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Multibeam Biperiodic Accelerating Systems

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ABSTRACT

This article discusses the issue of increase in intensity of electron flow in small-size accelerator for efficient application in industry, medicine, and other fields of science and engineering, where the sizes of unit are important. A possible approach to solve this problem is to combine acceleration and focusing of flow of charged particles in a single structure. Comparison of various types of accelerating structures demonstrates that at injection voltages not higher than 100 kV, the most preferred are biperiodic decelerating structures. Since the increase in intensity of beams of accelerated particles only by improvement of acceleration and focusing has certain limits, then it is proposed to improve technical and economic specifications of accelerator by conversion from regular accelerating system to multichannel design. Transportation and focusing of beams in multibeam structures, which significantly improve acceleration efficiency without noticeable increase in transversal sizes of radiating unit, seems to be possible only by means of high frequency focusing.

Key words: electron linear accelerator, multichannel accelerating system, accelerating unit, coupled cell, oscillation type, wavelength.

1. INTRODUCTION

The interest to electron linear accelerators (linacs) for application purposes can be attributed not only to their high efficiency but also to simple injection and ejection of accelerated particles. This allows to obtain strictly oriented beams of fast electrons and braking radiation. In addition, such accelerators are characterized by simple control of energy and power of braking acceleration even at comparatively moderate energies of accelerated electrons.

At present, linacs are widely used in industry [1], medicine [2], for sterilization of toxic wastes, etc. The main fields of engineering application of linac can be subdivided as follows: processing of materials, synthesis and polymerization of composite materials, introscopy and tomography of engineering products [3].

One of the main requirements to modern electron accelerators is the requirement of deep retuning of beam parameters, hence, engineering solutions providing wide variation range of output parameters of accelerator are of great importance.

At present, a promising trend of nondestructive instruments includes container inspection systems with possibility of atom number identification of objects for customs and security services [4]. This problem is generally solved using accelerators of charged particles.

Nowadays the attention of researchers in the field of accelerating tools is attracted by linear accelerators of charged particles for low energies since the accelerators, rated mainly up to 10-20 MeV, became essential for application studies in medicine, biotechnology, and microelectronics.

In addition to beam properties, which are defined by application field of an accelerator, it is required to solve some engineering issues: selection of working wavelength, efficiency of accelerating structure, type of focusing and injection energy, geometrical sizes of accelerating section, electrical strength of structure and its processability, allowances both for accuracy of manufacture and for high frequency parameters. These issues are interrelated and their final solution depends on specific application of accelerator [5].

While developing linear resonant accelerators of charged particles, it is required to take into account certain factors which are common for all accelerators independent on regime, type of accelerated particles and accelerating structure, as well as difference in output energy and current of accelerated beams.

Increase in intensity of beams of accelerated particles only by improvement of acceleration and focusing has certain limits.

A possible approach to improve technical and economic specifications of linear accelerator is conversion from regular accelerating system to multichannel design.

It should be mentioned that application of accelerators in industry and medicine leads to more stringent requirements to beam current and type of accelerated particles. Upon development and independent application of low energy accelerator, there appear certain specific issues: selection of efficient accelerating structure, simplicity of its fabrication, relatively low cost, low occupied space, and moderate operation costs [6].

A promising approach to solve this problem is to combine acceleration and focusing functions in a single structure. Comparison of various type of accelerating structures demonstrates that in centimeter wave range and injection voltages up to 100 kV, the most preferred are multichannel accelerating structures. Such structures are characterized by high shunt impedance and small sizes due to independence of their transversal sizes on working wavelength. Embodiment of such structures allows to achieve the most efficient focusing types in this energy range [7].

Development of portable sources of beams of charged particles is an urgent scientific and engineering task. Multichannel accelerating systems for linacs with standing wave were discussed in [8], it was demonstrated that standing wave linacs with accelerating systems based on BSS provided significant increase in acceleration efficiency due to oscillations of higher order.

