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THE EFFECT OF THE TRANSIENT PROCESS ON THE OUTPUT PROPERTIES OF THE ELECTRON BEAM OF A LINEAR ACCELERATOR WITH A STANDING WAVE

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ABSTRACT

The process of loading high-frequency energy into the resonator accelerating sections of a linear electron accelerator occurs with a significant time constant since the accelerating sections have a high Q factor. At the beginning of a high-frequency accelerating pulse, an accelerating electron beam lacks energy and a significant average energy bundle scatter occurs at the output of the accelerator. If one delays the electron injection pulse relative to the high-frequency accelerating pulse, then the spectrum of the electron beam can be improved and the average energy bundle scatter at the accelerator output can be reduced. Such experiments are already used for ion accelerators. This article investigates the aforementioned technique for improving the spectral properties of a beam in a two-section linear electron accelerator with a standing wave. For this, a high-frequency power system with adjustment of the high-frequency energy level in the accelerating sections is used, which can completely decouple the high-frequency generator from high Q load. Such a system can significantly improve the output properties of an electron beam. The accelerator under consideration consists of two high-Q accelerating sections based on a biperiodic decelerating structure, which are powered from a magnetron via a 3-dB bridge. The article presents the results of analytical and experimental studies.

Keywords: linear accelerators, biperiodic slowing structures, high frequency, electron accelerators, injection delay.

INTRODUCTION

Transient process in high Q accelerating sections is a drawback of standing wave electron linear accelerators (linac). This leads to lower energies obtained by beam at initial stage of high frequency (HF) pulse and occurrence of medium energy scattering of bundles [1]. This scattering can be eliminated by various methods. Generally accelerating system of such facilities is comprised of contoured resonators of biperiodic slowing structures (BSS) of various types [2]. Accelerating sections of such linacs are powered by HF energy from magnetron or klystron amplifier, and generator is decoupled from high Q accelerating resonators by means of ferrite valves, circulators, or HF bridges [3].

Power circuit of linac accelerating sections from magnetron via waveguide bridge in terms of such properties as efficiency coefficient, dimensions and maintainability, cost of main and auxiliary equipment is preferable in comparison with other power circuits [4]. In addition, with appropriate selection of bridge properties it is possible to provide stabilization of magnetron frequency more than by an order of magnitude. In such accelerator two identical accelerating sections are connected to output ports of HF bridge, which decouples generator from high Q load. HF energy reflected from section during transient process of setting of electromagnetic fields is fed to waveguide absorbing load. The level of HF energy supplied to bridge input is adjusted by attenuator, thus enabling variation of electron energy at linac output.

At present numerous attenuator designs are known, which operate at high energy level [5]. In [6] attenuator of adsorption type is used, characterized by compactness, simplicity, and usability. Such attenuator is composed of a segment of rectangular waveguide, narrow wall of which is connected to two low Q alsifer coated tunable prismatic resonators at the distance of $\frac{3}{4}\Lambda$, where Λ is the wave length in waveguide.

The resonators are coupled with waveguide via holes in waveguide narrow wall and retuned by means of short-circuit choke plungers. Such attenuator enables fourfold tuning of passing HF energy at relatively low reflections at it in overall tuning range. However, the considered attenuator adsorbs some energy even at strong detuning of its resonators, besides, it is impossible in principle to achieve it complete matching with carrier line link in total range of energy tuning.

In order to improve beam output properties HF systems of standing wave linac are considered, which enable deep retuning of HF energy supplied to accelerating sections and providing complete decoupling of generator from high Q load, thus improving significantly beam output properties.

The output properties of standing wave electron accelerators operating in pulse mode are strongly influenced by transient process of setting of accelerating fields in high resonator sections. Its duration at HF pule characteristic time of 3 μs is about 1 μs. Due to the transient process electron beam gains lower energy at initial stage of HF pulse, in addition, there occurs medium energy scattering of particle bundles.

This can be avoided by means of delay of electron injection pulse. It demonstrated in [7] that the use of delay of electron injection pulse with regard to HF pulse significantly improves properties of standing wave linac. However, the efficiency of the facility decreases due to increase in unproductive loss of HF energy upon transient process. High loss of HF energy due to transient process occur even in facilities without delay of electron injection pulse with regard to HF pulse.

Let us consider this statement. It is known that active power varies as follows:

$$P(t) = P_0 \left[1 - \exp\left(-\frac{\omega_0}{Q_l}\right)\right] \quad (1)$$

where P_0 is the steady state value of resonator active power, $Q_l = \frac{Q_0}{1+\chi}$ is the loaded Q factor of resonator, Q_0 is the basic Q factor of resonator, χ is the coefficient of resonator coupling with inlet waveguide, t is the time, $\omega_0 = 2\pi f_0$, f_0 is the resonator eigenfrequency.

