Experimental determination of the energy relations for charge-density waves in electron beams

B. I. Ivanov and D. V. Gorozhanin

Khar'kov Physicotechnical Institute of the Academy of Sciences of the Ukrainian SSR

The energy relations which establish for the charge-density waves in electron beams the relation between the energy of the wave, the energy of the longitudinal directed motion of the particles in the beam, and the energy of the "internal" (oscillator) motion of the electrons were investigated experimentally. The physical meaning of the energy relations and their importance for rf generators and collective ion accelerators, based on excitation of charge-density waves, was determined. The efficiency with which the kinetic energy of the directed motion of the beam is converted into the energy of rf radiation or energy of accelerated ions was determined. The efficiency with which ions are accelerated by means of direct collisions with electrons is compared with the efficiency of acceleration with the help of charge-density waves excited by the electron beam via the anomalous Doppler effect. The experimental results agree satisfactorily with the theory.

1. INTRODUCTION

The study of charge-density waves (CDWs), excited in intense beams of charged particles play an important role in the investigation of a wide range of problems associated with collective effects in such beams (plasma electronics, induced radiation of beams, collective methods of acceleration[1-3]). In particular, slow cyclotron and plasma waves (SCWs and SPWs) of charge density,[3-7] which are excited via the anomalous Doppler effect or the collective Cherenkov effect[2,8-11] when electron beams interact with electrodynamic retarding structures or directly with ion beams, are promising for collective acceleration of ions.[5-7]

In order to excite an instability via the anomalous Doppler effect it is necessary to ensure (see, for example, Refs. 11 and 12) that the slow CDWs, which are negative-energy waves, are synchronized with positive-energy waves propagating in electrodynamic structures or in ion beams. Ions can also be accelerated by fast cyclotron and plasma waves (FCWs and FPWs), which are excited via the normal Doppler effect and propagate in a direction opposite to the electron beam. (The normal Doppler effect in electron beams in the region of the electron cyclotron resonance was studied experimentally in Ref. 13.) In the cases studied the charge-density wave plays the role of an intermediate link in the process of energy transfer from the unperturbed electron beam to the oscillations excited in the retarding structures or to the accelerated ions. In the process definite energy relations are satisfied. These relations establish the relation between the radiated energy or the energy transferred to the ions, the energy of the charge-density wave, the energy of the longitudinal directed motion, and the energy of the oscillator ("internal"[8]) motion of the electrons.

The energy relations were investigated theoretically in Ref. 8 for an oscillator radiating via the anomalous Doppler effect, in Refs. 2, 14, and 15 for induced radiation from electron beams (including under conditions of plasma--beam interaction) and in Refs. 16 and 17 for charge-density waves in electron beams. In this paper we present results of experimental investigations of the energy relations for slow cyclotron waves and slow plasma waves, we analyze the physical meaning of the energy relations and their importance for the efficiency of rf generation and collective acceleration, and we compare the efficiency of ion acceleration by collisions with electrons with the efficiency of acceleration by charge-density waves excited by an electron beam via the anomalous Doppler effect.

2. THEORETICAL RELATIONS

The energy relations for cyclotron charge-density waves in the linear approximation (sufficient, in particular, for a theoretical verification of the antiresonance method of acceleration[4-6]) have the form[16]

$$\frac{|P_{\text{SCW,FCW}}|}{\pm P_{\pm}} = \frac{P}{\pm P} = \frac{\omega}{\omega_c} = \frac{v_{\text{ph}}}{v_0 - v_{\text{ph}}}, \tag{1}$$

where $P_{\text{SCW,FCW}}$ is the power of the cyclotron wave, P is the power given up by the beam to rf radiation or to acceleration of the ions, $P_{\perp}$ is the change in the power (energy flux) associated with the transverse motion of the electrons ($+$ for SCW and $-$ for FCW), ω is the frequency of the oscillations, ω_c is the cyclotron frequency, v_0 is the velocity of the beam, and v_{ph} is the phase velocity of the wave. The physical meaning of this relation is that in the anomalous Doppler effect, according to Ref. 8, the energy of the directed motion of the oscillators (in this case the Larmor oscillators) is expended both on rf emission and acceleration of ions as well as on increasing the internal energy (i.e., the energy of the transverse motion). In accordance with the relations (1) the energy is redistributed in proportion to the frequency of the oscillations. By analogy with electrodynamic systems we can talk about the active and reactive power of the wave, and in addition their ratio is all the lower the greater the retardation of the wave. The active power goes into the microwave generator or into acceleration, while the reactive power is carried off together with the beam and, in principle, must be recovered in the output devices. A relation analogous to (1) is also satisfied for the slow plasma wave, which is excited via the anomalous Doppler effect in the flow of longitudinal (plasma) oscillators moving with velocity $v_0 > v_{\text{ph}}$. In the case of emission, the energy of the longitudinal oscillations increases to a value determined by the expression[17]

