PERFORMANCE ANALYSIS OF $30\,MeV$ ELECTRON LINAC WITH A NEW INJECTOR SYSTEM

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The present paper deals with the problems of $30\,MeV$ electron linear accelerator (LINAC-30) upgrading to attain optimum beam spectral characteristics. As one of the LINAC-30 upgrading variants, consideration has been given to a possible use of the injection system for LINAC-30, which is in general similar to the $60\,MeV$ electron linear accelerator (LINAC-60) injector and which includes a low-voltage $25keV$ electron source and a five-cavity standing-wave buncher. Two possible configurations of the upgraded accelerator have been considered. Schematically, they can be represented as follows: 1) a new injector and a long section ($4.41\,m$) of the basic accelerating channel; 2) a new injector, a short ($0.83\,m$) section (section $N\,1$) currently operating at a retarded phase velocity of the wave, and a long section (section $N\,2$). Numerical modelling of particle dynamics in the accelerating channel has been performed for the two cases. Based on the results obtained, assumptions are made as to the most optimum configuration of the upgraded accelerator.

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1. INTRODUCTION

One of the main objectives of the current LINAC-30 upgrading program is to reduce the energy inhomogeneity of the accelerated beam. This is necessary, first of all, for improving the efficiency of near-threshold nuclear-physical experimentation at the accelerator, when it is of importance to provide the highest electron density on the working target in a narrow energy range. An important task is also to reduce the beam losses due to the energy spread during beam formation and transport with an aim to improve the radiation environment in the whole accelerator-physical complex. This is of particular importance when the accelerator is operated at maximum current conditions ($\sim$100 μA) for supporting all nuclear-physics and radiation programs. From general physical considerations and operational experience of the basic facility LINAC-30, it appears possible to solve successfully the assigned tasks and to reduce the energy spread (half-width of the spectrum) to less than 5% for the accelerator operation under steady-state conditions only upon an essential improvement in the conditions of electron bunch formation and upon attaining small phase widths ($\sim$15°). This can be provided only with radical improvement of the injector system. Another mandatory requirement here is an accurate adjustment of the microwave power supply system of the sections and the minimization of amplitude-phase instabilities due to pulse modulator imperfection of klystrons (i.e., obtaining small-front modulating voltage impulses of klystrons with small amplitude fluctuations of no more than 1% within a pulse and from pulse to pulse).

2. CALCULATION OF DYNAMICS OF PARTICLES IN THE LINAC-30 WITH A VARIOUS CONFIGURATION OF ACCELERATING STRUCTURES

The paper deals with possible ways of improving the injector system of the accelerator LINAC-30. As a variant of LINAC-30 modernization (as an alternative to the traditional method of using a two- or three-cavity prebuncher), consideration can be given to the device similar on the whole to the injector of the linac LINAC-60 [1], which includes a low-voltage ($25\,keV$) electron source and a 5-cavity standing-wave buncher. The main rated parameters of one of the modifications of this injector (according to the data of the designers of the "Accelerator" Complex NNC KIPT) are given in Table 1.

Table 1. *The main rated parameters of one of the modifications of this injector*

Gun current, A	1.1
Beam current, A	0.89
Bunch repetition frequency, MHz	2797.15
Microwave power, MW	1.5
Phase extent (for 70% of particles), degrees	14.7
Energy spectrum width (for 70% of particles), %	4.4
Peak energy of the spectrum, keV	970

We have considered two possible variants of LINAC-30 upgrading, which can be presented schematically as follows: - a new injector and a long section (4.41 m) of the main accelerating channel; - a new injector, a short (0.83 m) section with a reduced phase velocity of the wave, and a long section.

In the second case, the microwave power supply is provided by two klystrons KIU-12AM with the use of a universal controlled waveguide system that can provide the serial feed regime for the two sections from one klystron, the split-feed regime of the sections and the regime of power summation at the input of the second section. The process of steady longitudinal interaction of the electron beam with a travelling wave was modeled on the basis of the nonlinear theory for the traveling-wave tube.

