POSSIBILITY OF STABILIZING THE BEAM ENERGY IN RESONANT ACCELERATOR ON THE LEADING EDGE OF THE MICROWAVE PULSE

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Abstract

The effect of transients in the accelerating cavity by successive switching of generator and beam is discussed. The possibility of stabilizing energy increase in the process of transition oscillation in the cavity is demonstrated. With allowance made for the beam current the delay of injection can be chosen in such a way that the amplitude and phase of oscillation in the cavity change so that the two factors compensate for each other. It allows to eliminate the energy spread caused by the transients.

Transients in standing-wave acceleration structures (resonators) are one of the causes for the particle energy spread to occur in accelerators exited by pulsed microwave field. The energy spread on the trailing edge of the microwave pulse can easily be eliminated by interrupting the beam injection. This work considers possibility of stabilising the beam energy on the leading edge of the microwave pulse, which does not require to interrupt transients in the resonator.

To evaluate the energy spread due to the transients, it is necessary to take the fact that the accelerating resonator is exited by two sources: the external generator and beam. Transients in the resonator can be described in terms of the method of counter-propagating waves [1] developed in [2-4]. Further, we use this method to analyze the resonator with the beam operated in various modes.

The method of counter propagating waves yields the following equations for the normalized complex amplitude of oscillations v in the resonator:

$$\frac{dv}{dt} + [\frac{\omega_0(1+k)}{2Q_0} + i\Delta\omega]v = \sqrt{\frac{\omega_0 k}{Q_0}}\, a - \alpha I_0, \qquad (1)$$

where ω_0 is resonator's eigenfrequency, k is the coupling coefficient between the resonator and the feeder line, $\Delta\omega$ is the difference between the generator's and resonator frequencies, Q_0 is the resonator unloaded Q factor, and a is the normalized amplitude of the wave in the feeder line.

The load due to the current is taken into account by the term αI_0, where I_0 is the complex amplitude of the fundamental harmonic of current and α is the positive real number, which characterizes the effect of current on oscillations in the resonator. The equation implies that the particles are bunched and the bunches follow at a rate equal to the generator's frequency.

In the beam grouped into short bunches, all particles acquire the same energy proportional to the accelerating voltage.

$$u(t) = \sqrt{\frac{\omega_0 Z_e L}{2Q_0}} Re\{v(t)\}, \qquad (2)$$

where Z_e is effective shunting impidance, and L is the resonator length.

For a beam grouped into short bunches, I_0 is twice as high as the average beam current I. Representing a in terms of power P and phase φ of the generator ($a = \sqrt{2P}\exp(i\varphi)$), Eq. 1 can be written as

$$\frac{dv}{dt} + \left(\frac{\omega_0(1+k)}{2Q_0} + i\Delta\omega\right)v = \sqrt{\frac{2\omega_0 P}{Q_0}}\left(\sqrt{k}\exp(i\varphi) - \beta\right), \qquad (3)$$

where $\beta = [Z_e L I^2/(4P)]^{1/2}$ is the current-load factor (beam current-to-critical current ratio at $k = 1$).

The general solution to Eq. (3) has the form

$$v(t) = v_p + v_d \exp\left[-(1/\tau + i\Delta\omega)t\right], \qquad (4)$$

where v_p is the normalized amplitude of the steady-state oscillations, v_d is the initial normalized amplitude of the damped eigen oscillations, and $\tau = 2Q_0/[\omega_0(1+k)]$ is the time constant of these oscillations.

Each of the amplitudes v_p and v_d is a sum of two terms, which refer to oscillations exited by the generator and beam.

When $\Delta\omega = 0$, the normalized amplitude of steady-state oscillations exited, respectively, by the generator and beam are

$$v_g = \frac{2}{1+k}\sqrt{\frac{2Q_0 kP}{\omega_0}}\exp(i\varphi), \qquad v_b = -\frac{2\beta}{1+k}\sqrt{\frac{2Q_0 P}{\omega_0}}. \qquad (5)$$

By representing the sum of amplitudes in the exponential form, the normalized amplitude of steady-state oscillations can be written as

$$v_0 = \frac{2}{1+k}\sqrt{\frac{2Q_0 P}{\omega_0}}\left(\sqrt{k - \beta^2\sin^2\psi_0} - \beta\cos\psi_0\right)\exp(i\psi_0), \qquad (6)$$

where ψ_0 is determined from the equality

$$\cos\psi_0 = \frac{\sqrt{k}\cos\varphi - \beta}{(k + \beta^2 - 2\beta\sqrt{k}\cos\varphi)^{1/2}}. \qquad (7)$$

According to the expression (2), normalized amplitude of the oscillations corresponds to the accelerating voltage

$$u_0 = \frac{2\sqrt{Z_e LP}}{1+k}(\sqrt{k - \beta^2\sin^2\psi_0} - \beta\cos\psi_0)\cos\psi_0. \qquad (8)$$

At a given ψ_0, accelerating voltage (8) attains its maximum when the resonator's coupling factor takes the optimum value

$$k_{opt} = (1 + 2\beta^2) + 2\beta\sqrt{1+\beta^2}\cos\psi_0. \qquad (9)$$

Then the accelerating voltage is

$$u_m = \frac{\sqrt{Z_e LP}\cos\psi_0}{\sqrt{1+\beta^2} + \beta\cos\psi_0}. \qquad (10)$$

To evaluate the energy spread caused by transients on the leading edge of the microwave pulse, it is necessary to calculate v_d, which depends on the initial conditions.

