CHARACTERISTICS OF THE MODEL OF LINEAR ACCELERATOR BASED ON PARALLEL COUPLED ACCELERATING STRUCTURE WITH BEAM LOADING

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Abstract

The 5-cavity model of linear accelerator based on parallel coupled accelerating structure (LAPCAS) with periodic permanent magnet focusing system (PPMFS) and RF-controlled three-electrode electron gun is under study. The work of the accelerator with electron beam is demonstrated. Parameters of short pulses mode are the following: electron energy – 4 MeV, pulse current – 0.3A, pulse duration - 2.5 ns; parameters of long pulses mode are the following: energy – 2.5 MeV, pulse current – 0.1A, pulse duration – (0.1 - 4) μs. Working frequency of the accelerator – 2.45 GHz. In RF-controlled mode the capture about 100 % has been demonstrated. Beam loading effect in the LAPCAS takes place. Data of observation of this effect and compensation of energy spread of accelerated electrons by delaying the moment of injection in the LAPCAS are demonstrated. The equations describing the transient process in the accelerating cavity which is powered by an external RF generator and excited by electron bunches are presented in a simplified form.

INTRODUCTION

Parallel coupled accelerating structure (PCAS) is a new type of the structures and consists of separate accelerating cavities feeding from common exiting cavity in parallel [1]. The structure is equipped with an inside installed reverse periodic permanent magnet focusing system (PPMFS). The possibility to use the PCAS in the accelerator technique demands experimental studies. Accelerating cavities of PCAS work in standing wave regime and beam loading effect – dependence of average energy of accelerated electrons on time during the pulse takes place in this structure. The methods of compensation the energy spread of accelerated electrons in the standing wave and traveling wave structures have been discussed for a long time [2-5]. Now in some installations the issue came into practical implementation [1,6,7]. One of the methods to reduce this negative effect – injection the electron pulse with delay relatively to pulse of feeding RF power, so called ∇T-method. In this paper the equations describing the transient process in the accelerating cavity which is powered by an external RF generator and at the same time excited by electron bunches in a simplified form are obtained and data of experimental observation of the beam loading characteristics, beam loading effect and compensation of energy spread in the LAPCAS by ∇T-method are represented. For experimental observation of the beam loading effect we used energy spread measurements by method of absorption in retarding metallic plates [8].

THEORY

Beam loading is defined as the energy reduction of charged particles due to their interaction with an accelerating structure [2]. Charged bunches, when passing through the structure, generate RF oscillations that decelerate the subsequent bunches. As a result average energy of accelerated beam depends on time during the pulse. To evaluate the energy spread due to the transients, it is necessary to take into account that acceleration voltage on the accelerating cavity is excited by two independent sources: the external RF generator and modulated electron beam. In the theoretical description we assume that the electron beam consists of a train of short bunches, RF pulse is an ideal step-function and that all charged particles travel with the speed of light, the difference between the frequencies of generator, cavities and moving bunches is zero.

Evaluation of complex magnitude of equivalent acceleration voltage U in the standing wave accelerating cavity, which is powered by an external RF generator and at the same time excited by electron bunches can be described, as may be shown from [5], by the following equations:

$$\tau \frac{dU}{dt} + U = U_G - U_{B0} ,$$

$$\tau = \frac{2Q_0}{\omega_0 (1+k)}, U_G = U_{G0} \exp(i\theta),$$

$$U_{G0} = \frac{2(kZLP_G)^{1/2}}{(1+k)}, \quad U_{B0} = \frac{IZL}{(1+k)} \qquad (1)$$

where τ is the filling time constant of these evaluations; U_G is complex amplitude of equivalent acceleration voltage on the cavity, excited by the generator; U_{G0} and U_{B0} are steady-state values of amplitudes of equivalent acceleration voltage on the cavity, excited by the generator (U_{G0}) and beam (U_{B0}) correspondently, real positive quantities; ω_0 is cavities eigenfrequency; k is the coupling coefficient between the cavity and feeder line; Q_0 is the cavities unloaded Q - factor; Z is effective shunt impedance per unit length; L is the length of the accelerating cavity; P_G is the RF power which excites the cavity; $\theta - \pi$ is the phase of generator-induced oscillations relatively to beam-induced

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oscillations. The load due to the current is taken into account by the term $U_{B0} = \dfrac{IZL}{(1+k)}$, where I is average current. The definitions of U, τ, k, Q, Z are taken from [3,4].

