COLLECTIVE ACCELERATION AND THE PROPAGATION OF INTENSE BEAMS INTO VACUUM*

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Introduction

Studies of the collective acceleration of positive ions by the space charge fields of intense relativistic electron beams have been pursued at various laboratories for about the last fifteen years.[1-15] Interest in this field of study has arisen in large part because of the very high electric fields (in many cases as high as 1000 MV/m) that can be generated using such beams, and the potential of these high fields to provide very high accelerating gradients for the ions.

Much of the research in the field has centered around investigation of what has been termed "naturally occurring" collective acceleration; the acceleration of ions that occurs whenever an intense, relativistic electron beam is injected into a neutral gas filled drift tube or into an evacuated drift tube with a localized ion source at the injection point. Although this terminology does a disservice to the hard work performed by those conducting this research and to the significant progress they have made in controlling and enhancing the acceleration process, it does allow us to distinguish this group of experiments from those in which an attempt is made to control the rate of ion acceleration. Usually this is achieved either by control of the beam front velocity (Beam Front Accelerators) or by controlling the phase velocity of a slow space charge or cyclotron wave grown on the beam in which ions may be trapped (Wave Accelerators).

Since the early studies by Graybill, et al.[1] and Luce,[2] significant progress has been made in our understanding of both the potential and limits of collective accelerators. The richest harvest of results has come from the "naturally occurring" collective acceleration experiments. Collective acceleration of protons to energies as high as twenty times the electron beam energy has been observed,[4] and peak proton energies in excess of 50 MeV have been achieved.[5] Heavy ions have been accelerated to energies in excess of 10 MeV/amu,[6] and Xe ion energies approaching 1 GeV have been reported.[7] Medically interesting quantities of positron emitting isotopes have been generated by collectively accelerated deuterons striking selected target materials,[8] and collective accelerators are now under consideration for application as intense neutron sources[9] and as injectors for conventional accelerators.[10] Theoretically, it is now understood that collective acceleration in such systems does not occur unless the injected electron beam current is in excess of the space charge limiting value, given approximately by

$$I_\ell = \frac{17{,}000\,(\gamma_o^{2/3} - 1)^{3/2}}{[1 + 2\,\ln(\frac{b}{a})](1 - f)} \qquad [A]$$

where γ_o is the relativistic mass factor for the electrons, a is the beam radius, b is the drift tube radius, and $f = n_i/n_e$ represents any neutralization provided by positive ions. A beam injected into a drift tube at a current level in excess of this value cannot propagate, and forms a "virtual cathode" immediately downstream of the injection point. This potential well has been shown to have a depth comparable to the energy of the injected electrons and characteristic electric field strengths of 300-1000 MV/m.

Significant results have also been achieved in both Beam Front Accelerator studies and in Wave Accelerator research. In the first category, the Ionization Front Accelerator proposed by Olson[11] has demonstrated that the motion of the potential well associated with an intense relativistic electron beam front can be controlled by providing neutralization for the beam electrons in a carefully controlled manner. In this concept, the neutralization is provided by laser ionization of a background "working gas" that cannot be ionized by the beam electrons, and the controlled motion of the beam front is achieved by careful control of the region of laser ionization in time. A second experiment in this category currently under investigation at the University of Maryland involves the control of the beam front velocity by the use of a helical conducting boundary. In this concept, a beam injected into the helix at a current level less than the space charge limit will be able to propagate at a velocity determined by the helix pitch, and a gradual change in the helix pitch can result in a controlled motion of the beam front. In experiments to date, some control over the beam front velocity has been achieved and modest increases in accelerated ion energies have been observed.[12,13] In the Wave Accelerator category, significant results have been reported by the Cornell group. Slow space charge waves with phase velocities of 0.06 c and associated electric fields of several MV/m have been grown on 300 kV electron beams propagating at current levels about half the space charge limit.[14] Details on these experiments and more recent results are reported elsewhere at this conference.

In this paper, we detail new experimental work that has relevance to both the "naturally occurring" collective acceleration experiments and to the Beam Front Accelerators. The relationship between the collective acceleration of ions and the resultant propagation of the injected electron beam into vacuum has been explored. These results have shed valuable new light on the acceleration process in localized ion source experiments, and may allow a more careful design of Beam Front Accelerators designed to further enhance the accelerated ion energy.