The simplest mathematical approximation variant, earlier described by Masunov [2], has been chosen, according to which the average electron bunch energy is determined on the assumption that a pre-bunched electron beam with the bunch phase extent of no more than 50° is injected into the waveguide section. In our case this requirement is fulfilled with a safety margin.

Below we give a nonlinear self-consistent set of differential equations, which describe the process dynamics. The set was solved numerically with the use of the FORTRAN programming language involving the universal IMSL program package.

$$\frac{d}{dx}U(x) = A(x)\cdot\cos(\varphi(x)),$$

$$\frac{d}{dx}A(x) = -P_\alpha\cdot A(x) - J_0\cdot m\cdot\cos(\varphi(x)), \quad (1)$$

$$\frac{d}{dx}\varphi(x) = 2\pi\cdot[\frac{1}{\beta_W} - \frac{U(x)}{\sqrt{U(x)^2-1}}] + \frac{J_0\cdot m}{A(x)}\cdot\sin(\varphi(x)),$$

where:

U(x) - average energy of the electron bunch in units m_0c^2 ($m_0c^2 = 0.511\,MeV$);
$x = z/\lambda_0$ - dimensionless distance;
z - longitudinal coordinate of the bunch;
λ_0 - free-space wavelength;
P_α - field attenuation within the wavelength;
$\varphi(x)$ - phase of bunches in relation to the total self-consistent field;
$\beta_W = \frac{\gamma_W}{c}$ - relative phase velocity of the wave in the section (c - speed of light);
$A(x) = \frac{e\cdot\lambda_0\cdot E(x)}{m_0c^2}$ - dimensionless amplitude of the total self-consistent field;
$m = \frac{e\cdot R_s\lambda_0^2\cdot I_1}{4m_0c^2}$ - current load factor ;
J_0 - pulsed beam current;
R_s - series impedance of the structure;
$I_1 \sim 2$ - dimensionless 1st harmonic amplitude of current for electron bunches of phase extent.

The results of the LINAC-30 performance analysis for the two variants of upgrading through the use of a new injector system are presented below.

3. USE OF THE NEW INJECTOR SYSTEM WITH REFERENCE SECTION OF THE LINAC-30

This variant 1 implies the electron bunch injection from the injector output to the standard LINAC-30 section of length $L = 4.41\,m$. It is the constant-structure section with radial cuts of diaphragms ($R_n = 635\,Om/cm^2$, the field attenuation being $\alpha = 6.8\times10^{-4}\,cm^{-1}$). The dynamics and phase-energy characteristics of the electron beam were calculated for the zero and optimum current values. The input beam parameters were conditionally chosen to be the same for the both cases ($U_0 = 0.97\,MeV$). The optimum current is taken to mean its such value, at which the highest beam energy (the derivative with respect to z is zero) at a given accelerating field intensity E_0 is attained at the end of the section. To calculate the optimum current, we use the equation of point bunch energy gain in the relativistic approximation

$$\Delta U(z) = \frac{E_0\cdot(1-e^{-\alpha\cdot z})\cdot\cos(\varphi)}{\alpha} - \frac{R_s\cdot J}{2}\cdot\frac{\alpha\cdot z - 1 + e^{-\alpha\cdot z}}{\alpha^2}. \quad (2)$$

At $z = L$ and $\Delta U(z) = 0$, we have

$$J_{lim} = \frac{2\alpha\cdot E_0}{R_s}\cdot\frac{1-e^{-\alpha\cdot L}}{\alpha\cdot L - 1 + e^{-\alpha\cdot L}};\, J_{op} = \frac{J_{lim}}{2}\cdot\delta. \quad (3)$$

Were J_{lim} is limiting current on the section. The coefficient δ is dependent on the parameters of the section and, in our case, $\delta \approx 0.9$ (if $\alpha = 0$, then $\delta = 1$, i.e., only in the absence of attenuation the optimum current is equal to 0.5 of the limiting current).