2. METHODS

Accelerating resonators of regular standing wave are equipped with cylindrical resonators with E_010 oscillations optimized in terms of shunt resistance, which leads to comparatively high losses of high frequency (HF) energy in resonator walls due to relatively low Q factor of accelerating cells with this oscillation type. In addition, distribution of accelerating field in accelerating cell is characterized only with one high e-field region, thus, only one beam can be accelerated, its current is limited by size of hole for its transmission [8]. When the hole diameter is increased, the shunt resistance of accelerating resonators decreases, and finally the electron efficiency of the accelerator decreases.

Possible increase in efficiency of standing wave linear accelerators is reported in [9] in the case of application of resonators with E_110 working oscillations, the design of such accelerator is also presented. This oscillation type is characterized by two high e-field regions located at the distance of 0.466R to the resonator axis, where R is the radius of the structure.

It should be mentioned that in the considered structure, the directions of electric field lines in two high e-field regions at certain time are opposite, hence, it is possible to accelerate two beams, whereas one beam will be accelerated in even half-periods of accelerating electric field, and the other beam – in odd half-periods. Injection can be performed from two sources with the same high voltage potential. Since the aforementioned work considers accelerator design for heavy particles, protons, then the resonator is loaded with two rows of drift tubes fixed on its side wall by means of special supports. The shunt resistance of such system is by 1.5 times higher than that of regular structure, which is stipulated by high concentration of electric field lines in high e-field regions at E_110 oscillations, which is superior to the concentration at E_010 oscillations. However, the system Q factor in this case decreases by 17% due to additional supports. Nevertheless, this results in cumulative positive effect and the system efficiency increases.

The efficiency of standing wave linac on the basis of biperiodic slowing structure (BSS) also can be significantly increased due to oscillations of higher order used for acceleration. Then some designs of standing wave linac based on this principle are considered.

The first structure differs from conventional BSS with lateral coupled cells by the fact that the internal diameter of accelerating resonators is selected so that at working frequency, E_l10 oscillation is excited, where l=1,2,…

This system operates as follows. It is excited at $\pi/2$ oscillations via the input unit of HF energy connected to any accelerating resonator so that the direction of HF fields in resonator coincides with the direction of the fields near the coupled hole of input unit of HF energy. Each accelerating resonator 1÷6 (Fig. 1) is excited in opposite phase with respect to neighboring accelerating resonators located at the distance of $\beta\lambda/2$. The field in the coupled resonators 7÷11 is nearly zero.

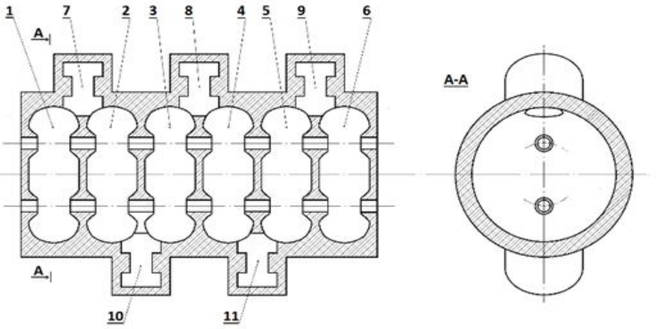

Figure 1: Multichannel BSS with E_210 oscillations: 1, 2, 3, 4, 5, 6 – accelerating resonators; 7, 8, 9, 10, 11 – coupled resonators.

It is known [10] that the Q factor of cylindrical resonators at E oscillations can be determined as follows:

$$Q = \frac{\mu_{lm}\lambda}{\pi(2 + {}^{D}/_{L})\sigma},$$

where: μ_{lm} is the n-th root of the Bessel function, D is the resonator diameter, $\sigma = (\frac{\lambda\rho}{120\pi^2\mu})^{1/2}$ is the depth of skin layer, ρ is the specific resistance of resonator walls, L is the resonator length, μ is the relative magnetic permeability of resonator walls.

The table 1 summarizes the main interrelations for certain E oscillations, which can be used for acceleration of electrons.