Experiments

The basic experimental configuration used for these studies is shown in Fig. 1. An intense, relativistic electron beam (1 MeV, 30 kA, 30 ns) is emitted from a 6 mm diameter tungsten cathode located about 12 mm upstream of a stainless steel anode. A 25 mm aperture in the anode allows almost all of the beam electrons to pass through the anode plane into the downstream drift region. The diameter of the drift tube for most experiments is 15 cm. Ions to be accelerated are produced by electron impact ionization

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(and eventually ion-ion avalanche ionization) of a localized gas cloud located immediately downstream of the anode aperture. The localized gas cloud is produced by a fast gas puff valve, whose firing delay is adjusted to ensure that the gas cloud is localized within 2-3 cm of the anode plane at the time of electron beam injection.

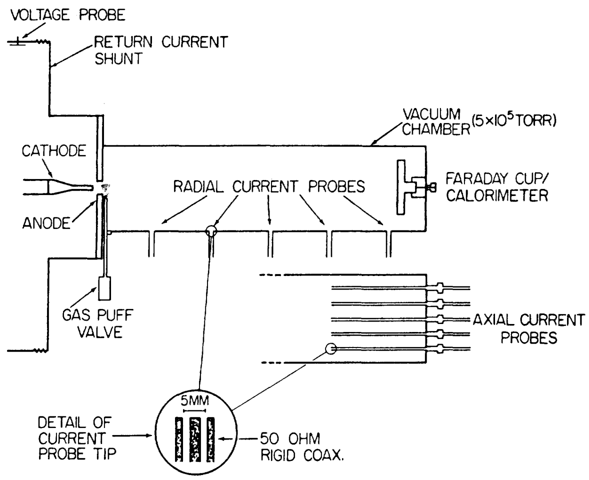

FIG. 1. Basic experimental configuration.

Previous experiments using this configuration have employed diagnostics primarily intended to explore the characteristics of the accelerated ions. In order to explore the propagation of the injected electron beam into vacuum after passing through the localized gas cloud, a number of current probes were installed to measure both the axially propagating current and the radial current at the drift tube walls at different axial positions. In addition to these probes, a 7.5 cm diameter combination Faraday cup/calorimeter was employed to measure the integrated net axial beam current and energy propagation at various axial positions. Radial confinement of the beam electrons was determined by the axial current probe array and confirmed by witness plate measurements. Radial confinement of the beam ions has also been measured using a target activation radiography technique described later in this paper.

A. Net Current Propagation. Measurements of the net current propagated to a given axial position have been measured using the Faraday cup, and the results of these experiments are detailed in two papers published previously.[15,16] When the peak pressure of the localized gas cloud is adjusted to an optimum value (about 35 mTorr), beam current many times the space charge limiting value can be propagated down the drift tube as shown in Fig. 2. In the absence of the ion source, only currents below the space charge limit are observed.

B. Measurements of the Radial Profile of the Propagating Current. Using the radial array of axial current probes shown in Fig. 1, measurements have been made of the radial distribution of the propagating current for different peak pressures of the localized gas cloud. Although we have included estimates of the inferred current densities measured by these probes, considerable uncertainty persists in the determination of their actual effective area. Results are shown in Fig. 3 for an axial position of 54 cm. Several features are worthy of mention in these results: (1) the current profile is virtually flat and the measured current levels are very low when no localized ion source is present at the injection point, (2) the best radial confinement of the beam electrons is observed at a peak gas cloud pressure of about 35 mTorr (corresponding to the optimum pressure for peak net current propagation discussed above), and (3) a hollowing out of the beam is observed when the gas cloud peak pressure exceeds this optimum value. These results have been confirmed using witness plates of various types. In fact, the witness plate measurements indicate that under the optimum conditions the radial confinement of the propagating beam can be such that our probe array cannot adequately resolve the profile.