$$\frac{|W_{\mathrm{pl}}|}{\widetilde{W}_{\|}} = \frac{|P_{\mathrm{pl}}|}{\widetilde{P}_{\|}} = \frac{2v}{v_0 - v}, \quad \frac{W_{\|}}{W_{\|}} = \frac{P_{\|}}{P_{\|}} = \frac{1}{2}, \quad (2)$$

where W_{pl} is the energy of the plasma wave, $\widetilde{W}_{\|}$ and $W_{\|}$ are the kinetic and total energies of the longitudinal oscillations of the electron beam, and P_{pl}, $\widetilde{P}_{\|}$, and $P_{\|}$ are the corresponding powers. The formulas (2) were derived in the approximation $\omega_b \ll \omega$, where ω_b is the plasma frequency of the beam. The energy relations can also be derived qualitatively from the laws of conservation of energy and momentum for the wave-particle interaction:[8]

$$\Delta W_0 = W + W_{\mathrm{in}}, \quad m\mathbf{v}_0(v_0 - v) = \hbar(\omega + \omega_0), \quad m(v_0 - v) = \hbar\mathbf{k}, \quad (3)$$

where ΔW_0 is the change in the kinetic energy of the radiator ($\Delta W_0 \ll W_0$), v_0 and v are the initial and final velocities of the radiator, W_{in} and ω_0 are the internal energy and characteristic frequency of the radiator, and W, ω, and $\mathbf{k}$ are the energy, frequency, and wave vector of the radiation. It follows directly from Eqs. (3) that

$$\hbar\mathbf{k}v_0 = \hbar k_z v_0 = \hbar\omega + \hbar\omega_0,$$

$$\frac{v_0 - v_{\mathrm{ph}}}{v_{\mathrm{ph}}} = \frac{\omega_0}{\omega} = \frac{W_{\mathrm{in}}}{W}, \quad \omega_0 = \begin{cases} \omega_c, & \text{MCW} \\ \omega_b, & \text{MPW} \end{cases} \quad (4)$$

In accordance with Eqs. (1)–(4), in the case of the anomalous Doppler effect (excitation of slow cyclotron waves and slow plasma waves) the longitudinal kinetic energy is converted into the radiation energy and "internal" energy, i.e., the energy of rotation or longitudinal oscillatory motion. In the case of the normal Doppler effect, under conditions of backward radiation (which corresponds to fast cyclotron waves and fast plasma waves propagating counter to the beam) the internal energy of the oscillators is converted into the radiation energy and it is also expended on increasing the energy of their longitudinal motion. The relation (1) can also be derived from the integrals of motion, found in the fixed-field[18] and self-consistent-field[19,20] approximations. In particular, with the help of the results of Ref. 18 it is possible to derive an equation for the power generated by cyclotron instability:

$$P = \frac{mc^2}{e} I\beta_{\mathrm{ph}}(\beta_i\gamma_i \cos\theta_i - \beta_f\gamma_f \cos\theta_f), \quad (5)$$

$$\beta_{\mathrm{ph}} = \frac{v_{\mathrm{ph}}}{c}, \quad \beta_{i,f} = \frac{v_{i,f}}{c}, \quad \gamma_{i,f}^{-2} = 1 - \frac{v_{i,f}^2}{c^2}$$

where e and m are the electron charge and mass, I is the beam current, c is the velocity of light, θ_i and θ_f are, respectively, the initial and final angle between the velocity of the electrons and the magnetic field, and v_i and v_f are the corre-

sponding values of the electron velocity. For θ, $\Delta\gamma/\gamma \ll 1$ the expression (5) transforms into Eq. (1).

