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Acceptances of Accelerating Sections and Maximum Beam Emittances at Output of Electron Linear Accelerators

Vladimir Kuzmich Shilov, Aleksandr Nikolaevich Filatov, Aleksandr Evgenevich Novozhilov

Abstract*: Requirements to beam current and type of accelerated particles become more stringent in the case of application of accelerators in industry and medicine. Certain specific issues arise upon application of low energy accelerators, such as selection of efficient accelerating structure, the simplicity of fabrication, moderate cost, low occupied space, and low operation costs. Increase in beam intensity of accelerated particles only by virtue of improved acceleration and focusing has certain limits. Technical and economic performances of linear accelerators can be improved, for instance, by conversion from conventional accelerating system to a multichannel system. This article discusses the issue of the electron wiring harness in small size accelerator aimed at efficient use in industry and medicine where the facility dimensions are of high importance. Increase in beam intensity of accelerated particles by means of improvement of acceleration and focusing depends greatly on the procedure of prediction of particle dynamics. A simple procedure of prediction is proposed, the results of the study of particle dynamics in standing wave accelerators are given which confirm the possibility of maximum beam wiring harness.

Index Terms*: electron linear accelerator, acceptance of accelerating sections, beam emittance, biperiodic slowing structure.

I. INTRODUCTION

Nowadays, electron linear accelerators (linac) are widely used in industry [1], medicine [2], for the preservation of food products, sterilization of toxic wastes, and so on. Linacs can be applied in nondestructive testing of engineering products, synthesis and polymerization of composite materials, material processing, etc. [3].

The interest in the use of linacs for application purposes can be attributed not only to their high efficiency but also to simple input and output of accelerating particles, which makes it possible to obtain strictly directed bunches of fast electrons and Bremsstrahlung; simple adjustment of radiation energy and intensity; high Bremsstrahlung intensity even at comparatively moderate energies of accelerated electrons.

One of the major requirements to modern electron accelerators is the possibility to fine tune the bunch parameters, hence, such technical approaches are valuable which provide a wide range of output parameters of the accelerator. One of the main trends of development of nondestructive testing is radiation monitoring systems of containers with the possibility to identify the atomic number of substance in the container for customs and safety purposes [4]. As a rule, this is aided by accelerators of charged particles. In addition to bunch properties which are determined by the accelerator purpose, it is required to solve some technical issues: selection of wavelength, efficiency of accelerating structure, focusing type and injection energy, geometrical sizes of accelerating section, electric strength of structure and its maintainability, tolerances for accuracy of manufacturing, for high frequency (HF) parameters, costs. These issues are interrelated and their final solution depends on the specific use of the accelerator [5]. Upon development of linear resonant accelerators of charged particles, it is required to consider certain factors which are common for all accelerators irrespective of accelerated particles and type of accelerating structure, accelerator operation mode, as well as variations in currents of accelerated bunches and output energy. At present, the attention in the field of accelerating equipment is attracted by linear accelerators of charged particles for low energies of 10-20 MeV. This is related with the fact that accelerator became an essential device for research in power engineering, medicine, biotechnology, and microelectronics. It should be mentioned that the application of accelerators in industry and medicine leads to more stringent requirements to bunch current and type of accelerated particles. Upon development and independent use of low energy accelerator, some specific issues arise, such as selection of efficient accelerating structure, its simple fabrication, relatively low cost of production, moderate occupied space, as well as low operating costs. Increase in beam intensity of accelerated particles only by virtue of improved acceleration and focusing has certain limits. Technical and economic performances of linear accelerators can be improved, for instance, by conversion from conventional accelerating system to a multichannel system.

One of the most promising approaches to the solution of this problem is the combination of accelerating and focusing functions in a single structure [6].

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* Correspondence Author

Vladimir Kuzmich Shilov*, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russian Federation.

Aleksandr Nikolaevich **Filatov**, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russian Federation.

