SELF-OSCILLATORY MODE OF ACCELERATION IN ELECTRON LINAC WITH FEEDBACK

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Abstract

The self-oscillatory mode of acceleration is studied both theoretically and experimentally with a versatile injector complex installed on a 300 MeV electron linac. It is shown that using feedback in linacs it is possible to produce modulated relativistic beams.

The theory of self-excited oscillations based on the mathematical principles formulated by A. Adronov has been developed extensively in recent years. It is interesting to analyze the behavior of both relatively simple systems with phase space dimensions $n > 2$ and essentially nonlinear systems with many degrees of freedom. The development of this theory is greatly encouraged by the experiments showing evidence for the existence of the phenomena predicted in various fields of science and technology.

Extensive studies of self-excited oscillations led to the complex oscillatory processes being discovered in the systems traditionally regarded as simple from a dynamic standpoint – electron linacs, for example. Owing to the implementation of novel RF systems with feedback[1,2] it was found that the acceleration of intense beams was accompanied by self-excited oscillations.

Theoretical and experimental investigations carried out with a versatile injector complex (VIC) installed on a 300 MeV electron linac of the Kharkov Institute of Physics and Technology indicate that the use of feedback in accelerating long-pulse intense beams with electron linacs offers expanding possibilities. In the first place, it is possible to accelerate beams with currents in excess of the limiting current in an accelerating section without feedback.[3] This is achieved by changing over from the resonance to the antiresonance conditions when the amplitude of the beam-induced field exceeds that of the generator field at the end of the section, and by choosing a proper value of the coupling factor (μ) of the variable input directional coupler. Moreover, the feedback in the injector section permits the self-oscillatory mode of acceleration to be realized, with the beam parameters being modulated. These conditions, however, are not favorable for solving traditional problems in nuclear physics therefore one has to examine the above phenomena so as to find the ways of suppressing them as was in the case of beam blowup. On the other hand, multi-frequency modulated beams can be used in various fields of physics, in particular, to study collective effects in matter.

This paper is devoted to the theoretical and experimental studies of the self-oscillatory mode of acceleration carried out with the VIC.

Experimental Procedure

The feasibility of the self-oscillatory mode of acceleration was studied with the VIC bunching section. RF input power $P = 6$ MW was delivered to the directional coupler to the bunching section. The output RF signal from the section was sent via the directional coupler to the detector and subsequently to the oscilloscope. The electron source provided the current of ~ 2 or 3 A. On reaching the prebuncher the electron beam was density-modulated, increasing in energy, and then was accelerated in the bunching section. Figure 1 shows the RF pulse envelopes recorded without the beam (upper one) and with the beam (lower one) under resonance conditions for the optimum coupling factor ($\mu \simeq 0.42$; horizontal scale division for all the records shown $\Delta t = 0.5$ μs). As can be seen, due to beam loading, the output signal decayed in amplitude considerably. This can be explained by two factors: firstly, by the energy transfer to the beam, and secondly, by the modified dynamics of the RF field build-up in the circuit since in the presence of the beam the out-of-phase composition of the generator and the section output fields occurs in the variable input directional coupler. The circuit phase changing (Fig. 2: upper oscillogram obtained with the beam present, lower one without the beam) resulted in the field amplitude decreasing without the beam and increasing with the beam, which was accompanied by the self-excited oscillations. As the beam current decreased, the oscillation amplitude decreased too and at a certain threshold value self-oscillations were no longer excited. Similar phenomena were observed as the optimum μ value was exceeded. The self-excited oscillation frequency corresponded to the time $T_o = T + L/v_g$.

