Collective acceleration of ions by a relativistic electron cloud

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(Submitted 22 November 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 2, 100–103 (20 January 1980)

We report the first results of experiments on collective acceleration of ions by a cloud of relativistic electrons produced on a thin foil as a result of injecting a high-current relativistic electron beam into a vacuum.

PACS numbers: 29.15. — n

The formation of a dense cloud of relativistic electrons as a result of injection of a relativistic electron beam (REB) with a supercritical current through a thin foil into a vacuum was investigated theoretically and experimentally in Refs. 1 and 2. If a plasma layer is formed on the surface of the foil, then, as mentioned in Refs. 2 and 3, a collective acceleration of ions may occur due to the energy of the stored relativistic

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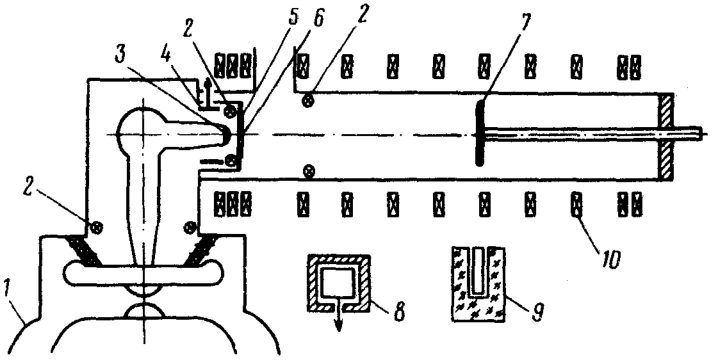

FIG. 1. Experimental setup: 1, accelerator; 2, Rogowski loops; 3, cathode; 4, capacity divider; 5, anode foil; 6, dielectric film; 7, graphite collector; 8, time-of-flight neutron detector; 9, activation detector; 10, magnetic-field coils.

electrons. In this paper we report the first results of the experiments on acceleration of ions in this way, which were performed with use of the "KRAB" facility.

The experimental setup is shown in Fig. 1. A relativistic electron beam ($I_{max} \sim 20$ kA, $E_{max} \sim 1$ MeV, $\tau \sim 50$ nsec, diameter = 3 cm) was injected into a vacuum chamber through the foils 5 and 6. The aluminum foil 5 was the anode foil of the accelerator. A dielectric film 6 was placed several millimeters from it [a 6-μm-thick Teflon film coated with a layer of deuterated polyethylene $(CD_2)_n$ approximately 10 μm in thickness]. The electron beam and the accelerated ions are received by the mobile graphite collector 7, connected to the anode of the accelerator through return conductors. The accelerator's diode and the vacuum chamber were placed in a 10-kOe external longitudinal magnetic field.

In the experiments the accelerated deuterons were recorded from the products of the nuclear reaction $^{12}C(\alpha,n)^{13}N(\beta^+)^{13}C$ in the graphite collector. The number of N^{13} nuclei, which were the positron source, was determined from the annihilation γ-quanta by the coincidence method using two scintillation counters with a NaI(Tl) crystal. The total number of neutrons produced in the reaction was determined by the activa-

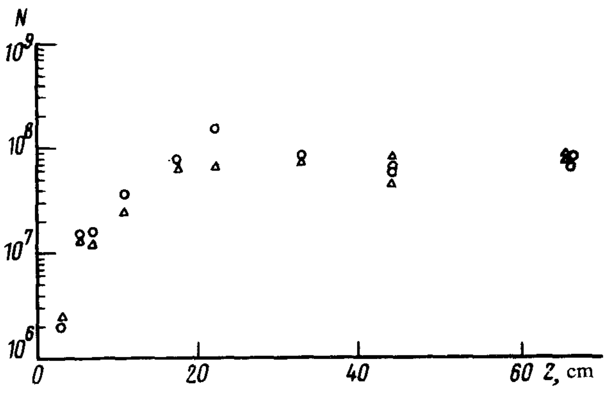

FIG. 2. Dependence of the number of nuclear reactions N on the distance between the graphite collector and the anode foil; ●, activation detector; ▼, $\gamma-\gamma$ coincidence counter.

