CZ9726784 P-2-42

The EMP Excitation of Radiation by the Pulsed Relativistic Electron Beam

V.A. Balakirev, G.L. Sidel'nikov

National Science Center "Kharkov Institute of Physics and Technology"
Academicheskaya St. 1, Kharkov, 310108, Ukraine
e-mail: kfti@rocket.kharkov.ua

Abstract. The mechanisms of the excitation of ultra-wideband electromagnetic pulses (EMP) by short pulses of high-current relativistic electron beams are proposed and investigated. It is shown that the transformation efficiency of the bunch kinetic energy to the excited energy of the EMP may be very significant.

Introduction

By now, on the base of high-current relativistic electron beams (HCREB) the generators and amplifiers of various types (carcinotrons, magnetrons, gyrotrons, vircators and other) with a power level of $(10^8–10^{10})$w and a pulse duration of $(10^{-8}–10^{-6})$s were developed.

However, these high-power generators are intended for generation of narrow-band pulse signals, with pulse duration τ_p significantly exceeding the period of high-frequency electromagnetic oscillations ($\tau_p/T \gg 1$). These generators are not suitable for generation of powerful electromagnetic pulses (EMP), with $\tau_p \lesssim T$.

This is caused by a resonant character of the process of energetic exchange between electrons and those of excited electromagnetic field. Therefore, it is clear that for the effective EMP generation by high-current bunches it is necessary to use the non-resonant (impact) mechanism of radiation, for example, such, as spontaneous coherent transition radiation or bremsstrahlung radiation in the external magnetic field. Short electron bunches with a duration of (0.1–10)ns, an energy of (0.5–1)Mev and peak currents of (10–100)kA can be obtained either by transformation of the continuous electron bunches to a sequence of electron pulses (modulated beams) [1], or by direct HCREB generation of a short and ultra-short duration in high-current devices [2].

1. The transition radiation of EMP during the crossing of the conducting screen by the electron bunch

Consider model of a radiating device represented in Fig.1. From the drift chamber 1 through the foil 2 the electron bunch goes out in the free space. When the electron bunch crosses the conducting plane, including the foil 2 and the conducting screen 3, the EMP is formed. Consider the radius of the screen to be unlimitedly large to provide simplicity. Besides, we neglect by the change of the form pulsed current during its propagation.

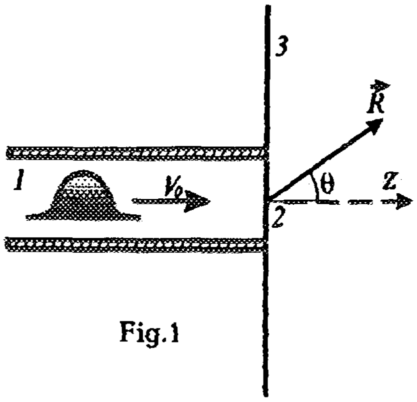

Fig.1

In the far zone the pulse of electromagnetic radiation is described by the term [3]

$$H_\varphi = -\frac{2}{cR} I(t - R/c) \frac{\beta \sin\theta}{1 - \beta^2 \cos^2\theta}, \qquad (1)$$

$\beta = V_0/c$, V_0 is the speed of the beam, c is the speed of the light in vacuum, R is the distance between the coordinates origin and the observation point, θ is the angle between the longitudinal axis of symmetry and the vector $\vec{R}$, $I(t)$ is the total current of the bunch, t is the time. Expression (1) is valid for the electron bunches of small cross size

$$r_b/ct_b\gamma \ll 1,$$

where r_b is the bunch radius, t_b it is duration, γ is the relativistic factor. This condition, as a rule, is satisfied.

Important conclusion follows from the expression (1), namely, that the radiation pulse precisely copies the current pulse, i.e. the beam antenna on the transition radiation has the wideband properties. The complete radiated energy may be calculated by the expression

$$W_{rad} = (1/c)F(\beta)\int_{-\infty}^{\infty} I^2(t)\,dt, \tag{2}$$

where
$$F(\beta) = \frac{1}{2(\gamma-1)}\left(\frac{1+\beta^2}{\beta}\ln\frac{1+\beta}{1-\beta} - 2\right).$$

Let us determine the efficiency of the beam radiator as the ratio of the radiated energy (2) to the beam kinetic energy

$$\eta = W_{rad}/W_{kin}, \tag{3}$$

where $W_{kin} = Qmc^2(\gamma-1)/e$, $Q = \int_{-\infty}^{\infty} I(t)\,dt$ is the complete bunch charge, e is the charge of the electron. For the Gauss bunch $I(t) = I_b \exp(-t^2/t_b^2)$ the efficiency of a beam radiator dictates by expression

$$\eta = \sqrt{2}F(\beta)I_b/I_A,$$

where I_b is the peak current of the bunch, $I_A = mc^3/e = 17$kA. For the electron beam with the maximum current 8kA and the energy 1Mev about 40% of the kinetic energy is transformed to the EMP energy.

