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Adjustment of High Frequency Properties of Linear Electron Accelerator.

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ABSTRACT

This article describes designs of coupling cells and input unit of high frequency energy of linear standing-wave accelerator, which facilitate adjustment of accelerating current upon maintaining of optimum electron acceleration performance or adjustment of output beam energy at fixed accelerating current. Accelerator properties after addition of re-tunable cells into its accelerating system are described.

Key words: linear electron accelerator, slowing structure, high frequency system, accelerating cell, bunching cell, adjusting coupling cell.

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INRODUCTION

Due to their unique properties the linear electron accelerators (LEA) become valuable tools in certain technological processes and experimental studies. Technical and economical performances of such accelerators are mainly determined by the properties of accelerating sections. In linear accelerators ranged up to 10 MeV accelerating standing-wave systems are widely applied on the basis of biperiodic slow-wave structures (BSS).

The scope of application of linear electron accelerators (LEA) becomes wider and wider in industry (Zavadtsev et al., 1994), medicine (Agafonov, 1996), and experimental researches (Dovbnya et al., 2009; Belovintzev et al., 1994), as well as in numerous engineering processes (Abramyan, 1975; Bogdanovich et al., 1997). Simplicity and reliability of operation enable rapid activation and deactivation of the assembly, energy and intensity of charged particle beam can be varied in wide range from control panel, radiation flux can be easily controlled by means of electromagnetic lenses and scanning devices. The beam utilization factor for such devices can be as high as 70%. In deactivated state such accelerators are absolutely safe in terms of radiation, thus providing the possibility of in-line technical maintenance. In certain cases the assemblies can operate without construction of special premises with protection against radiation.

More frequently such accelerators are applied in radiation chemistry, non-destructive examination (Nikolaev et al., 1971), sterilization of medical preparations and commercial wastes. In agriculture, for instance, radiation of potato tubers in minor amount leads to stimulation of growth, escalation of stability and increase in starch content (Petrosyants, 1979).

Certain chemical processes can be initiated by accelerated electron beams or by slowing radiation flux (Lebedev and Shal'nov, 1991). Besides, using radiation of electron accelerator it is possible to improve significantly the properties of various polymers. LEAs are essential support of medical doctors in treatment of various cancerous diseases, their importance as a tool of radiation therapy cannot be overestimated (Karzmark and Pering, 2012; Volobuev et al., 2012; Zhang et al., 2013). This evidences the necessity of further improvement of LEA, increase their cost efficiency, simplicity of operation and compactness.

Technical and economical performances of LEA are mainly determined by high frequency (HF) properties of accelerating sections. Conventional type of accelerating sections is presented by traveling wave sections. In order to accelerate charged particles in round diaphragm-type waveguide (RDW) in standing wave mode it is reasonable to apply oscillations of π-type. Contrary to other types, this one involves the 1st harmonic of inverse wave, therefore, the shunt resistance is higher than for other oscillation types.

Hence, π-type standing-wave LEA are more preferred in comparison with traveling-wave accelerator in terms of energy gaining. However, it should be mentioned that operation of RDW with π-type oscillations is accompanied by poor frequency separation of operating and adjacent oscillation types. Thus, slight deviations in operation mode of HF generator concerning accelerating particle current or existence of other perturbing factors lead to unstable operation of overall assembly.

Development of various modifications of accelerating standing-wave systems resulted in their wide implementation in assemblies ranged up to 10 MeV, as they are characterized by numerous obvious advantages in this energy range (Kutsaev et al., 2011). The mentioned disadvantages were eliminated in biperiodic slow-wave structures. Their development is based on the fact that in standing wave in RDW with $^{\pi}/_{2}$-type oscillations, selecting locations of short-circuiting plates, it is possible to achieve alternative excitation of cells.

The cells with unfilled energy can be significantly decreased in longitudinal direction or removed from the system axis in general, and their capacitance coupling with excited cells can be substituted by inductive coupling. Then, for structure with lateral coupling cells the resonators on the system axis operate in the mode of π -type, though the structure retains oscillations of $^{\pi}/_{2}$-type. On the one hand, this provides operation stability, and on the other hand, high value of effective shunt resistance. This effect can be interpreted alternatively: all slowing structure becomes a combination of two structures, each operates on oscillations of π -type.

