BEAM LOADING EFFECTS IN LINACS WITH RESONANT LOADED RF-POWER UPGRADE SYSTEM.

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Abstract

The RF power upgrade systems with microwave energy compression are using for accelerating wave power increase [1-3]. The energy compression systems (ECS) with a resonant loading present the certain interest for practical use because of their specific properties [4]. They are capable to increase an accelerating wave power up to 50...100 times (up to 20 dB) and keeps this wave in accelerating structure for a longer time then conventional ECS. The resonant load is an essential part of the system and renders influence significantly on its parameters. The system consists of two connected resonators, one of which is using as a storing element and the second — as a load. Load may be a standing or a traveling wave resonator (TWR) formed by accelerating structure. Beam loading effects would change the properties of RF field in the load resonator. ECS characteristics and the accelerated beam parameters are discussed.

Introduction

The main principle of the system with resonant loading operation is based on using connected resonators [4]. Wave emitted from storing cavities (SC) pass through TWR (see Fig. 1) and becomes incident wave for SC. The resultant wave amplitude at the accelerator structure is equal sum amplitudes of those waves. This process continues while all energy primarily stored in SC passes by terns to TWR. So it causes significant field increase at accelerating structure.

Schematic drawing of the ECS with resonant load is submitted on Fig.1. Accelerating structure input and output connect through switched coupler and SC and form the TWR. The switched coupler transfers the system operation mode from storing energy to its use. During the energy storing period (state A) the coupler connects generator output to storing cavities and the acceleration structure output — to an absorbing load. To use the stored energy (state B) the coupler is switched in such way that the acceleration structure output becomes connected to storing cavities, forming TWR.

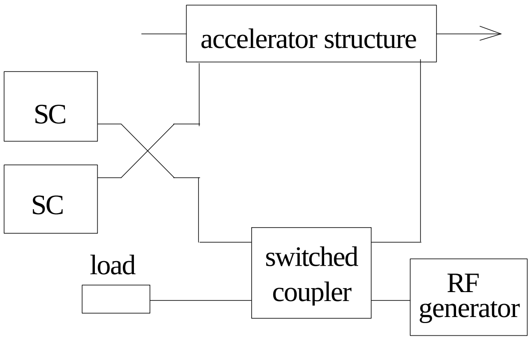

Fig. 1. Microwave energy compression system with a resonant load.

At state A (see Fig. 2) energy storage occurs in SC. The wave, reflected from storing resonators, passes through a TWR and arrives in a load. When the energy storing process ends the coupler transformed in state B. The wave coming to SC is a wave leaving from accelerating structure. A wave phase shift in a TWR is chosen so that the wave coming on SC has the same phase as the wave emitted from it. Amplitude of a wave circulating in TWR ring will grow so long as all accumulated in SC energy will not pass completely in TWR. After this the return swapping of energy from TWR to SC will begin. The qualitative graph of the circulating in TWR wave average amplitude variations is shown on Fig. 2.

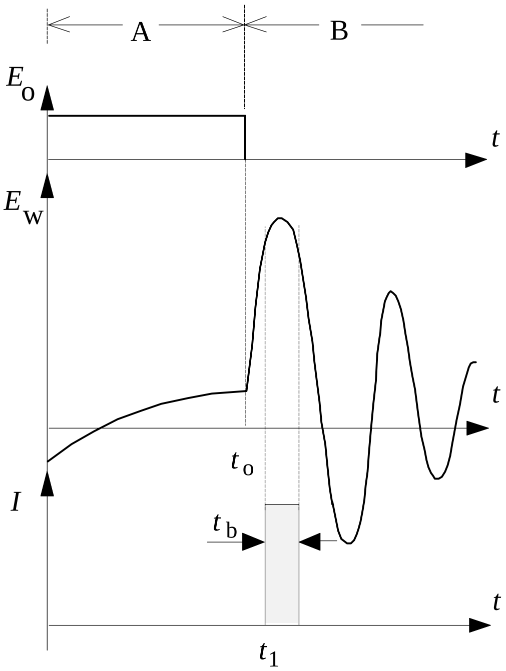

Fig. 2. The RF wave average amplitude variations in a system with a resonant load (E_O - generator wave amplitude; E_W - wave in TWR ring; I - beam current).