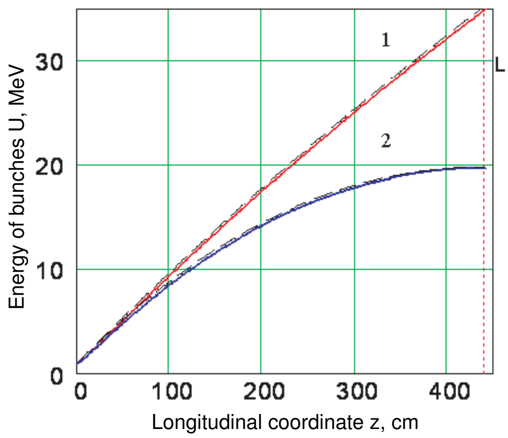

Fig.1. *Beam energy dependence of the longitudinal coordinates: curve 1 - for $J = 0$, curve 2 - for $J = J_{op}$ cross-hatching curves shows the dependence $U(z)$ calculated by the formula (2) in the relativistic assumption*

Figure 1 shows the average bunch energy in the accelerating section as a function of the longitudinal coordinate at the initial energy $U_0 = 0.97\,MeV$, the field intensity $E_0 = 90\,kV/cm$ ($E_0 = \sqrt{R_s\cdot P_0}$,

$P_0 = 12.756\,MW$) and the initial phase of injection $\varphi_0 = 64°$. Curve 1 corresponds to the zero beam current, and curve 2 - to the optimum current $J_{op} = 0.5502\,A$. Figure 2 shows the bunch phase relative to the external field of the generator (curve 1) and to the total self-consistent field of both the generator and the beam (curve 2) versus the longitudinal coordinate at the same initial phase of injection.

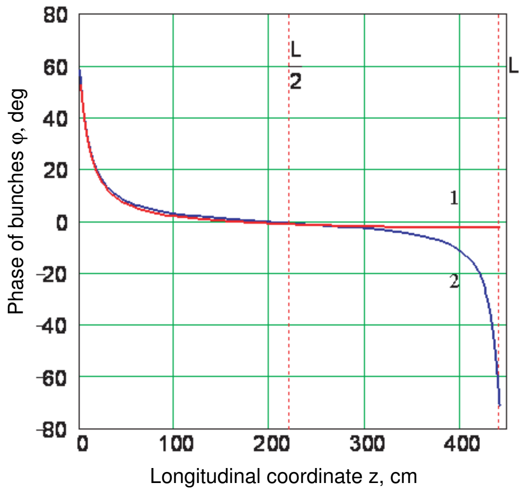

Fig.2. *Dependence of the bunches phase from the generator field (curve 1) and total self-consistent field of generator and electron beam (curve 2) from longitudinal coordinate.*

Figure 3 illustrates the average bunch energy at the accelerating section output as a function of the injection phase at the same initial conditions for both the zero (curve 1) and optimum (curve 2) beam current values.

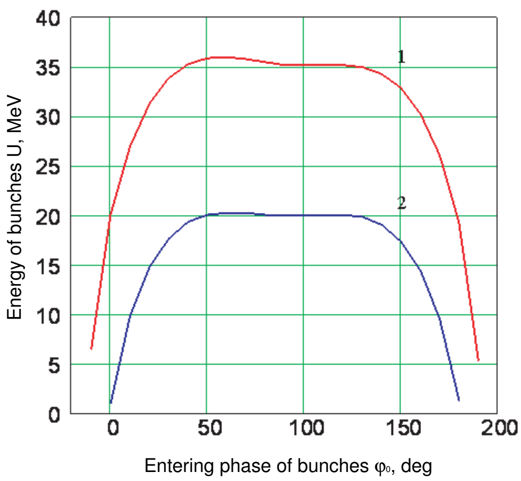

Fig.3. *Dependence of the bunch energy from injection phase: curve 1 - for $J = 0$, curve 2 - for $J = J_{op}$*

As it follows from the data in Figs. 1 and 2, irrespective of a considerable phase slipping of bunches at the beginning of the section, their average energy is little different from the limiting values calculated by formula (2), which describes the acceleration process in the relativistic treatment of the problem. The presence of flat regions on the curves of Fig. 3 in a wide range of injection entrance angles demonstrates practically ideal forming properties of this combination of accelerating components, which appears weakly sensitive to amplitude-phase instabilities in the microwave power supply system. In this case one should expect the occurrence of most favorable conditions for attaining a low electron-beam energy spread at the output of the accelerator. The disadvantage of this variant of LINAC-30 upgrading is the presence of some limitations (on account of using one klystron) in achieving higher levels of beam energy and power, this essentially restricting possible use of the accelerator in different nuclear-physics and application programs.

