Heavy-particle acceleration by charge-density waves in vacuum and in plasma

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Methods are described of producing regular intense longitudinal electromagnetic waves in vacuum or in plasma which were reported in individual communications from the Kharkov Physico-Technical Institute. Such waves are produced in vacuum if beams are passed through spatially-periodic fields of a parametric resonance region. Slow waves are produced due to the anomalous Doppler effect. When beams are passed through a region containing plasma, a wave with a broad frequency spectrum is formed due to plasma-beam instabilities. Such a wave is regularized by the superposition of a small amplitude periodic signal. Slow waves are produced by subjecting the plasma to an external magnetic field. The possibility is discussed of utilizing the fields so obtained to accelerate ions to high energies.

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We shall review new methods for the acceleration of heavy charged particles, which were proposed and are currently under development at the Physicotechnical Institute of the Ukrainian Academy of Sciences. Much of this effort was stimulated by the work of V. I. Veksler on collective methods of acceleration.[1]

It is well known that the collective method of acceleration is based on direct conversion of the energy of a high-current electron beam into the kinetic energy of ions injected into the beam. The ions are thus accelerated by the self-consistent electric fields up to energies much higher than the kinetic energy of the primary electrons.

The acceleration of ions to high energies by the high-frequency field of a high-current electron beam must occur over a large number of cycles of this field, and this is only possible when the field is sufficiently regular and the conditions ensuring synchronism between the accelerated particle and the traveling electromagnetic wave are satisfied. The maximum strength of the self-consistent electric field in beams is[2,7] $E_{max} \approx 4\pi n_0 e \xi$ (we shall be using the Gaussian system of units) where n_0 is the electron density in the beam, ξ is a characteristic linear dimension equal to c/Ω_p in the plasma variant and to the beam deformation ξ_m in the vacuum variant, e is the electron charge, c is the velocity of light, and Ω_p is the electron plasma frequency of the medium. It is well known that c/Ω_p determines the depth of penetration of the high-frequency field into the plasma, and ξ_m is the maximum shift of an electron from the position which it would have occupied in a uniformly moving undisturbed beam.[7] The field E_{max} can, theoretically, assume very high values. When the electron density is varied from 10^{12} to 10^{16} cm^{-3}, this field varies from 0.1 to 10 GV/m. The question is how to excite waves of this intensity.

The formation of regular high-frequency fields with variable phase velocity of the charge-density waves in high-intensity electron beams is attracting most attention at present. The physical mechanisms used to establish the fields are different in the plasma and vacuum variants. Let us consider them separately.

High-intensity longitudinal waves are excited in the plasma variant by means of building up beam-plasma instabilities.[2] The particular advantage of this method is the possibility of very high rates of energy input into the plasma through the beam. Nonlinear theory of the phenomenon, and experimental investigations, have confirmed that 10–40% of the kinetic energy of the beam is transformed into the energy of the electromagnetic oscillations.[4] High-frequency power levels of 5×10^{8}–6×10^{8} W[6,11] have been achieved for beam power of 10^{10} W under nonoptimum conditions. These fields act over distances of 50–60 cm and, if they were sufficiently monochromatic, they would ensure a longitudinal electric field of the order of 150–300 kV/cm.

The present authors have shown, already in 1955, that acceleration of particles in plasmas is characterized by simultaneous radial and phase stability,[2] so that the current density of the accelerated ions may reach very high values. The ion density n_i may be shown to be $n_i \approx n_0(m/M)\sqrt{v_{ph}/v_{Te}}$, where v_{ph} and v_{Te} are the phase and thermal velocities of the wave and electrons, respectively. There are well-known methods for controlling the phase velocity of waves in a plasma waveguide.[5]

Despite the clear advantages of the above method of acceleration, its implementation was delayed because nonlinear effects impeded the excitation in plasmas of regular monochromatic waves, and led to the broadening of the spectrum. The first step was, therefore, to develop methods for compressing and stretching the spectra along the phase velocity and frequency axes, i.e., to develop effective methods for controlling beam-plasma instabilities. It was also essential to prevent heating of the plasma and its diffusion due to growing instabilities.

A method for controlling instabilities was proposed, theoretically investigated, and experimentally confirmed. It is based on applying a regular signal at

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the input of the beam-plasma system, which exceeds the level of fluctuations, or on producing an initial beam modulation which leads to the excitation of waves at the signal or the modulation frequency and to the suppression of all other waves. The wave energy is thus transferred to a narrow spectral region, or into a single monochromatic wave. The nonlinear theory that has been developed, and the subsequent experiments, have shown that the power necessary for this control procedure is only 10^{-4}–10^{-6} of the power carried by the excited oscillations.[6] The next problem is to extend these instability control methods to much larger installations.

The transition to much higher levels of *hf* oscillations has its own particular features. On the one hand, when large-amplitude waves are excited, the precision of maintaining the frequency and the degree of monochromaticity of the wave, which are necessary for stable particle acceleration, can be substantially reduced. However, as the wave amplitude grows, there is an increase in its reaction on the plasma which is subjected to density modulation. In addition, other conditions are established under which it becomes essential to ensure the stability of the waves against decay, modulation, and parametric and other types of instability, so that measures have to be taken to avoid effects leading to the saturation of the amplitude of the excited oscillations. Some of these problems have already been solved; others are being successfully tackled.

Figure 1 shows some of the results of experiments on the compression of the spectrum of oscillations excited in the plasma by a beam to a single frequency. It also shows calculated correlation functions demonstrating the regularity of the excited signal.