Aleksandr Evgenevich Novozhilov, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russian Federation.

Comparison of various types of accelerating structures demonstrates that at injection voltage not higher than 100 kV the most preferable are the structures operating in standing wave mode. These structures are characterized by sufficiently high shunt impedance, they are compact due to in the dependence of their transversal sizes on working wavelength and they are maintainable in fabrication. Design of such structures makes it possible to implement the most efficient in this energy range focusing types [7].

In the low energy range, the travelling wave linear accelerators are most widely used. In travelling wave linac a particle gains energy only upon synchronous motion with accelerating wave. Due to comparatively low shunt resistance of accelerating structures operating in traveling wave mode, the accelerated particle should be in the maximum of accelerating field. Continuous impact on the particle by the radial component of electric field deflecting from the axis is the reason that the external focusing elements, especially at acceleration start, became an inevitable component of travelling wave accelerators. This requires additional energy consumption and makes the accelerator design more inconvenient.

When a small-sized accelerator with a waveguide length of 0.3-0.5 m, electron energy of 4-8 MeV and low current bunch is required, then the standing wave accelerators are more advantageous. Linac operation modes have been compared in [8]; it has been demonstrated that the development of standing wave accelerators for low and moderate energies is quite reasonable.

Aperture for beam travelling in biperiodic slowing structure (BSS) is about 10 mm in diameter. The wiring harness though overall accelerator can be implemented by means of external focusing magnetic fields, they require for application of solenoids. These solenoids can increase significantly transversal dimensions of linac, which is highly undesirable when the accelerators are used in nondestructive testing and medicine.

A key issue occurring upon designing of standing wave linac is wiring harness via BSS aperture. A successful solution to the problem of particle dynamics exerts significant influence on efficiency and simplicity of overall accelerator design.

Development of small-sized powerful sources of charged beams is not only of researching but also of engineering concern. It was shown in [9] that in linacs, operating in standing wave mode and equipped with accelerating system based on BSS, the accelerating efficiency due to oscillations of higher types significantly increases.

II. METHODS

While studying the particle dynamics in linac, it is possible to apply the notion of acceptance of the accelerating section [10]. Since electron bunch in standing wave resonant accelerator is formed completely in buncher [11], then the introduction of the notion of acceptance of accelerating section can promote the solution to the problem of wiring harness through the accelerator.

Such an approach does not provide a complete pattern of bunch formation in the considered structure which is especially important for buncher, hence, it would be reasonable to apply it for accelerating sections with relative phase velocity β_w equaling to unity, where already formed bunches are formed and instability of radial motion of particles decreases with in an crease in their velocity [12].

Let us consider accelerating part of three-section accelerator based on BSS with internal coupled cells comprised of two accelerating sections with β_w=1 and drift gap between them. Radial dynamics of particles without external magnetic field depends on the distribution of components of the electric field along the length and radius of a shaped resonator [13], in the tensity of electric field in resonator E, drift gap length L, relative velocity and entry phase of the particle β_z and φ_0.

For nominal operation mode (P=614 kW,I=43 mA) E=120 kV⁄cm,L=3.08 cm, and the velocity of particles entered into the first accelerating section is β_z=0.91. If we assume that the particle bunches have low phase length, then for each entry phase of the bunch φ_0 it is possible to plot the acceptance of accelerating part. With this aim on the phase plane (r,r^') the distribution of representation points is preset, their coordinates are used as initial terms upon digital integration of equations of particle motion in order to determine the entry phase φ_0. The representation points corresponding to the particles passing through overall accelerator determine the acceptance of the accelerating part.

III. RESULTS

Fig. 1 illustrates the acceptance of the accelerating sections for three values of the entry phase: $\varphi_0 = -0.4\pi, \varphi_0 = -0.5\pi, \varphi_0 = -0.6\pi$ at $L = 3.08\ cm$. The intensity of the electric field in the sections upon variation in the range of $100 \div 160\ kV/cm$ actually does not effect on the acceptance value, though, the output kinetic energy of bunches varies.