Theory

Traveling wave resonator is forming at the end of storage period (at moment t_0) by the switched coupler. RF generator is connected with an absorbing load and accelerating section output — with storing cavities. The wave, emitted from the SR, is added to a wave circling in the TWR. In this case the amplitude of a summarized wave at the acceleration structure entrance during the energy use period is described by a following expression [4]:

$$E_w(t) = \begin{cases} (-\frac{2\beta}{1-\beta}(1-e^{-t/\tau})+1)E_0\ , & \text{for } 0 \le \mathrm{t} < \mathrm{t}_0 \\ \sum\limits_{n=0}^{N} E_{wn}(t)\ , & \text{for } \mathrm{t} \ge \mathrm{t}_0 \end{cases} \qquad (1)$$

where:

$$E_{wn}(t) = -\frac{2\beta}{1+\beta}E_0(1-e^{-\frac{t_0}{\tau}})e^{-n\alpha}e^{-\frac{t-t_0-T}{\tau}}F(-n,1,\mathrm{A})$$

$$F(-n,1,A) \ = \sum_{k=0}^{n}\frac{C_n^k}{k!}(-1)^n A^n \ ;\ A = \frac{2\beta}{1+\beta}\cdot\frac{t-t_0-nT}{\tau}$$

$N = [(t\text{-}t_0)/T]$ - number of wave revolutions in TWR, T - time duration of one turn-over of a wave in a TWR.

For function $F(-n, 1, A)$ evaluation one can use formula:

$$F(-(n+1),1,x) = \frac{2n+1-x}{n+1}F(-n,1,x) - \frac{n}{n+1}F(-(n-1),1,x)$$

where $F(0, 1, A) = 1$ and $F(-1, 1, A) = 1\text{-}A$.

The expression (1) describes microwave amplitude at accelerating section without current loading. Coupling factor β depends on the storing energy duration period t_0.

In case, when the current loading appears essential, it is necessary to take into account changes of wave amplitude falling on cavities. Using principle of independence of fields, it is possible to consider that two waves exist: one wave is connected with RF energy in SC, second — will be formed by electron beam. The expression for field amplitude of the beam radiation wave at any point of accelerating section with coordinate z, has a kind:

$$E_b(t) = \begin{cases} -IR(1-e^{-\alpha z}) + \sum\limits_{n=0}^{N} E_{bn}(t-t_1-\frac{z}{v})e^{-\alpha z}\ , & \\ & \text{for } \ t > t_1 + T \\ -IR(1-e^{-\alpha v t}), & \text{for } t - t_1 \le T \end{cases} \qquad (2)$$

Where designations are used:

$$E_{bn}(t) = \frac{2\beta}{1+\beta}E_1 e^{-(n-1)\alpha l}e^{-\frac{t-nT}{\tau}}\sum_{i=0}^{n-1}(1-\frac{2\beta}{1+\beta})^i \times$$

$$\times F(-(n-1-i),1,\frac{2\beta}{1+\beta}\frac{1-nT}{\tau}) + (1-\frac{2\beta}{1+\beta})^n E_1 e^{-(n-1)\alpha l}$$

$E_1 = -IR(1-e^{-\alpha l})$, I - beam current, R - shunt impedance of accelerating section, ν - group velocity of accelerated wave, t_1 - beam injection moment, l - accelerator structure length.

The resulting amplitude of a high-frequency wave at accelerating section input is determined by addition of two waves E_w (t) and E_b (t):

$$E(t) = E_w(t) + E_b(t) \qquad (3)$$

Analytical expression of beam energy is enough difficult problem. For this reason the determination of beam energy of linear accelerator was carried out in numerical kind by using formula:

$$W_b(t) = \int_0^l (E_w(t-t_0-\frac{z}{v}) + E_b(t-t_1-\frac{z}{v}))e^{-\alpha z}dz \qquad (4)$$

ESC with resonant loading give increased amplitude RF wave on extent several turn-overs of a wave on TWR. So it can receive much longer pulses of an accelerated beam in comparison with other type compression systems. For example, we have obtained RF pulses with 15...17 dB multiplication factor and about 0.5 μs pulse duration for accelerating section filling time about 24...40 ns [4]. The electric field is considerably changed in time at accelerating section at one turn-over period. However, it does not result in increase of beam energy spectrum. It is possible to assume, that stored in traveling wave resonator energy is almost in accelerating section. So the beam energy is close to constant during one turn-over period.

Calculation results

Calculation was made for following parameters of ESC and accelerating section: power of the generator output P_0 = 10 MW, Q-factor Q_0= $90 \cdot 10^3$, shunt impedance of accelerating section R = 40 MOm/m, t_0 = 2.5 μs, power decrease per unit of acceleration section α = 0.04 and 0.08 m^{-1}, accelerator section feeling time T = 40 and 60 ns.

