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THE USE OF ELECTROMAGNETIC FIELD FOR GUIDING THE BEAM IN LINEAR ELECTRON ACCELERATORS WITH STANDING WAVE

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ABSTRACT

A principal possibility is demonstrated of focusing electrons by the own high-frequency fields of the accelerating cavities in the linear accelerators with standing wave constructed on the basis of biperiodic retarding structures. The results of numerical calculation of the dynamics of electrons in such structures for various initial conditions are presented. The obtained results are used in the designing of accelerators, for which the calculated and experimental data are given.

Keywords: electron linear accelerator, biperiodic retarding structure, electromagnetic field, cell, the drift sleeve, range, stable radial motion, acceleration range, drift channel.

1. INTRODUCTION

The intensive development of accelerator technology for the fundamental physics research and significant progress in other areas of science and technology have provided the possibility of practical use of accelerators in the economic activity (Zavadtsev*et al.,* 2011) and medicine (Zhang *et al.,* 2013).

Accelerators significantly improve the efficiency of industrial production in the areas such as: radiation flaw detection (Dovbnya *et al.,* 2000; Auditore *et al.,* 2006), radiation chemistry (Nikolaev, 1971), sterilization of medical products, tools and food (Vakhrushin *et al.,* 1995), element activation analysis (Zavadtsev *et al.,* 2006). A large economic effect is produced by the use of accelerators for radiation logging of wells (Bogdanovich *et al.,* 1997).

In linear electron travelling-wave accelerators (LEA), the particle gains energy only under the condition of synchronous movement with the accelerating wave(Val'dner *et al.,* 1969), which requires additional energy costs and makes the accelerator design more cumbersome. Because of comparatively low shunt resistance of the accelerating structures, the accelerated particle should be at the maximum of the accelerating field.

The constant impact on the particle of the deflecting from the axis radial component of the electric field is the reason that the external focusing elements, especially in the beginning of acceleration, have become an integral part of the accelerator design.

In a biperiodic retarding structure (BRS), the aperture is approximately 10 mm in diameter, whereas it is possible to guide the beam through the accelerator only by means of external focusing magnetic fields of solenoids. Solenoids significantly increase the transverse dimensions of LEA, which is extremely undesirable when using accelerators in defectoscopy and medicine. One of the problems in the design of LEA with standing wave is the problem of guiding the beam through the BRS aperture, which is related to the dynamics of the particles in the accelerating section.

2. METHODS

2.1. Background information

A biperiodic retarding structure (BRS) with standing wave can be considered as a chain of accelerating cavities, arranged on the same axis and linked by connection cells (Novozhilov *et al.,* 2014). Since the connection cells are free from electromagnetic fields and not involved in the acceleration of particles, they may be placed outside of the accelerating structure. The oscillations of electromagnetic fields in the adjacent accelerating cavities are different in phase by π, so the particle must cover the distance between the centers of the adjacent cavities during the time equal to half of the period of electromagnetic oscillations. Only in this way synchronization between the particle and the accelerating field can be achieved.

If, at a fixed time moment, one considers the electric field strength distribution along the axis of BRS with standing wave, one can see that it is an alternation of pulses of different polarity with the spatial period equal to the generator wavelength.

Such distribution function can be decomposed into a Fourier series, and the standing wave field can be represented by a sum of harmonics (Vygodsky, 2006). The particle interacts effectively only with the harmonic, the phase velocity of which coincides with the velocity of the particle motion. Consequently, the longitudinal dynamics of particles in the LEA with standing wave can be studied by the methods used in the travelling-wave accelerators.

The creation of new types of high-frequency (HF) structures will allow organizing the manufacturing of LEA on the basis of various modifications of BRS, working in the standing wave mode. They have a number of significant advantages over conventional travelling-wave accelerators for the energy of 10 MeV and the pulse current up to 500 mA. First of all, let us point to much smaller dimensions of the accelerating system, which is due to a substantially higher value of shunt resistance than for the travelling-wave LEA. In addition, the electrons in the structures with travelling wave gain energy only under the condition of synchronous movement with this wave, whereas due to relatively low shunt resistance of these structures it is necessary to place the particles into the maximum accelerating field. But in this case, the electrons are continuously affected by the radial component of the electric field, deflecting them from the axis, which leads to the need to include the external focusing elements into the accelerator structure. This increases the weight of the installation and its dimensions; also, additional energy costs are required for powering the focusing elements.

