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CALCULATION OF BUNCHERS IN LINEAR ELECTRON ACCELERATORS WITH STANDING WAVE

Vladimir Kuz'mich Shilov, Aleksandr Nikolaevich Filatov and Aleksandr Evgen'evich Novozhilov
National Research Nuclear University, Kashirskoye Shosse, Moscow, Russian Federation
E-Mail: fila-tov@bk.ru

ABSTRACT

The paper considers the method for calculating bunchers for electron accelerators with the accelerating structure that works in the standing wave mode. The aim of the work is to determine the geometric dimensions and parameters of the grouping cells which create the particle bunches. The calculated buncher scan be successfully used to form beams with the purpose of their further carrying through the accelerating structures without the use of external focusing elements.

Keywords: buncher, drift channel, phase bunching, standing wave, radial bunching, the electric field strength.

1. INTRODUCTION

The development of accelerator technology for physics research has provided the possibility of practical use of accelerators in industry and medicine (Zavadtsev *et al.,* 2011)The interest in the use of linear electron accelerators (LEA) in industry and medicine is due to a number of their advantages: the ability to create directed beams of fast electrons and the deceleration radiation; high power of the dose of the deceleration radiation at low energies of the accelerated electrons.

It is known (Val'dner*et al*., 1969) that in the LEA,the particle gains energy on the traveling wave only under condition of synchronous movement with the accelerating wave. Because of the low shunt resistance of the accelerating structures in the traveling wave mode,the 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 have become an integral part of the design of the traveling wave accelerators. This requires additional energy costs and makes the accelerator design more cumbersome.

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 fluctuations of electromagnetic fields in the adjacent accelerating cavities are different in phase byπ,so the particle must cover the distance between the centers of 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 fieldis achieved.

If, at a fixed time moment, one considers the electric field strength distribution function 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.

Under certain conditions (Vygodsky 2006), such distribution function can be decomposed into a Fourier series and the standing wave field can be represented bya sum of harmonics. The particle interacts effectively only with the harmonic, the phase velocity of which equals 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 traveling wave accelerators.

2. METHODS

2. 1 Bunchers based on a biperiodic retarding structure

In the initial portion of any accelerator, the phase formation of the accelerated beam takes place, which largely determines its output characteristics (Kutsaev *et al.,* 2011). This part of the traveling wave accelerator is called a buncher, the main purpose of which is the grouping in bunches of the continuous flow of the injected particles. At the same time, the radial formation of the accelerated beam is realized by the external focusing devices, the role of which in the initial part of the accelerator is significant (Val'dner *et al.,* 1969).

The initial cells of the accelerators with standing wave will be also called a buncher, but in this case we do not limit ourselves to the phase grouping of the beam. Using the focusing action of the high-frequency (HF) field itself, we will simultaneously form the beam with respect to radius without external focusing devices (Novozhilov*et al.,* 2015). The beam, formed in this way with respect to phases and radius, can be further accelerated without the application of external focusing elements (Ono*et al.,* 1973).

The principle of klystron bunching can be most organically implemented in BRS (Akhiezer *et al.,* 1962). Since BRS operates inthe standing wave mode, the role of accelerating gap can be performed bythe interval between the drift sleeves, whereas the role of the drift area, by the space under the drift sleeves in the connection cell that is free from electromagnetic fields. These considerations were put as the basis of studying the bunchers that are capable of providing both longitudinal and radial formation of the electron beam.

Structurally, the buncher can be separated from the accelerating section (Filatov *et al.,* 1984) ; it can be its initial part and contain internal or external connection

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cells. Let us consider two types of bunchers, consisting of three or two cells. Using the examples of these bunchers, let us demonstrate their operation principle and the method of their calculation. As the conducted calculations show, the use of more complex bunchers, consisting of a larger number of cells does not make sense, since the processes of the beam formation into bunchers ends at a distance of the order of one wavelength.

2.2 A buncher consisting of three cells

The construction of a buncher with inner connection cells is shown in Figure-1. It consists of three accelerating cells and two connection cells. The connection cells are identical, whereas the accelerating cells differ from one another by the distance between the drift sleeves, the accelerating gap g,and by the length D of the cell itself.