2. Transition Excitation of EMP by a High Current Electron Beams in the Coaxial Line

The transformation of the energy of the relativistic electron beam to the EMP energy may be accomplished by the special device—converter. The possible schematic diagram of such device is represented in Fig.2. From drift chamber, made in the form of the circular waveguide, the pulse electron bunch falls on the central cylindrical conductor, positioned coaxially with the waveguide. The TEM pulsed field excites, as the result of the transition radiation of the beam in the coaxial line. Let us consider the electron bunch of the tubular form

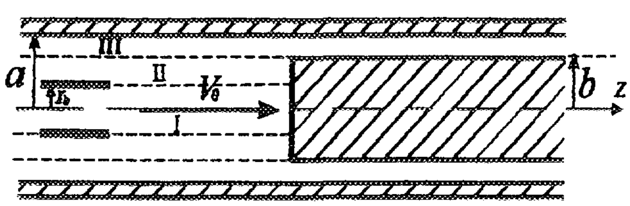

Fig.2

$$\vec{j} = -I_b\frac{\delta(r-r_b)}{2\pi r_b}T(t - z/V_0)\,\vec{e}_z, \tag{4}$$

where $\overrightarrow{j}$ is a current density, $\delta(r)$ is the delta-function. The function $T(t)$ describes a longitudinal structure of the bunch. The bunch radius is less then the radius of the internal conductor. We calculate pulsed radiation by using the method of Hilbert boundary problem. Let us find the solution in the form of an integral on the longitudinal wave numbers of the cylindrical waves. In the domains I—$\{r < r_b,\ z < 0\}$, II—$\{b > r > r_b,\ z < 0\}$ and III—$\{a > r > b,\ -\infty < z < \infty\}$ the amplitudes of the field may be written in the form

$$
\begin{aligned}
E^{I}_{z\omega} &= \int\limits_{-\infty}^{\infty} e_1(k) J_0(\mathrm{v}r) e^{ikz}\, dk, \\
H^{I}_{\varphi\omega} &= -ik_0 \int\limits_{-\infty}^{\infty} \mathrm{v}^{-1} e_1(k) J_1(\mathrm{v}r) e^{ikz}\, dk, \\
E^{II}_{z\omega} &= \int\limits_{-\infty}^{\infty} \left[e_2(k) J_0(\mathrm{v}r) + e_3(k)\Delta_0(\mathrm{v}r, \mathrm{v}b)\right] e^{ikz}\, dk, \\
H^{II}_{\varphi\omega} &= -ik_0 \int\limits_{-\infty}^{\infty} \mathrm{v}^{-1} \left[e_2(k) J_1(\mathrm{v}r) + e_3(k)\Delta_1(\mathrm{v}r, \mathrm{v}b)\right] e^{ikz}\, dk, \\
E^{III}_{z\omega} &= \int\limits_{-\infty}^{\infty} e_4(k)\Delta_0(\mathrm{v}r, \mathrm{v}b) e^{ikz}\, dk, \\
H^{III}_{\varphi\omega} &= -ik_0 \int\limits_{-\infty}^{\infty} \mathrm{v}^{-1} e_4(k)\Delta_1(\mathrm{v}r, \mathrm{v}b) e^{ikz}\, dk,
\end{aligned}
\tag{5}
$$

where $\quad \Delta_n(\mathrm{v}r, \mathrm{v}b) = J_n(\mathrm{v}r) N_0(\mathrm{v}b) - J_0(\mathrm{v}b) N_n(\mathrm{v}r), \quad n = 0, 1.$

Having used the boundary conditions for the fields, we will obtain the system of a functional equations, which may be reduced to the singular integral equation for the function $æ = æ^+ - æ^-$, $æ^+$ is analytical function in the upper half-plane, $æ^-$ is analytical function in the lover half-plane

$$
2Z_1 \hat{L} æ - Z_2 \hat{L} æ - \hat{L}\left(Z_2 æ\right) = -\frac{4I_\omega}{ca} \frac{h}{\pi\left(k^2 - h^2\right)} \frac{J_0\left(\mathrm{v}r_b\right)}{J_0(\mathrm{v}a)}, \quad Z_2 = \frac{k_0}{\mathrm{v}} \frac{\Delta_1\left(\mathrm{v}a, \mathrm{v}b\right)}{\Delta_0\left(\mathrm{v}a, \mathrm{v}b\right)}. \tag{6}
$$