It should be noted that the relations (1) and (2) were derived in the linear approximation, which is primarily employed to verify the collective methods of acceleration. The relations (1) and (2) must be taken into account when estimating the efficiency of collective wave accelerators. In this case the efficiency, expressed in terms of the change in power $\Delta P_{0,\|} = P_A + P_R$ of the directed motion of the beam, must be multiplied by a factor that takes into account the ratio of the active (P_A) and reactive (P_R) components of the power of the wave:

$$\eta_{ew} = \frac{P_A}{P_A + P_R} = \frac{\Delta P_{0,\|}}{P_{0,\|}} \frac{v_{\mathrm{ph}}}{v_0}. \quad (6)$$

3. EXPERIMENT

Figure 1 shows a diagram of the experiment. The electron beam, focused by the external magnetic field, was injected along the axis of the system in the region of excitation of the slow plasma wave or the slow cyclotron wave and entered the measuring collector unit. When the slow cyclotron wave was excited the region of excitation formed a retarding structure (RS)—a single-winding right-handed helix, placed in a cylindrical resonator with below-cutoff waveguides,[16] and in the case when the slow plasma wave is excited the region of excitation forms a spatially periodic retarding structure of type H.[21,22]

The parameters of the experiment were as follows: energy of the electron beam $W = 5$–30 keV, current $I = 10^{-3}$–1 A, beam diameter $a = 1$ cm, width of the pulse about 100μs, magnetic-field strength 0.1–1 kOe (the nonuniformity and instability were $< 1\%$), and residual-gas pressure $\lesssim 10^{-6}$ torr. The parameters of the resonator with the helix were as follows: length 30 cm, diameter 10 cm, helix pitch 0.46 cm, winding diameter 3.5 cm, wire diameter 0.07 cm, and winding length 28.8 cm; the parameters of the resonator in the spatially periodic retarding structure were length $L = 30$ cm, diameter 10 cm, spatial period $D = 7.2$ cm, and aperture 2 cm.

3.1. Measurement of the energy relations for slow plasma waves

Slow plasma waves were excited when the beam interacted with the + 1-st harmonic of the spatially periodic retarding structure under the resonance condition

$$\omega = k_{\|}v_0 - \omega_q, \quad (7)$$

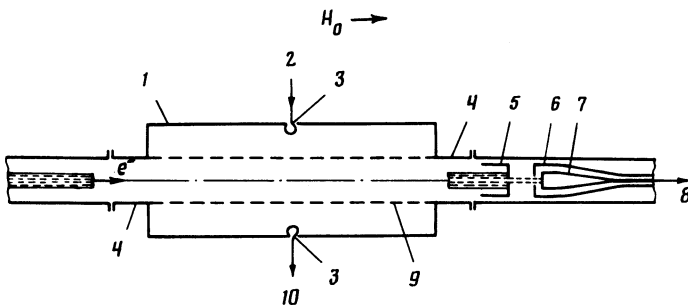where ω is the frequency of the oscillations, v_0 is the velocity

FIG. 1. Measurement setup: 1) resonator, 2) from rf generator, 3) coupling loops, 4) below-cutoff waveguides, 5) collector, 6, 7) coaxial rf collector, 8, 10) to stepped attenuator, 9) retarding structure.

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of the beam, $k_{\parallel} = k_0 \pm k_z$ is the longitudinal wave number ($k_0 = 2\pi/D$, $k_z = \pi/L$), $\omega_q = q\omega_b$ is the reduced plasma frequency of the beam, and q is the reduction factor, which accounts for the decrease in the frequency of longitudinal oscillations in a bounded beam ($q \approx 0.3$ under the conditions of the experiment). The magnetic field was chosen from the condition $\omega_c \gg \omega_b$, where

$$\omega_c = eH_0/m_0 c\gamma$$

is the electron cyclotron frequency and

$$\omega_b = (4\pi e^2 n/m_0 \gamma^3)^{1/2}$$

is the plasma frequency of the beam. Simultaneously with the excitation of the slow plasma wave the structure was excited at the fundamental frequency $\omega/2\pi = 624$ MHz (oscillations of type π).

The measured dependence of v_0 on ω_q, corresponding to excitation of a slow plasma wave, agreed satisfactorily with the theoretical dependence determined by the condition (7). The absolute value of the rf power in the resonator (P_{rf}) was measured using coupling loops and an rf receiver, precalibrated with the help of a standard-signal generator and a stepped attenuator with a step of 1 dB. The measured attenuation coefficients of the exciting and receiving coupling loops of the resonator were equal to 11 ± 1 dB and 9 ± 1 dB, respectively. The power of the rf oscillations (P_{rf}), excited when a definite fraction of the beam ($\sim 5\%$) was incident on the screened coaxial rf collector, whose characteristic impedance ($\rho = R = 75$ Ω) was matched to that of the measuring rf receiver (see Fig. 1), was measured simultaneously. The measured values of P_{rf} and $\overline{P}_{rf}$ were compared with one another for different parameters of the beam. The electron density in the beam and the frequency ω_b were determined based on the current, the beam cross section, and the accelerating voltage.