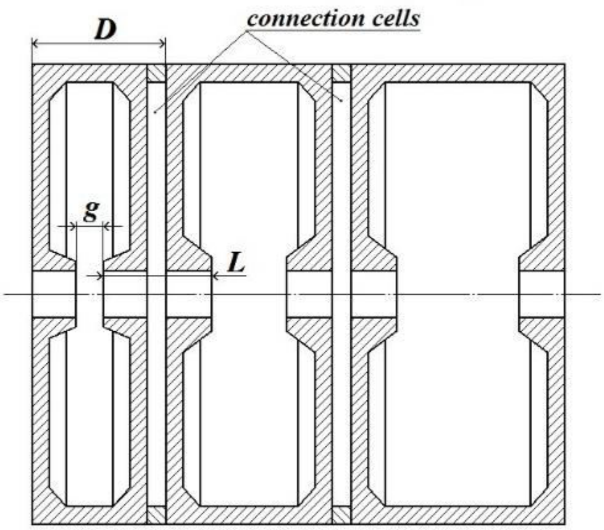

Figure-1. Sketch of a buncher, consisting of three cells.

Each of the three accelerating cell has its own specific purpose. Consider the mechanism of beam formation by each accelerating cell. The first cell, where the klystron bunching is used, realizes the phase-energy formation of the beam. The role of accelerating gap is fulfilled by the interval between the drift sleeves, whereas drift and grouping of the particles with respect to phases takes place in the space indicated in the figure by the letter L.

The second cell carries out the focusing of the bunched beam. This cell uses the focusing action of the radial components of the HF field. Focusing is realized by "landing" of the bunch into the respective phase of the electromagnetic field, which leads to its asymmetric sliding relative to the maximum of the accelerating wave.

The third cell coordinates the beam with the accelerating section of the accelerator, so at its exit the beam must be already sufficiently "rigid" to ensure the optimum acceleration regime. The role of this cell increases, if the buncheris structurally connected with the accelerating section, that is, it is a part of it. In this case, the cell must carry out "landing" of the formed bunch into the phase of the HF field of the accelerating section corresponding to the optimum acceleration regime.

It should be noted that the energy characteristics of the beam also depend on the bunching quality, so the major portion of computing the particle dynamics in the accelerator as a whole is connected with the calculation of the buncher. The preliminary calculations of such BRS revealed the degree of influence of each parameter on the process of the beam formation. The goal of the buncher calculation is to determine the accelerating gaps $g$and the lengths$D$ of accelerating cells, as well as the intensity of the accelerating field in each cell. In this case, we assume that the lengths of connection cell sare the same and equal 4 mm.

We illustrate the calculation method on the example of a buncher, operating in the S-range of wavelengths. All the calculated characteristics are obtained under the assumption that, at the buncher entrance, the beam has the following characteristics: the initial beam radius is 2 mm, the initial divergence is4°,the injection energy is$40\ keV$.

After passing the first cell, a continuous beam is grouped into bunchers according to phases. As the grouping takes place in space and time, the parameters characterizing this process will be the coordinate $l_g$along the z axis, where the beam is maximally grouped, and the phase $\varphi_w$of the bunch relative to the accelerating wave at this point. The dependencies of the beam parameters φ_w and $l_g$on the electric field strength $E_1$for various accelerating gaps $g$are shown in Figure-2.

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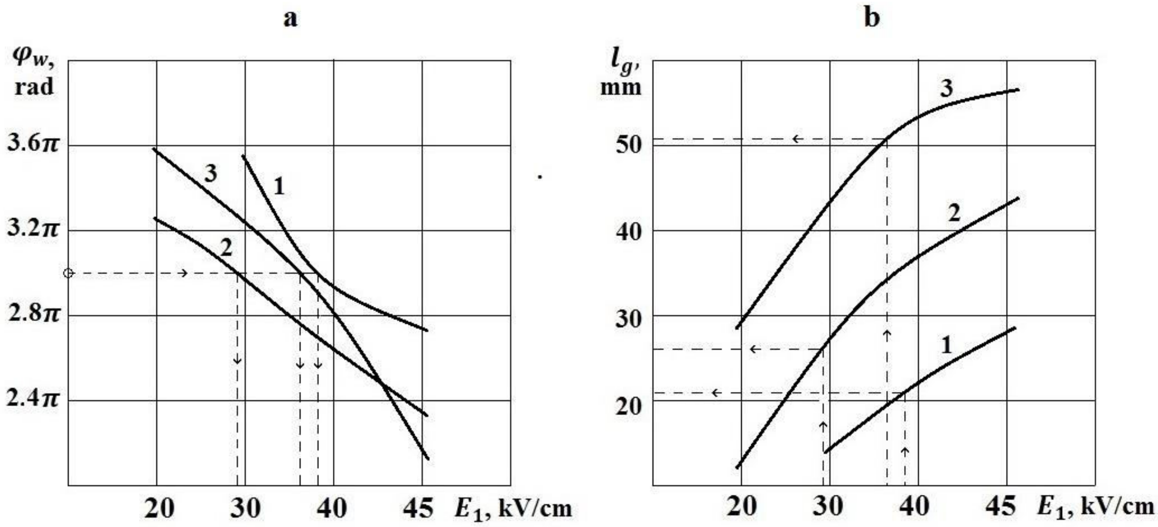

