EFFECT OF RAPID WAVE SCATTERING ON A "CORRUGATED" ELECTRON BEAM AND ITS USE FOR MICROWAVE PULSE COMPRESSION

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ABSTRACT

The purpose of rf compressors is transformation of long low-power input pulses into short high-power output ones. Their active varieties are based on storage of the energy of the input wave in a cavity and subsequent quick extraction of the energy by a rapid decrease of the Q-factor of the cavity. In this work, a spatially-modulated ("corrugated") electron beam is proposed as an active element of rf compressors. The main idea is the use of Bragg-type scattering of waves on the beam in order to provide a quick transformation of a high-Q pumping wave into a low-Q output one.

INTRODUCTION

The interest to methods of microwave pulse compression is connected mainly with the necessity to obtain high-power nanosecond pulses, which are used in electron-positron supercolliders. The main idea of rf compressor is to transform a long low-power input rf pulse into a short high-power output pulse. Active varieties of RF compressors (see e.g. [1-4]) are based on storage of the energy of the input wave in a cavity and subsequent quick extraction of the energy by a rapid decrease of the Q-factor of the cavity. The latter is provided by "fast" switching of an active element (gas or plasma switches of various configurations). In this letter, a spatially-modulated (corrugated) electron beam is proposed as the active element for rf compressors. The main idea is the use of Bragg-type scattering of waves on the beam in order to provide a quick transformation of a high-Q pumping wave into a low-Q output one.

WAVE SCATTERING ON A "CORRUGATED" ELECTRON BEAM

As a simple model, one considers a thin quasi-sheet electron beam moving along the z-axis in a waveguide, which is formed by two infinite metallic walls parallel to the (*x*,*z*) plane (Fig. 1). The beam is supposed to have a sinusoidal (corrugated) form, $y_{\mathrm{e}}(z) = y_0[1+\alpha\cos(h_{\mathrm{u}}z)]$, This is provided by electron oscillations in a magnetostatic field, which is composed by a uniform longitudinal field, $\mathbf{z}B_0$, and a periodical "undulator" field, $\mathbf{B}_{\mathrm{u}}$, having the period $\lambda_u = 2\pi/h_{\mathrm{u}}$. There are two ways to provide such type of the electron trajectory. If the longitudinal field, B_0, is relatively small, then, similar to most of free-electron lasers (FELs), the undulator field should have *x*-component, $B_{\mathrm{x}} = B_{\mathrm{x}_0}\sin h_{\mathrm{u}}z$, as well as the corresponding *z*-components. In the opposite case, when B_0 is large, it is more effective to provide *y*-component of the transverse undulator field, $B_{\mathrm{y}} = B_{\mathrm{y}_0}\cos h_{\mathrm{u}}z$, so that electrons move along the line of the total magnetostatic field.

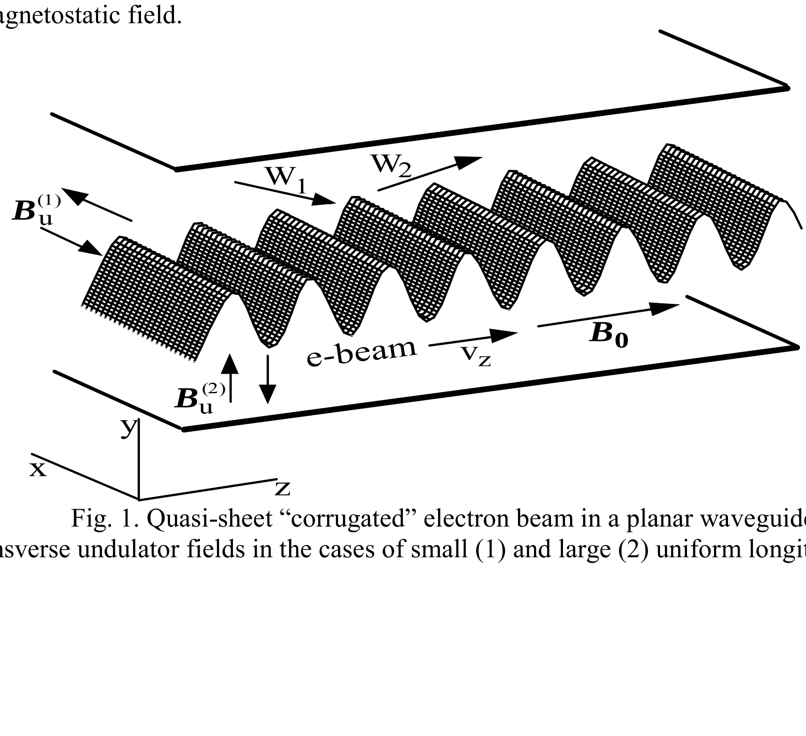

Fig. 1. Quasi-sheet "corrugated" electron beam in a planar waveguide.
Transverse undulator fields in the cases of small (1) and large (2) uniform longitudinal field.

