Collective Acceleration of Heavy Ions

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Results of experiments on the collective acceleration of H, He, N, Ne, Ar, and Kr ions with an intense relativistic electron beam (1.5 MeV, 30 kA, 30 ns) are reported. Using time-of-flight diagnostics, we found that the ion beam front velocity was approximately $v \approx 0.1c$ for each particle species. This corresponds to a maximum kinetic energy of 390 MeV for Kr.

The idea to use the self-fields of intense relativistic electron beams (IREB) for collective acceleration and/or focusing of positive ions was first proposed by V. I. Veksler and G. I. Budker in 1956.[1] During the past ten years, many experiments were performed at several laboratories, a variety of different methods were proposed or studied, and many theoretical papers dealing with the subject have been published. The latest developments were presented at the Third International Conference on Collective Methods of Acceleration at Irvine, California.[2] A comprehensive review of the literature may be found in the book of Olson and Schumacher.[3] A major motivation in this new area of research—apart from the interest in the physics of the observed collective effects—is the fact that the electric fields in IREB's are one to two orders of magnitude higher than in conventional accelerators. Thus, collective accelerators offer the promise of achieving high energy in a relatively small device and at a low cost when compared with conventional systems.

Collective acceleration of positive ions by injecting an IREB into a gas-filled drift tube was first reported by Graybill and Uglum[4] in 1970; The maximum energies observed in that experiment ranged from 5 MeV for protons to 20 MeV for nitrogen ions. A few years later, Luce demonstrated that collective ion acceleration also occurs when an IREB is injected into a vacuum drift tube through an insulated anode with a dielectric insert.[5] The highest energy in a collective-ion-acceleration experiment reported to date was achieved with such a Luce-type anode by Destler *et al.*,[6] who accelerated carbon ions to a kinetic energy of 170–200 MeV with use of a 6-MeV, 190-kA electron beam.[6] All collective-ion acceleration experiments so far have been carried out essentially with light ions below mass 20.

Recently, at the University of Maryland, we started a program to modify the Luce-type anode in an effort to obtain a better control of ion formation and to study the collective acceleration of heavy ions above mass 20. In the new geometry, a stainless steel anode is being used and a well-localized plasma containing the desired ion species is formed with the aid of external means behind the anode slit through which the IREB passes into the vacuum drift tube. First experiments with this new configuration in which we employed a 1-J laser to form a carbon plasma were reported elsewhere[7] (together with a crude theoretical model to explain the acceleration mechanism). Since the laser energy available was found to be somewhat too low for generation of an adequate high-density plasma from solids, we switched to a different approach using gaseous substances. Here, a small gas cloud is injected through a fast-rise puff valve just prior to the arrival of the IREB. The electrons in the leading part of the pulse ionize the gas, and a well-localized plasma is formed from which the positive ions are accelerated into the vacuum drift tube. In past experiments, we had used nuclear diagnostics to infer the ion energy. However, as the ion mass increases, the Coulomb barrier increases and nuclear diagnostics become increasingly difficult. We therefore developed time-of-flight diagnostics that employ two intercepting current probes. In this Letter, we report collective acceleration of hydrogen, helium, nitrogen, neon, argon, and krypton ions to maximum energies of about 4.7 MeV/nucleon. The krypton result of 390 MeV constitutes, to our knowledge, the heaviest ion and the highest kinetic energy observed so far in a collective-ion-acceleration experiment.

The experimental configuration used for these studies is shown in Fig. 1. An intense, relativistic electron beam (1.5 MeV, 30 kA, 30 ns full width at half maximum) is emitted from a 4-mm-diam tungsten cathode located 6 mm from a stainless steel anode. A 12-mm hole in the anode allows most of the electrons to pass into a 30-cm-diam drift tube. The gas puff valve is located

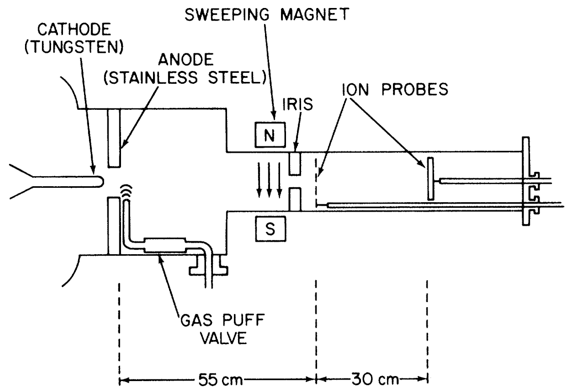

FIG. 1. Schematic of experimental setup.