In the BRS-based LEA, working in the standing wave mode, it is possible to provide focusing the accelerated particles with the help of HF fields without the use of external focusing elements. Figure-1 demonstrates the accelerating cell of BRS and presents the calculated distribution in it of the longitudinal and radial components of the electric field. In such a cell, because of the presence of far protruding drift sleeves, the electric field lines get strongly curved, which leads to the appearance in the areas adjacent to these sleeves of a significant radial component of the electric field. The particles entering the accelerating gap experience a force directed toward the axis of the system (the focusing one), whereas at the exit, a force directed away from the axis (the defocusing one). As is known, under certain conditions, the alternation of focusing and defocusing fields can lead to a common focusing effect (Filatov, 1984).

2.2. Dynamics of electrons in the accelerating cell of BRS

For an individual period of BRS with external connection cells, equal to the length of the accelerating cell, we define the phase areas of focusing in the radial direction $(\Delta p_\rho < 0)$, where $\Delta p_\rho$is the change of the radial momentum of the particle under the passing of the BRS period, and the longitudinal acceleration $(\Delta p_z > 0)$, where $\Delta p_z$is the change in the longitudinal momentum of the particle under the passing of the BRS period. If we assume that the velocity of the electrons is close to the speed of light, i.e. $v_z \approx c$, then for the BRS working at$\frac{\pi}{2}$oscillations, the condition of particles synchronization with the accelerating field can be written as $D = \frac{\lambda}{2}$, where$D$is the BRSperiod, λ is the wave length of the generator.

The presented in Figure-1b distribution of the intensity components of the HF field in the drift channel area allows constructing a simplified model of the cell and, using simple analytical expressions, determine the phase region in which the simultaneous accelerating and radial focusing of the accelerated particles are possible.

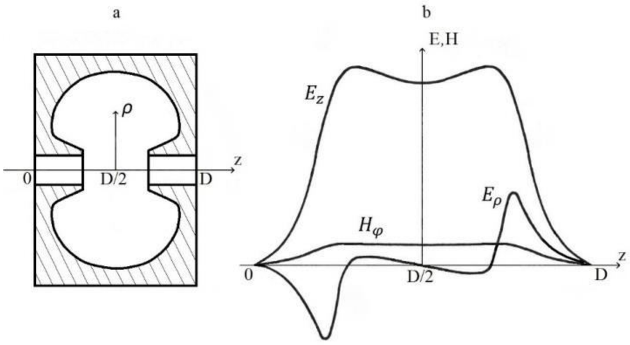

Figure-1. Profile of the accelerating cell of BRS (a) and the relative distribution of the longitudinal and transverse components of the electric field and the azimuthal component of magnetic field in the drift channel area of BRS cell at some distance from the axis (b).

Let us consider separately the radial motion of electrons associated with the action of the radial component of the electric field strength $E_\rho(\rho_0, z)$and the azimuthal component of the magnetic field intensity$H_\varphi(\rho_0, z)$. We assume that the charged particle passes the BRS period at a certain distance $\rho_0$from the z axis. First we determine the influence of the electric field on the radial movement. The distribution of the radial component of the intensity $E_\rho(\rho_0, z)$of the electric field along the z axis can be represented as in Figure 2a. For the symmetric accelerating cell, $z_2 - z_1 = z_4 - z_3 = \Delta z$. Passing the period$D$, the electron change sitsra dial momentum by the quantity

$$\Delta p_\rho = e\int_0^{D/\rho_z} E_\rho(\rho_0, z)\cos(\omega t + \varphi_0)dt,(1)$$

where φ_0 is the entry phase of the particle at $z = 0$; t is time; f is the generator frequency $(\omega = 2\pi f)$.