4. USE OF THE NEW INJECTOR SYSTEM WITH SHORT AND REFERENCE SECTION OF THE LINAC-30

In this case (variant 2) we assume to keep the existing accelerating system of LINAC-30 (long and short accelerating sections) and to inject the beam from a new injector into the short section, which will be operated under usual temperature conditions providing $\beta_W = 1$ and will play the part of an additional accelerating section. By this variant, the system of universal microwave power supply of the two sections is also retained. Its circuit is supplemented with a directional power coupler to energize the 5-cavity bunching facility of the new injector from the first klystron. The process of a steady-state longitudinal interaction of electron bunches with the travelling wave was modelled for three possible variants of feeding the accelerating sections at optimum current conditions. The main initial data for modelling are given in Table 2.

Table 2. *$*$-Serial feed regime ($\mu = 1$);*
$**$-Split-feed regime ($\mu = 0$);
$***$-Combined power regime ($\mu \approx 0.5$).

	$*$ $\mu = 1$	$**$ $\mu = 0$	$***$ $\mu \approx 0.5$
Section 1 field, E_{01}, kV/cm	90	90	90
Section 2 field, E_{02}, kV/cm	72.77	92.6	114.03
Optimum beam current, J_{op}, A	0.4449	0.5661	0.6971

(The tabulated data correspond to the klystron output power $P_{k1} \approx 14.9\,MW$ with allowance for $\sim 1.5\,MW$ to energize the 5-cavity buncher of the injector, and $P_{k2} \approx 13.5\,MW$). The modelling results are presented in the plots (Figs. 4 to 9).

The bunch energy in section 1 as a function of the longitudinal coordinate is shown in Fig. 4 for the regime of serial microwave feed of the sections. With the section length of 83 cm and a current of $\sim 0.4\,A$ the conditions appear to be far from optimum, and this function is practically linear. For the same regime, fig.5 shows the phase as a function of the distance travelled in section 1. It can be seen that an intense slipping of bunches relative to the self-consistent field, which characterizes the process of bunch formation, takes place. Figure 6 shows the beam energy at the output of section 1 versus the phase of input bunches. As it can be seen from the figure, this is not such an ideal curve as it was obtained in the description of variant 1

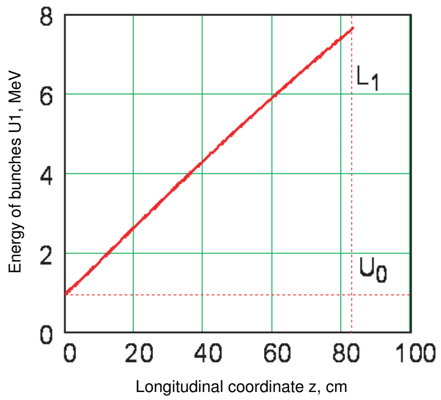

Fig.4. *Dependence of the bunch energy in section 1 from longitudinal coordinate.* $(E_{01} = 90\,kV/cm,\ J \approx 0.44\,A)$

of LINAC-30 upgrading (see Fig. 3). However, there are the phase sections on the curve that encourage to optimization of the working parameters of the beam.