According to Eq. (1), power loss during transient process are defined as follows:

$$W_{el} = \frac{P_0\, Q_0}{(1+\chi)\omega_0}$$

Loss is especially high in the case of systems with high Q factors and can constitute significant portion at low durations of HF pulse. For the considered class of accelerators the pulse duration is in comparatively narrow range of about $1.5 \div 5$ µs, which is defined, on the one hand, by setting time of oscillations in self excited generator (magnetron), and, on the other hand, by sparkling, cathode emission drop, and transition of generation frequency to another type of oscillations [8]. Therefore, energy loss due to transient process in standing wave linac can achieve some tens of per cent.

Cascade circuit of HF bridge makes it possible to improve output properties of multi-section linacs with simultaneous increase in their efficiency. With this aim the output arms of the first bridge are connected to two grouping sections. The second input arm of the latter bridge includes dissipative load. Herewith, the following conditions are valid:

$$\chi_0 = \frac{2P_g - P_{01} + 2\sqrt{P_g^2 - P_g P_{01}}}{P_{01}} \quad (2)$$

$$\chi_k = 2(N-k) - 1 + 2\sqrt{(N-k)(N-k-1)} \quad (3)$$

where χ_0 is the coupling coefficient of grouping sections with the arms of the first bridge, P_g is the rated active power of HF generator, P_{01} is the rated active power of grouping sections, χ_k is the coupling coefficient of each pair of accelerating sections with the arms of connected bridge, N is the total number of HF bridges, $k - 1, 2, \ldots, N-1$ is the number of pair of accelerating sections connected to one bridge.

Generally, buncher consumes minor portion of supplied energy from HF generator, hence, in the considered case the main portion of falling wave is reflected from it. According to Eq. (2), the value of the coupling coefficient with supplying waveguide corresponds to the mode of strong over coupling. Hence, the duration of transient process is significantly reduced, the time constant of the process is $\tau = \frac{Q_0}{(1+\chi)\omega_0}$, where $\chi_0 \gg 1$.

In subsequent sections the transient process is accelerated both due to increase in χ_k, and due to increase in HF energy supplied to section input in comparison with steady mode as a consequence of reflections from previous sections. Therefore, even in the last pair of accelerating sections operating in the mode of critical coupling the transient process is accelerated to some extent.

MATERIALS AND METHODS

Insufficient energy gained by beam at initial stage of HF pulse and occurrence of medium energy scattering of bundles [9] can be eliminated by injection pulse delay with regard to HF pulse. Experimental results of application of such method both abroad [10] and in Russian ion accelerators [11] are known. The required delay time τ_{opt} can be calculated on the basis of equivalent circuit illustrated in Figure-1a. The circuit is comprised of oscillating circuit with Eigen frequency $\omega_n = 1/\sqrt{LC}$, coefficient of coupling with waveguide $\chi = Y_0 Z_{sh} l/2$, and time constant $\tau = C Z_{sh} l(1+\chi)$, where L is the inductivity, C is the capacitance, Y_0 is the equivalent conductance of external waveguide, $T^2 Z_{sh} l = W_{max}^2 / P_{loss}$ is the effective shunt resistance of accelerating structure with the length l, W_{max} is the maximum energy increment, P_{loss} is the loss power, T is the factor of flight time in this structure.

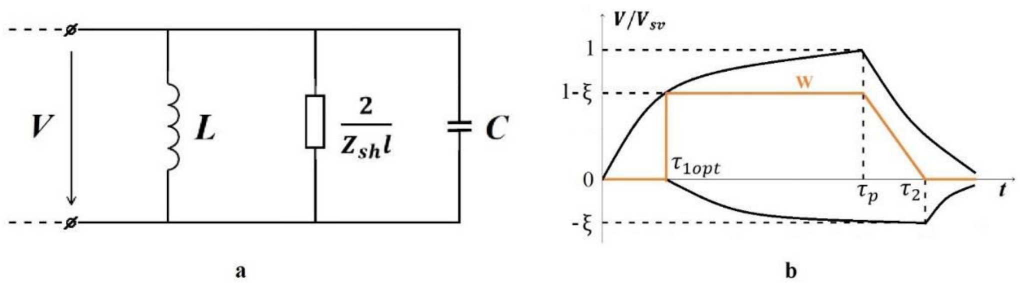

Figure-1. Equivalent circuit of standing wave system (a) and output energy of W bundles as a function of time (b).