Figure-2. The dependence of the middle phase of the bunch for $z = l_g$ (a) and the length of the drift area (b) on the electric field intensity in the first cell: $1 - g = 5\ mm, 2 - g = 10\ mm, 3 - g = 15\ mm.$

Analyzing the obtained results, it is possible to determine the parameters of the first two cells. To provide asymmetrical slip of the bunch relative to the maximum of the accelerating wave,it is necessary that the bunch isat the maximum of the accelerating field at the entrance of the accelerating gap of the second cell, which corresponds to the wave phase in the cosine reference system $\varphi_w = 3\pi$.This phase is marked in Figure 2a and is provided bythe intensity of the accelerating field in the first cell $E_1 = 38, 29, 36\ kV/cm$with the respective lengths of accelerating gaps $g = 5, 10, 15\ mm$.At such combinations of the first cell parameters,one should expect good phase-energy characteristics of the beam.

On the other hand, the beam must enter the accelerating gap of the cell being maximally grouped in phase, which is achieved by equality between the geometric size $L$of the buncher and the beam parameterl_g. It is seen from Figure-2b that, for the selected variants of the first cell, the beam parameter $l_g$equals $21\ mm$, $26\ mm$ and $51\ mm$. These dimensions can be practically implemented in the design of the buncher; therefore, the final selection can be made by comparing the phase-energy characteristics of the beam. A variant will be considered the best, for which the spread with respect to energy and phases of particles is minimal. According to this criterion, the beam has the best characteristics at $E_1 = 38\ kV/cm$. Thus, thefollowingparametersof the buncheraredetermined: $g = 5\ mm$, $L = 21\ mm$, $E_1 = 38\ kV/cm$.

To maximize the focusing effect of the HF field, the strength of the accelerating field in the second cell should be maximum achievable in such a resonator. When selecting the geometric dimensions of the second cell according to the maximum of the effective shunt resistance, the intensity E_2can reach the value 200 kV/cm. The purpose of the third cell of the buncher is to maximally accelerate the formed bunch in order to prevent its slipping relative to the accelerating wave in the section with the relative phase velocity $\beta_w = 1$. As the calculations show, β_{w3}in the third cell should differ little from unity, whereas the geometric dimensions of the cell are selected from the condition of maximum effective shunt resistance. For the case when the buncher is not structurally connected with the accelerating section, the third cell is characterized by the values$\beta_{w3} = 0.93$and$E_3 = 200\ kV/cm$.

2.3 A buncher composed of two cells

Let us consider the calculation of a buncher on the example of BRS with external connection cells shown in Figure-3. The operation of the buncheris based on the same principles as for the three-cell one. However, since the buncher consists of only two cells and simultaneously is a part of the accelerating section, the purpose of the second cell will be slightly different.

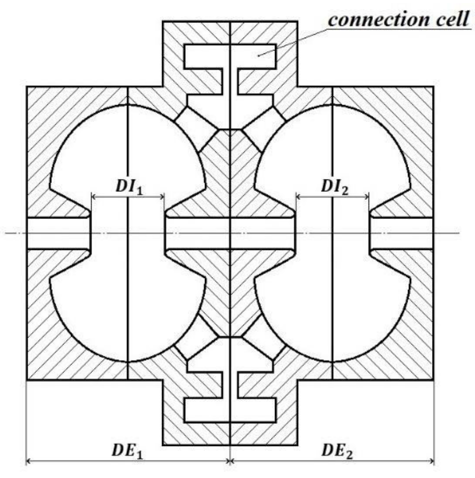

Figure-3. Sketch of a two-cell buncher.

In the first cell, as before, the phase grouping of the bunchtakes place. However, in the second cell, in addition to focusing the beam, one should realize such phase motion of the bunch, with which it is possible to further effectively accelerate it in the accelerating cells with $\beta_w = 1$;that is, the second cell assumes the function of the last two cells of the three-cell buncher.

As a result of calculation, it is necessary to determine the buncher dimensions DE_1, DI_1, DE_2, DI_2, shown in Figure-3, and the intensity of the accelerating field in the cellsE_1andE_2.