To achieve maximum beam energy it is need choice coupling factor β for an energy storage period t_0. Dependencies of maximum value $\mathrm{E_w/E_0}$ and optimum coupling factor β are shown on Fig. 3.

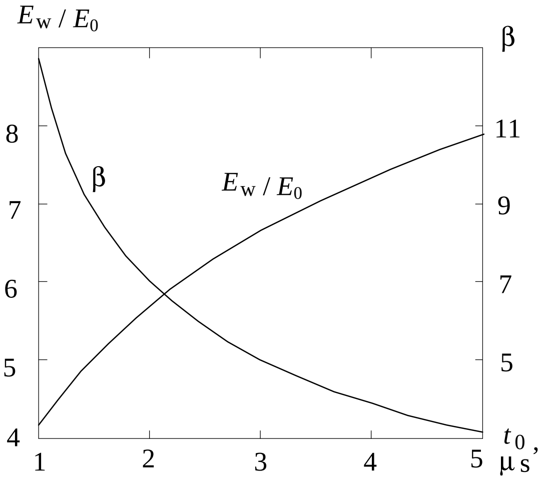

Fig. 3. Dependence of maximum averaged wave amplitude at an accelerating structure entrance E_w / E_0 and coupling factor β on an energy storage period t_0 (T=40 ns).

The accelerator beam energy W_b (normalized to W_0 - accelerator energy without any ECS) depend upon time t as shown at Fig. 4. Width electron energy spectrum remains practically constant ($\Delta W_1 \approx \Delta W_2$) for current values from 0 up to 1.5...2 A. At given current pulse of beam duration t_b the influence of a beam loading has an effect on average energy of particles. The maximum beam energy with minimum spectrum width can be achieved by appropriate choice of an injection moment t_1. Spectrum width less then 3...5% can be obtained for current pulse about $t_b \leq 2.3T$ for pulse current values up to 2 A.

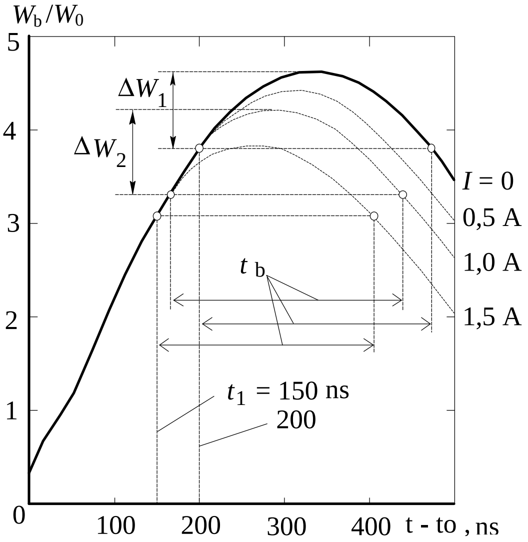

Fig. 4. Dependence of beam energy W/W_0 at output accelerating structure from time $t - t_0$ (T=60 ns).

The typical beam energy dependence from accelerating structure length l at output TWR accelerating section is shown in Fig. 5.

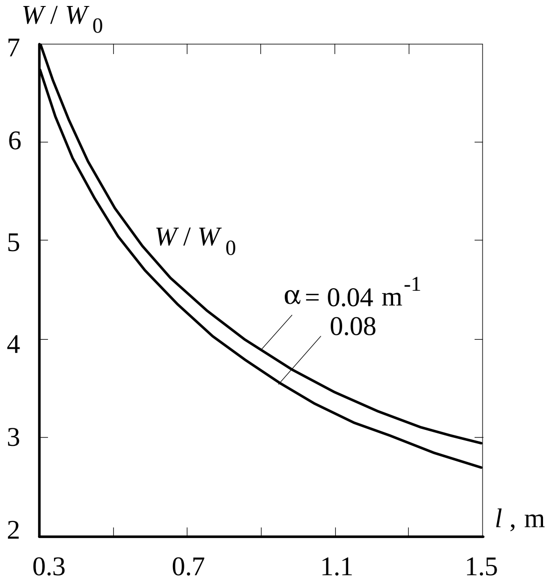

Fig. 5. Dependence of maximum accelerator energy from accelerating structure length l (T=40 ns).

The normalized energy W/W_0 of accelerated beam grows with reduction of length accelerating section (filling time of accelerating section is proportional to its length). Absolute value of beam energy appears higher for longer sections. Therefore to achieve higher energy long accelerating of section should be apply.

References

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