Then real part of U determines the energy gain U_A of the beam, is expressed in term of angle θ:

$$U_A = (U_{G0}\cos\theta - U_{B0})[1-\exp(-t/\tau)] \qquad (2)$$

In accordance with relation (2) average energy of accelerated charged particles depends on time.

Situation changes if the beam injects with delay t_B relatively to the start of RF pulse.

Total acceleration voltage after moment t_B is:

$$U_A = U_{A,G} - U_{A,B} = (U_{G0}\cos\theta - U_{BO}) + [U_{G0}\cos\theta\exp(-t_B/\tau) - U_{BO}]\times \exp(-(t-t_B)/\tau)), \qquad t \geq t_B \qquad (3)$$

Dependence on time disappears if:

$$U_{G0}\cos\theta\exp(-t_B/\tau) - U_{BO} = 0. \qquad (4)$$

This equation determines the moment t_{B0} of beam injection:

$$t_{B0} = \tau \ln \frac{2(kZLP_G)^{1/2}\cos\theta}{IZL} \qquad (5)$$

For $\theta = 0$ the same expression is obtained in [4].

If the beam injects with delay time $t_B > t_{B0}$, in accordance with equation (3) real part of equivalent voltage U_A decreases with time and correspondently average energy of the beam decreases. If $t_B < t_{B0}$, then real part of equivalent voltage U_A increases and average energy of the beam increases with time.

EXPERIMENTALS

Experimental observations of the beam loading characteristics were done on the electron accelerator, which consists of 5-cavities model of PCAS and pulsed three-electrode RF controlled DC high voltage electron gun [1]. The RF-controlled gun forms RF-modulated electron beam, which consists of a train of grouping charged bunches on the frequency 2450 MHz with duration of every bunch about 0.2 ns and with variable parameters: energy 0 - 50 keV, value of pulse current 0-0.5 A, pulse duration 0.1-5 µs. Delay time of the moment t_B of beam injection may be changed from 0 up to 5 µs. Accelerating structure feeds on the klystron KIU-111 [9]. In the experiments RF pulse duration of the klystron was 5 µs, pulsed RF power varied up to 2 MW.

Beam loading effect and application of ∇T-method for compensation of this negative phenomenon are successfully investigated on the LAPCAS. The

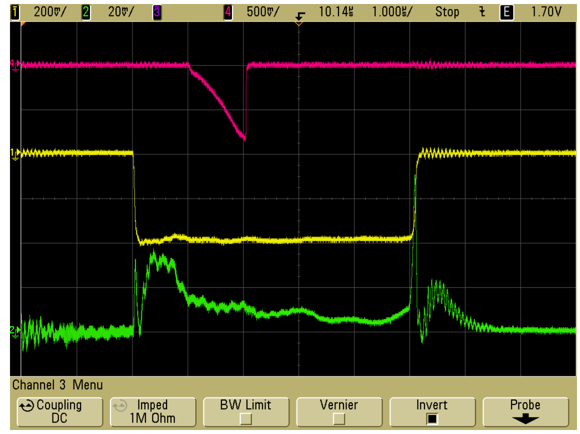

Figure 1: Delay time of electron pulse (red) is 1 µs.

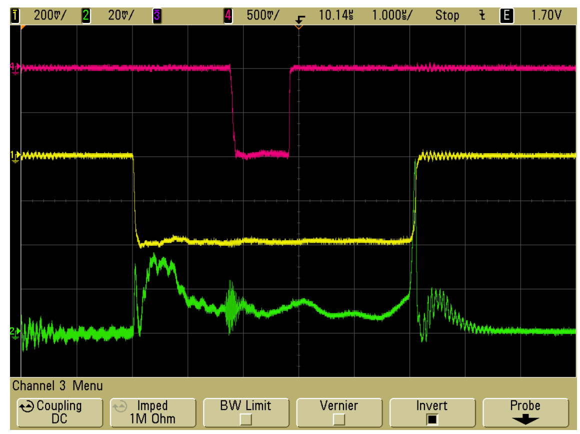

Figure 2: Delay time of electron pulse is 1.8 µs.