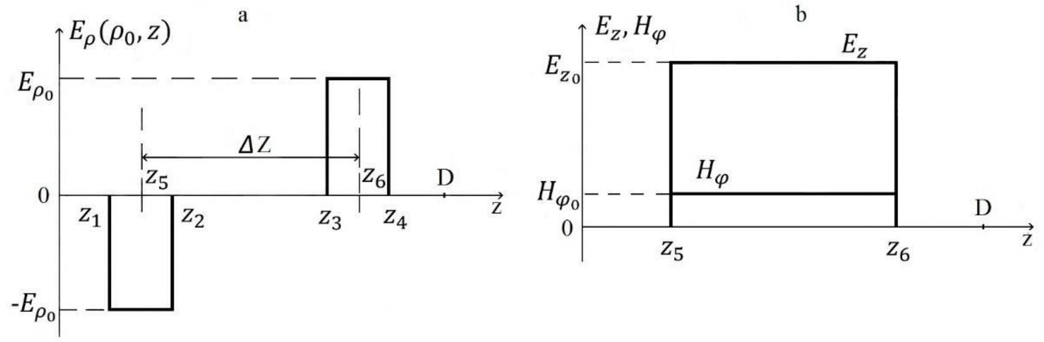

Figure-2. Simplified representation of the distribution of the radial (a) and the longitudinal component of the electric field and the azimuthal component of the magnetic field at the distance $\rho_0$from the axis (b).

Since $v_z t = z$, it is convenient to pass in the equation (1) to the integration with respect to the coordinate

$$\Delta p_\rho = \frac{e}{v_z}\int_0^D E_\rho(\rho_0, z)\, cos\left(\omega \frac{z}{v_z} + \varphi_0\right) dz.$$

Taking into account the distribution of the radial component of the electric field (Figure 2a), the last equation can be written in the form

$$\Delta p_\rho = \frac{e}{v_z} E_{\rho_0}\left[-\int_{z_1}^{z_2} cos\left(\omega \frac{z}{v_z} + \varphi_0\right) dz + \int_{z_3}^{z_4} cos\left(\omega \frac{z}{v_z} + \varphi_0\right) dz\right].$$

After a number of transformations, we obtain the following expression:

$$\Delta p_\rho = -4\frac{e}{\omega} E_{\rho_0} \sin\left(\frac{\omega}{2v_z}\Delta z\right) \sin\left(\frac{\omega}{2v_z}\Delta Z\right) \sin\left(\frac{\omega D}{2v_z} + \varphi_0\right). \quad (2)$$

Since $0 < \Delta z < \Delta Z < D = \frac{\lambda}{2}$, *we have* $0 < \frac{\omega}{2v_z}\Delta z < \frac{\omega}{2v_z}\Delta Z < \frac{\pi}{2}$.

Thus, the radial electric field will have a focusing impact in the phase domain, for which the expression (2) is less than zero. This is true for $\sin(\frac{\omega D}{2v_z} + \varphi_0) > 0$, that is:

$$0 \pm 2\pi k < \frac{\pi c}{2v_z} + \varphi_0 < \pi \pm \pm 2\pi k, \text{where} k = 1,2,3, \ldots \quad (3)$$

The final inequality (3) will have the form

$$\frac{\pi}{2}\left(0 - \frac{c}{v_z}\right) \pm 2\pi k < \varphi_0 < \frac{\pi}{2}\left(0 - \frac{c}{v_z}\right) \pm 2\pi k.$$

For the considered case, $v_z \approx c$; therefore, the phase interval φ_0, in which the radial focusing takes place, can be written as

$$-\frac{\pi}{2} \pm 2\pi k < \varphi_0 < \frac{\pi}{2} \pm 2\pi k. \quad (4)$$

The distribution of the azimuthal component of the magnetic field intensity $H_\varphi(\rho_0, z)$along the z-axis is represented in Figure-2b. It should be noted that the time shift between the azimuthal magnetic field and the longitudinal electric fields is a quarter of the period of high frequency oscillations. Then the change in the radial momentum of the particle under the influence of H_φ can be written as follows:

$$\Delta p'_\rho = -e\mu v_z \int_0^{D/v_z} H_\varphi(\rho_0, z) \sin(\omega t + \varphi_0)\, dt = -e\mu H_{\varphi_0}\int_{z_5}^{z_6} sin(\omega t + \varphi_0)\, dz,$$

where μ is the absolute magnetic permeability.
After simple transformations, we have

$$\Delta p'_\rho = e\mu H_{\varphi_0}\frac{v_z}{\omega} sin\left(\frac{\omega}{2v_z}\Delta Z\right) sin\left(\frac{\pi c}{2v_z} + \varphi_0\right).$$

