A. A. Kolomenskiĭ, *Collective Methods for the Acceleration of Particles.* Over the last few years, the Laboratory for New Accelerators of the Lebedev Physics Institute has proposed and investigated, both theoretically and experimentally, various methods for the collective acceleration of ions and electrons, based on the use of high-current relativistic electron beams (HCB). These methods include the following:

1. Acceleration of ions during transverse or longitudinal scanning of an HCB or its focus.[1]

2. Acceleration of particles by fields excited during the passage of an HCB through resonating or waveguide structures, including self-acceleration of electrons[2,3] and acceleration of ions.[4]

3. Acceleration of ions by the collective fields of a closed HCB during its rotation as a whole (the gyrotron accelerator[5]).

4. Acceleration of ions during the passage of an HCB through a low-pressure gas, or through a vacuum during the irradiation of solid targets.[6]

All the experiments have been based on the high-current pulsed electron generators Impul's-1 and Impul's-2, developed and built in the Laboratory, and producing 0.5–1.0 MeV electrons at about 30 kA and pulse lengths of 30–50 nsec.

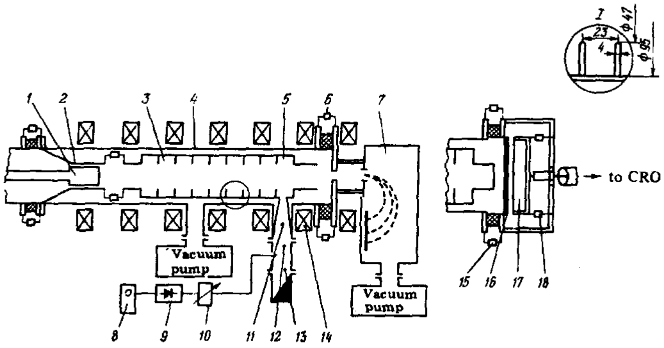

FIG. 1. Experiment on the self-acceleration of a high-current electron beam: 1—cathode; 2—anode; 3—waveguide; 4—vacuum chamber; 5—wave-mode converter; 6—shunt; 7—magnetic analyzer; 8—oscillograph; 9—calibrated detector; 10—calibrated attenuator; 11—extraction of microwave power; 12—calibrated coupler; 13—load; 14—solenoid coil; 15—total current shunt; 16—foil; 17—Faraday cup; 18—shunt for Faraday cup.

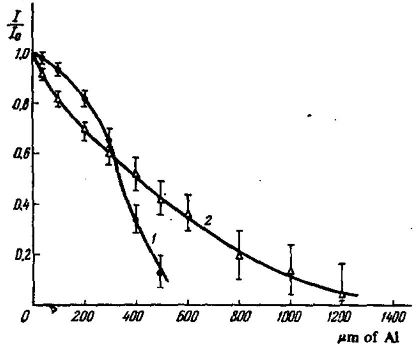

FIG. 2. Absorption curves for the high-current electron beam: 1—passage through a tube in the waveguide; 2—passage through a waveguide, 80 cm long (self-focusing effect).

Owing to a number of serious difficulties, the electron energy in modern high-current pulsed accelerators is usually restricted to values of the order of 1 MeV. Research on the self-acceleration of electrons aims to raise this energy to 10–100 MeV or more at about 10 kA. This problem must be solved through a redistribution of particle energies in the high-current beam by the collective fields appearing during the interaction between the beam and special electrodynamic structures. A definite fraction of the particles can then be accelerated by the field generated by the beam itself up to energies much higher than the initial value. Our experiments with continuous and tubular beams[3] passing through diaphragmed waveguides (Fig. 1) have shown that the spectrum of electrons with initial maximum energy of about 0.5 MeV is substantially shifted toward higher energies. Approximately 10% of the electrons double their energy as compared with the initial value, and 2% triple it (Fig. 2). When the shape of the initial voltage pulse is taken into account, it is found that electrons on the trailing edge of the pulse increase their energy by factors of 4–6. The self-acceleration process is accompanied by emission of strong microwave radiation, and the total measured intensity is 0.4–0.5 GW, which corresponds to about 20% of the beam power at entrance to the waveguide. The microwave radiation is of independent interest, and is also used for the di-