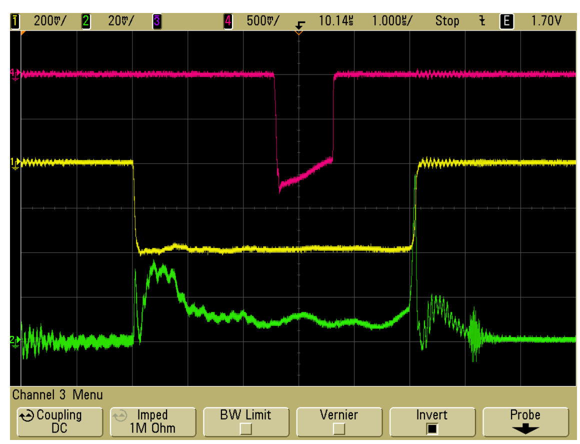

Figure 3: Delay time of electron pulse is 2.6 µs.

experimental observations of beam loading effect are performed by the following way. Pulsed electron beam of rectangular form with pulse duration of 1 µs (test pulse) with constant magnitude of injection current (0.1A) and variable delay time was injected into the accelerating structure. A Faraday cap with metal plates in front of them was installed at the exit of the accelerator. Electrons with high energy overcome the metal plates, and those

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with low energy get stuck in it. Part of accelerated beam overcoming the metal plate of any thickness and electrons passed through the plate fall into the Faraday cap and pulsed current is recorded by oscilloscope. On the total thickness of retarding plates 70-80 % of accelerated electron beam is absorbed.

As one can see from the equation (3), output beam energy and consequently the magnitude of a current recorded by oscilloscope will increase during a test pulse, if $U_{G0}\cos\theta\exp(-t_B/\tau)-U_{BO}>0$.

The magnitude of a current recorded by oscilloscope will decrease during a test pulse,

if $U_{G0}\cos\theta\exp(-t_B/\tau)-U_{BO}<0$.

The magnitude of a current recorded by oscilloscope will remain a constant during a test pulse, if

$U_{G0}\cos\theta\exp(-t_B/\tau)-U_{BO}=0$.

In other words, the dependence of beam energy on time becomes the dependence on time of magnitude of a current from Faraday cap recorded by oscilloscope. Thereby, for experimental observation of beam loading effect we used energy spread measurements by method of absorption in retarding metallic plates [8] in pulse regime.

Pulse-energy characteristics of the accelerated beam are represented on Fig. 1-3. Curves registered by oscilloscope: 1- RF pulse of klystron (yellow); 2- reflected signal from accelerating structure (green); 4 - pulse form of accelerated beam (red). Electron pulses from injector were of rectangular form. Delay time of beam injection t_B relatively to RF pulse changed from approximately 1µs (Fig. 1) up to 2.6 µs (Fig. 3). Figure 2 represents a point on the time scale, t_{B0}=1.8 µs, where the conditions (4), (5) take place, therefore, the recorded current pulse has a rectangular shape. In this case it means that average energy of accelerated electrons does not depend on time.

CONCLUSION

The work of LAPCAS with electron beam in different regimes is demonstrated. Short pulses mode: electron energy – 4 MeV, pulse current – 0.3A, pulse duration -2.5 ns; long pulses mode: electron energy – 2.5 MeV, pulse current – 0.1A, pulse duration - 0.1-4µs. When the electron gun worked in RF-control regime the capture about 100 % was achieved. Beam loading effect in LAPCAS takes place. Method of compensation of energy spread of accelerated electrons by delaying the moment of injection in the LAPCAS gives encouraging results. The equations in the simplified form describing transients allow interpreting the experimental pulse dependences obtained by a method of retarding metallic plates in pulse regime.

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