Similar to corrugation of waveguide walls used often in FELs [5], such corrugation represents a Bragg-type scattering structure. Namely, it provides coupling (mutual scattering) of two waves, if their frequencies coincide and the difference between their longitudinal wavenumbers coincides with the corrugation wavenumber,

$$h_1 - h_2 = h_u \quad . \tag{1}$$

For instance, let us consider two waves, whose electric field has the only x-component of the electric field so that their vector-potentials have following form, $\mathbf{A}_j = \mathbf{x}_0 f_j(y)\,\mathrm{Re}\,\tilde{A}_j \exp(i\theta_j)$ (j=1, 2), where $\theta_j = \omega t - h_j z$, and functions $f_j(y)$ describe the transverse structure of the waves. In the wave equation,

$$\frac{1}{c^2}\frac{\partial^2 A}{\partial t^2} - \frac{\partial^2 A}{\partial z^2} - \Delta_\perp A = \frac{4\pi}{c}\rho \mathrm{v}_x \ , \tag{2}$$

the electron density is described by the formula $\rho(z,y) = \rho_0\, d_y \delta(y - y_e)$, where d_y is the beam thickness. The x-component of the electron velocity imparted by the waves, v_x, can be found from motion equations:

$$\frac{d}{dt}\Big[\mathrm{v}_x - \frac{e}{mc\gamma}\sum_j f_j(y)\,\mathrm{Re}\,\tilde{A}_j \exp(i\theta_j)\Big] = \Omega_c \mathrm{v}_y \ , \quad \frac{d\mathrm{v}_y}{dt} = -\Omega_c \mathrm{v}_x - \frac{e\mathrm{v}_x}{mc\gamma}\sum_j \frac{\partial f_j(y)}{\partial y}\mathrm{Re}\,\tilde{A}_j \exp(i\theta_j) \ .$$

Here $\Omega_c = eB_0 / mc\gamma$ is the electron cyclotron frequency and γ is the electron Lorentz-factor. In the linear approximation, when $f_j(y) \approx f_j(y_0) + y_0\alpha\cos(h_u z)\left.\frac{\partial f_j}{\partial y}\right|_{y=y_0}$, these equations give the following solution describing electron oscillations with phases of the waves, θ_j,

$$\mathrm{v}_x = \frac{e}{mc\gamma}\mathrm{Re}\Big[S_1 f_1 \tilde{A}_1 \exp(i\theta_1) + S_2 f_2 \tilde{A}_2 \exp(i\theta_2) + S_2\frac{y_0\alpha}{2}\frac{\partial f_1}{\partial y}\tilde{A}_1 \exp(i\theta_2) + \frac{y_0\alpha}{2}S_1\frac{\partial f_2}{\partial y}\tilde{A}_2 \exp(i\theta_1)\Big]_{y=y_0} , \tag{3}$$

where coefficients $S_j = \dfrac{(\omega - h_j \mathrm{v}_z)^2}{(\omega - h_j \mathrm{v}_z)^2 - \Omega_c^2}$ describe the influence of the non-resonant (being far from the cyclotron resonance) longitudinal magnetic field on electron oscillations in the field of the waves [6], and v_z is the averaged translational electron velocity. Taking into account in the right-hand part of (2) only resonant term determined by Bragg resonance condition (1), one obtains equations of scattering:

$$\frac{\partial \tilde{A}_1}{\partial t} + \mathrm{v}_1\frac{\partial \tilde{A}_1}{\partial z} = \frac{-i\pi e\rho_0 d_y}{m\omega\gamma N_1}F\tilde{A}_2 \ , \quad \frac{\partial \tilde{A}_2}{\partial t} + \mathrm{v}_2\frac{\partial \tilde{A}_2}{\partial z} = \frac{-i\pi e\rho_0 d_y}{m\omega\gamma N_2}F\tilde{A}_1 \ . \tag{4}$$

Here v_j are the group velocities of the waves, $N_j = \int f_j^2(y)dy$, and $F = \frac{y_0\alpha}{2}\Big[S_1 f_1\frac{\partial f_2}{\partial y} + S_2 f_2 \frac{\partial f_1}{\partial y}\Big]_{y=y_0}$ is the factor of wave coupling. Transformation of the waves on the corrugated electron beam does not lead to a change of the total power of the waves. Actually, according to (4), $d\,P_1/dz = -d\,P_2/dz$, where $P_j \propto \mathrm{v}_j N_j |\tilde{A}_j|^2$ are the wave powers and $d/dz = \partial/\partial z + \mathrm{v}_j^{-1}\partial/\partial t$. This means that the average electron energy is also constant.