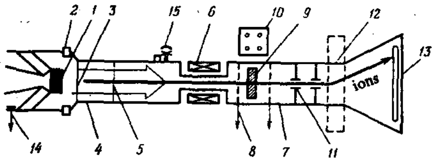

FIG. 3. Experiment on the acceleration of ions out of a gas during passage of a high-current electron beam: 1—flat graphite cathode; 2—current measuring shunt; 3—titanium foil anode (50 μm); 4—accelerating section of the drift chamber; 5—aluminized mylar wall; 6—magnet for deflecting electrons; 7—diagnostic section of drift chamber; 8—collector grid; 9—graphite target; 10—paraffin block with geiger counters; 11—collimators; 12—magnetic analyzer; 13—x-ray film; 14—capacitative probe used to measure the voltage across the diode gap; 15—gas leak and pressure gauges.

agnostics of the various phenomena taking place.

These and other results show that the self-acceleration mechanism can, in fact, be used within sufficiently broad limits to vary the spectrum, the pulsed power, and the maximum energy of the electrons. Further improvements in the efficiency of this mechanism will depend on further work on the optimization of the shape of the initial beam pulse and the configuration of the resonating structure.

We note that theory shows that the transmission of a high-intensity tubular beam through a smooth waveguide can be used to achieve sufficient acceleration of a sufficiently dense ion bunch by a mechanism such as the inverse Vavilov–Cerenkov effect.[4] However, this requires detailed experimental verification.

A number of our experimental and theoretical investigations has been devoted to the collective acceleration of ions out of a gas through which the HCB has been passed. The parameters of the HCB at entry to the drift chamber were: 0.6–0.8 MeV, 15–20 kA, 40–50 nsec. The experimental setup is illustrated schematically in Fig. 3. Even with these modest values of the HCB parameters, it has been possible to produce proton and deuteron beams of considerable energy and intensity. The maximum number of particles per pulse was 8×10^{11} for deuterons and 10^{12} for protons, and these figures were achieved at a pressure of 0.12 Torr. Most of the ions had energies of about 2 MeV, but the maximum energy was up to 4–8 MeV. The effective accelerating field was 0.1–0.3 MV/cm. In experiments with other gases (helium, nitrogen, argon, and xenon) the energy of the accelerated ions was proportional to the charge, but the intensity was found to be much lower than for protons, especially for the heavier ions (up to 10^9 per pulse for argon).

The passage of the HCB through the gas is a complicated process accompanied by a number of elementary and collective effects. Under certain definite conditions, this process is accompanied by the formation of an effective potential well capable of trapping ions for certain intervals of time. The problem is to find reliable ways of controlling the velocity of the well so that the ions contained in it could be displaced as far as possible together with the well. This will enable us to extend the proton energies to values of the order of some tens or hundreds of MeV. In particular, in our experiments, we used a special drift chamber consisting of individual sections with length and pressure independently variable. We have also investigated a specific phenomenon which we have called "selective acceleration": for example, protons are preferentially accelerated out of a hydrogen-deuterium mixture even if the mixture consists almost entirely of deuterium. Experiments have demonstrated that it is possible to control the rate of displacement of the well and, at the same time, have shown that the quality of the HCB must satisfy certain special conditions. More direct control methods have also been considered, for example, programmed scanning of the HCB crossing drift chamber.

Accelerated ions have also been produced during the interaction between a high-current electron beam and a localized source (target) placed in its path (in a gas or vacuum). Appropriate experiments with solid hydrogen-containing targets[6] have resulted in energies and intensities of protons comparable with those obtained during the interaction between the high-current electron beam and the gas.

Another way of controlling the motion of the potential well is to use a "gas lens," i.e., a limited layer of gas through which the high-current electron beam is passed.[1] Because of gas ionization, the successively arriving portions of the electron beam become more compressed and the focus of the beam moves through the vacuum in the longitudinal direction. The focus forms a potential well for ions and, by suitably choosing the parameters of the lens, it is possible to achieve synchronism between the motion of the well and the motion of the ions.

The most important feature of the results obtained in these experiments is that it is possible to produce collective fields of the order of fractions of MV/cm, and that there is complete agreement between experimental and theoretical data obtained by different methods. This provides the foundation for the development of specialized installations based on the collective acceleration principle.

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