Collective "gasdynamic" acceleration of heavy ions

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We report results of experiments on collective acceleration of heavy ions (mainly carbon) by a "gasdynamic" method. The ions are accelerated along a longitudinal magnetic field by the energy of a relativistic electron beam (1 MeV, 20 kA, 50 nsec) injected in vacuum through a sandwich of a conducting foil and a dielectric film. A plasma, the source of the accelerated ions, is produced above the film by the action of the oscillating electrons. If a fluoroplastic (Teflon) film is used in the sandwich, the ion beam consists of carbon ions with unequal charges. The spectrum of the accelerated ions is measured, the ion current and the number of accelerated particles are determined, and the acceleration efficiency is estimated. When a CsI film was deposited on the dielectric film, ions with atomic weight $A \approx 130$ were observed in the ion beam. The obtained acceleration efficiency is compared with the theoretical value.

1. INTRODUCTION

In earlier experiments[1–4] it was shown that it is possible to obtain a dense cloud of oscillating relativistic electrons, and to accelerate collectively with high efficiency light ions with the aid of this cloud by a "gasdynamic" method.[5–7] The beams obtained in Refs. 4 and 8 by this method contained, besides light ions, also heavy ions ($A = 12 - 16$). Both from the physical point of view, and in connection with the possible application of high-power ion beams, particularly for plasma heating in solenoidal systems,[6] it is of interest to obtain and investigate high-power pulsed beams of heavy ions.

Collective acceleration of heavy ions with the aid of high-current relativistic electron beams (REB) by other methods were investigated in a number of experiments (see, e.g., Refs. 9 and 10). As a rule, the acceleration efficiency of these methods is relatively low. In the "gasdynamic" scheme the acceleration efficiency can in principle be independent of the masses of the accelerated particles, provided that the conditions are such that the energy lost in the anode foil is negligible compared with the energy lost by the REB to ion acceleration.[7–11]

Heavy-particle beams of sufficient efficiency can be obtained by direct (rather than collective) acceleration methods (reflecting systems, magnetically isolated diodes, and others),[12–14] with the ion energy dependent on the applied voltage. In "gasdynamic" acceleration the ions acquire a broad energy spectrum. The energy of some of the ions exceeds by several times the voltage applied to the diode, and this can be of interest for some applications. It appears that, to obtain with high efficiency, dense beams of heavy ions the "gasdynamic" procedure can be preferable. From the experimental point of view, to obtain acceleration by this method it is necessary to produce a dense cloud of oscillating electrons as well as a plasma layer consisting of heavy ions.

In this paper we present the results of an experimental study of the collective acceleration of heavy ions by the "gasdynamic" method, determine the characteristics of the accelerated-ion beams, and estimate the acceleration efficiency.[1)]

2. EXPERIMENTAL SETUP AND MEASUREMENT METHODS

The experiments were performed with the "KRAB" apparatus.[2–4] A schematic diagram of the experiment is shown in Fig. 1. The REB was shaped in a vacuum diode consisting of a graphite cathode 1 and a thin anode foil 2 (aluminized lavsan polyester 6 μm thick). The parameters of the REB were: $E_{max} \approx 1$ MeV, $I_{max} \approx 20$ kA, $\tau \approx 50$ nsec, and diameter 3 cm. The accelerator diode and the vacuum chamber (15 cm diam) were placed in a longtudinal magnetic field up to 20 kOe, produced by solenoid 4 of length 100 cm. The dielectric film 3 placed behind the anode foil served as the source of the plasma produced by the oscillating electrons.[2)] The ions of this plasma are accelerated when the cloud of relativistic electrons, which oscillate near the anode foil and the dielectric film, expands into the vacuum along the magnetic field. The anode foil was fluoroplastic [Teflon, $(CF_2)_n$] 5 μm thick. Ions with $A \approx 12$ were accelerated from a plasma produced on the surface of this film. To obtain ions with $A \approx 130$, the same film was coated with a layer of cesium iodide (CsI) 5–10 μm thick. The layer was produced by evaporating an iodine solution of CsI poured on the fluoroplastic surface.