Table 1: Main interrelations for certain E

1. Oscillation type	2. E_{010}	3. E_{110}	4. E_{210}	5. E_{020}
6. ν_{mn}^{E}	7. 2.405	8. 3.832	9. 5.136	10. 5.520
11. D	12. $2\lambda/2.613$	13. $2\lambda/1.640$	14. $2\lambda/1.223$	15. $2\lambda/1.143$

Figure 2 illustrates rated Q factor as a function of the relations of main geometric factors of resonator for the same types. It can be seen that for the proposed system, upon operation at E_{110} oscillations the Q factor increases by 25%, and upon operation at E_{210} oscillation – by 40%.

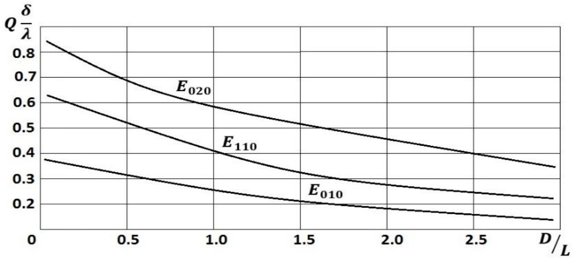

Figure 2: Rated Q factor as a function of ratio of main geometric sizes of resonators for E oscillations.

The increase in Q factor together with simultaneous increase in shunt resistance provides significant increase in electron efficiency of the system. In addition, since instead of one high e-field region of longitudinal constituent, the system has $2l$ high e-field regions, then it is possible to split the accelerated beam into $2l$ beams, which creates more favorable conditions for radial movement of particles, and it is possible to increase the increased current. Optimization of accelerating resonators in terms of shunt resistance leads to occurrence of drift tubes in the high e-field regions of longitudinal constituent of electric field. These tubes increase frequency separation of working and neighboring oscillations.

The second design makes it possible to accelerate particles at oscillations of higher order in the so-called designs with washers and discs, which are characterized by coupling coefficient being higher by an order of magnitude, which decreases significantly requirements to allowances of sizes of the accelerating system. Using E_{l10} oscillations for acceleration in addition to already mentioned advantages leads to additional increase in Q factor of accelerating cells since the supports used for fixation of washer to resonator walls are in principle in the field zero (Fig. 3).

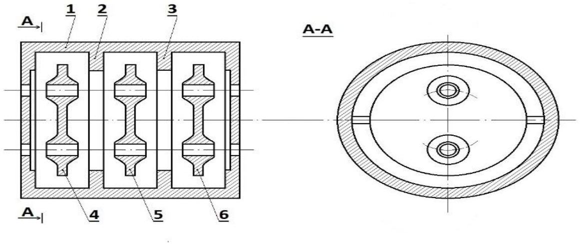

Figure 3: Multichannel BSS with washers and discs: 1 - structure body; 2, 3 - discs; 4, 5, 6 - washers; 7, 8 - supports.

Such design simplifies preliminary tuning of accelerating system because position of the supports provides minimum frequency shift and does not distort the field. Existence of drift tubes leads to frequency separation of oscillations sufficient for steady operation of the structure.

The third design illustrated in Fig. 4 has its certain features. In this design, the odd accelerating cells, counting from any edge, are made in the form of coaxial resonator with E_l10^ʘ oscillations, where l=0,1,2,… , and the even cells are made in the form of cylindrical resonators with E_020 oscillations.

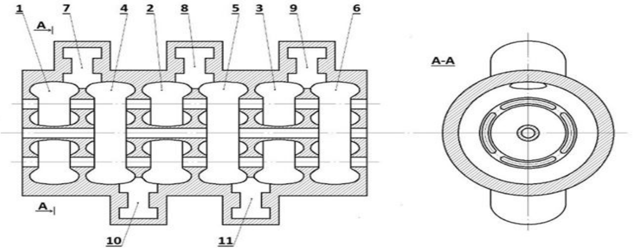

Figure 4: Multichannel periodic HF structure with $E_{020}^{\odot}$ and $E_{l10}^{\odot}$ oscillations: 1, 2, 3 – coaxial resonator with $E_{l10}^{\odot}$ oscillations; 4, 5, 6 – cylindrical resonator with $E_{020}^{\odot}$ oscillations; 7, 8, 9, 10, 11 – coupled resonator.