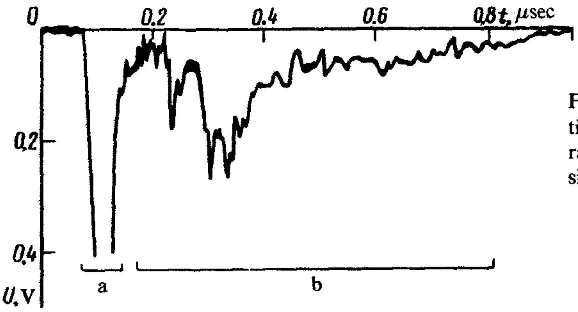

FIG. 3. Oscillogram of the signal from the time-of-flight neutron detector: a, hard x-ray radiation from the accelerator; b, neutron signal.

tion method. A silver foil radioactive indicator was placed into a paraffin neutron moderator having the geometry of a long counter.[4] The detectors was calibrated by radioactive sources before the experiment. The neutron pulse was also recorded by the time-of-flight detector which was situated 4 meters from the graphite collector. This was accomplished by recording the recoil protons in a plastic scintillator placed into a lead container that weakened the hard bremsstrahlung radiation of the accelerator. By measuring the time of flight of the neutrons from the collector to the detector, we were able to determine their energy spectrum and then to estimate the energy spectrum of deuterons. The other method of determining the energy of the accelerated deuterons was based on measurement of the relative activity of separate parts of the graphite collector, which were covered by aluminum foil of different thickness (filter method). The measured radioactivity of graphite was compared with the calculated radioactivity for different energies of deuterons transmitted through the filters. The measurements were performed with the help of a differential collector, which was also used to determine the angular divergence of the accelerated deuteron beam.

The main results of the experiment are as follows. A cloud of oscillating relativistic electrons was formed near the anode foil of the accelerator as a result of injecting a relativistic electron beam with a 20-kA current that exceeded the limiting vacuum current (4 kA). A plasma layer is formed near the surface of a dielectric film by passing a REB through it.[5] Under the influence of the cloud's gas kinetic pressure this layer expands, thereby accelerating the ions. The energy of the ions increases in proportion to the expansion of the layer. Figure 2 shows the dependence of the number of radioactive ^{13}N nuclei (triangles) and of the total number of neutrons (circles) on the distance z between the collector and the accelerator's anode foil. It can be seen that the number of nuclear reactions initiated by deuterons increases to 10^8 per pulse with the variation of z from 3 to 20 cm, and then remains practically constant. Analysis of the accelerated deuterons according to the energies using the filter and the time-of-flight methods shows that at $z < 10$ cm we recorded ions, whose energy was not higher than the initial energy of the beam electrons. The energy of the accelerated deuterons increases with increasing distance z. At $z \geqslant 20$–30 cm the deuteron spectrum extends to the energy of 4–7 MeV. The signal from the time-of-flight detector at $z = 20$ cm is shown in Fig. 3 in which a signal produced by neutrons appears after the first peak caused by the γ radiation of the accelerator. This signal allowed us to reconstruct the energy spectrum of both the neutrons and the deuterons. The main part of the accelerated deuterons has an energy of $\leqslant 1$ MeV. About 10% of the deuterons acquire higher energies, and their energy spectrum extends up to 4–7 MeV. A 20 to 30-cm scale is characteristic for acceleration of deuterons. The total number of deutrons with energy $\geqslant 0.4$ MeV amounts to 10^{14} particles per pulse. Using a 10-μm-thick polyethylene film as a dielectric in the anode assembly, we recorded 2×10^{14} accelerated protons per pulse. The shape of the current pulse of the protons was determined from the instantaneous γ radiation from the Teflon target by using a method similar to that described in Ref. 6. The maximum proton current amounted to 1.5 kA, which indicates that the acceleration of ions, which is much higher than that produced by injecting the REB into a gas[7] and which is comparable with the efficiency obtained by using Luce diodes[8] and a reflex tetrode,[5,9] is highly efficient.

To determine the angular divergence of the beam of accelerated ions, we measured the variation of the radial profile of the activity of the graphite target as a function of the distance z. It was established that the cross-sectional area of the graphite target, which has the activity, exceeds slightly the diameter of the REB, and the angular divergence of the obtained ion beam amounts to 2°–3°.

Thus, we showed experimentally that a highly efficient collective acceleration of ions is possible by a cloud of oscillating relativistic electrons.

The authors are sincerely grateful to D. D. Ryutov for his interest in this work and for useful discussions and to A. V. Arzhannikov, V. V. Konyukhov, and V. N. Rotaev for their help with the experiment.

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