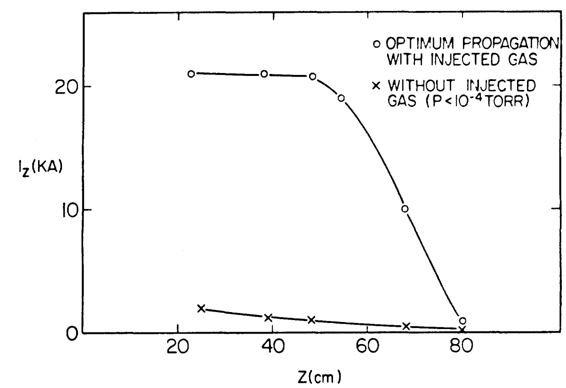

FIG. 2. Peak propagating current as a function of axial position for both optimized propagation with hydrogen injection, and without hydrogen injection.

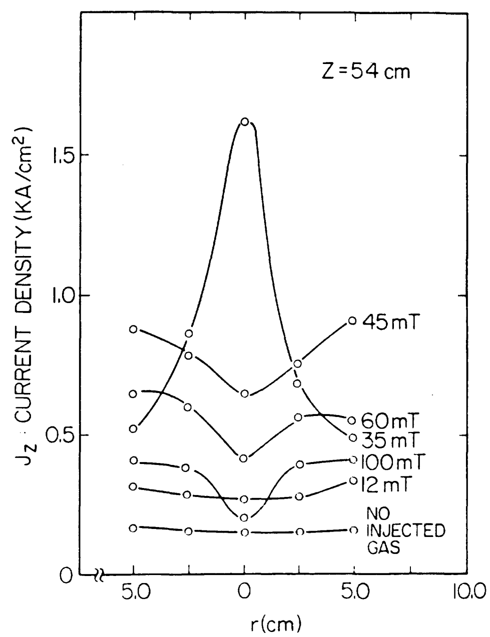

FIG. 3. Measurements of the radial distribution of the propagating current for different peak pressures of the localized gas cloud. Results for an axial position of 54 cm are shown.

C. Measurements of Radial Currents at the Drift Tube Wall. Using the array of wall probes installed to measure the radial current flowing to the walls of the drift tube, we have obtained considerable insight into the electron/ion beam propagation process. Figure 4 shows the results of measurements of this radial current at the drift tube wall as a function of the peak pressure of the localized gas cloud for three different axial positions. Several features are again worthy of note: (1) with no localized ion source at the injection point, the wall currents are quite high at the injection end of the drift tube and fall off to very low values as the probe axial position is increased; (2) for the probe closest to the injection point the observed current is lowest at a peak localized gas cloud pressure of about 30 mTorr, the same pressure at which the high downstream wall currents are observed; and (3) gas cloud pressures above the optimum result in higher wall currents at the injection end of the drift chamber.

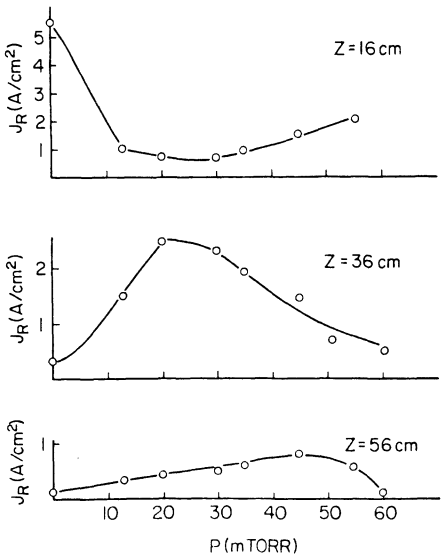

FIG. 4. Plots of wall current versus peak gas cloud pressure for three different axial positions.

D. Beam Front Velocity Measurements. The propagating beam front velocity as a function of axial position has been measured using two different techniques. In the first, the beam front velocity was inferred from the time delay between the first current peaks on adjacent radial current probes. The results of these measurements, shown in Fig. 5(A), indicate that the beam front velocity increases with axial position in a systematic manner. A second measurement of the beam front velocity was made by measuring the arrival time of the peak of the net current signal measured by the Faraday cup relative to the first rise of the diode voltage waveform for several different axial positions. Since the Faraday cup can only measure this arrival time for a single axial position on one shot, we have plotted this time versus axial position (where each point represents a different shot) in Fig. 5(B). Nevertheless, the inferred beam front velocity agrees well with the results shown in Fig. 5(A) from the wall probes. Typical current waveforms for these measurements are shown in Fig. 6.