The energy relations (2) can be rewritten, with the help of the relation (7), in the form[17]

$$\tilde{P}_{\parallel}/P_{rf} = \omega_q/2\omega, \tag{8}$$

where $\tilde{P}_{\parallel}$ is the kinetic power of longitudinal oscillations of the particles in the beam and P_{rf} is the power of the rf oscillations in the resonator with the retarding structure.

The power of the longitudinal oscillations of the electrons is determined by the expression

$$\tilde{P}_{\parallel} = \frac{m\tilde{v}^2}{2e} I_0,$$

where I_0 is the beam current and $\tilde{v}$ is the oscillatory speed of the electrons. Assuming that the dependence of the variable quantities of the slow plasma wave is of the form $\propto \exp[i(\omega t - k_{\parallel} z)]$ and using the equation of continuity we establish a relation between $\tilde{v}$ and the alternating component of the current density of the beam $\tilde{j}$:

$$\frac{\tilde{v}}{v_0} = \frac{\tilde{j}}{j_0}\left(1 - \frac{v_0}{v_{ph}}\right) = -\frac{\tilde{j}}{j_0}\frac{\omega_q}{\omega}, \tag{9}$$

where v_0 and j_0 are the unperturbed velocity and current density of the beam, and the $-$ sign on the right side indicates the antiphase nature of the oscillations of $\tilde{v}$ and $\tilde{j}$ that is inherent to slow plasma waves. With the help of Eq. (9) the expression for the power of the longitudinal oscillations can
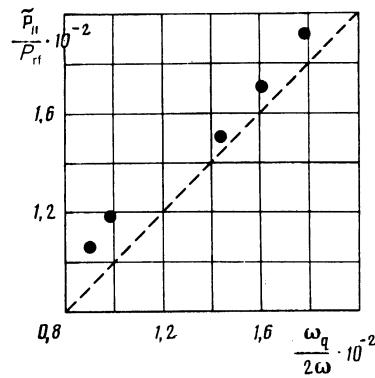
be written in the form

$$\tilde{P}_{\parallel} = \tilde{P}_{rf}\frac{U_0}{I_0 R}\left(\frac{I_0}{I_{cc}}\right)^2\left(\frac{\omega_q}{\omega}\right)^2, \tag{10}$$

where P_{rf} and I_{cc} are the power of the rf oscillations and the dc component of the beam current in the coaxial collector (see Fig. 1), U_0 and I_0 are the accelerating voltage and the unperturbed value of the total current of the beam, and R is the input impedance of the rf receiver. Combining Eqs. (8) and (10) we obtain the energy relation, checked in the experiment, for the slow plasma wave:

$$\frac{\tilde{P}_{rf}}{P_{rf}}\frac{U_0}{I_0 R}\left(\frac{I_0}{I_{cc}}\right)^2\left(\frac{\omega_q}{\omega}\right)^2 = \frac{\omega_q}{2\omega}. \tag{11}$$

The results of measurements for different parameters of the beam are presented in Fig. 2, where the theoretical dependence (8) is plotted as the dashed line and the dots are the experimental data for Eq. (11).

3.2. Measurement of the energy relations for slow cyclotron waves

Slow cyclotron waves were excited when the beam was made to interact with the $-$1st azimuthally asymmetric wave of the helical resonator under the resonance condition

$$\omega = k_z v_0 - \omega_c, \tag{12}$$

where k_z is the longitudinal wave number for a wave with the azimuthal index $m = -1$. For the selected type of oscillations of the structure $\omega/2\pi = 1727$ MHz and $k_z = 1.96$ cm^{-1}.

The excitation of the slow cyclotron wave was accompanied by generation of rf oscillations in the resonator and an increase in the transverse component of the velocity of the particles in the beam. The experimentally measured dependence of v_0 on ω_c, corresponding to excitation of a slow cyclotron wave, agreed satisfactorily with the theoretical dependence, determined by the condition (12).