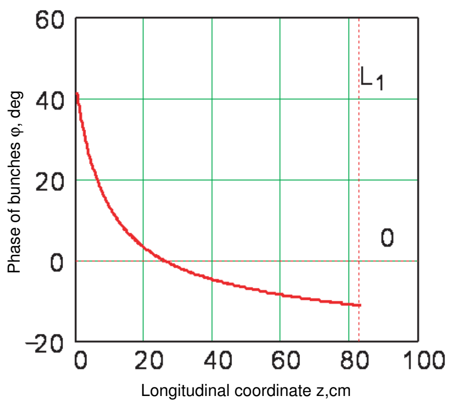

Fig.5. *Dependence of the bunches phase from longitudinal coordinate.* $(E_{01} = 90\,kV/cm,\ J \approx 0.44\,A)$

Figure 7 shows the beam energy in section 2 as a function of the longitudinal coordinate of the beam motion. The same figure shows the function U_{2rel} calculated by formula (2) in the relativistic approximation. As it is obvious from the figure, the curves are coincident. Figure 8 shows the phase dependence on the longitudinal coordinate in section 2. It is seen that at the initial energy $U_{02} \approx 7.7\,MeV$ an insignificant phase slipping of bunches takes place for the optimum injection phase $\varphi_{02} \approx 6.0°$.

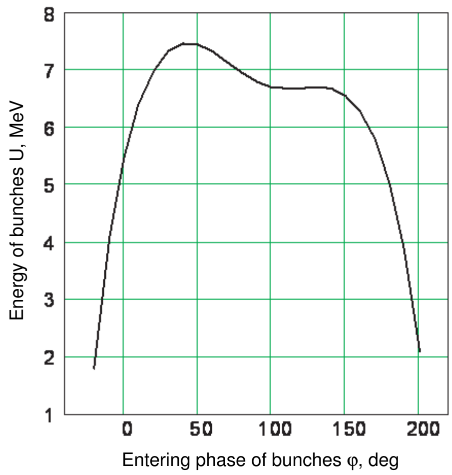

Fig.6. *Dependence of the beam energy at the output of section 1 from phase of input bunches.* $(E_{01} = 90\,kV/cm,\ J \approx 0.44\,A)$

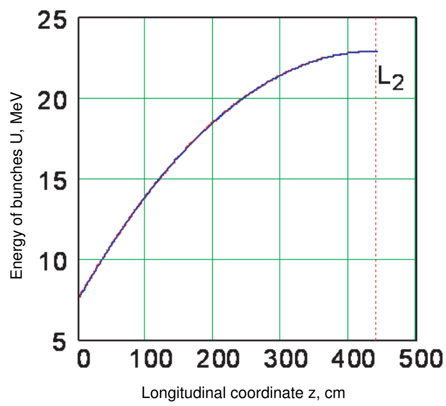

Fig.7. *Dependence of the beam energy in section 2 from the longitudinal coordinate*

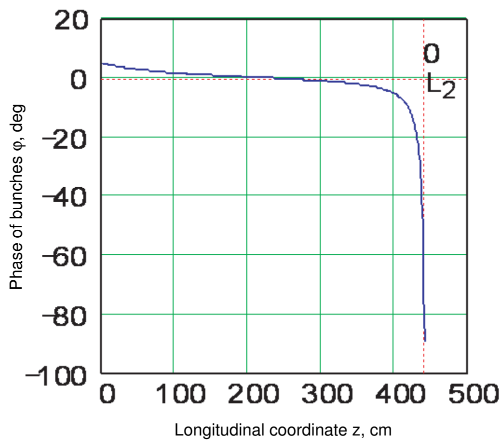

Fig.8. *Dependence of the phase from the longitudinal coordinate in section 2*

Figure 9 shows the beam energy at the output of section 2 as a function of the initial phase of bunches, this function being one of the main characteristics of the accelerator. It will be recalled that all the above-described dependences were obtained for the regime of serial microwave feed of the sections, i.e., at the initial conditions given in column 1 of Table 2. In what follows we shall not describe in detail all the dependences for other power supply regimes for the sections. They are alike, in principle. We shall dwell only on the main characteristics and their comparison.