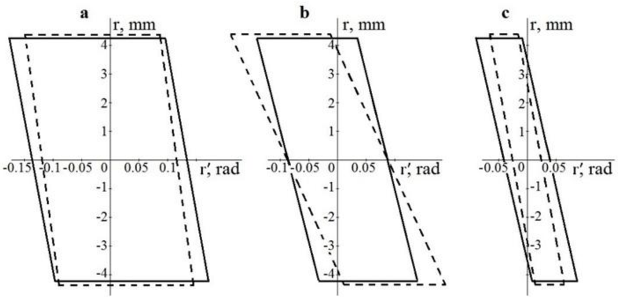

Fig. 1. Acceptances of accelerating sections for various initial phases:
$a)\ \varphi_0 = -0.4\pi;\ b)\ \varphi_0 = -0.5\pi;\ c)\ \varphi_0 = -0.6\pi.$

Fig. 2 illustrates the average kinetic energy W_{av} and acceptance of the accelerating part as a function of the entry phase φ_0 at $E = 100, 120, 140, 160\ kV/cm$.

It can be seen that the particle bunches can pass through accelerating sections only of $-0.6\pi < \varphi_0 < -0.3\pi$. When φ_0 increases from -0.6π to -0.3π the surface area of acceptance increases but the average kinetic energy of bunches decreases. Increase in the surface area of acceptance indicates at the increase in accelerator capacity, that is, at the improvement of high frequency focusing properties of the electromagnetic field. At $\varphi_0 = -0.3\pi$ the acceptance increases by about three times but the particles lose about 30% of energy.

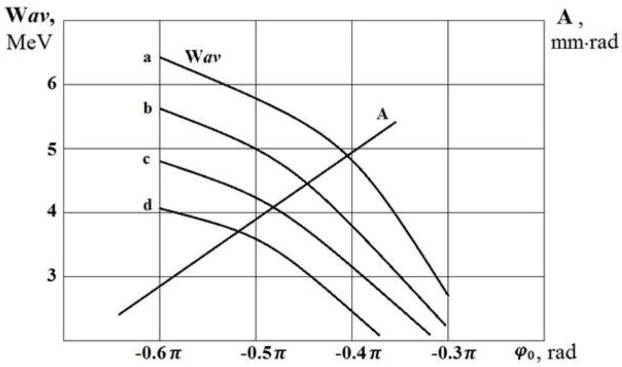

Fig. 2. The average kinetic energy of bunch and acceptance of accelerating sections as a function of entry phase:
a) $E = 100\ kV/cm$; ***b***) $E = 120\ kV/cm$;
c) $E = 140\ kV/cm$; ***d***) $E = 160\ kV/cm$.

If the phase length of the bunch is $\Delta\varphi = -0.2\pi$, then at the accelerator output the scatter of particle energy will be at least 30%. This scatter can be decreased by variation of the drift gap length between the sections. As shown by the predictions, at $L = 2\ cm, \Delta\varphi = 0.2\pi, E = 120\ kV/cm$ the relative energy scatter is $\Delta W/W = 15\%$. Acceptances for this variant are illustrated in Fig. 1 by the dashed line.

IV. DISCUSSION

Wiring harness through accelerating sections can be provided without loss when the beam emittance at section input does not exceed acceptance of accelerating sections. Let us assume that the beam emittance coincides with the acceptance of sections. In order to determine the beam emittance at accelerator output, it is required to set the points representing the input beam emittance for entry phases corresponding to bunch length as initial terms upon the solution of equations of particle motion in the considered accelerator. Thus predicted coordinates and divergences of particles at accelerator output are applied onto the phase plane (r, r'). The combination of representation points determines the beam emittance, which characterizes its quality. Beam with lower emittance can be easier transported to the target.