The domain of radial focusing under the action of the azimuthal component of the magnetic field is the phase domain φ_0, for which $\Delta p'_\rho < 0$, that is $sin\left(\frac{\pi c}{2v_z} + \varphi_0\right) < 0$, or

$$-\frac{\pi}{2}\left(2 + \frac{c}{v_z}\right) \pm 2\pi k < \varphi_0 < \frac{\pi}{2}\left(0 - \frac{c}{v_z}\right) \pm 2\pi k,$$

taking into account $v_z \approx c$

$$-\frac{3}{2}\pi \pm 2\pi k < \varphi_0 < -\frac{\pi}{2} \pm 2\pi k.$$

Thus, the phase domains φ_0, for which the radial focusing is carried out under the action of the radial component of the electric field and the azimuthal component of the magnetic field, do not coincide and are shifted from each other by π. Depending on which component of the HF field has more significant impact in the radial direction on the accelerated particles, the radial focusing domain will be either

$$-\frac{3}{2}\pi \pm 2\pi k < \varphi_0 < -\frac{\pi}{2} \pm 2\pi k, \quad (5a)$$

or

$$-\frac{3}{2}\pi \pm 2\pi k < \varphi_0 < \frac{\pi}{2} \pm 2\pi k. \quad (5b)$$

The case (5a)corresponds to the use as the accelerating cavities the unshaped cylindrical ones, in which the value of the radial component of the electric field is close to zero. In the case of using a BRS with the optimized with respect to shunt resistance shape of accelerating cells, there holds the expression (5b).

Let us consider separately the longitudinal motion of electrons and determine the domain of longitudinal acceleration. Let us write the change of the longitudinal momentum of the electron passing the BRS period as

$$\Delta p_z = e\int_0^{D/v_z} E_z(\rho_0, z)\, cos(\omega t + \varphi_0) dt \quad (6)$$

or, taking into account the shown in Figure 2b distribution of the longitudinal component of the electrical field intensity over the period length,

$$\Delta p_z = \frac{e}{v_z}\int_0^D E_z(\rho_0, z)\cos\left(\omega\frac{z}{v_z}+\varphi_0\right)dz$$
$$= \frac{e}{v_z}E_{z0}\int_{z_5}^{z_6}\cos\left(\omega\frac{z}{v_z}+\varphi_0\right)dz.$$

After some transformations, we get

$$\Delta p_z = 2\frac{e}{\omega}E_{z0}\sin\left(\frac{\omega}{2v_z}\Delta Z\right)cos\left(\frac{\pi c}{2v_z}+\varphi_0\right). \quad (7)$$

The longitudinal acceleration of electrons, i.e. when $\Delta p_z > 0$, is possible only under the condition

$$cos\left(\frac{\pi c}{2v_z}+\varphi_0\right) > 0, \quad (8)$$

Thus,

$$-\frac{\pi}{2}\pm 2\pi k < \frac{\pi c}{2v_z}+\varphi_0 < \frac{\pi}{2}\pm 2\pi k$$

or for $v_z \approx c$,

$$-\pi \pm 2\pi k < \varphi_0 < 0 \pm 2\pi k. \quad (9)$$

4. DISCUSSION AND RESULTS

Comparing (5b) and (9), we can see that the phase domains of radial focusing and longitudinal acceleration of electrons are shifted relative to each other by $\pi/2$. The common part for both domains is the interval of the initial entry phases

$$-\frac{\pi}{2}\pm 2\pi k < \varphi_0 < 0 \pm 2\pi k. \quad (10)$$

Within this range, the changes of φ_0 exist simultaneously with the possibility of radial focusing and acceleration of particles. Thus, using the considered type of focusing, the maximum admissible phase length of the bunch of particles under the injection into the accelerating section should not exceed $\pi/2$.

