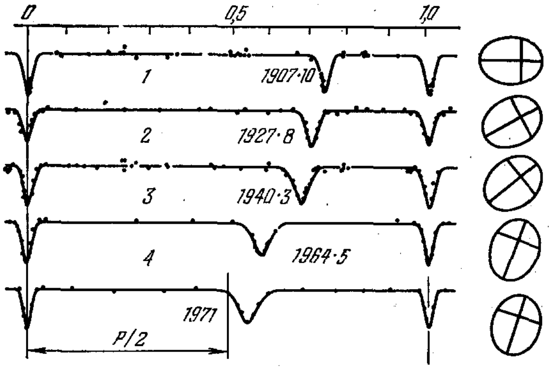

first curve was obtained from Wendell's observations, and the others from the author's own.

A. A. Kolomenskiĭ, M. S. Rabinovich, and Ya. B. Faĭnberg. Collective Methods of Particle Acceleration in a Plasma and in Heavy-Current Electron Beams

Great strides have been made in recent years in the development and construction of various types of accelerators. However, it is becoming increasingly difficult to link further substantia-progress with even greater enlargement of the scales of classical installations, and the future development of this field will depend in many respects on radical increases in acceleration efficiency. Collective methods of acceleration, which, in principle, will make it possible to raise the specific energies by more than one or two orders of magnitude and obtain increments per meter of 0.1—1 GeV and more, are highly promising in this respect. The paper discusses certain methods that do not involve the use of relativistic electron rings (see, for example, Usp. Fiz. Nauk **96**, 377 (1968)[Physics Today **21**(2) (1968) and are under development at the P. N. Lebedev Physics Institute of the USSR Academy of Sciences and the Physico-technical Institute of the Ukrainian Academy of Sciences (Khar'kov).

There are two basic known sources of strong collective electric fields: the dense plasma and heavy-current relativistic electron beams. The Physico-technical Institute of the Ukrainian Academy of Sciences is doing original work on the acceleration of ions in density waves in a plasma, on the excitation of strong electric fields in the plasma-beam interaction, and on the suppression of instabilities and regularization of oscillations in plasma; a linear plasma betatron has been built.

The waves in the plasma that are necessary for particle acceleration can be excited either with external microwave generators in plasma waveguides or by electron fluxes. It appears that use of the interaction of strong relativistic electron beams with the plasma is especially promising. In essence, instability is used to excite plasma waves, and the most important problem in the development of plasma accelerators is to find ways to control the instabilities and, if necessary, suppress them. The following methods have been proposed and investigated for instability control: (1) preliminary modulation of the electron fluxes (in density and velocity) and (2) the use of an inhomogeneous plasma. Experiments have shown that impression of a signal at the system input whose strength is a very small fraction of that of the oscillations generated is sufficient to control the instability spectra.

The Academy of Sciences Physics Institute is conducting research toward the development of new collective methods using relativistic electron beams in which the beams are scanned and self-accelerated and ions are accelerated in self-phased electron plasmoids and in an ionization front in a gas. In the scanning method, an electron beam emanating from a certain point is rotated and forces trapped ions to accelerate. At a constant angular velocity of this rotation, it becomes possible to accelerate the ions continuously (and not pulsewise, as in other methods). In the self-acceleration method, some of the energy of the heavy-current beam goes into excitation of accelerating fields in passive structural elements (resonators, lines). This is accompanied by a redistribution of energy within the beam, i.e., some of the particles are accelerated at the expense of others.

In the acceleration of electrons and ions in self-phased electron bunches, the latter excite strong fields in a decelerating system, e.g., a waveguide with diaphragms or a chain of resonators. A large electron current corresponds to an high amplitude level of the longitudinal field. This is because the heavy-current beam can transport a large volume energy density through the waveguide and do so at relativistic velocity.

The method of ion acceleration by passage of an electron beam through a gas is being developed on the basis of an experimentally observed phenomenon in which a rather large number of ions acquired energies of the order of several MeV per nucleon. This effect arises from the fact that the electron beam in the gas forms ions and creates a comparatively slow-moving charge potential well, in which these ions are accelerated.

Research on collective methods has, incidentally, produced certain results that are of independent interest and presage the development of high-power microwave generators and the feasibility of efficient heating of plasma electrons and ions. Heavy-current pulsed electron accelerators developing energies of MeV order, in the development of which great progress has been made in recent years, constitute the main experimental base for the development of collective methods.

The following literature on the subject of the paper can be cited: Ya. B. Faĭnberg, Trudy VII konferentsii po uskoritelyam (Trans. 7th Conference on Accelerators), Vol. 2, Erevan, 1970, p. 465; M. S. Rabinovich, Trudy I Vsesoyuznogo Soveshchaniya po uskoritelyam (Trans. First All-union Conference on Accelerators, Vol. 2, Moscow, 1970, p. 473; A. A. Kolomenskii and I. I. Logachev, Proc. of the 8th Intern. Conference on High-energy Accelerators, Geneva, CERN, 1971, p. 587; L. N. Kazanskiĭ et al., Atomnaya Énergiya **30**, 27 (1971).