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The circuit is excited by harmonic wave with complex envelope $\dot{U}_g = \sqrt{2P_g/Y_0}\, e^{i\varphi_g}$ and frequency ω, as well as by induced current beam with the same frequency; P_g is the generator power at section input; φ_g is the initial phase of envelope variations. The complex envelope of the first current harmonic induced by ultrarelativistic beam in the form of sequence of point bundles is as follows: $I_{el} = -2TI_0$, where I_0 is pulse averaged beam current. This equation accounts for the fact that the beam excites slowing field for itself in the structure.

Oscillations in high Q resonant systems can be analyzed on the basis of abridged equations with regard to relatively slowly varying complex envelopes. Let us denote the complex envelope of harmonic oscillations with frequency ω in circuit $\dot{V} = V^{i\Psi}$. Then, the abridged equation is as follows:

$$\dot{V} + \frac{1+ia_p}{\tau}V = \frac{2\chi}{\tau(1+\chi)}\left(U_g + \frac{I_{el}}{2Y_0}\right) = \frac{2\sqrt{\chi}}{\tau(1+\chi)}\sqrt{Z_{sh}lP_g}\left(e^{i\varphi_g} - \xi\right) \quad (4)$$

where $\xi = \sqrt{T^2 Z_{sh} l/4\chi P_g}$; $a_p = \tau(\omega - \omega_n)$ is the generalized detuning. Assuming that V equals to the potential difference in the gaps of real structure, the bundle energy can be expressed as $W = Re\{TV\}$. Let the generator is activated at the time $t = 0$, and the bundle with delay $t = \tau_1$. Then, solving Eq. (4), it is possible to derive the law of variation of bundle energy during HF pulse:

$$W = Re\left\{\frac{2\sqrt{\chi}}{(1+\chi)(1+ja_p)}\sqrt{T^2 Z_{sh} l P_g}\left[e^{i\varphi_g} - \xi + \left(e^{i\varphi_r} - \xi e^{\frac{\tau_1}{\tau}(1+ia_p)}\right)e^{\frac{t}{\tau}(1+ia_p)}\right]\right\} \quad (5)$$

where $\tau_1 \le t \le \tau_p$, τ_p is the duration of accelerating pulse.

It is obvious that when the conditions are met:

$$\tau_1 = \tau_{1opt} = \tau_p \ln\frac{1}{\xi} \quad (6)$$

$$a_p\frac{\tau_{1opt}}{\tau_p} = \varphi_g \quad (7)$$

There are no terms in Eq. (5) obviously depending on time, that is, variations of energy gained by beam in generator field and lost for radiation are cancelled out. Eq. (7) demonstrates that the effect is possible upon arbitrary phase of bundles in the field of accelerating wave. In practice Eq. (7) is implemented by selection of phase difference between grouping and accelerating sections or by election of detuning a_p. It follows from Eq. (6) that elimination of energy scattering can be achieved at any bundle current. This is the main equation in this calculation.

RESULTS AND DISCUSSIONS

Figure-1b illustrates the plot of Eq. (2) at $a_p = 0, \varphi_g = 0, \tau_1 = \tau_{1opt}$. In particular, it follows from the plot that in resonator accelerators energy scattering is possible due to occurrence of pulse drop. In order to eliminate this scattering, as seen in the figure, it is required to terminate beam injection until termination of HF pulse, that is at $\tau_2 \le \tau_p$.

Results of application of pulse delay in two-section accelerator with the parameters: $T^2 Z_{sh} l = 51 m\Omega, \tau_p = 0.47\mu s, \chi = 2.3, \tau_p = 3\mu s$ are illustrated below.

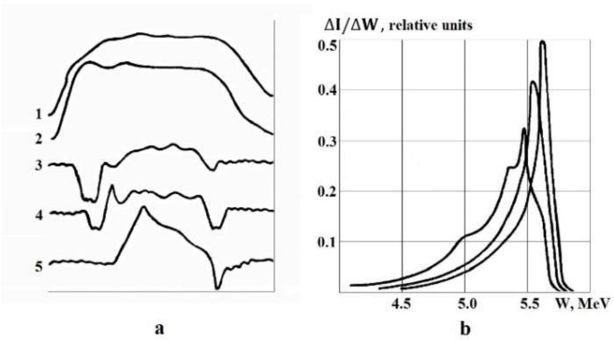

Figure-2. Oscillograms of pulses in two-section accelerator (a) with horizontal scan $0.5\mu s/cm$ and energy spectra at accelerator output (b) at $\xi = 0.1, \tau_p = 3\mu s$.