E. Measurements of the Radial Confinement of the Ions. A photograph of the relative radial distribution of the ions in the propagating electron/ion beam has been obtained by using nuclear activation techniques. In these experiments, deuterium was used for the localized gas, and a carbon beamstop was located at a position about 50 cm downstream of the injection point. The accelerated deuterons in the electron/ion beam activate the carbon through the reaction $C^{12}(d,n)N^{13}$, and the activated beamstop is placed in contact with a sheet of Polaroid 612 film for a period of about 10 minutes. The N^{13} decays through positron emission, which exposes the film, and the resultant photograph displays the relative activity of various points on the beamstop. A typical photograph, shown in Fig. 7, indicates that under the proper experimental conditions the radial confinement of the ions can be comparable to that of the electrons, a result in contrast to the poor ion beam confinement observed in previous collective acceleration experiments where careful control over the ion source extent and density was not possible.

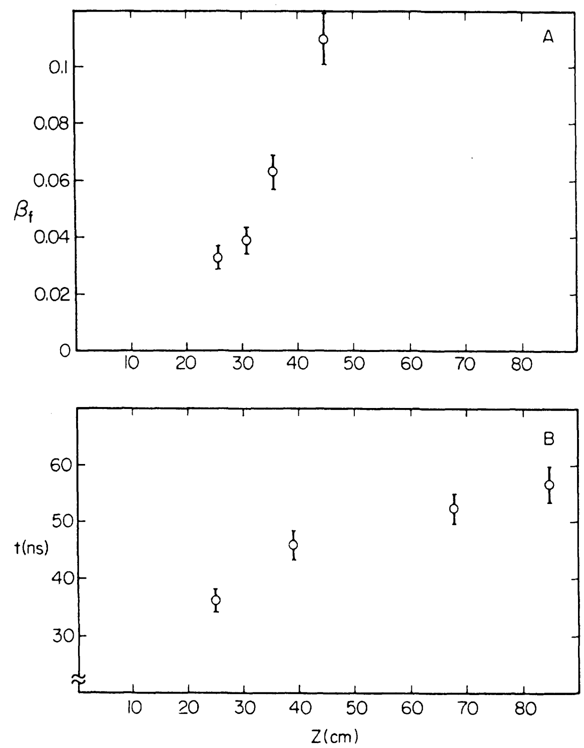

FIG. 5. (A) Beam front velocity normalized to the speed of light (β_f) as a function of Z as inferred from the time between the first current peaks on adjacent radial current probes. (B) Arrival time of axial current peak referred to the first rise of the diode voltage, as a function of Z.

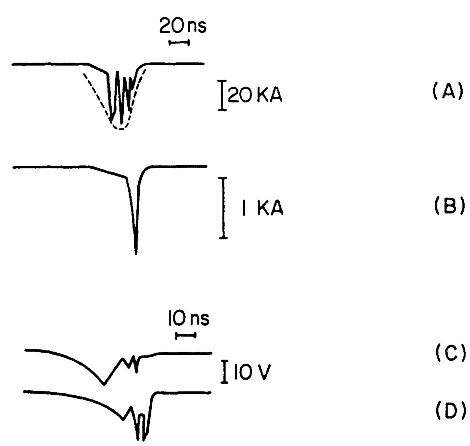

FIG. 6. Typical current waveforms. (A) Axial current profile for optimized propagation with hydrogen injection at Z = 25 cm (dashed curve indicates injected current profile), p = 40 mTorr and (B) Optimized axial current for Z = 85 cm and p = 40 mTorr. Typical radial current probe traces used for time-of-flight measurements at (C) Z = 26 cm and (D) Z = 46 cm, p = 40 mTorr.

F. Beam Propagation in a Large Diameter Drift Tube. To ensure that these effects were not strongly influenced by image currents in the drift tube walls, the study of the net current propagated to the 7.4 cm diameter Faraday cup as a function of the peak pressure of the gas valve was repeated using a 60 cm diameter drift tube. The results, shown in Fig. 10 for an axial position of 40 cm, show clearly that effective propagation can occur even when the drift tube walls are well removed from the propagating beam.