Variations of the surface area of maximum output beam emittance at several values of the accelerating field are illustrated in Fig. 3.

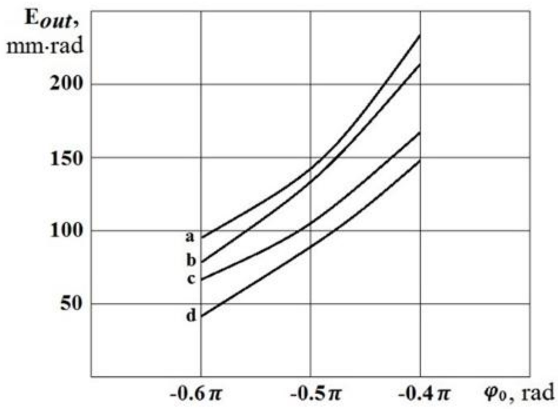

Fig. 3. Maximum output beam emittance as a function of entry phase:
a) $E = 100\ kV/cm$; ***b***) $E = 120\ kV/cm$;
c) $E = 140\ kV/cm$; ***d***) $E = 160\ kV/cm$.

These data were obtained at $L = 3.08\ cm$. In order to estimate the influence of the accelerating sections on output properties of the beam, it is possible to apply the ratio of surface area of input to output emittance. These data are summarized below in Table 1 for the intensity of the accelerating field of $E = 120\ kV/cm$.

Table 1.

φ_0, rad	E_{in}, mm · mrad	E_{out}, mm · mrad	E_{in}/E_{out}
-0.6π	800	80	10
-0.5π	1800	135	13.3
-0.4π	2800	225	12.4

For any phases of bunch entry $-0.6\pi < \varphi_0 < -0.4\pi$ the accelerating sections decrease the input beam emittance by at least 10 times. From this point of view, the most optimal is the entry phase $\varphi_0 = -0.5\pi$. Fig. 3 shows that the increase in the intensity of accelerating field in the sections leads to decrease in the output bunch emittance, which is attributed to the dependence of HF field action on its amplitude [14, 15].

Fig. 4 illustrates output beam emittances for the considered case which explain maximum cross-section and maximum divergence of the beam upon bunch entry phases of $\varphi_0 = -0.4\pi, \varphi_0 = -0.5\pi, \varphi_0 = -0.6\pi$.

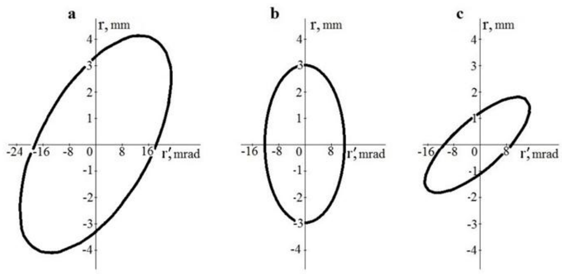

Fig. 4. Maximum output beam emittance for various initial phases:

$a)\ \varphi_0 = -0.4\pi;$
$b)\ \varphi_0 = -0.5\pi,;$
$c)\ \varphi_0 = -0.6\pi.$

V. CONCLUSION

While studying particle dynamics in linear resonator electron accelerators, it is reasonable to apply the notion of acceptance of the accelerating section since the formation of electron bunch in such standing wave accelerators takes place completely in buncher. The notion of acceptance of the accelerating section would facilitate the solution of the problem of wiring harness through the accelerator.

The obtained results of optimal entry phase are the most important for the accelerators where buncher is a part of accelerating section, that is, where the phase ratios between HF fields of buncher and accelerating section are steady and, hence, the phase of bunch entry into accelerating section should be predicted in advance.

Acceptances of accelerating sections were predicted for three-section accelerator, the range and optimal phase of bunch entry into accelerating sections were determined for implementation of HF focusing, the average beam energy as a function of entry phase was determined for various intensities of accelerating field in the sections, as well as the maximum values of beam cross sections and divergence.

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