In the experiments we monitored the REB parameters (diode voltage and current, vacuum current) and carried out the diagnostics of the ion beam. The ion current and its radial distribution were measured with Faraday microcups in a distorted magnetic field (see Ref. 4). The energy spectrum

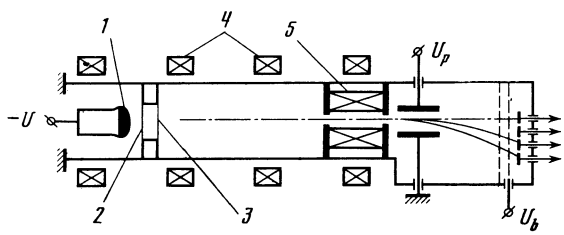

FIG. 1. Experimental setup: 1—graphite cathode; 2—anode foil; 3—dielectric film, 4—solenoid; 5—copper cylinder, U_p—analyzing voltage, U_b—bias voltage.

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and the mass composition of the ion beam were determined with an electrostatic analyzer. Prior to entry into the analyzer, the ion beam was "rid" of the accompanying electrons by passage through a copper cylinder 5 in which the magnetic field was greatly decreased. The ions passed next through a collimator, were deflected in a transverse electric field, and gathered by five collectors. The distance from the anode unit of the accelerator to the collectors was 150 cm. The particle energy was determined from the deflection in an electric field, and the mass (or charge) from the time of flight. The collectors were covered by two grids. The outer grid (relative to the collector) served as a screen and was at zero potential. A bias could be applied to the other grid. At positive bias ($U_b = +100$ V) on this grid the ion currents were measured in a secondary-emission regime. In this case the collector current was $I_{col} = I_i + I_{se}$, where I_i is the ion current and I_{se} the secondary-electron current. When the secondary emission was suppressed ($U_b = -100$ V), the true ion current was measured. The reversal of the bias polarity made it possible to determine the secondary-emission coefficient for the heavy ions as a function of the energy under the actual experimental conditions. The equivalent current of the neutral particles passing through the analyzer without being deflected in the electric field was estimated from the secondary-electron current and from the measured secondary-emission coefficient.

3. EXPERIMENTAL RESULTS

The time-of-flight analysis of the signals obtained with the electrostatic analyzer (see Fig 2a) has shown that the peaks observed on the oscillograms correspond to carbon ions with various charges. No fluorine ions from the dielectric film were recorded. Hydrogen ions were recorded only in isolated shots (apparently as a result of accidental contamination of the film surface). The observed ion-beam composition is similar to that observed in experiments[17] with a magnetically isolated diode. In all probability, the resultant mass composition of the accelerated ions is determined by the composition of the plasma produced on the dielectric-film surface. It appears that the number of positive fluorine ions on it is much smaller than the number of carbon ions, a rather natural situation, since fluorine has a higher ionization potential. Furthermore, fluorine is an electronegative element, so that positive fluorine ions can become rapidly neutralized by electron capture and have no time to participate in the acceleration process. Nor can we exclude the possibility of formation of negative fluorine ions that cannot be accelerated in the direction of the electron-cloud expansion. The ion beam obtained from the plasma produced on the fluoroplastic surface consists therefore mainly of carbon nuclei.

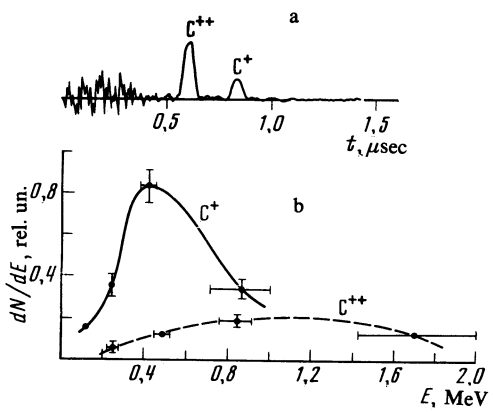

FIG. 2. Oscillogram of signal from the collector of an electrostatic analyzer recording ions with $E_i/Z = 240$ keV (a) and distribution of carbon ions in energy (b).

The spectra of the singly- and doubly-charged carbon ions, obtained by reduction of the analyzer oscillograms, are shown in Fig. 2b. It can be seen that the carbon ions have the broad energy spectrum typical of "gasdynamic" acceleration and similar to the energy distribution previously obtained for protons and neutrons (see Refs. 2–4). It follows from the form of the spectrum as well as the time-of-flight measurements that the ion energy is apparently proportional to their ionization multiplicity. This means that the multiply charged ions are contained in the plasma produced on the surface of the dielectric film and are not produced in the course of acceleration and propagation of the ion beam. The ion beam contains $\approx 60\%$. C^+ ions and $\approx 30\%$ C^{2+} ions. In individual shots we recorded also C^{3+} ions. A noticeable fraction (several percent) of the ion beam constitutes neutral particles. The equivalent current of the neutral particles was measured with a collector that gathered the particles that were not deflected by the analyzer. The signal appeared only when the collector operated in the secondary-emission mode and had an appreciable delay (~ 0.3 μsec) at a duration of ~ 1 μsec, in analogy with the carbon-ion current.