The presence of the non-resonant uniform magnetic field, $\mathbf{z}B_0$, is important. In the most natural situation, its value is "lower" than the both cyclotron resonances, $\Omega_c < \omega - h_j \mathrm{v}_z$, so that the danger of spurious cyclotron oscillations is minimal. In this case $S_j > 1$, and, therefore, the coupling factor, F, increases due to increase of amplitudes of electron oscillations imparted by the waves.

FREE-ELECTRON RF PULSE COMPRESSOR

The use of a corrugated electron beam as an active element providing the mode transformation in rf compressors has a number of advantages. First, only the Bragg resonance condition (1) is required for an effective mode transformation. Since it includes neither the frequency nor the electron velocity, in principle, relatively high frequencies could be achieved by using moderately relativistic electron beams and long-period undulators. This means also that the device should be insensitive to the spread in electron velocity. Second, in contrast to gas/plasma switches, free-electron active elements do not cause the breakdown. Third, the proposed scheme requires no small-scale elements inserted inside the microwave system; this can provide operation at shorter wavelengths. Fourth, the active elements are electron beams of conventional (for electron masers) structure; a very advanced technique of electron-beam sources allows formation of high-quality short-front electron pulses. A possible disadvantage of the proposed scheme could be loss of the energy spent for the electron-beam formation. However, since the electron energy does not vary in the mode transformation process, it could be recovered (returned to the power supply) by using a simple single-stage depressed collector.

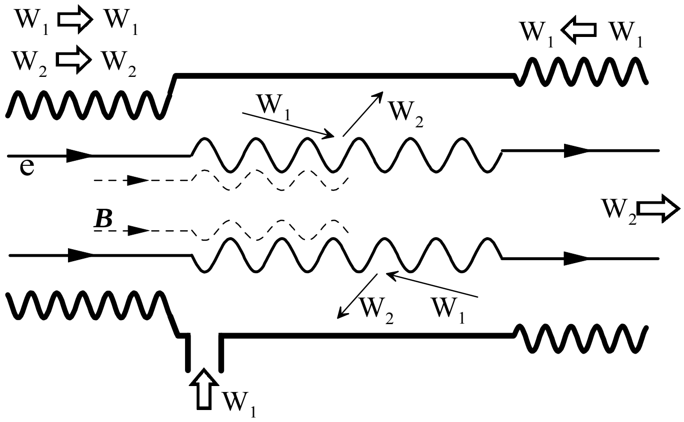

Fig. 2. Schematic of a free-electron compressor.

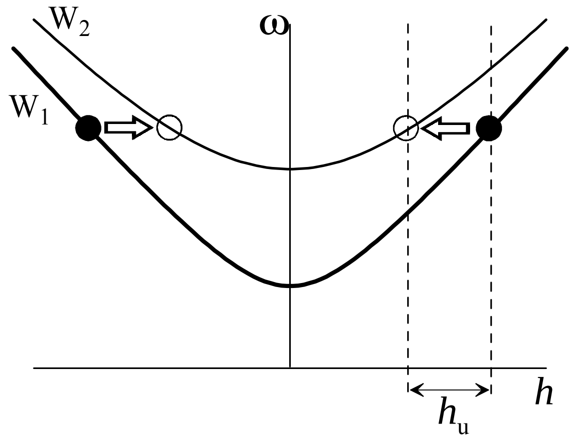

Fig. 3. Dispersion diagramm.

A possible scheme of using a free-electron rf pulse compressor is illustrated in Fig. 2. The operating waveguide is formed by a piece of circular waveguide and two (input and output) reflectors (for example, of the Bragg type), which close the pumping wave “1”. When an enough energy of the wave “1” is accumulated, a hollow electron beam is injected into the cavity; its corrugation is provided by electron motion along a profiled guiding magnetic field. The beam transforms forward and backward travelling components of the accumulated wave “1” into the corresponding components of the output wave “2”, which has a smaller group velocity (Fig. 3). The backward component of the wave “2” should be reflected from the input end of the cavity (for example, by using narrowing being cutoff for this wave), whereas its forward component provides the output of the compressed rf signal.

