric permeability, which makes it possible to increase the group speed of the wave in this waveguide and slightly reduce the dimensions of the entire structure. In our example, the use of fluoroplastic in waveguide *3* makes it possible to increase the group speed to $0.5c$. At the same time, the central angle will be 215º. With a turning radius of 21 cm the length of waveguide *3* is 39.66 cm, and the length of the electron path is 78.9 cm.

According to the results of work carried out at the Brookhaven National Laboratory (BNL ATF) [15] and the results of experimental work [11], the transport of short relativistic electron bunches in the dielectric structure leads to a change in the profile and deformation of the electron bunch under the action of its own wakefield. Additionally in our case, a transverse magnetic field leads to a transverse expansion of bunches, which will be proportional to the energy width of the bunch. Therefore, to ensure the optimal acceleration mode, it is necessary to be able to adjust the magnitude of the magnetic field, as well as the phase shift in the additional waveguide using a phase shifter.

The scheme of acceleration of a part of electrons of a single EB can be used in the case of any sequence of bunches. The energy additionally obtained by the selected part of electrons, with optimal dimensions of the dielectric structure, depends on the charge of the electron bunch, the Q factor of the system, and the amount of charge of the selected part of electrons.

## CONCLUSIONS

The paper proposes schemes for the self-acceleration of a small part of electrons from each of a long sequence of electron bunches, as well as a part of a separate electron bunch by the wakefield, which is excited by the bunches themselves in the dielectric structure. The considered methods of acceleration are probably the simplest methods of acceleration by the Cherenkov wakefield. They do not require external sources of electromagnetic radiation, nor the creation of a separate electron bunch for acceleration. In the scheme of acceleration of a small part of electrons from each of the long sequences of electron bunches, a phase shift of the wake wave relative to the electron bunches is created when the geometric length of the wake wave path increases. At the same time, the acceleration of a small part of the bunch electrons selected by the collimator is not due to the field of this bunch, but due to the wakefield excited in the resonator dielectric structure by all previous bunches. It is also proposed that half the length of the resonant wake wave should be slightly longer than the length of the electron bunches, which will allow increasing the amplitude of the wakefield.

The scheme of acceleration by the wakefield, which is excited by a single bunch, of part of the electrons of the same bunch in the dielectric structure is based on the fact that the ratio of the path of the selected electrons to the path of the wake wave is equal to the ratio of the group speed of the wave to the speed of electron bunches. The application of this acceleration wave to high-energy bunch and small transverse size poses technical difficulties but has significant advantages over other methods of acceleration by the wakefield.

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## СХЕМИ ПРИСКОРЕННЯ ЧАСТИНИ ЕЛЕКТРОНІВ ДРАЙВЕРНИХ ЕЛЕКТРОННИХ ЗГУСТКІВ КІЛЬВАТЕРНИМ ПОЛЕМ У ДІЕЛЕКТРИЧНІЙ СТРУКТУРІ

***А.Ф. Лінник, Г.О. Крівоносов, О.Л. Омелаєнко, Г.В. Сотніков***

Представлені схеми для додаткового прискорення невеликої частини електронів кожного з довгої послідовності електронних згустків, а також частини окремого електронного згустка кільватерним полем, яке збуджується самими згустками в діелектричній структурі. Виділена частина електронів потрапляє в прискорювальну фазу кільватерного поля завдяки різниці геометричної довжини шляху між виділеними електронами і збудженим кільватерним полем.