Here $\hat{L}$ is integral dyadic with the Cauchy kernel. Let us find the solution of the integral equation (6) in the quasistatic approximation $k_0 a \ll 1$. This case is most interesting because the contribution of the waveguide modes in the radiation field is negligibly small. The main expenses of the bunch kinetic energy will be used to the TEM field excitation in the coaxial waveguide. The solution of the integral equation (6) makes find the magnetic field in the coaxial line

$$
H^{III}_{\varphi\omega} = -i\frac{2I_\omega}{ca} \int\limits_{-\infty}^{\infty} \frac{X^-(h)}{X^+(k)} \frac{\Delta_1\left(\mathrm{v}a, \mathrm{v}b\right)}{\Delta_0\left(\mathrm{v}a, \mathrm{v}b\right)} \sqrt{\frac{k_0 - h}{k_0 - k}} \frac{e^{ikz}}{2\pi(k - h)}\, dk. \tag{7}
$$

The expressions for the functions $X^{\pm}(k)$ have the form [4]

$$
X^+ = \sqrt{\frac{i}{\ln(a/b)}} \frac{1}{\sqrt{\left(k_0 + k\right) a}}, \quad X^- = \sqrt{\frac{\ln(a/b)}{i}} \sqrt{\left(k_0 - k\right) a}, \tag{8}
$$

The residue in the pole $k = k_0$ of the integrated function (7) gives the field of the coaxial TEM wave

$$H^{III}_{\varphi\omega} = -(2I_\omega/cR)\exp(ik_0 z).$$

We will receive a simple expression for the excited TEM pulse executing the inverse Fourier transformation

$$H^{III}_{\varphi} = -\frac{2I(t-z/c)}{cR}. \tag{9}$$

It follows from this formula that the form and the amplitude of the TEM pulse is determined only by the bunch current. For the efficiency of the radiator (3) we have the simple formula

$$\eta = \frac{2\ln(a/b)}{(\gamma-1)I_A}\left(\int\limits_{-\infty}^{\infty} I^2(t)\,dt \Bigg/ \int\limits_{-\infty}^{\infty} I(t)\,dt\right). \tag{10}$$

For the Gauss beam we find from (10) that

$$\eta = \frac{\sqrt{2}\ln(a/b)}{\gamma-1}\frac{I_b}{I_A}.$$

In particular, the transformation efficiency of the bunch energy to the TEM pulse energy for $a \approx 2.7b$, the of bunch energy 1Mev, of the current 10kA is 40%.

Conclusions

The results of theoretical researches of powerful EMP generation by high-current relativistic electron bunches of the short duration on the basis of transition radiation is presented. The schemes of beam radiators are proposed as well. It is shown that the transition radiation is effective mechanism of the powerful EMP excitation with the pulse duration (0.1–10)ns. The frequency spectrum of the EMP is close to the frequency spectrum of the HCREB and can be changed by varying the current pulse parameters. The advantages of the EMP generators based on the transition radiation of HCREB, are their high efficiency and constructive simplicity, as well as the possibility to regulate the spectrum of excited EMP. Generation process of EMP by the electron bunch in a coaxial line is investigated. A efficiency of beam radiators, using beams with a current (5 – 20)kA and energy (0.5 – 1)Mev, may reach (30 – 60)%.

The perspective mechanism of EMP excitation is the radiation, formed by the short-pulse HCREB under formation of a virtual cathode.

References

[1] Friedman M., Serlin V., Lau Y.Y., Krall J. Proc. of 8 Int. Conf. on High-Power Particle Beams. (BEAMS'90). 1990. Novosibirsk. V.1. P.53.

[2] Chaika V.E., Goncharuk I.M. Materials Conf. "SHF-engineering and space communication". Sevastopol. Ukraine. 26–28 September. 1994. V.2. P.393. (in Russian).

[3] V.A. Balakirev, G.L. Sidel'nikov Transition radiation of modulated electron beams in an inhomogeneous plasma. Survey. Kharkov. 1994. 104p. (in Russian).

[4] Vainshtein L.A. Theory of diffraction and method facrtorisation. M.: "Soviet radio". 1966. 431p. (in Russian).