Herewith, operating point, corresponding to π-type of each structure, corresponds to $^{\pi}/_{2}$ -type in the combined structure/ Since the coupling aperture is located far from the axis, the configuration of accelerating cell can be optimized with regard to shunt resistance.

EXPERIMENTAL

General principles

The level of HF energy supplied to the system of two-section accelerators is adjusted by absorbing attenuator, which is a further modification of attenuator design developed for travelling-wave accelerator. Peculiar features of our developed design are increased range of adjustment of passing HF energy and minimization of its reflection to generator. This facilitates application of this design in standing-wave LEA, which is characterized by compactness and operation convenience for portable accelerators on the basis of BSS with bridge-type power supply.

The attenuator is composed of two prismatic resonators in the form of segments of rectangular waveguide, connected to narrow wall of major waveguide so that two T-junctions are generated in **H**-plane. Each resonator is a port of T-junction and circuited by movable choke plunger at the end. The distance between the resonator centers is three quarters of wavelength in the waveguide.

Both resonators are enclosed into a common shell cooled by running water. The coupling coefficients of resonators with waveguides are different, since they provide equality in terms of absolute values of waves reflected from these heterogeneities, which have inverse signs and provide zero reflection towards generator upon summation. When eigen frequencies of resonators are detuned from operating frequencies by means of the plungers, the attenuator transmits maximum HF energy into accelerating sections.

When the resonators are tune to operating frequency, they absorb up to 75% of transmitted energy, which facilitates significant reduction (up to two times) of energy of accelerated electrons at the assembly output. However, such attenuator absorbs a portion of HF energy even at strong detuning of its resonators and, in addition, it is impossible in principle to achieve complete coordination with HF channel in overall range of energy adjustment.

Accelerators on the of standing-wave BSS and HF power supply from magnetron generator cannot be implemented with accelerating system of arbitrary length. Upon increase in the number of resonator cells the scatter in frequencies between operating and adjacent oscillation becomes insufficient (in a system of N resonators N oscillation types can be excited in operating frequency band), the conditions of one-frequency excitation are violated, and the accelerator–magnetron system stops operation. According to the same reason at comparatively long accelerating sections (the number of accelerating cells is more than 10) without supplemental measures the accelerator will operate rather unstable.

HF systems of standing-wave LEA make it possible to increase by at least two times the frequency separation between operating oscillations and adjacent types. As a consequence, operation stability of such accelerators is improved or they can made with higher length without supplemental measures in comparison with increase in output energy of standing-wave LEA.

The first variant of HF system with increased separation of oscillation types (Vikulov & Milovanov, 1966) is composed of accelerating system in the form of BSS, input of HF energy into this system is provided by waveguide T-junction. Two ports of the T-junction are connected via coupling apertures to two accelerating cells, and the third one is connected to HF generator via ferrite valve and phase inverter.

Adjustment of high-frequency properties of linear electron accelerator

Possibility to adjust output energy in linear electron standing-wave accelerators by means of compact and comparatively simple units makes them more versatile upon solution of wide range of radiation issues. The work (Kalyuzhnyi & Shilov, 1984) discusses a design of two high-frequency electron accelerators operating in standing-wave mode. These systems enables adjustment of HF energy supplied to input of accelerating system in wide ranges.

In the first case this is aided by an absorbing attenuator, comprised of two prismatic resonators at the distance of $\frac{3}{4}\lambda_w$ (where λ_w is the wavelength in the waveguide) which are adjusted by choke plungers, their internal surface is covered by Al-Si-Fe alloy. This attenuator can absorb up to 75% of passing HF energy thus twice reducing the intensity of accelerating field in the structure.

In the second case the adjustment range of input energy is even more significant. In this system the generator HF energy is supplied to the input of waveguide coupler with coupling ratio α. One output port of the coupler is equipped with absorbing load, and the other output port is connected to the input of HF bridge, two accelerating resonator sections are connected to its output ports. The second input of HF bridge is connected via phase inverter to the second input of waveguide bridge. By means of the phase inverter the input power can be varied in the range of $\left(\frac{1-\alpha}{1+\alpha}\right)^2 P_g \leq P \leq P_g$, where P_g is the generator power.