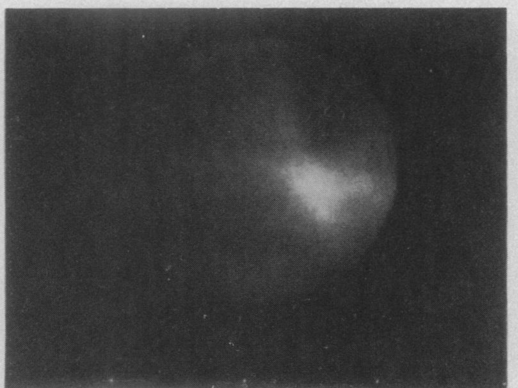

FIG. 7. Photograph of ion-induced activity of a carbon beamstop. The beamstop diameter is 5.5 cm.

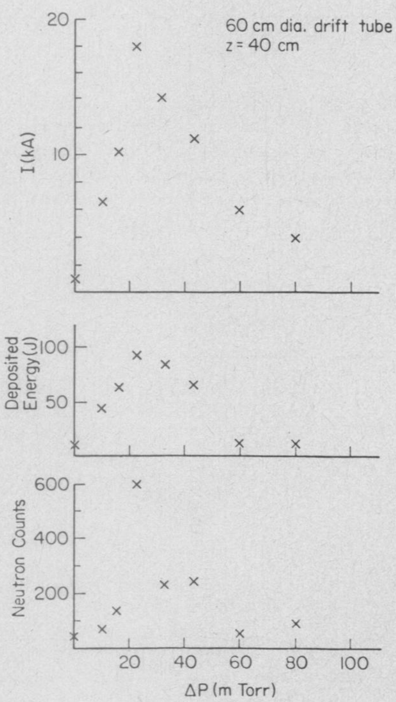

FIG. 8. Net current and energy propagated to the 7.4 cm diameter Faraday cup in a 60 cm diameter drift tube as a function of the peak pressure of the gas valve. Neutrons counts from ions striking the drift tube walls are also shown.

G. Beam Propagation in a Dielectric Lined Drift Tube. In a related experiment, the beam was injected into a 10 cm diameter drift tube lined with a thin polyethylene (CH_2) sheet. No localized gas cloud was provided as it was expected that beam electrons striking the drift tube walls could provide sufficient ionization to allow beam propagation. In these experiments, about 20 kA of electron beam current was observed to propagate to a Faraday cup 60 cm downstream of the injection point.

Discussion

In previously published work on this subject[15,16] we have proposed a simple model of the acceleration/propagation process in which the electron beam, upon injection into the drift tube at a current level well in excess of I_ℓ, forms a virtual cathode at the entrance point. The strong electric field of the virtual cathode accelerates positive ions from the plasma, and these ions form a partially charge and current neutralizing channel through which the full electron beam current arriving later in the pulse can propagate. In this manner, the virtual cathode moves steadily downstream of the injection point as the ion channel is established, and the axial extent of propagation is limited only by the pulse duration of the injected electron beam or by depletion of the source of ions at the injection point. Analytical theory supporting this concept has been reported by Reiser, et al,[17] and numerical simulations of these effects have been reported by Striffler, et al.[18]

The experiments reported herein have added substantially to our knowledge of the details of this process and have important implications for the design of Beam Front Accelerators of various types. In particular, we have shown that effective electron beam propagation into vacuum at currents far above the space charge limit can be achieved without the use of applied magnetic fields or gas/plasma filled drift tubes. We have shown that by careful control of the density of a localized ion source at the injection point the electron beam can draw out and accelerate ions into the drift region and thus provide its own neutralizing channel behind the beam front. We have demonstrated that the radial confinement of both the electrons and the ions under optimum conditions can be surprisingly good in contrast to previous experiments in which much poorer confinement of the ions was observed. We have seen that for ion source densities below the optimum the propagating beam is poorly focused, and for densities above the optimum the beam tends to hollow out.