It is not difficult to determine that the external points of the changing range of φ_0 correspond to two different regimes: $\varphi_0 = -\frac{\pi}{2}$ is the phase, corresponding to the maximum gain of energy, and $\varphi_0 = 0$ is the phase, corresponding to the most complete usage of the focusing properties of the HF fields of the accelerating cell. Depending on the conditions, which should be realized in each particular case, the injection phase of the bunch should be selected closer to this or that end of the admissible interval.

The obtained results correspond to the case of parallel motion of particles along the cell axis under various assumptions simplifying the analytical study. To determine the possibilities of such focusing, we carried out a complex of calculations of the dynamics of particles by a numerical method for a real distribution of HF fields in the accelerating cell. With this purpose, we performed integration of the equations of the electron motion under various initial phases of entering the accelerating cell. The results of the performed calculations are presented in the graphs.

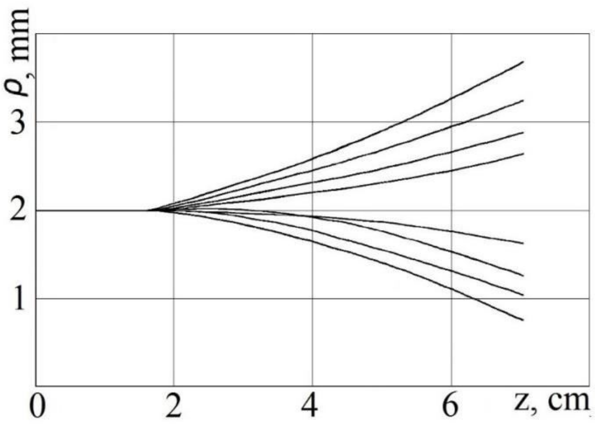

Figure-3. Trajectories of the particles inside and at the exit of the accelerating cell for various phases of entering under the electrical field intensity 120 kV/cm onthe cell axis.

Figure-3 presents the trajectories of the particles inside and at the exit of the accelerating cell. It is seen from the figure that, depending on the entry phase of the particle, the cell acts analogously to a focusing or defocusing lens.

This is demonstrated more graphically in Figure-4, where the dependencies are shown of the relative radial velocity (a) and the kinetic energy of the electron (b) at the exit from the cell on its entry phase under the electrical field strength on the cell axis 100 (1), 200 (2) and 140 kV/cm (3). The particles fly into the cell parallel to the axis at the distance of 2 mm from it. It is seen from Figure-4a that the cell, as a focusing lens, acts on the particles that have the entry phases $1.45\pi < \varphi_0 < 2.45\pi$, while the maximal effect is achieved at $\varphi_0 = 2.04\pi$. On the other hand, the acceleration regime is realized for the entry phases $0.94\pi < \varphi_0 < 1.94\pi$ (Figure-4b).

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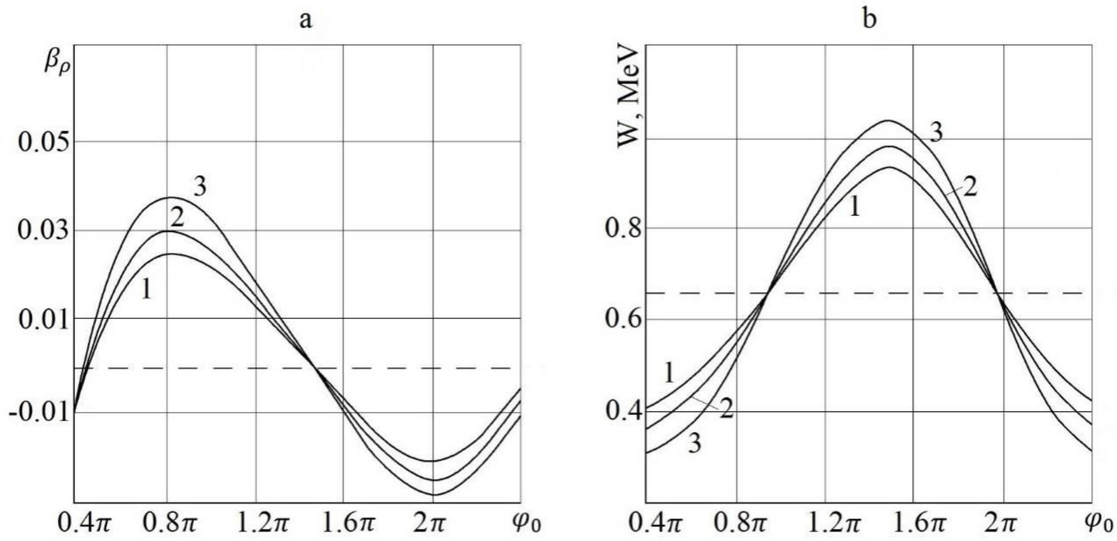