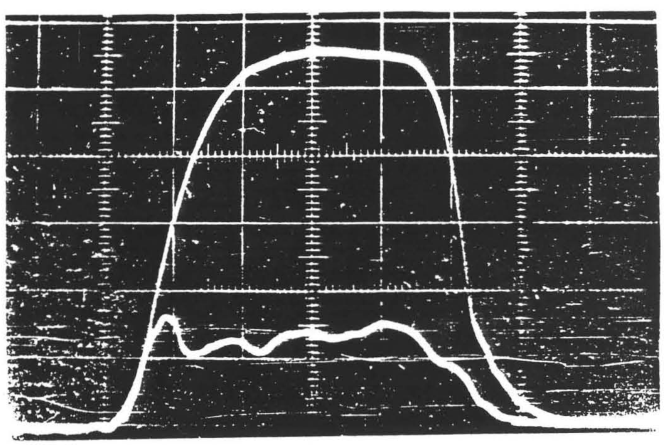

Fig. 1

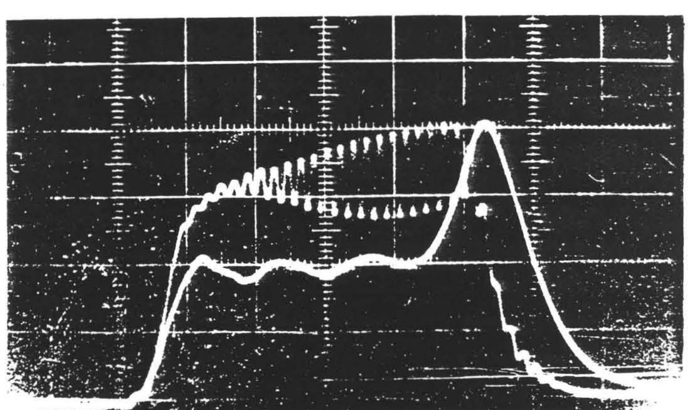

Fig. 2

Under the optimum conditions one can obtain self-excited oscillations of higher amplitude (Fig. 3). Three VIC sections were operated without feedback ($\mu = 1$), each being supplied with RF power of 6 MW. The recorded output current pulse is shown in Fig. 4. It is evident that under steady-state oscillations the current pulse is completely time-modulated.

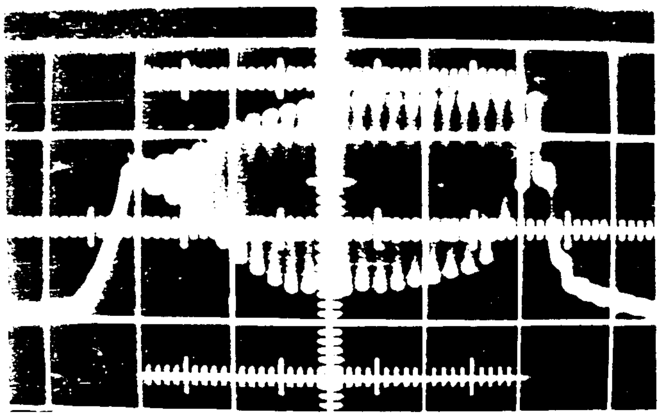

Fig. 3

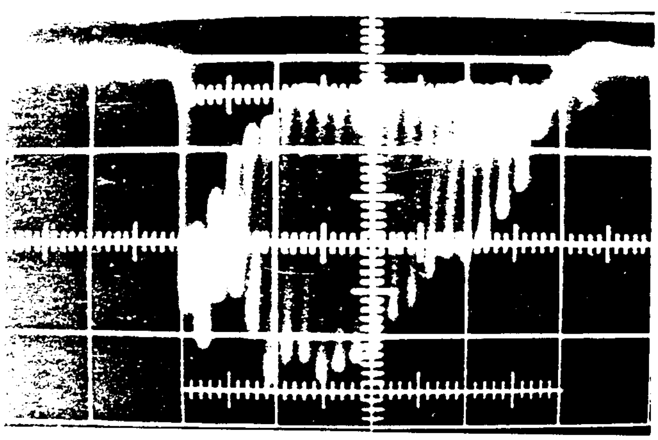

Fig. 4

Computer Simulation of Self-Excited Oscillations

The field generated in the bunching section by the beam and external source can be determined using a general theory of waveguide excitation. Assuming the time of the RF field variation in amplitude and phase to be considerably larger than the period of the RF oscillations, one can obtain the following set of integro-differential equations to describe the nonsteady dynamics of the electron beam