The influence of the first cell on the beam can be characterized by two parameters: $\mathcal{T}$, the phase of the bunchrelative to the HF field at the exit of the first cell, and $\mathcal{L}$, the distance from the end of the first cell, at which the maximum grouping of the particles with respect to phasetakes place. The following parameters are taken as the initial for the beam: the beam radius is $1\ mm$, the beam divergence is no greater than 1°,the injection energy is$40\ keV$.

The method of calculating the two-cell buncher involves the following sequence of steps: first, one analyzes the results of calculation of the particle dynamics in the first cell with respect to the parameter $\mathcal{T}$; second, analyzing the results of calculation with respect to the parameter $\mathcal{L}$ (at the desired value of $\mathcal{T}$), one determines the geometric dimensions of the first cell and the intensity of the accelerating field; at the third stage, the radial and phase characteristics of the beam in the second cell are simultaneously considered and its geometrical dimensions are determined.

3. DISCUSSION AND RESULTS

If a buncher is a part of the accelerating section, then, selecting the geometric parameters of the third cell,it is necessary to consider an additional condition: the phase of the bunch at the center of accelerating gap of the next cell must correspond to the maximum of the accelerating field.

The final version of a three-cell buncher can have the following parameters: $\beta_{w1} = 0.35, \beta_{w2} = 0.67, \beta_{w3} = 0.93, E_1 = 35$ kV/cm, $E_2 = E_3 = 200$ kV/cm.Figure 4 shows the output phase-energy characteristics of the beam for this type of buncher in the form of dependence of the relative spread $\Delta W/W$with respect to energy and the phase $\Delta\varphi$of the bunch particles on the value of intensity of the accelerating field in the first cell.

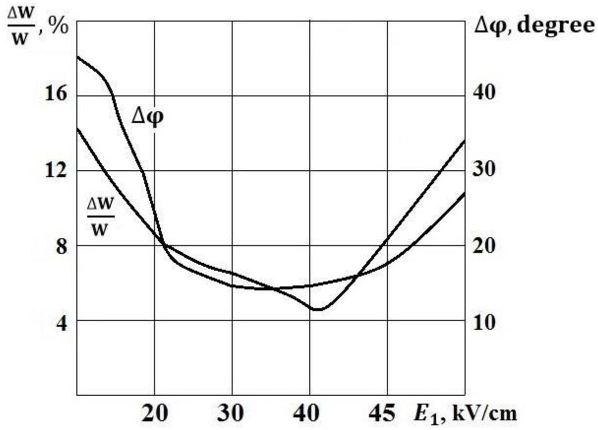

Figure-4. Dependence of the spread with respect to energy and phase of the bunch particles at the buncher exit on the accelerating field in the first cell.

As can be seen from the figure, the beam parameters are the best at$E_1 = 35$ kV/cm. Under the 50% capture of the injected particles, the bunches have the phase length of about $15^{\circ}$and $\Delta W/W \sim 5\%$.For the previously set input parameters of the beam, its diameter at the buncher exit does not exceed 4 mm.

When calculating the two-cell buncher, one must remember first of all that the cell sizes DEandDI are connected by the following relation $DE/DI = k$, where $k = 0.4 \div 0.7$(Bulykin*et al.* 1979). Let us set the variation range of $DE_1$from 1.5 to4 cm, assuming$DI_1 = 0.6\ DE_1$,and define the beam parameter $\mathcal{T}$ for different values of intensity of the accelerating field in the first cell. For simultaneous focusing and effective accelerating of the beam in the second cell,the parameter $\mathcal{T}$ should be equalto2.4π.

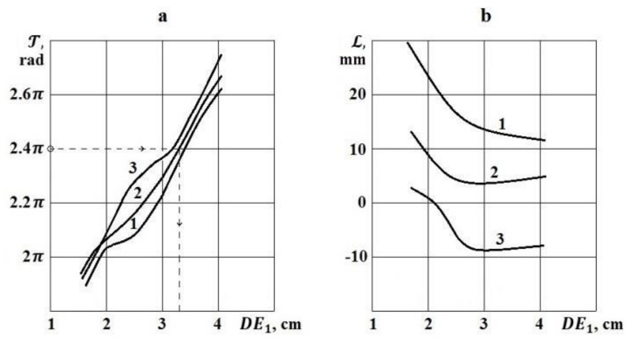

Figure-5. Dependence of the beam parameters$\mathcal{T}$ (a) and$\mathcal{L}$ (b) on the length of the first cell:$1 - E_1 = 20\ kV/cm$, $2 - E_1 = 30\ kV/cm$, $3 - E_1 = 40\ kV/cm$.