As an example, one considers the case when a moderately relativistic electron beam (having parameter typical for modern gyrotron guns, 80 keV and 50 A) transforms the pumping $TE_{0,1}$ mode into the output $TE_{0,2}$ mode at the wavelength of 8 mm. The form of the corrugated electron beam is described by formula $R_e = \overline{R}_e(1 + 0.3\cos h_u z)$, where the mean radius, $\overline{R}_e$, is close to the half-radius of the cavity (this corresponds to the maximum of coupling factors for the chosen modes). According to simulations, the optimal cavity length is 150 cm. The input power of the pumping mode is assumed P_{in} =1MW, and the pumping process is limited by a value of rf electric field of 300 kV/cm; this corresponds to the pumping pulse duration of 700 ns and the circulating rf power of 42MW. In this case, the pumping process finishes far from the saturation of the cavity and, therefore, ohmic losses are quite small (about of 30%). Naturally, at a fixed breaking electric field, increasing the input power results in a decrease of ohmic losses and of the compression ratio, but does not affect the output power.

Transformation of the accumulated $TE_{0,1}$ mode into the output $TE_{0,2}$ mode is simulated on the basis of equations analogous to (4); certainly, equations of scattering should are written for both forward and backward components of the modes and include the ohmic losses. According to simulations, the best results are achieved when there is a significant difference between group velocities of the waves; in this case, the direct “operating” scattering of the accumulated wave into the output one is faster as compared to the opposite process. Figure 4 illustrates the case of $v_1/c = 0.88$ and $v_2/c = 0.49$, that corresponds to the corrugation period $\lambda_u = 2.1$ cm. In the case of a relatively low value of the uniform magnetic field (curve 1, $\Omega_c\gamma_0/\omega = 0.3$) the compression factor, P_{out}/P_{in}, is about of 12. Increase of the magnetic field (curve 2, $\Omega_c\gamma_0/\omega = 0.5$, and curve 3, $\Omega_c\gamma_0/\omega = 0.6$) results in a significant enhancement of the peak power (up to 40 MW) whereas the output rf pulse shortens down to 10-20 ns. The increase of the coupling factor, which is caused by effect of the uniform longitudinal magnetic field, enables to decrease the electron current (curve 4, $\Omega_c\gamma_0/\omega = 0.6$, electron current is 30 A). In all cases, the operating e-beam-pulse duration is close to the output rf pulse duration. Thus, these examples illustrate a possibility to get a short output signal with a peak power of 20-40 MW using a short-pulse electron beam and a long-pulse rf pumping having significantly lower powers (4.0-2.4 MW and 1 MW, respectively). In the optimal case (curve 3) the output pulse duration is close to the round-trip travel time of the output wave over the cavity. Evidently, this time determines the minimal possible length of the output pulse (and, correspondingly, the maximal compression factor). It is important that the output pulse length can be driven by a change of either the electron current or the magnetic field. For example, a 100 ns output pulse is provided when the electron current is about of 40 A and $\Omega_c\gamma_0/\omega = 0.3$. Naturally, the output power in this case is quite low (about of 5 MW). Obviously, higher output powers could be achieved by using operating mode with higher radial indexes.

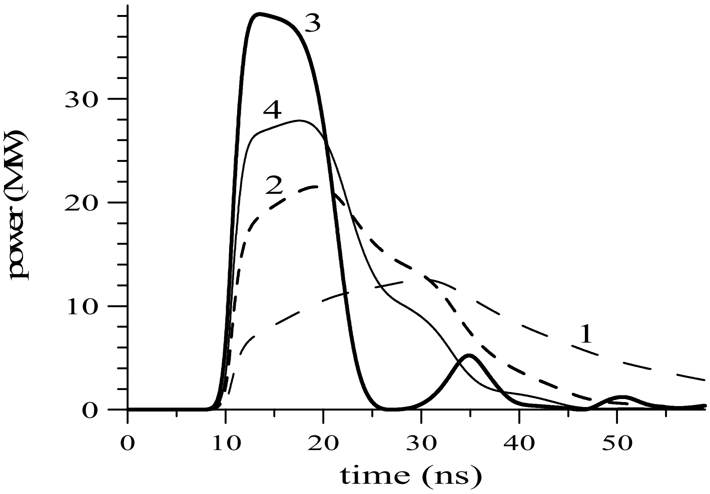

Fig. 4. Free-electron compressor. Power the output wave versus the time.

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