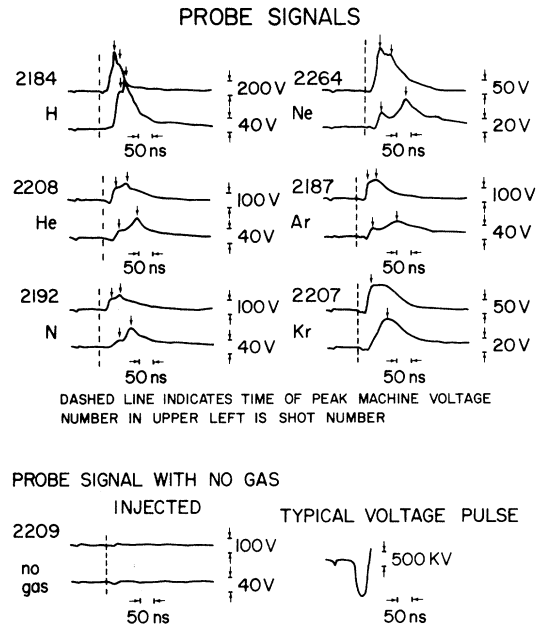

FIG. 2. Current probe signals for different ion species.

near the anode inside the drift tube, as shown in the figure. The firing of the gas valve is timed so that the gas arrives at the region of the anode slightly in advance of the beam electrons. This firing delay between the puff valve and the electron-beam injection must be increased as the atomic mass of the injected gas increases. If the gas vavle is fired too early, the gas penetrates into the anode-cathode gap and diode shorting occurs. Effective ion acceleration is not observed under these conditions. Fast-ionization-gauge measurements of the gas pressure profile versus time indicate that the gas is confined to within 2 cm of the anode at the time of electron-beam injection.[8] All experiments were performed in a background vacuum of about 5×10^{-5} Torr.

Experiments reported previously[7] showed that propagation of the electron beam downstream of the anode is not observed unless ions are present at the anode at the time of electron-beam injection. When ions are present, the electron beam propagates with a beam front velocity that is considerably less than the speed of light. The accelerated ions can be measured directly only if the electrons are deflected by a magnetic field. In our experiments, a permanent magnet ($B\approx0.2$ T over a distance of $\Delta z\approx1$ cm) and an iris (with a 2.5-cm-diam hole) were used to separate the electrons from the ions. Two intercepting current probes, spaced 30 cm apart, are used to measure the ion time of flight in the drift region. The upstream probe is a circular screen, 5 cm in diameter and 62% transparent, connected to the center conductor of a 50-Ω coaxial cable. The second proble, a distance $L=30$ cm downstream, is a solid brass disk, 7.5 cm in diameter, connected to a second coaxial cable. Both cables have identical lengths and are connected to a fast dual beam oscilloscope. The simultaneity of the firing of both oscilloscope traces is checked on each shot by fiducial signals placed by a time-mark generator on each trace of the electron-beam generator-voltage and current-monitor signals.

Figure 2 shows typical data obtained when the electron beam is fired through H, He, N, Ne, Ar, and Kr gas clouds, as well as an example of the probe signals obtained when no gas is present at the anode. These data were selected from many samples taken under various experimental conditions. They represent, in the case of the heavy ions, the fastest observed ion velocity for each species. In the case of hydrogen, we have observed higher energies in past studies; however, we included the data shown because it was obtained during the same experimental period as the heavy-ion results. We conclude that these signals represent ions of the species injected because (1) no ions are observed when no gas is injected; (2) nuclear diagnostics[8] have verified the acceleration of H, He, and N to energies above the respective reaction thresholds with the reactions $Cu^{63}(p,n)Zn^{63}$, $Cu^{65}(p,n)Zn^{65}$, $Ni^{60}(\alpha,n)Zn^{63}$, $Al^{27}(N^{14},\alpha 3n)Cl^{34m}$, and $Al^{27}(N^{14},N^{13})Al^{28}$; (3) no neutrons (due to proton reactions, for instance) above the background level were observed for injected gases heavier than neon, although the probes detected comparable ion currents for all species above hydrogen; in particular, proton-induced reactions were not observed in He and N shots and vice versa; and (4) initial results of track-etching experiments with use of metal foils of known stopping power placed in front of cellulose nitrate films indicate that the range of ions detected varies as expected with the species of injected gas. Note that Zn^{63}, Cl^{34m}, and Al^{28} have been identified by their γ spectra and respective half-lives. When the sweeping magnet is not used, negative signals typically ten times or greater in magnitude than the ion signals are observed to arrive at approximately the same time as the ions. This indicates that a strong coupling exists between electron and ion motion, which results in a beam-front propagation velocity of $v \lesssim 0.1c$.

The general features of the current traces in Fig. 2 show that the beam front, comprising the fastest ions, rises almost linearly to a first peak (or plateau), which represents ions o an intermediate energy. This peak is then in most cases followed by a second peak representing a low-energy group of particles. The travel times (between the two probes) associated with these features are summarized in Table I. Note that t_1 is the time of flight for the leading edge of the pulse (where the current signals begin to rise towards positive values), t_2 refers to the first current peak, and t_3 to the second peak. To avoid ambiguity, we marked the points that correspond to times t_2 and t_3 on the traces in Fig. 2.