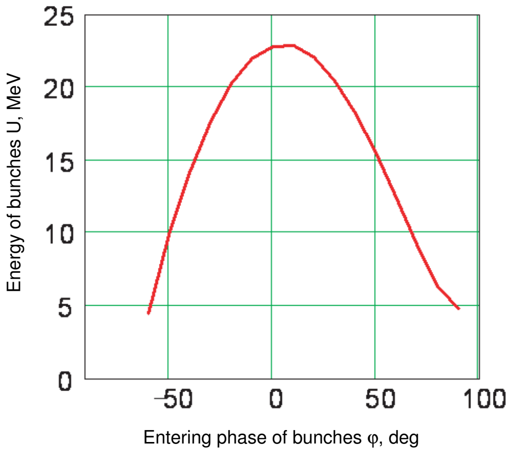

Fig.9. *Dependence of the beam energy at the output of section 2 from the initial phase of bunches*

For comparison, Fig. 10 presents the beam energy versus the phase of input bunches for all three regimes of microwave feed of the sections at initial conditions given in Table 2. Curve 1 corresponds to the serial feed regime, curve 2 - split-feed regime, and curve 3 - power summation. It can be seen that the optimum phases for all three regimes are practically the same ($\sim 7^\circ$). The curves are sinusoidal in shape, this being characteristic of a strongly relativistic case.

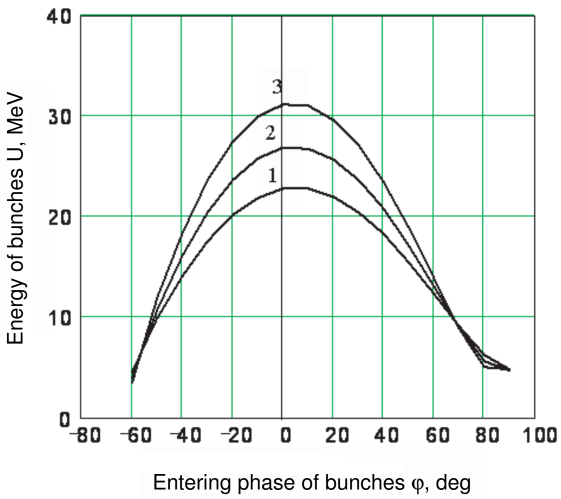

Fig.10. *Dependence of the beam energy from the phase of input bunches: curve 1 - the serial feed regime; curve 2 - the split-feed regime; curve 3 - power summation regime*

Figure 11 displays load characteristics of the accelerator LINAC-30 with a new injector system at all possible regimes of microwave feed of the sections, which were calculated by the given technique in the current range between 0 and $1A$. Graphic pairs $1, 2, 3$ are, respectively, for serial feed, split feed and power summation. The straight lines represent the energy dependences, and the curves show the average beam power versus current (at current pulse time $\tau = 1.7\,\mu s$ and pulse repetition frequency $F = 100\,Hz$).

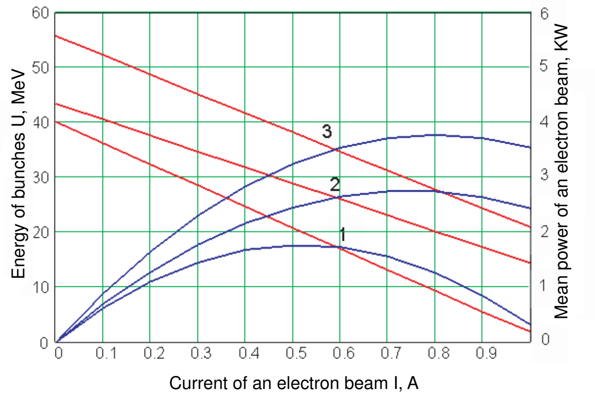

Fig.11. *Load characteristics of the LINAC-30 at all possible regimes of microwave feed of the sections (red lines - energy of bunches, blue lines - power of an electron beam): curve 1 - for serial feed regime; curve 2 - the split-feed regime; curve 3 - power summation regime. The straight lines represent the energy dependences; curves show the average beam power versus current ($\tau = 1.7\,\mu s$, $F = 100\,Hz$)*

The realization of the second variant of LINAC-30 upgrading will provide a substantial improvement in the beam parameters at all modes of operation due to a more perfect injection system. However, an ultimate energy increase at the power summation regime (up to $50\,MeV$) is practically impossible. As operation experiment with the universal power system of the sections has shown, there are the limitations connected with an insufficient electrical strength of both the waveguide elements and the section. The generation of power above $17\,MW$ at the input of section 2 seems to be very problematic. At the same time, at operation even in the most economy mode of serial feed of the two accelerator sections from one klystron at a pulsed current of $\sim 0.5\,A$, the electron beam energy may attain $\sim 20\,MeV$ (at zero current $\sim 40\,MeV$). That is to say, in this case a rather wide range of nuclear-physics and applied research can be successfully performed at the accelerator.