Figure-2a illustrates oscillograms of pulses at $P_g = 1.5MW$ and $I_0 = 50mA$ $(\xi = 0.1)$, which is close to rated values. Pulse 1 is the envelope of HF oscillations in the section, 2 - is the voltage at injector (14kV/cm). Pulses 3-5 are acquired from two-plate sensor of energy and current, they can be considered as variation of medium energy of bundles during current pulse (zero level corresponds to 5MeV). Oscillograms at $\tau_1 = 0\,(3), 1.0\,(4), 1.5\mu s\,(5)$ are shown, and the value of 1.0 μs, according to Eq. (3), is optimum for the mentioned data. As follows from the analytical consideration, at optimum delay there are no variations of medium energy, if deviations in the range of $\pm 1.5\%$ due to intrapulse instability of HF powering parameters are not accounted.

Figure-2b illustrates energy spectra of beam at the same data obtained by means of magnetic analyzer. At optimum delay the width of distribution function and half height is 4.5% (curve 2), which is by 1.6 times lower than without delay (curve 1). At the same time medium beam energy slightly increases. Spectrum at duration of injection pulse 1.5μs and $\tau_1 = 1.0\mu s$ (curve 3) is also shown. In this case scattering due to acceleration at HF pulse drop is eliminated, and the spectrum width decreases to 3%.

Similar measurements with various P_g and I_0 demonstrate that the spectrum width without delay equals to 7-10%, and from 3.5 to 6% at optimum delay; at half duration of injection pulse without delay: 5–6 and with optimum delay: 2–3.5%.

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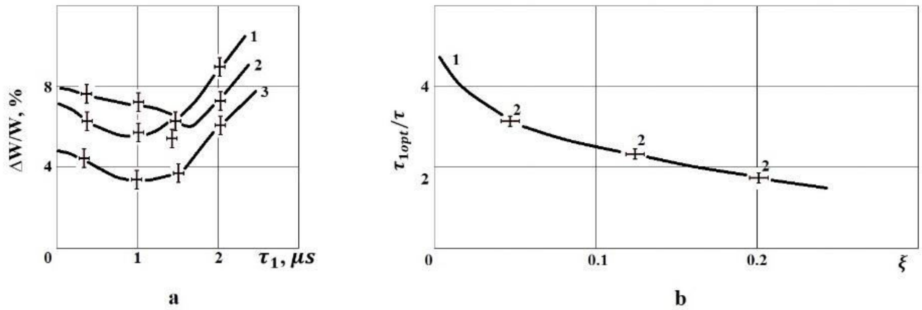

Figure-**3.** Spectrum width as a function of delay time τ_1 (a) and optimum delay as a function of parameter ξ (b).

Spectrum width as a typical function of delay time is illustrated in Figure-3a. Here, the injection pulse is 3μs, $\xi = 0.1$ (curve 1) and 0.05 (curve 2); the injection pulse is 1.5μs, $\xi = 0.1$ (curve 3). Figure-3b illustrates τ_{1opt} as a function of parameter ξ, where 1 is the analytical dependence, 2 - is the experimental points obtained by measurements. Here $\tau_1 = \pm 0.1$μs, which equals to step of delay adjustment in the used instrumentation. The error $\Delta\xi/\xi = \pm 0.2$ was calculated at typical for HF values:

$$\Delta\tau_p/\tau_p = \pm 0.1,\ \Delta\chi/\chi = \pm 0.1, \Delta P_g/P_g = \pm 0.1,\ \Delta(T^2 Z_{sh} l)/T^2 Z_{sh} l = \pm 0.1, \Delta I_0/I_0 = \pm 0.05.$$

CONCLUSIONS

Therefore, the following conclusions can be made. Scattering of medium energies in resonator electron accelerators caused by transient processes in sections is completely eliminated by delay of injection and shortening of current pulse. Implementation of these measures makes it possible to raise the spectrum width of two-section accelerator to 2–3%. Further narrowing is restricted to existence of energy scattering in bundle due to longitudinal dynamics, as well as due to intrapulse instability of HF powering parameters.

The performed analysis on the basis of equivalent circuits [12] does not consider in full extent for phenomenon in accelerator related with beam dynamics, for instance, no capture of particles during initial stage of transient process is considered [13]. Nevertheless, the applied method provides quite satisfactory equations for engineering computations of optimum delay time. Eq. (6) in the range of achievable measurement accuracy agrees well with the experimental results.

The obtained results demonstrate that the use of injection delay in commercial standing wave electron accelerators makes it possible to decrease significantly the energy spectrum width of accelerated particles, raising it to 2%, thus, improving significantly their operation performances. Herewith, engineering implementation of the delay is not difficult and does not result in significant complication of facility.

We propose to perform further investigations into design of coupling cells and HD energy input unit of standing wave linac and HF focusing [14], which would enable adjustment of accelerated current with retention of optimum mode of electron acceleration and adjustment of beam output energy at fixed value of accelerated current taking into account the forces of space charge [15, 16].

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Conflicts of interest: none.
Authors have no any competing interests to declare.

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