The absolute value of the rf power generated by the beam in the structure was measured using calibrated coupling loops and detecting apparatus. The signal attenuation introduced by the exciting and receiving coupling loops were equal to 21 ± 1 dB and 25 ± 1 dB, respectively. The increase of the transverse component of the electron velocity upon excitation of the slow cyclotron wave in the beam was recorded with the help of axial and transverse current collec-
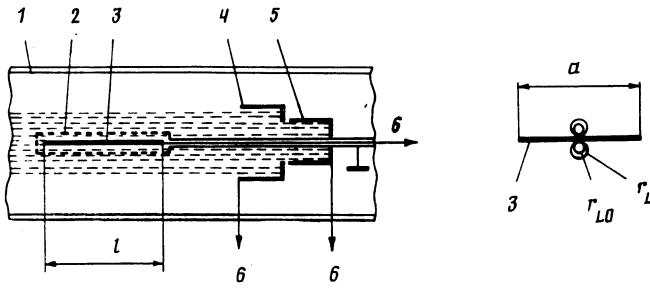
FIG. 3. Diagram of measurements of $P_\perp$: 1) drift chamber, 2) screen, 3) transverse current collector (plate), 4) collector, 5) longitudinal current collector, 6) to oscillograph.

tors placed at the point of exit of the beam from the region of excitation (see Fig. 3). The first collector was a Faraday cylinder (whose diameter was less than the diameter of the beam) and was used to measure the density of the longitudinal component of the beam current, while the second collector was a flat probe, whose plane was perpendicular to the cross section of the beam and passed through the axis of the beam—it was used to record the transverse current density of the beam. The conditions

$$l > 2\pi v_0 / \omega_c, \quad a > d, \quad \delta \ll r_L,$$

where d is the diameter of the beam, δ is the thickness of the flat probe and r_L is the Larmor radius of the electrons, were satisfied in the longitudinal and transverse directions. To avoid pickup the flat probe was placed in a grounded screen.

Figure 4 shows three series of oscillograms, illustrating the correlation of the rf signal in the retarded structure with the magnitude of the accelerating voltage and the beam current. In each series the top trace shows the accelerating-voltage pulse on the gun, the second and third traces (from the top) show the current pulses in the axial and transverse current collectors, respectively, and the bottom trace shows the detected rf signal, proportional to the amplitude of the rf oscillations generated in the helical resonator by the beam, from the coupling loop of the retarding structure at the given frequency. The series 1, 2, and 3 correspond to different amplitudes of the accelerating voltage on the gun and are arranged in order of increasing amplitude.

The resonance condition (12) was satisfied for the accelerating voltage of series 1 at the time corresponding to maximum voltage, when the maximum rf generation was observed. When the accelerating voltage is increased (series
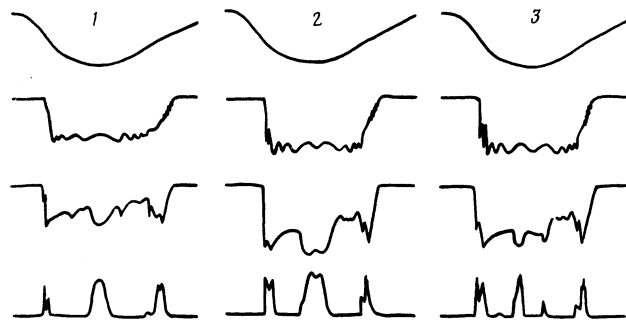
2 and 3) the rf pulse splits, since the conditions of generation are satisfied to the left and right of the maximum voltage. The decrease in the half-width of the generated rf pulses in the series 2 and 3 is due to the more rapid passage of the resonance compared with v_0, and the difference between the left and right resonances is due to the difference of their rate of passage, as well as to a hysteresis effect for the direct and backward passage of $U(t)$.

There is a correlation between the generation pulses and the "dips" of the current of the axial current collector, as well as between the "spikes" on the current pulses on the transverse current collector. This fact is explained by the increase of the transverse beam-electrons velocity component under the resonance conditions (12) and hence of the Larmor radius of the electrons. In addition, the current to the transverse current collector ($I_\perp$), determined by the "untwisting" of the electrons, increases and the current to the axial collector decreases owing to the increase in the effective diameter of the beam.