As seen from Figure 5a, in this region of phases, the curves for different $E_1$are located closest to one another and, for all E_1at $\mathcal{T} = 2.4\pi$, the size of the first cell is 3.25 cm. Figure 5b shows the dependences of the beam parameter $\mathcal{L}$on DE_1;as is seen from the figure, the value$\mathcal{L} = 4$ mmcan be considered the best, as in this case

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a bunch, completely formed with respect to phases, enters the accelerating gap of the second cell. From the analysis of the dependencies depicted in Figure-5, one can make the final choice of the first cell parameters: $\mathrm{DE}_1 = 3.2$ cmand $\mathrm{E}_1 = 30$ kV/cm,the size $\mathrm{DI}_1$is determined from the relation $\mathrm{DI}_1 = 0.6\ \mathrm{DE}_1$.

To determine the size DE_2, we use the condition that the bunch has to fly out of the second cell with a strictly definite phase. The value of this phase is equal to $\varphi = 3.5\pi$.If the second cell provides the predetermined phase motion of the bunch, then its further acceleration in the section will occur in the optimal regime. Let us analyze the dependence of the entry phase of the bunch on the length $\mathrm{DE}_2$of the second cell. The intensity $\mathrm{E}_2 = 160$ kV/cmof the accelerating field in the second cell was taken equal to the value most likely to be implemented in the structure. Forthegiven$\varphi = 3.5\pi$, one can determine$\mathrm{DE}_2 = 3.5$ cm.

Consequently, the parameters of the second cell are as follows: $\mathrm{DE}_2 = 3.5$ cm, $\mathrm{E}_2 = 160$ kV/cm and $\mathrm{DI}_2 = 0.6\ \mathrm{DE}_2$. We can assume that the buncher calculation is completed at this point. The beam diameter at the buncher exit does not exceed 6 mmand up to 60% of the injected particles are captured into the acceleration mode. The energy spread of the bunch particles equals 6%, whereas the phase length of the bunch$\Delta\varphi = 20^{\circ}$.

Thus, the calculated bunchers can be successfully used to form beams for the purpose of their further carrying through the accelerating structures without using external focusing elements.

When considering the radial motion of the particles, it is necessary to note the fact that the longitudinal and radial movements are closely linked and their equations must be solved jointly. In the case of LEA with standing wave on the basis of BRS, one can note specificities in the calculation of the radial motion of the particles. For the resonators of complex shape, optimized with respect to shunt resistance, there are no analytical expressions for the electromagnetic field components. The distribution of the electromagnetic field components with respect to longitudinal coordinate and radius, obtained with the help of numerical methods, must be specified in the form of tables across the entire aperture of the drift channel.

The presence of far protruding drift sleeves in the accelerating cells is the cause of strong curvature of the electric field lines, which leads to the appearance of a significant transverse electric field at the place of greatest curvature. In addition, the drift sleeves shield a certain segment of the drift channel from the electromagnetic field, resulting in the appearance of periodically alternating electromagnetic-field-free portions in the accelerating structure.

The essence of the calculation comes down to the step-by-step determining the parameters of the buncher from the first to the third cell on the basis of the calculated characteristics of the beam.

The greatest attention should be paid to the analysis of operation of the first cell, from which there begins the most important stage in the formation of the beam, the phase grouping. The calculation of the first cell aims to obtain certain relationships between the output characteristics of the beam and the cell parameters.

First of all, it should be noted that in order to implement the principle of klystron bunching at the accelerating gap of the first cell, the intensity of the electric field must be of the same order as the beam injection voltage. Therefore, the admissible range of variation of the electric field intensity $\mathrm{E}_1$of the first cell was taken as 20-50 kV/cmwith three values of the accelerating gap $g = 5, 10, 15$ mm.

4. CONCLUSIONS

The calculation of the buncher was reduced to the determination of the phase velocities and the electric field strength in all the cells of the buncher. The greatest attention was paid to the analysis of the first cell, on the work of which the phase-energy characteristics of the beam are largely dependent. At the same time, one should provide asymmetrical slip of the bunch of particles relative to the accelerating wave in the next cell. In the accelerating gap of the second cell, the bunch should be at the maximum of the accelerating field. All these considerations formed the basis for the choice of the geometry of the buncher cells and the electric fields in them.

As a next step, the authors intend to consider a methodology for taking into account the spatial charge forces in the bunchers of accelerators with standing wave for accelerating the charged particle beams of high intensity.

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