However, both systems have the same disadvantage: upon decrease in the energy supplied to accelerator the intensity of accelerating field decreases along the whole length of accelerating structure, including buncher. As a consequence, capture of particles decreases upon acceleration and beam spectral properties are impaired. This can be avoided if the buncher is autonomous and provides sufficient acceleration and bunching of electrons into clusters, passing subsequently via accelerating system, where the intensity of accelerating field is adjusted in wide range. However, this is accompanied by significant complication of the HF system and sometimes is unreasonable.

Let us consider the HF system of standing-wave accelerator which provide adjustment of electron output energy in the range of 0.2-1.of nominal value with retaining of optimum capture of electrons into acceleration mode and acceptable spectral properties of beam in all operation modes. The assembly is a two-section resonant accelerator with HF power supply via waveguide bridge, to output ports of which accelerating sections are connected, and an absorbing load is connected to the second input. In this arrangement the supplying waveguides are short circuited at end by movable choke plunders, and accelerating resonator sections at equal distances from waveguide bridge are connected to the lateral walls of these waveguides by means of coupling slots.

When the choke plungers are at the distance of $\frac{1}{4}\lambda_w(2n+1)$ (where $n = 0, 1, 2 \ldots$) from the center of coupling apertures, the energy of HF generator is transmitted to the accelerating sections. Upon travelling of short circuiting plungers a portion of energy supplied to resonator sections will decrease and drop to zero when the plungers are at the distance of $\frac{1}{4}\lambda_w$ with regard to the initial position. In this case all energy of the generator will dissipate in waveguide load. All this is valid also for the case of positioning of coupling apertures in wide walls of waveguide with the only difference that all energy of the generator is supplied to the accelerator when the choke plungers are at the distance of $2n\frac{1}{4}\lambda_w$ (where $n = 0, 1, 2 \ldots$) from the center of coupling apertures.

An adjusting coupling cell is also added to the system, which makes it possible to maintain optimum value of accelerating field in the axis of bunching cell at variable accelerating fields in the remaining portion of the accelerator. The adjustment is aided by two choke plungers. The cell is excited at $H_{101}^{\square}$ oscillations. While the plungers move in one direction so that the cell frequency is constant, it is possible to maintain constant field intensity in the bunching cell due to the fact that magnetic field near slots of coupling with bunching cell varies to significantly higher extent than that near slots of coupling with accelerating cells. Even wider possibilities are provided by application of coupling cells which enable variation of accelerating electric field in the axis of buncher. Herewith, the buncher properties vary without depressurization and additional assembling of the structure.

RESULTS

Figure 1 illustrates accelerating structure with axial coupling cells, one of which has the form of prismatic resonator equipped with two re-tunable choke plungers. The cell is excited at $H_{101}^{\square}$ oscillations. While the plungers move in one direction so that the cell operation frequency is not constant, it is possible to adjust the coefficient of coupling between the cells, since the magnetic field varies significantly near the slot of cell coupling with the bunching cell, slightly varying in the vicinity of two cells of coupling with accelerating structure. This is stipulated by the shape of spatial distribution of magnetic field at $H_{101}^{\square}$ oscillations.

In order to maintain constant cell frequency the plungers move slightly uneven with respect to each other. Herewith, electromagnetic energy is redistributed between accelerating cells and the accelerating section is nearly coordinated with the generator in overall range of variation of electron output energy.

In addition to optimization of buncher properties upon operation of the assembly in various current modes such cell can be applied also for adjustment of electron output energy. Thus, in the accelerator when accelerating particles are focused by focusing properties of eigen high frequency fields (Novozhilov *et al.*, 2015), modification of accelerating electric field in the axis of bunching cell leads to the fact that focused electron clusters pass via the centers of subsequent accelerating cells in the phases differing from that of HF field, corresponding to maximum energy gain.

Therefore, the kinetic energy of electrons at the output depends on the value of accelerating field in bunching cell or, finally, on position of choke plungers in the prismatic coupling cell. Calculations aided by software of numerical integration of electron travelling in HF fields of BSS with internal coupling cells made it possible to determine the properties of accelerator upon application of re-tunable coupling cell.