The powers P_{rf} and $P_\perp$ were found experimentally as follows. The power P_{rf} was determined from oscillograms, similar to those presented in Fig. 4, at the maximum of generation by comparing with the known power of a standard generator, with allowance for the attenuation introduced by the coupling loops and the graduated stepped attenuator (with a step of 1 dB). The attenuator setting was chosen to make the readings of the detecting unit indentical during, both measurement and calibration. The increment to the power $P_\perp$ in the case when the conditions over the cross section of the beam are uniform is determined by the expression

$$P_\perp = \frac{1}{2} m_0 v_0 S \left[\int_0^\infty v_\perp^2 f(v_\perp) \, dv_\perp - \int_0^\infty v_\perp^2 f_0(v_\perp) \, dv_\perp \right], \quad (13)$$

where S is the cross section of the beam, $f(v_\perp)$ is the distribution function of the electrons over the transverse velocities at the maximum of rf generation, and $f_0(v_\perp)$ is the same in the absence of generation.

In the presence of a distinct maximum in the distribution function we have

$$P_\perp \approx {}^1/_2 m_0 n_0 v_0 S (v_\perp^2 - v_{\perp 0}^2) = {}^1/_2 m_0 n_0 v_0 S \omega_c^2 r_{L0}^2 (r_L^2 / r_{L0}^2 - 1),$$

$$(14)$$

where v_{10} is the most probable transverse velocity of the electrons in the beam in the absence of generation, $v_\perp$ is the same at the maximum of generation, r_{L0} and r_L are the Larmor radii of the beam electrons corresponding to the indicated velocities, and n_0 is the electron density in the beam.

A "hole" probe,[16] placed at a distance $l = \pi v_0 / \omega_c$ from the opening and emitting some of the electrons through an opening in the collector (radius of opening $\ll r_L$) and strike a luminescent screen, can be used to determine r_{L0} in the case when the rf field is uniform over the cross section of the beam (which holds for the mode $|m| = 1$, if the radius of the beam is significantly smaller than the radius of the helix). In the process, the electrons with longitudinal velocity v_0 and transverse velocity $v = r_{L0} \omega_c$ will display on the screen a circle with radius $r_L = 2 r_{L0}$. The value of r_{L0} measured in this manner was equal to 0.1 cm. The ratio of the Larmor radii of the electrons r_L / r_{L0} was determined from the ratio of the beam currents in the transverse current collector
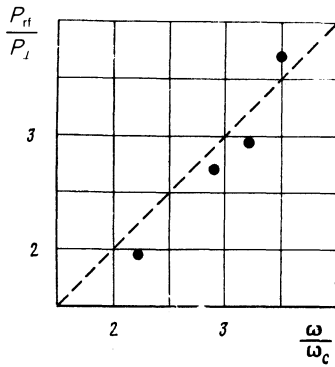

FIG. 4. Oscillograms: 1) $U = 16$ kV, 2) $U = 16.5$ kV, 3) $U = 17$ kV; $H = 218$ Oe, $I = 0.2$ A, and the sweep time is equal to $250\ \mu s$.

FIG. 5.

$I_\perp/I_{\perp 0}$ from the oscillograms similar to those presented in Fig. 4. Since $I_\perp = 4r_L dj$, where j is the current density of the beam at the exit from the structure, the expression for $P_\perp$ (for $r_L \ll d$) can be written in the form

$$P_\perp = \frac{m_0}{2e} r_{L0}{}^2 \omega_c{}^2 I\left(\frac{I_\perp{}^2}{I_{\perp 0}{}^2} - 1\right), \tag{15}$$

where I is the beam current at the exit from the retarding structure, $I_{\perp 0}$ is the beam current to the transverse current collector in the absence of generation, and $I_\perp$ is the same at the maximum of generation with resonant excitation of a slow cyclotron wave.

The results of the measurements of the ratio $P_{\rm rf}/P$ as a function of ω/ω_c for different parameters of the beam are presented in Fig. 5, where the dashed line is a plot of the theoretical dependence (1) and the dots are the experimental data.

As one can see from Figs. 2 and 5, good agreement was obtained between the theoretical and experimental data on the energy relations for the slow plasma waves and slow cyclotron waves.