$$\frac{\partial V}{\partial \xi} + \alpha V + q\frac{\partial V}{\partial \tau} = I\sigma_T \frac{\int_{\tau-\pi}^{\tau+\pi} d\tau_o f(\tau_o) e^{i\Delta(\tau_o,\xi)}}{\int_o^{2\pi} d\tau_o f(\tau_o)} , \qquad (1.a)$$

$$\frac{d\Delta}{d\xi} = p\left[\frac{\gamma}{\sqrt{\gamma^2-1}} - \frac{1}{\beta_p}\right] , \qquad (1.b)$$

$$\frac{d\gamma}{d\xi} = -\sigma Re\left[V(\tau_o,\xi)e^{-i\Delta}\right] , \qquad (1.c)$$

where V is the accelerating field complex amplitude normalized to a certain value of E_o ($E = VE_o \exp(ikz - i\omega t)$); $\alpha \equiv \alpha_o L$, α_o is the damping factor in the section; L is the section length; $\xi \equiv z/L$, $\tau \equiv \omega t$, $\tau_o \equiv \omega t_o$, ω is the external source frequency; t_o is the time of particle entrance to the section; $q \equiv \omega L/v_g$, v_g and v_p are the group and the phase wave velocities, respectively, at $\omega(\beta_p \equiv v_p/c)$; $f(\tau_o)$ is the beam distribution function; $I \equiv \frac{|e|n_o v_o R e^2}{2\pi I_o} \cdot \int_o^{2\pi} f(\tau_o)d\tau_o$ is the normalized to I_o beam current averaged over the RF structure of the beam; $\sigma_T \equiv I_o R_s L/2E_o$, R_s is the series resistance; $\Delta \equiv \omega t_e - kz$, $t_e(t_o, z)$ is the electron arrival time at the point z, $t_e(t_o, 0) = t_o$, k is the wave vector at ω; $\gamma \equiv (1 - v^2/c^2)^{-1/2}$, $\sigma \equiv |e|LE_o/mc^2$, $p \equiv \omega L/c$.

Set of Eqs. (1) is obtained on the assumption that within the time of flight of an individual particle the field in the accelerating section is practically unchanged.[4]

As the beam was allowed to drift from the prebuncher cavity directly into the bunching section, we could assume the initial beam distribution function $f(\tau_o)$ to be the form

$$f(\tau_o) \equiv \sum_{i=1}^{N} \delta(\tau_o - 2\pi i) \qquad (2)$$

i.e. the beam represents a series of point bunches. All the bunches have similar energy $W = mc^2(\gamma_o - 1)$.

The feedback circuit with the variable input directional coupler can be characterized as follows

$$V(0,\tau) = \mu\sqrt{H}\ V_o + \sqrt{1-\mu^2}\ He^{i\Delta\phi}V(1, \tau - T) , \qquad (3)$$

where μ is the coupling factor, $H \equiv e^{-\alpha_2 \ell}$, α_2 and ℓ are the damping coefficient and the feedback circuit length, respectively; V_o is the complex field amplitude created by the external source at $\mu = 1$, $\Delta\phi$ is the circuit phase shift, and T is the delay time.

Figures 5 and 6 show the calculated beam dynamics in the bunching sections for $\gamma_o = 1.6$ and $I = 1$ A. Theory is in good agreement with experimental data.

In conclusion, our study of the accelerator operation in the self-oscillatory mode indicates that using feedback in the linear accelerators it is possible to obtain modulated relativistic beams.