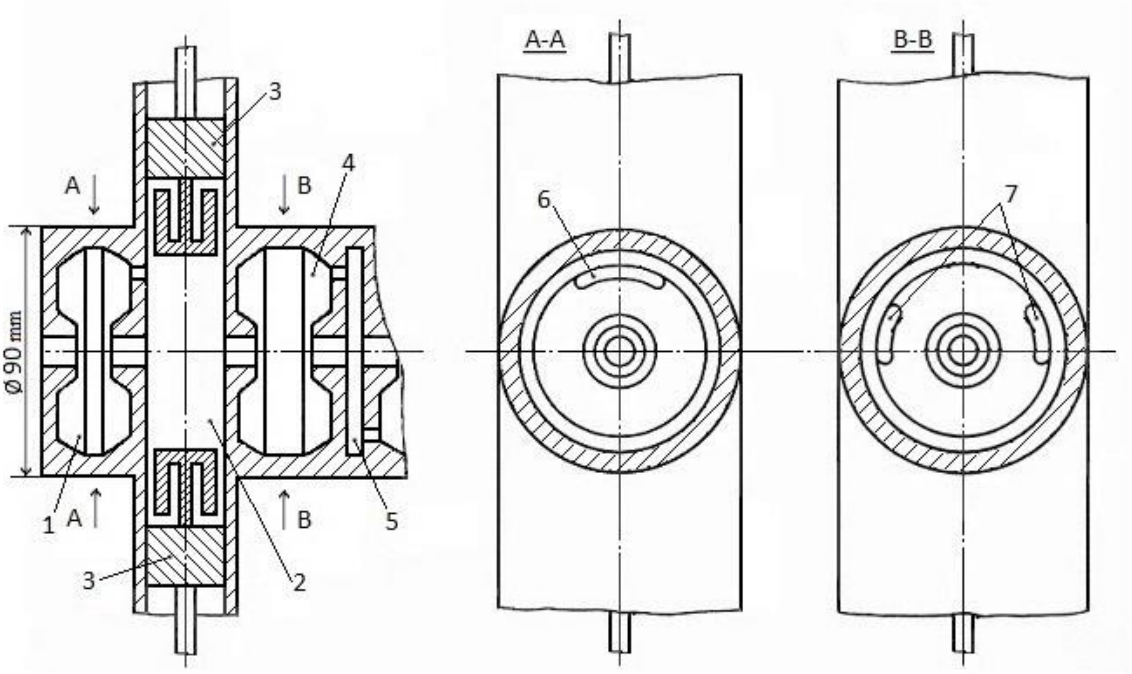

Fig. 1. Schematic view of accelerating cell with re-tunable coupling cell. 1- bunching cell, 2- re-tunable prismatic cell, 3- choke plungers, 4- accelerating cell, 5- cylindrical coupling cell, 6- coupling slot of re-tunable coupling cell with bunching cell, 7- coupling slot of re-tunable coupling cell with accelerating cell.

Figure 2a illustrates the maximum W_{max} and average W_{av} electron energy at accelerator output as a function of the value of accelerating field in the center of bunching cell, and Fig. 2b depicts the coefficient of electron capture during acceleration – зависимость от того же аргумента значения коэффициента захвата электронов в процесс ускорения k_c and the width of energetic spectrum $\Delta W/W_{max}$ at half-height of electron energy distribution at 1.4 MW rated power of HF generator. The re-tunable coupling cell provides variation in the range of $0.4 - 1.0$ of nominal valye at acceptable capture and spectral properties of the beam.