To prove that the signal observed is really due to fast heavy atoms and not, say, to slow hydrogen atoms, control experiments were performed with a hydrogen-containing film placed in the anode unit of the accelerator. What was accelerated in this case was mainly hydrogen (see also Ref. 4) and the character of the "neutral" current was strongly altered. The delay, duration, and amplitude of the signal decreased. The hydrogen-atom spectrum obtained by time-of-flight analysis agreed with the one previously obtained from an analysis of the ranges of fast hydrogen atoms in nuclear emulsion.[4] It can thus be concluded that the neutral-particle beam observed in the experiments with a fluoroplastic film in the anode unit consists of carbon atoms. Estimates show that the neutral particles observed in the ion beam may be due to charge exchange of the carbon ions with the residual gas in the drift chamber.

To determine correctly the energy spectrum of the ions, account must be taken of the energy dependence of the ion angle spread at the entrance into the analyzer. The angular distribution of the ion beam entering the analyzer was determined by measuring with a collector the spread of the ion beam after passing through the region of nonadiabatic variation of the magnetic field. The scheme of these measurements and the angular distribution obtained at a fixed instant of time (in other words, at a fixed ion energy) are shown in Fig. 3. The angle spread of the carbon ions amounted according to these measurements to $(\overline{\theta}^2)^{1/2} \approx 3°$ at an energy 0.5–1 MeV and increased with decreasing ion energy. These measurements yield the upper bound of the angle spread of

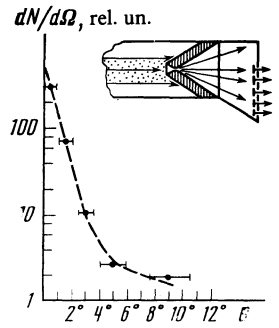

FIG. 3. Angular distribution of carbon ions ($E_i \approx 0.5$ MeV).

the beam in the drift chamber, since the ions passing through the region of the abrupt change of the magnetic field acquire an additional angle spread $\theta_0 \sim \Delta l / R_i$, where Δ l is the scale of variation of the magnetic field, and R_i is the ion Larmor radius. We note that the instrumental angle spread θ_0 can contribute to the dependence of θ on the energy $\theta_0 \propto 1/E_i^{1/2}$).

The radial distribution of the carbon-ion current density was measured in one shot using five identical Faraday cups with distortion of the magnetic field. The measurement setup is shown in Fig. 4, and the pickup is described in Ref. 4. The figure shows also the radial profile of the accelerated-ion current density at a distance 72 cm from the anode unit of the accelerator at the instant of time $t = 300$ nsec. It can be seen that the ion-beam radius is close to the REB radius (1.7 cm). This points to a small ($\approx 2°$) angular divergence of the ion beam as it moves through the magnetic field. It can be concluded from the measurements of the angle spread of the beam after nonadiabatic extraction from the magnetic field, and from measurements of the angle divergence, that the initial angle scatter of the generated carbon-ion beam does not exceed 2–3°. Such an angle spread makes feasible a ballistic focusing of the ions to obtain atomic beams with high equivalent current density.[18]

Measurements of the radial profile of the ion-current density yielded the total ion current of the accelerated carbon ions, as well as their total number. Figure 5a shows an oscillogram of the signal from the Faraday cup located at the center of the chamber. The ion current shown by this oscillogram is positive. The negative spike at the start of the oscillogram is due to the vacuum electron current that penetrates partially into the Faraday cup. The observed shape of the ion current can be explained on the basis of the measurements of the spectrum and composition of the ion beam. Assume that ions having the spectrum and charge composition shown in Fig. 2 are produced instantaneously and propagate next freely along the drift chamber. This is a natural assumption, since the REB duration is much shorter than the ion time of flight to the recording point. The ion-current shape calculated from the ion spectrum and from the time of flight is shown in Fig. 5b. The first ion-current peak corresponds to C^{2+} ions that reach the collector ahead of the C^+ ions (the second peak on the oscillogram). On the whole, the measurements of the shape and magnitude of the ion current (time-of-flight measurements) and of the ion spectrum are in good agreement.