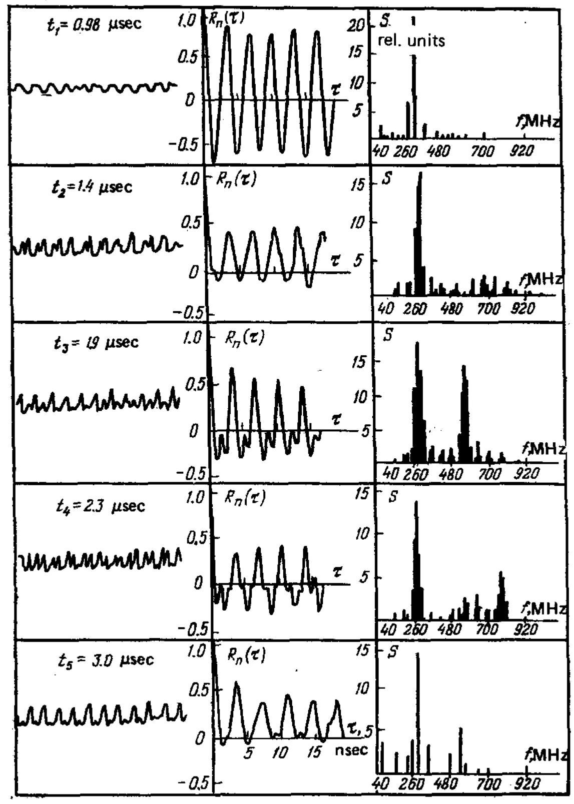

FIG. 1. Oscillograms of oscillations, their autocorrelation functions $R_n(\tau)$, and frequency spectra $S(f)$ for different instants of time during the interaction between a modulated electron beam and plasma.[10] The parameters of the beam and plasma were as follows: beam energy 25 keV; current 25 A; current pulse length 4.5 μsec. Power of initial modulation 6.5 kW; frequency of modulating signal 291 MHz; output signal power 100–150 kW.

In the vacuum variant, parametric instability is used to excite the large-amplitude charge-density wires in powerful electron beams. The elementary process in this instability is the parametric Cherenkov effect,[6] and the phase velocity of the waves is controlled by the anomalous Doppler effect.

It is known that the initial velocity modulation of the beam in the drift space leads to deep density modulation (klystron particle buncher), but Coulomb forces tend to prevent this. The demodulating effect of Coulomb forces can be substantially reduced if the electron beam is allowed to pass through a drift space loaded with spatially inhomogeneous static fields. When the natural frequency of the beam is equal to a load transit frequency, parametric instabilities are excited in the beam at the frequency equal to the modulation frequency and reduce or even totally compensate the demodulating effects of the Coulomb forces.[7] It is important to emphasize that deep modulation of the high-current electron beam is then produced by a relatively weak modulating signal. Parametric excitation of high-intensity charge-density waves has been investigated theoretically[7] and also experimentally[8] for low current electron beams. The problem now is to extend the successes achieved so far to high-current electron beams.

There is no doubt that the demands on the beam will be much greater than in the plasma variant, so that the transition to high-current beams will be subject to greater difficulties. However, the attractive feature is that a large fraction of the beam energy (up to 35%) can be transformed in the vacuum variant into the energy of the first field harmonic which takes the form of a regular monochromatic wave.

The phase velocity of the charge-density waves in the electron beam is equal to the electron velocity v_0, so that these waves are not directly useful for the acceleration of ions. However, when the field potential on the beam axis is modulated with a certain spatial period L, the anomalous Doppler effect produces waves with phase velocity $v_{ph} = v_0/[1 + (\pi v_0/\omega L)]$, which can be equal to the velocity of the ions.

It has now been experimentally confirmed that it is possible to produce low phase-velocity charge-density waves in fast electron beams, and that ions are indeed trapped into the acceleration process.[9] A tube with a periodically varying radius was used as the spatially inhomogeneous system. Since the radial profile of the potential in the beam depends on the distance between the beam boundary and the wall, periodic variation in the wall radius leads to the appearance of a longitudinal

TABLE I.

Energy of beam electrons, keV	Beam current, A	Effective accelerating field E_{acc}, kV/cm	Focusing magnetic field, tesla
100	200	80	4
200	560	160	5.7
300	1020	240	7.0

modulating field on the beam axis. Moreover, the tube segments with the larger radius may be looked upon as cavity resonators producing the parametric excitation of large-amplitude charge-density waves. The combination of these two functions in a single periodic structure gives rise to no fundamental difficulties because the beam modulation depth is essentially determined by the smaller radius of the apertures, whereas the resonance frequencies of the cavities are determined by the larger radius of the tube. To illustrate the possibilities of the vacuum variant, we list (see Table I) the necessary beam parameters and the parameters of the focusing magnetic field (the transverse linear dimensions of the electron beam are of the order of 1 mm).

We note in conclusion that these experimental results are in good agreement with the theoretical predictions, which leads us to hope that the collective method of acceleration that we have been describing will achieve a practical realization. Preliminary work in this direction (theory of parametric Cherenkov effect and studies of the dynamics of charged particles in plasma waveguides) has been carried out jointly by the present authors. Subsequent development of plasma methods of acceleration was carried out by Ya. B. Faĭnberg, A. K. Berezin, Yu. V. Tkach, V. D. Shapiro, V. I. Kurilko, V. I. Shevchenko, L. I. Bolotin, A. I. Egorov, and others. The vacuum variant was investigated by N. A. Khizhnyak, A. G. Lymar', V. V. Belikov, N. S. Repalov, V. F. Tyrnov, A. I. Pasynok, and others.

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