4. ENERGY RELATIONS AND ION ACCELERATION

It is interesting to compare the efficiency with which the energy of the electron beam is converted into the energy of accelerated ions in a collective wave accelerator with the efficiency of direct transfer of energy from an electron to an ion by central impact. Examining the relativistic form of the laws of conservation of energy and momentum for an elastic collision of particles[23] and assuming that v_i/c, $v_i^2/v_e^2 \ll 1$ and $\gamma_e \ll m_i/2m_e$, we obtain the following result:

$$\eta_{ei} = \frac{\Delta W_i}{W_e} = \frac{2\gamma_e v_e{}^2}{(\gamma_e-1)c^2}\left(\frac{v_i}{v_e-v_i} + \frac{m_e}{m_i}\frac{\gamma_e v_e}{v_e-v_i}\right), \tag{16}$$

where m_e, m_i, v_e, v_i, W_e, and W_i are, respectively, the mass, velocity, and kinetic energy of the electron and ion, and $\gamma_e = (1 - v_e^2/c^2)^{-1/2}$ is the relativistic factor. For $\gamma_e \ll m_i v_i/m_e v_e$, $W_i \gtrsim 10^5$ eV, which corresponds to typical energies of ions injected into the accelerator, we obtain

$$\eta_{ei} = \frac{2\gamma_e v_e{}^2}{(\gamma_e-1)c^2}\frac{v_i}{v_e-v_i}. \tag{17}$$

Comparing the expressions (6) and (17) (taking into account the fact that $v_0 = v_e$, $v_i = v_{\rm ph}$, and $v_e \gg v_i$) shows that the efficiency of ion acceleration (in the case of direct

energy transfer from the electrons as well as energy transfer by means of the slow wave excited via the anomalous Doppler effect) is proportional to the factor $v_i/v_e \ll 1$. Physically this is determined by the fact that in both cases analogous energy and momentum conservation laws hold.

We shall now examine some questions connected with the energy relations in collective methods of acceleration, based on the use of slow cyclotron waves or slow plasma waves. It is well known that in such methods slow charge-density waves (SCDWs) are generated by the transiting ($v_0 \gg v_{\rm ph}$) electrons, which are subjected to sign-alternating forces generated by the space charge. This can produce significant accelerating fields ($\gtrsim 10^5$–10^6 V/cm), which are all the stronger the higher the ratio $v_0/v_{\rm ph}$. Unfortunately, in this case, as follows from the expression (6), the efficiency with which the energy of directed motion of the electron beam is converted into the energy of slow space-charge waves and then into the energy of accelerated electrons is proportional to $v_{\rm ph}/v_0$. For $v_{\rm ph}/v_0 \ll 1$ most of the expended energy of the directed motion of the electrons is stored in the form of the "reactive" component of the energy of the slow space charge waves and is carried together with the beam out of the accelerator.

To increase the efficiency of collective wave methods of acceleration it is necessary to solve the problem of recovering the "reactive" part of the energy of the slow space charge wave and the unexpended kinetic energy of directed motion of the electron beam. A promising possibility here is alternation of the sections of the accelerator that are excited via the anomalous Doppler effect and on the normal Doppler effect (SCW–FCW, SPW–FPW). In particular, as follows from expression (1), the generation of oscillations by the anomalous Doppler effect is accompanied by a decrease in the longitudinal and increase in the transverse electron pulses. Conversely, when oscillations are generated by the normal Doppler effect the transverse momenta of the electrons decrease.

To increase the efficiency and prevent a significant increase in the radius of the electron beam the sections of the accelerator with excitation of the field by the anomalous Doppler effect must be alternated with sections with excitation by the normal Doppler effect.[22,24] After the electron beam is extracted from the accelerator it can be directed into both a standard electrostatic regeneration unit and a regeneration unit consisting of an rf structure with $v_{\rm ph} \sim v$, with oscillations of the transverse type, which is located in a resonance magnetic field and generates at the working frequency of the accelerator. In such an rf regenerator it is possible to extract significant energy from the beam (the theoretical efficiency is close to 100% (Refs. 25 and 26), and it is possible to direct the rf power into the accelerator or to use the rectified voltage to power the electron injector, thereby increasing the overall efficiency.[22,24]

In conclusion we note that the energy relations in a charge-density wave are not always taken into account. For example, in Ref. 6, in calculations of an autoresonance accelerator which accelerates deuterons up to an energy of 10^9 eV with an average current of 1 A, judging from the values of the magnetic field strength presented in the tables as a function of the length $H(z)$, the restructuring of the longitudinal motion of the electrons into transverse motion was ignored. For $\beta_{\rm ph} \ll 1$ this restructuring is very significant: it results in sig-

nificant longitudinal deceleration of the electrons and, as a result, it leads to a severalfold decrease, compared with the data of Ref. 6, in the resonance value of $H(z)$ at the end of the first section.

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