The Q factor at $E_{l10}^{\odot}$ oscillations can be determined as follows:

$$Q\frac{\sigma}{\lambda}=\frac{\mu_{lm}}{\pi}\frac{(1-\eta^2H')}{2(1+\eta H')+R(1-\eta^2H')},$$

where $\eta=\frac{b}{a}$ (a is the coaxial outer diameter, b is the coaxial inner diameter), $R=\frac{a}{L}$ (L is the resonator length), μ_{lm} is the root of

$$J_l(\mu)Y_l(\eta\mu)=J_l(\eta\mu)Y_l(\mu),$$

J_l and Y_l are the Bessel functions of the first and the second order, respectively,

$$H'-\left[Z_l'(\eta\mu_{lm})/Z_l'(\mu_{lm})\right]^2.Z_l(\eta\mu_{lm})-Z_l(\eta\mu_{lm})-\frac{Z_l(\eta\mu_{lm})}{Z_l(\eta\mu_{lm})}Z_l(\eta\mu_{lm}).$$

3. RESULTS AND DISCUSSION

The parameters of coaxial cylindrical resonators can be determined using the function illustrated in Fig. 5.

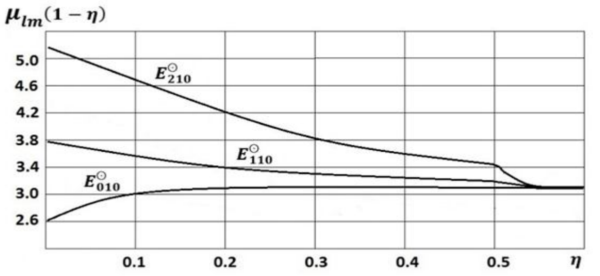

Figure 5: Q factor of coaxial and cylindrical resonators as a function of types of E oscillations.

The predictions have demonstrated that in the proposed system, upon operation at $E_{010}^{\odot}$ and E_{020} oscillation, the Q factor increases by 35%, and upon operation at $E_{110}^{\odot}$ and E_{020} oscillations – by 60%, in comparison with regular system at E_{010} oscillations. The diameters of accelerating cells of two types are about the same due to selection of sizes of drift tubes in these cells and, besides, due to selection of η in coaxial cylindrical resonators. Herewith, acceleration is applied to the beam flowing along the accelerator axis and tubular beam for $E_{010}^{\odot}$ passing across the second high-e-filed at E_{020} oscillation. It is possible to accelerate $2l$ beams instead of one tubular beam when $l \geq 1$, in this case, more favorable conditions are created for radial motion of accelerated electrons.

In addition, the predictions demonstrate that by selecting parameters of accelerating resonators, it is possible to achieve such position when the energies of particles passing along the periphery and center of the system are equal since the first particles are accelerated in each accelerating resonator in comparatively weak electric field, and the second particles – in one resonator but in higher field. Hence, at accelerator output without additional scanning device there is generated wide radiation area, and the longitudinal size of the unit decreases significantly

4. CONCLUSION

Transportation and focusing of beams in such multibeam structures, which allow to increase significantly acceleration efficiency without noticeable increase in transversal sizes of radiation unit, seem to be possible only by means of HF focusing, herewith, all recommendations for structures excited on E_{010} oscillations remain valid in this case.

Efficiency of standing wave linac can be increased by multibeam accelerating systems. Their optimum operation can be provided only by focusing by electromagnetic eigenfield [11, 12].

In addition, it is possible to improve focusing properties of accelerating systems of standing wave linac by modification of shape of accelerating cells, which provides better implementation of focusing capabilities of both radial component of electric field and azimuthal component of magnetic field.

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