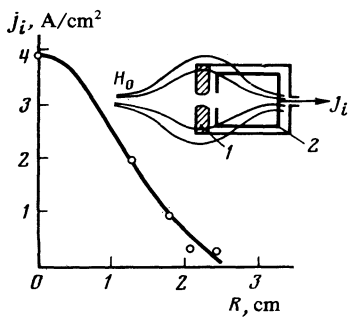

FIG. 4. Radial distribution of the ion-current density j_i: 1—copper disk, 2—Faraday cup.

The absolute value of the ion current depends on the distance between the anode unit and the recording point, and amounts to ~50 A at a distance 72 cm. According to estimates, the carbon-ion current near the anode foil can reach 1 kA. Since the ions have a broad spectrum, the duration of the ion current also increases with increasing time of flight. The total number of the accelerated carbon ions was determined from the charge recorded by the Faraday cup, with allowance for the charge composition and for the radial distribution of the ion-current density. The number of hydrogen ions accelerated per pulse was $(0.7–2)\times 10^{14}$. The acceleration efficiency was defined as $Q_i/Q_{\text{REB}} - Q_{\text{vac}}$), where Q_i is the energy carried by the accelerated ions, Q_{REB} is the energy of the injected electron beam, and Q_{vac} is the energy carried away by the vacuum current. The value of Q_i was estimated from measurements of the ion current and the spectrum of the accelerated ions, while Q_{REB} and Q_{vac} were determined from the oscillograms of the diode voltage and of the vacuum and diode currents. The estimates obtained in this manner yield for the efficiency of acceleration of heavy (carbon) ions an approximate value 10%.

Experiments were also performed on acceleration of ions having $A \approx 130$. To this end, as already noted, a thin CsI layer was depostied on the fluoroplastic film 3 (Fig. 1). In this case, an electrostatic analyzer recorded ions with $A = 130 \pm 20$, most probably Cs^+ ions (iodine, just as fluorine, is electronegative and is therefore not likely to be present in the ion beam). The spectra of these ions are similar to that of the carbon ions, and the number of particles having $A \approx 130$ is several percent of that of the carbon ions.

4. CONCLUSION

We compare now the experimental acceleration efficiencies with the theoretical value for the "gasdynamic" scheme. Earlier experiments[4] have shown that the proton-acceleration efficiency is ≈50%. It was established in the present study that the carbon-ion acceleration efficiency is ≈10%. Theoretical estimates[11] lead to the following expression for the acceleration efficiency:

$$\eta = 0.77/(1+6.44\delta W/eU)\,(M/m)^{1/3},$$

where δW is the energy lost by a beam electron in one pass through the anode foil, U is the diode voltage, and M/m is

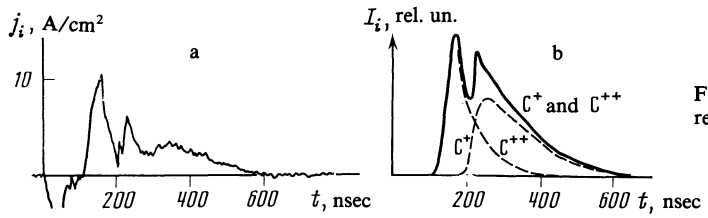

FIG. 5. Oscillogram of signal from ion-current collector (a) and ion-current shape reconstructed from the ion spectrum (b).

the ion/electron mass ratio. The quality $N = eU/\Delta W$ determines the number of passes of the electrons through the anode foil. In our experimental conditions N is estimated at 100–1000 for various relativistic-electron energies and anode-foil thicknesses. The acceleration efficiency estimated from the foregoing formula is 20–60% for protons, 3–10% for carbon, and ~1% for cesium, in fair agreement with experiment. These relations are physically explained by the fact that with increasing accelerated-particle mass the oscillating electrons lose their energy in the foil more rapidly than they transfer it to the accelerated ions. The obtained parameters of the heavy-ion beam are not the limiting values for the "gasdynamic" method. A number of means of increasing the acceleration efficiency have been proposed.[11,19]

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[1)]Some of the results of this paper were discussed at the ICPIG-15 Conference.[15]

[2)]A sandwich of two foils used earlier in reflecting systems.[16]

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