Figure-4. Dependencies of the relative radial velocity (a) and kinetic energy of the electron (b) at the cell exit on its entry phase under the electrical field intensity on the cell axis 100 (1), 120 (2) and 140 kV/cm (3).

It is necessary to note that the intensity of the accelerating field in the cell does not influence the size and arrangement of the phase domains of radial focusing and acceleration of electrons. As in the case of analytical study of the accelerating cell properties, the obtained domains are shifted by $\pi/2$ and their lengths completely coincide with the ones obtained earlier.

In the calculations, we considered the particles entering the cell parallel to the axis at various distances from it. We came to a quite clear result: the closer to the axis the particle flies; the less manifest is the focusing action of the HF fields. We also consider the cases of the particles flying into the cell under different angles; the most interesting is the case, when the particles enter under a negative angle, which corresponds to a beam converging at the entrance. In this case, for the initial angle $-1°$, the domain of radial focusing increases by 0.4π and already covers the domain of maximal acceleration. This allows using the regime of maximal acceleration without deterioration of the radial characteristics of the beam. It should be noted that obtaining the beams with negative convergence up to $-1°$ is not a difficult problem; and the use of electron guns with such beams allows identifying most completely the positive qualities of focusing the accelerating cells by HF fields. The influence of the initial angle of the particle entry with respect to the axis on the radial velocity of the particle at the cell exit is shown in Figure-5.

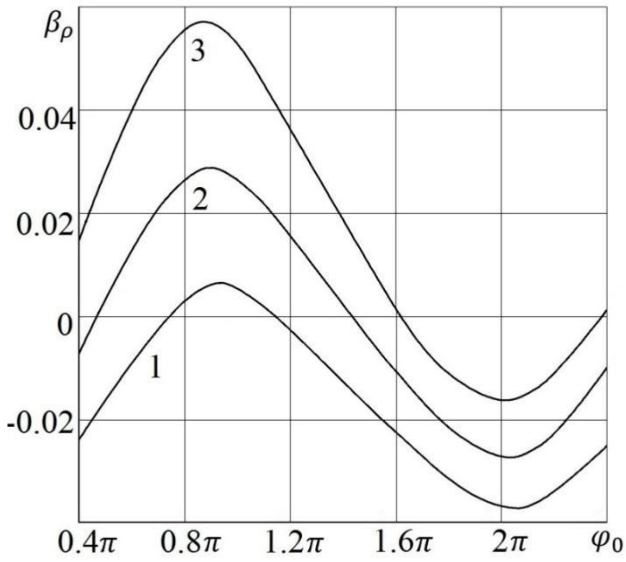

Figure-5. Dependence of the relative radial velocity of the particle at the cell exit on the entry phase for various initial values of the relative radial velocity: -0.016 (1), 0 (2) and 0.016 (3).

The above results were used in the creation of accelerators on the basis of BRS with standing wave. In addition, we had to choose the parameters of the grouping cells, which have a number of specificities, because the particle velocity in them is less than the speed of light. However, it is known (Vlasov, 1965) that in this case an additional positive effect of focusing is achieved due to an increase of the particle velocity in passing the cell, since, other things being equal, the electrons spend more time in the domain of action of the focusing electrical field than in the defocusing one.