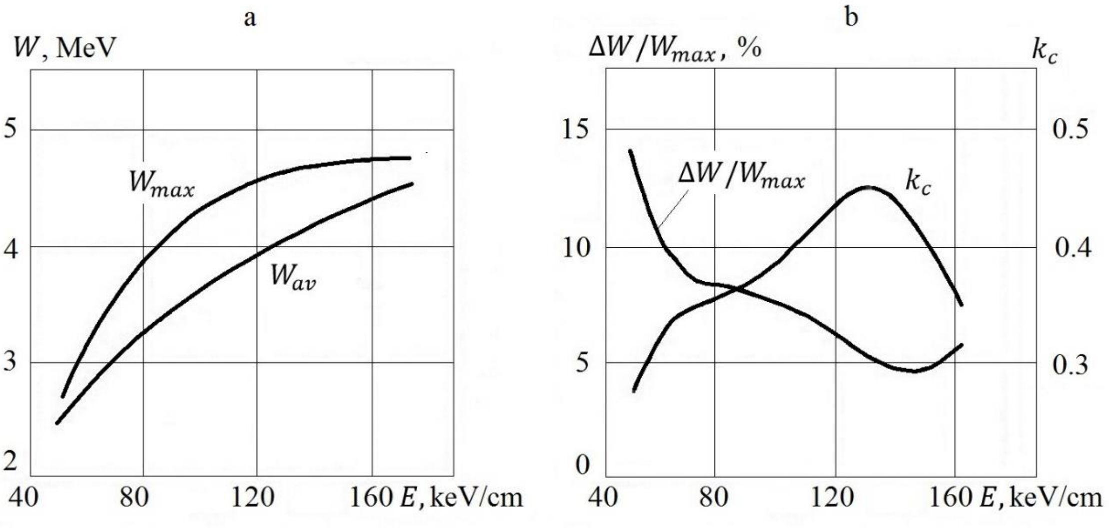

Fig. 2. Maximum and average output energy (a), as well as coefficient of election capture upon acceleration and width of energy spectrum at half-height of electron energy distribution (b) as a function of intensity of electric field on the axis of bunching cell.

Figure 3 illustrates schematic view of prismatic accelerating cell, into which the energy of HF generator is supplied. It is known that increase in the beam energy at accelerator output of certain HF structure depends mainly on the value of accelerating current and coefficient of section coupling with the inlet waveguide. The coefficient of reflection from accelerating section Γ provides the idea of ratio between the energies: supplied to the accelerator and reflected from it at operation frequency.

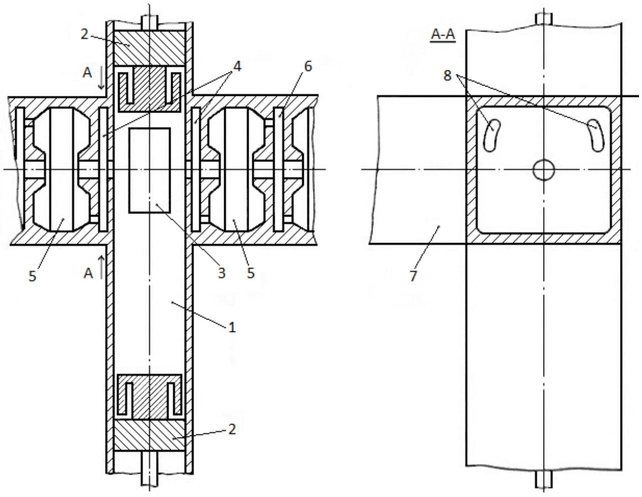

Fig. 3. Schematic view of accelerating system with re-tunable unit of HF energy input. 1- re-tunable prismatic accelerating cell, 2- choke plungers, 3- HF energy input aperture, 4-prismatic coupling cells, 5- cylindrical accelerating cells, 6- cylindrical coupling cells, 7-supplying rectangular waveguide, 8-coupling slots of re-tunable accelerating cell with prismatic coupling cells.

For ultrarelativistic point clusters located in maximum accelerating field the coefficient of reflection is as follows (Ono *et al.,* 1973):

$$\Gamma = (\beta_0 - 1)/(\beta_0 + 1) - \left[I\sqrt{\beta_0}/(\beta_0 + 1)\right]\sqrt{R_{sh}L/P_0},$$

where I is the pulse current, R_{sh} is the effective shunt resistance, β_0 is the coefficient of section coupling with inlet waveguide, L is the section length, P_0 is the HF power at input to the accelerating section.

DISCUSSION

In order to obtain maximum energy gain at various values of accelerating current it is required each time to provide fulfillment of the condition $\Gamma = 0$, that is, upon variation of I the value of β_0 should also vary. In common accelerating structure the sizes of apertures of HF energy input uniquely determine the value of β_0, corresponding to the mode of optimum acceleration only for one value of I, and upon any deviation of the accelerating current from the optimum value the acceleration efficiency decreases.