In addition to these results, which support our previously proposed model of the acceleration/propagation process, there is evidence that the propagation process does not proceed in quite the continuous manner described above. In particular, analytical theory by Reiser, et al,[17] predicts that the beam front velocity should reach a maximum very early in the propagation process, because after a short period of acceleration the energy of the injected electrons is used entirely to bring new ions in the channel up to the beamfront velocity. The experiments, however, show that the effective beamfront velocity increases as the beamfront moves down the drift tube. In these and previous experiments, the peak ion energies observed correspond to an ion velocity in the range 0.1–0.12 c, a result consistent with the peak beamfront velocity. Moreover, radial current waveforms such as those shown in Figs. 6(C) and (D) suggest that the process occurs in a pulsed manner. As can be seen from the waveforms, the first current peaks at the two probes are followed by subsequent peaks moving at a much higher velocity. Then it appears that the process described above may occur for a short time (~ 10 ns) until the ion channel density is reduced by its expansion down the drift tube to a value such that the electron beam can no longer propagate. At this point, the virtual cathode reforms near the injection point and the process repeats itself, resulting in an initially slowly moving beamfront being "overrun" by one or more subsequent fronts. The period of pulsation observed is roughly consistent with the neutralization time for such a configuration calculated by Olson.[11]

The implications of this work to the design of Beam Front Collective Accelerators may be summarized as follows: (1) Control of the beam front velocity by providing neutralizing ions in a controlled manner can be a very effective method of achieving controlled acceleration rates and this concept should be pursued using both the "working gas" concept inherent to the IFA (see Olson[11]) and simpler controlled ionization schemes such as time-sequenced laser plasma generation, etc., (2) Any system of this type must provide neutralizing ions in numbers sufficient to ensure that depletion of the ion channel density below the level required for effective beam propagation does not occur during the period of acceleration, and (3) Concepts such as the Helix Controlled Beam Front Accelerator[12,13] that do not use neutralization effects to control the beamfront velocity must be carefully designed such that the number of accelerated ions is small enough to ensure that neutralization does not dictate the propagation process.

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References

1. S. E. Graybill and J. R. Uglum, J. Appl. Phys. 41, 236 (1970).

2. J. S. Luce, Ann. N. Y. Acad. Sci. 20, 336 (1973).

3. J. W. Poukey and N. Rostoker, Plasma Phys. 13, 897 (1971).

4. R. Adler, J. A. Nation, and V. Serlin, Phys. Fluids 24, 347 (1981).

5. R. F. Hoeberling, in Collective Methods of Acceleration, edited by N. Rostoker and M. Reiser (Harwood, NY, 1979), p. 463.

6. J. T. Cremer and W. W. Destler, J. Appl. Phys. (to be published).

7. L. E. Floyd, W. W. Destler, M. Reiser, and H. M. Shin, J. Appl. Phys. 52, 693 (1981).

8. W. W. Destler, Rev. Sci. Instrum. 54, 253 (1983).

9. R. F. Hoeberling (private communication).

10. R. J. Faehl, W. K. Peter, paper E19 at this conference.

11. C. L. Olson and U. Schumacher, in Springer Tracts in Modern Physics: Collective Ion Acceleration, edited by G. Hohler (Springer, NY, 1979), Vol. 84

12. W. W. Destler, H. Kim, G. T. Zorn, and R. F. Hoeberling, in Collective Methods of Acceleration, edited by N. Rostoker and M. Reiser (Harwood, NY, 1979), p. 509.

13. W. W. Destler, P. G. O'Shea, M. Reiser, C. D. Striffler, D. Welsh, and H. H. Fleischmann, IEEE Trans. Nucl. Sci. NS-30, 3183 (1983).

14. A. Anselmo, D. L. Fenstermacher, S. Greenwald, J. Ivers, G. Kerslick, J. A. Nation, G. Provikades, and C. E. Seyles, Proc. 5th Int. Conf. on High Power Electron and Ion Beam Res. and Tech. (San Francisco, CA, 1983), p. 448.

15. W. W. Destler, P. G. O'Shea, and M. Reiser, Phys. Rev. Lett. 52, 1978 (1984).

16. W. W. Destler, P. G. O'Shea, and M. Reiser, Phys. Fluids 22, 1897 (1984).

17. M. Reiser and C. R. Chang, submitted to Appl. Phys. Lett., 1985.

18. H. Dantsker, L. E. Floyd, and C. D. Striffler, Bull. Am. Phys. Soc. 29, 1353 (1984).