L. S. Bogdankevich and A. A. Rukhadze. Problems of Heavy-current Relativistic Electron Beams.

In recent years, high-powered, heavy-current electron accelerators have been built in many laboratories around the world in connection with the development of pulsed high-voltage techniques. These accelerators have characteristic powers $W \approx 10^{11}-10^{12}$ W, beam currents $I \approx 10^5-10^6$ A, electron energies $\mathscr{E} \approx 1-10$ MeV, and pulse durations $\tau_0 \lesssim 10^{-7}$ sec. These electron accelerators and more powerful ones open access to a broad range of purely physical problems. In our view, the most important of these problems is that of heating plasma to thermonuclear temperatures with a heavy-current beam and obtaining pulsed thermonuclear fusion. Estimates[1] indicate that electron beams with energies of 10 MeV focused on an area of 0.3 cm^2 at a current of 10 mA and a pulse duration $\tau \approx 3 \times 10^{-8}$ sec will be required to attain this goal. According to theoretical calculations[2a], such currents can be obtained only with plasma focusing of the electron beams, with

$$I_{\text{lim}} \approx 17\,\gamma^3 \text{ kA}, \qquad (1)$$

where $\gamma = \mathscr{E}/mc^2 = [1 - (u^2/c^2)]^{-1/2}$ is the relativistic factor. At $\gamma \approx 20$ (i.e., at $\mathscr{E} \approx 10$ MeV), it follows from (1) that $I_{\text{lim}} \approx 10^8$ A. Focusing of the beam requires pulsed magnetic fields of intensity

$$B_0 \gtrsim (8\pi n_1 mc^2\gamma)^{1/2},$$

i.e., at $n_1 \approx 10^{17}$ cm^{-3} (which corresponds to a current $I \approx 10^8$ A), $B_0 \gtrsim 5 \times 10^6$ G. Such fields are technically quite within reach today.

A second problem for whose solution heavy-current electron beams are highly promising is that of collective acceleration of ions and the development of heavy-particle accelerators in the energy range ~100–1000 MeV at average currents ~1–10 A. The first experiments[3] on injection of a heavy-current electron beam into a gas showed that ions are trapped and accelerated in the beam-induced ionization front in the gas. The mechanism proposed for this phenomenon in[4], which is based on the notion of limiting currents in uncompensated and compensated electron beams, gives a good qualitative explanation for the features of the observed ion acceleration.

A third important scientific field in whose development relativistic electron beams may play a decisive role is that of plasma electronics. This field dates from Akhiezer and Faĭnberg's discovery[5] of the phenomenon in which electromagnetic waves are excited when an electron beam interacts with a plasma. Theoretical analysis of the problem of interaction of a monoenergetic ultrarelativistic electron beam with a plasma yields the following values for the efficiency of generation of electromagnetic waves by the beam and the relative generation line width[2b]:

$$\eta \approx (n_1/2n_2)^{2/3}, \quad \Delta\omega/\omega \approx (n_1/2n_2)^{1/3}/\gamma,$$

where the frequency of the radiation is determined by the plasma density: $\omega = 5 \times 10^4 n_2^{1/2}$ sec^{-1}. With beam currents $I \approx 10$ kA and energies $\mathscr{E} \approx 30-50$ MeV, it will be possible to build pulsed electromagnetic radiators in the centimeter and millimeter bands with relative widths $\Delta\omega/\omega \approx 10^{-2}-10^{-3}$. The development of such radiators is an altogether realistic project even today.

One of the most interesting problems of modern physics is that of phase transitions at high pressures. Relativistic electron beams may also be highly important in the solution of this problem. It is noted in[6] that relativistic beams can be used to create pulsed pressures of several million bars in a solid at relatively low ambient temperatures and then used in this way to investigate the possibility of producing metallic hydrogen.

Finally, we note that powerful heavy-current electron beams are excellent sources of directional x-radiation. When an electron beam with energy ~20–30 MeV at a current $I \approx 10^6-10^7$ A is accelerated, approximately 1% of the energy becomes x-ray energy. The power of such an x-ray source might range up to 10^{12} W with a directivity $\theta \approx 1°$. And it might even be possible to generate stimulated x-radiation by injecting such a beam into a dense gas.

The list of possible applications of heavy-current electron beams for solution of various physics problems might be lengthened to include the development of injectors for modern accelerators, sounding of the ionosphere and creation of artificial auroras, etc. However, it is sufficient to note that the mere interaction with matter of beams in which the magnetic energy of the current field greatly exceeds the particle kinetic energy is a totally unexplored field of physics, and one that conceals no small number of interesting discoveries.

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