If the generator and beam are enabled simultaneously at the moment $t = 0$ $v(0) = 0$. Then $v_d = -v_p$ and the accelerating voltage changes from zero to a steady-state value.

If the beam is enabled when oscillations produced by the generator have almost reached their maximum amplitude, then, taking the beam enabling time as the origin, we obtain the initial condition $v_0 = v_g$. Then $v_d = -v_b$ and accelerating voltage becomes

$$u(t) = u_0 + \frac{2\beta\sqrt{Z_e LP}}{1+k}\exp(-t/\tau). \qquad (11)$$

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At the optimum coupling coefficient, the accelerating voltage spread divided by u_m(relative energy spread) is

$$\frac{\Delta u}{u_m} = \frac{\beta}{\sqrt{1+\beta^2}\cos\psi_0}. \qquad (12)$$

For example, at $\beta = 0.5$ and $\psi_0 = 30°$, the relative energy spread is 0.51 and, at $\beta = 0.5$ and $\psi_0 = 0$, it equals 0.44.

The energy spread on the leading edge of the microwave pulse can be eliminated by enabling the beam with a certain delay after the generator is switched on. In the case, the condition $v_d = 0$ (interruption of the transient at the moment when the beam is enabled) can be satisfied. This is achieved when the damped eigenoscillations exited by the beam and generator are equal in amplitude and are in antiphase. For this situation to occur, the resonator's frequency must differ from the frequency of the generator by a quantity depending on the phase φ of the generator. This possibility is addressed in [5].

Let us consider how oscillations in the resonator tuned exactly to the generator frequency ($\Delta\omega = 0$) come to the steady state. If the beam is enabled at $t = 0$ with a delay t_b after the generator is switched on, $v(0) = v_g(1 - \exp(-t_b/\tau)$. At $t \geq 0$ the initial amplitude of the damped eigenoscillations is

$$v_d = -[v_b + v_g\exp(-t_b/\tau)]. \qquad (13)$$

The delay t_b can be chosen so that v_d takes a pure imaginary value. Then the accelerating voltage is independent of time and equals u_0. Thus, the energy can be stabilized by properly choosing t_b alone. At the optimum coupling coefficient (9), the necessary delay of the beam engagement relative to the microwave pulse is

$$t_0 = \tau\ln\frac{\sqrt{1+\beta^2}\cos\psi_0 + \beta}{\beta}. \qquad (14)$$

As follows from expressions (5), when the phase of the generator is $\varphi = 0$, the amplitudes v_g and v_b are real; therefore, the energy can only be stabilized at $v_d = 0$. When $\varphi \neq 0$, v_d, can take pure imaginary values. In this case, the transient is not interrupted at the moment when the beam is enabled. The phase and amplitude of oscillations in the resonator change so that the two factors compensate for each other and the change in the particle energy is independent of time.

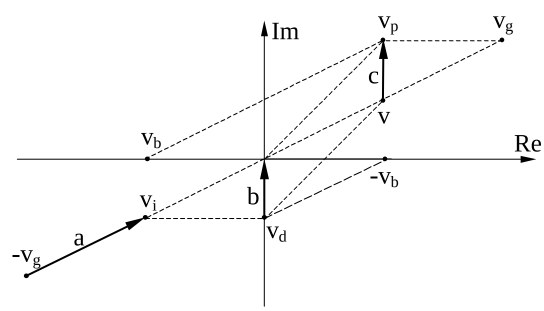

Figure 1: Complex plane of the normalized amplitudes: (a) extinction of oscillations produced by the generator before the beam is enabled, (b) extinction of the oscillations after the beam is enabled, and (c) evolution of the resultant oscillations in the resonator.

The figure gives a graphical interpretation of this effect on the complex plane of normalized oscillation amplitudes. At the moment when the generator is switched on, steady-state oscillations with the amplitude v_g and antiphase damped eigenoscillations with the initial amplitude $-v_g$ build up in the resonator. After the time t_b, when the amplitude of damped oscillations exited by the generator becomes $v_i = -v_g\exp(-t_b/\tau)$, the beam is enabled. Steady-state oscillations with the amplitude v_b and damped oscillations with the initial amplitude $-v_b$ are exited in addition to chose that already exist. A sum of amplitudes of the damped oscillations at this moment is the initial amplitude v_d for the subsequent time moments. The damped oscillations, which have an imaginary amplitude, do not affect the accelerating voltage.

Thus, the general expression for the accelerating voltage obtained in this paper can be used to evaluate the energy spread caused by the transients. It is shown that the energy spread can be eliminated in the process of transients to the steady state.

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