References

1. G. D. Kramskoj, V. B. Mufel', Zh. Tekhn. Fiz. 52, 465 (1982).
2. G. D. Kramskoj, L. A. Makhnenko, Zh. Tekhn. Fiz. 52, 1117 (1982).
3. N. I. Ajzatskij, S. N. Dyukov, L. A. Makhnenko, VANT, Ser. Experimental Techniques, N 3(15), Kharkov, 1985, p. 45.
4. N. S. Ginzburg, S. P. Kuznetsov, Relativistic RF electronics (in Russian), Gorky, 1981, p. 101.

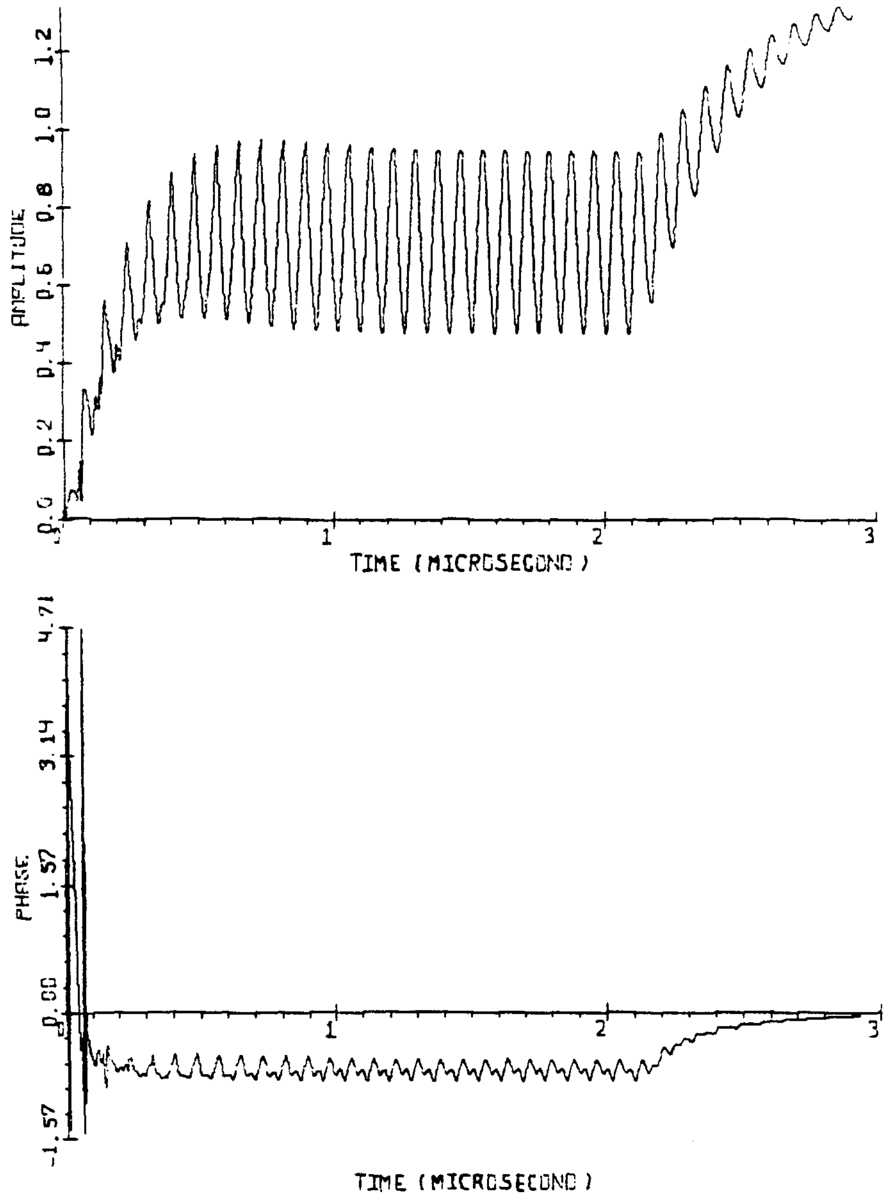
AMPLITUDE
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1
2
3
TIME (MICROSECOND)
PHASE
-1.57
0.00
1.57
3.14
4.71
1
2
3
TIME (MICROSECOND)