The beam velocity $v = L/t_1$ represents a lower limit for the peak energy in the particle distribution. We find that, in all cases, this velocity is within the range of $\beta = v/c = 0.10 \pm 0.02$, which is quite remarkable considering the fact that the ion mass covers a range of 84:1 (Kr vs H). The peak energy that corresponds to the value of $\beta = 0.1$ is indicated in the last column of Table I for each particle species. The velocities corresponding to the time of flight t_2 of the first discernible peaks are $v \approx 0.14c$ for Ne, $0.09c$ for He, and $0.07c$ for H, N, and Ar. With regard to the current peaks, it is not at all clear that they are comprised of the same group of particles; thus, the velocities that one infers from t_2 and t_3 cannot be directly correlated with particle energies. We have presented these numbers primarily to indicate the gross features of the observed ion pulses and the fact that there is a large group of ions with considerably lower energy than those near the beam front. It should also be pointed out that the current signals on the downstream probe are considerably lower than those on the first probe. We attribute this to the radial and axial spreading of the bunch after the separation from the electron beam.

Also listed in Table I are the widths τ_1 and τ_2 of the ion pulses at probes 1 and 2, respectively. In view of the rather long tail at the trailing edge of the pulse, τ_1 and τ_2 are defined as the full-width pulse length at $\frac{1}{4}$ of the peak current. In the next two columns of the table we show the peak current I_p and the total charge Q as measured at probe 1. It is important to note that secondary electrons emitted from the probes when ions strike the probe surfaces can give positive signals that may indicate higher ion currents

TABLE I. Probe-signal analysis. t_0 is time between peak of voltage and first rise of the first probe; t_1, time between first rises of the two probes; t_2, time between first peaks; t_3, time between second peaks; τ_1, duration of the first probe pulse ($\frac{1}{4}$ height); τ_2, duration of second probe pulse ($\frac{1}{4}$ height); I_p, inferred peak current on first probe; W_m, maximum kinetic energy inferred from t_1; Q_i/Q_{He}, ratio of total charge, $\int I dt$, in ion pulse at first probe to total charge in He pulse at first probe; $Q_{He} \approx 1.8 \times 10^{-7}$ C. Times are measured in nanoseconds; the errors are less than $\pm$ 2 ns.

Shot number	Gas species	t_0	t_1	t_2	t_3	τ_1	τ_2	I_p (A)	Q_i/Q_{He}	W_m (MeV)
2184	H	30	10	15	30	40	100	32	2.0	4.7
2208	He	30	10	11	30	140	135	6.9	1.0	18.6
2192	N	28	10	15	35	150	140	5.9	0.9	65
2264	Ne	30	11	7	50	120	290	8.3	1.3	77
2187	Ar	29	10	15	70	150	245	6.9	1.1	186
2207	Kr	27	10	•••	65	140	165	4.5	1.0	390

than are actually present. In this case, however, the high-impedance current probes that are used reach signal levels of several hundred volts, and many secondaries may be recaptured. In any event, since the iris allows only a small fraction of the ions to reach the probes, and since the charge state spectrum of the heavy ions is unknown, the actual particle currents cannot be inferred from the probe data. The important features that are evident from the results shown in Fig. 2 and Table I may be summarized as follows: (1) The velocity of the fastest ions appears to be independent of the ion mass and is approximately $0.1c$, corresponding to a maximum energy of 4.6 MeV per nucleon. (2) Significantly higher probe current is observed for protons than for heavier ions, perhaps because protons have a higher charge-to-mass ratio than do even highly stripped heavy ions. (3) When the hydrogen data is disregarded, the peak current as well as the total integrated charge $\int I(t)dt$ for each ion pulse does not change appreciably with the ion mass number.

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Observation of Collisional Velocity Changes Associated with Atoms in a Superposition of Dissimilar Electronic States

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Photon-echo measurements in atomic Na perturbed by He provide the first demonstration of the contribution of velocity-changing-like effects to the transverse relaxation of atoms in superposition of two states even *when the states follow different post-collision trajectories*. The apparent anomaly that broadening cross sections derived from either absorption line widths or photon-echo relaxation measurements are smaller than the total cross section for scattering of atoms in either pure state is explained.

The ability to study sub-Doppler collisional broadening of spectral lines, which has arisen concomitant to the development of high-resolution laser-spectroscopic techniques, has stimulated a thorough reanalysis of the basic concepts of collisional-broadening theories.[1] In particular the notion that a radiating atom (i.e., an atom in a linear superposition of two energy eigenstates) can generally experience identifiable collisionally induced velocity changes has been called into question.[2,3] The basis for the objection is that subsequent to a collision, mediated by a *state-dependent interaction*, the radiating atom finds itself in a *"superposition" of two trajectories* corresponding to the paths which would have been followed by an atom purely in one or the other of the two energy eigenstates. This leads to ambiguity in the concept of a past-collision atomic velocity, and raises questions as to the velocity-changing effects expected to be seen. If the collisional interaction is identical in both eigenstates only one final trajectory is expected and the ambiguity in final velocity disappears. In such cases the velocity-changing aspect of collisions leads to effects such as Dicke narrowing[4] and nonexponential decay of photon-echo intensity versus excitation-pulse separation.[5] Recently, it has come to be widely as-