The first installation of a series of accelerators with BRS is a three-section accelerator with internal connection cell and high-frequency supply from a magnetron of the power of 1.5 MW through a directional HF brancher and waveguide bridge. The first section is a buncher and contains 3 accelerating and 2 connection cells. Although in the creation of the accelerating system, there was set a task to provide gaining the maximum energy by the particles at the installation exit, i.e. the presence of an external focusing field was needed when using an electron gun with a divergent beam; nevertheless, a scheme with an autonomous buncher allowed testing the possibility of creating a LEA with standing wave without using the outer focusing. This was accomplished by selecting the phase shift between the buncher and the first accelerating section by means of the phase shifter in the supply waveguide.

The result was as follows: in the absence of an external focusing field, the coefficient of the electron capture into the acceleration mode was 20% compared to 30%, when it was present. At that, the measurements showed that, without a focusing magnetic field, the bulk of the beam was concentrated in a disc with a diameter of 5 mm, whereas when it was applied, in a 2.5 mm disc. The appropriate calculations gave the values of 5 and 3 mm, which confirmed the correctness of the proposed approach.

The second installation from the series of accelerators with BRS differs from the previous one by the type of accelerating system (with the external circular connection cells) and a simpler two-section scheme, while the grouping cells are the first two accelerating cells of the first section. In the designing of the accelerator, two versions were developed: one with focusing by the own HF fields of the accelerating cells and another, providing gaining the maximal energy, with an external focusing magnetic field. Their comparison shows that, under the regime of focusing by the own HF fields, the inevitable loss in the beam energy amounts to approximately 20%, in this case 1 MeV; however, in this case, the capture coefficient increases two times and amounts to 60% for the beam diameter 8 mm at the installation exit.

The third installation was made on the basis of a BRS with internal connection cells. Its distinctive feature is the possibility of changing the buncher, which is a component part of the first accelerating section and which consists of two accelerating cells and one connection cell, soldered into one block, which is attached to the main part of the accelerator with the help of a special female screw through an indium filling. The time of replacing one buncher by another and putting the installation to the operating mode is just several hours. Such construction allows significantly enlarging the domain of application of this type of accelerators, since by a change of bunchers, it is possible to realize, respectively, the regime of gaining the maximal energy at the installation exit and the regime of maximal capture of electrons in the acceleration process, as well as a number of compromise regimes depending on the specific problem. At that, the variants with using external focusing field and without it are implemented. It is possible to compare the regime of maximal energy gaining and maximal capture into the acceleration regime without external focusing field, respectively: $\mathrm{W} = 4.9$ MeV and 4.66 MeV; $k = 20\%$ and 35%; $\Delta W/W = 4\%$ and 8%. Here we denoted: W is the kinetic energy of electrons at the accelerator exit, k is the capture coefficient into the acceleration regime, $\Delta W/W$ is the width of the energy spectrum at half-height.

The use of electron guns with converging beam can make focusing by the own HF fields of the accelerating structures the most acceptable kind of focusing for a LEA with standing wave of the considered type (Novozhilov *et al.,* 2014), since it will allow not only to guide the beam, but also provide the energy gaining by the accelerated electrons.

5. CONCLUSIONS

The considered method of guiding the electron beam in linear accelerators is based on using the focusing properties of the radial component of the electric field. This component appears even at a lower type of oscillations in the conventional cylindrical resonator in the domain of drift tubes and, therefore, near the axis of the drift channel. This effect, which arises due to curvature of the electromagnetic field lines, may be promising also for the proton and ion linear accelerators.

The studies conducted with the help of mathematical modeling showed the prospects of this method for using in the technological fields of industry and medicine.

In the future, we plan a detailed study of the influence of changes in the shape of BRS resonators on the distribution of the electromagnetic field components in the domain of the drift channel. We will also study the conditions of efficient acceleration and radial stability in the design and construction of LEA without the use of external focusing devices. This will allow greatly reducing the dimensions and weight of the accelerator itself and increasing its effectiveness.

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