Fig. 5

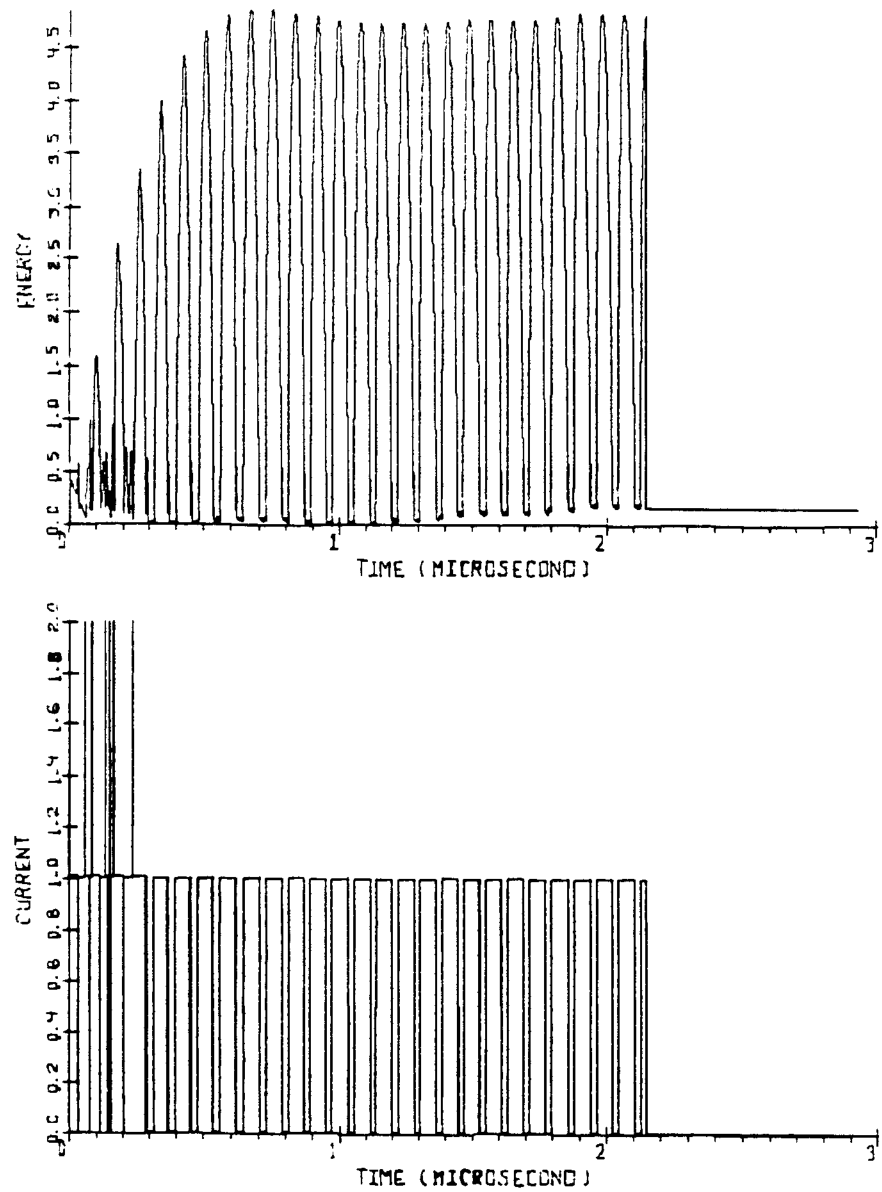
ENERGY
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
1 2 3
TIME (MICROSECOND)
CURRENT
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
1 2 3
TIME (MICROSECOND)

Fig. 6