5. CONCLUSION

From the carried out examinations it is possible to draw a deduction, that each of probable configurations of modernized accelerator LINAC-30 has the advantages and shortages. In case of injection of a electron beam immediately in reference section it is necessary to expect making of optimum requirements for deriving small energy scatters in an electron beam on an exit of the accelerator. Essential shortages of this variant of modernization, rather low levels of an energy and a potency of a electron beam are, that essentially restricts possibilities of application of the accelerator in various nuclear - physical and applied programs. Embodying of the second variant of modernization LINAC-30 also will allow to improve considerably parameters of an electron beam in all operating modes for the account of more perfect type of an injector system. However, to receive limiting raise of an energy in condition of addition of a potency (up to $50\,MeV$) practically is not possible in connection with poor electrical strength waveguide devices and section.

Thus it is necessary to note, that the universal microwave power supply system of both section can worsen some parameters of an electron beam owing to presence in it of transients. Thus, the final solution about a configuration of the modernized accelerator can be accepted radiating from priority the posed physical problems and available engineering possibilities.

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АНАЛИЗ ХАРАКТЕРИСТИК ЛУЭ-30 С НОВОЙ ИНЖЕКТОРНОЙ СИСТЕМОЙ

С.П. Гоков, Л.А. Махненко, И.В. Ходак, О.А. Шопен

Данная работа посвящена вопросам модернизации линейного ускорителя электронов (ЛУЭ-30) с целью получения оптимальных спектральных характеристик пучка. Как один из вариантов реконструкции ускорителя ЛУЭ-30 рассмотрена возможность использования в качестве инжекторной системы для него устройство, в целом подобное инжектору ЛУЭ-60, включающее низковольтный источник электронов 25 кэВ и 5-резонаторный группирователь на стоячей волне. Рассмотрены две возможные конфигурации модернизированного ускорителя, схемы которых можно представить как: новый инжектор и длинная секция (4.41 м) основного ускоряющего тракта; новый инжектор, короткая (0.83 м) секция (секция $N1$), работающая в настоящее время с пониженной фазовой скоростью волны, и длинная секция (секция $N2$). Для обоих случаев проведено численное моделирование динамики частиц в ускоряющем тракте. На основе полученных результатов высказываются предположения о наиболее оптимальной конфигурации модернизированного ускорителя.

АНАЛІЗ ХАРАКТЕРИСТИК ЛПЕ-30 З НОВОЮ ІНЖЕКТОРНОЮ СИСТЕМОЮ

С.П. Гоков, Л.О. Махненко, І.В. Ходак, О.О. Шопен

Дана робота присвячена питанням модернізації лінійного прискорювача електронів (ЛПЕ-30) з метою отримання оптимальних спектральних характеристик пучка. Як один з варіантів реконструкції прискорювача ЛПЕ-30 розглянута можливість використання в якості інжекторної системи для нього пристрій, в цілому подібний інжектору ЛПЕ-60, який включає в себе низьковольтне джерело електронів 25 кеВ і 5-резонаторний групирувальник на стоячій хвилі. Розглянуті дві можливі конфігурації модернізованого прискорювача, схеми яких можна представити як: новий інжектор та довга секція (4.41 м)основного прискорюючого тракту; новий інжектор, коротка (0.83 м) секція (секція $N1$), яка працює в даний час з пониженою фазовою швидкістюю хвилі, та довга секція (секція $N2$). Для обох випадків проведено чисельне моделювання динаміки часток в прискорюючому тракті. На основі отриманих результатів висловлюються припущення про найбільш оптимальну конфигурацію модернізованого прискорювача.