Application of prismatic accelerating cell with adjusting choke plungers enables adjustment of the coefficient of section coupling with inlet waveguide in wide range. The re-tunable accelerating cell is excited at $H_{102}^{\square}$ oscillations. Aided by coupling slots it is connected with two prismatic coupling cells, excited at $H_{101}^{\square}$ oscillations. In the considered cell in order to maintain the values of operation frequency the choke plungers move unevenly, as in the case of re-tunable coupling cell. Herewith, the coefficient of accelerating section coupling with waveguide channel varies in wide range (from the maximum, determined by maximum accelerating current, to zero), since the position of aperture of HF energy input in the accelerating cell varies and, hence, the conditions of HF fields excitation in the structure also vary.

Sizes of the coupling aperture correspond to the value of β_0 for maximum accelerating current when the center of coupling aperture is at the distance of ~ 0.25 of total length of resonator from the nearest choke plunger. Upon traveling of the plungers from this position the value of coupling coefficient decreases and reaches zero when the center of coupling aperture is in the middle of the accelerating resonator.

Figure 4a illustrates the additional gain in accelerator output energy $\Delta W/W_{max}$, obtained upon the use of this device, as a function of current I. It can be seen in the figure that the gain is especially high at deep retuning of accelerating current.

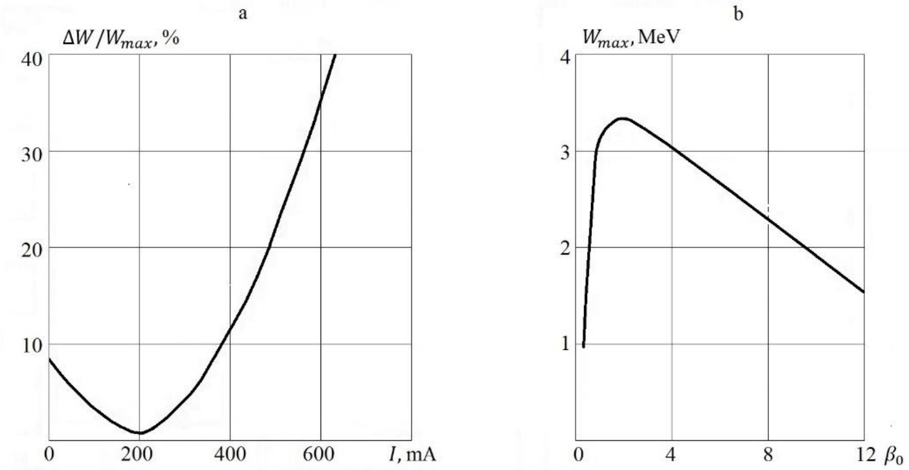

Fig. 4. Additional energy gain at accelerator output as a function of pulse current (a) and output electron energy as a function of coupling coefficient of accelerating sections with supplying waveguides at beam current of 200 mA (b) in the case of re-tunable accelerating cell.

CONCLUSIONS

Simultaneous operation of both devices provides the most versatile performances of accelerating system. In two-sectional accelerator prismatic re-tunable cells located at the place of energy input into each section make it possible to adjust the level of HF energy supplied to the section input at fixed current. Herewith, reflected energy is absorbed in waveguide load connected to the second input port of waveguide bridge.

In this case the re-tunable coupling cell makes it possible of maintain optimum value of accelerating field in the bunching cell, required for generation of "rigid" electron clusters. These clusters subsequently are accelerated in eigen accelerating structure where the level of accelerating field varies in wide range. Such accelerating flowchart makes it possible to obtain optimum spectral properties of electron beam at accelerator output. The output beam energy W_{max} as a function of coupling coefficient of resonator section with waveguide β_0 is illustrated in Fig. 4b at nominal value of accelerated current of 200 mA.

Application of devices aimed at wide adjustment of accelerating beam without impairment of its properties in the accelerating and high-frequency systems enables successful solution of numerous experimental and practical issues by means of modular units. Such versatility would permit serial production and provide successful implementation of such accelerators.

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