PARTICLE ACCELERATION AND INTENSE ELECTRON-BEAM FRONT VELOCITIES

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Ions are accelerated when a high-current relativistic electron beam is injected into a low-pressure gas-filled region. A correlation is observed between electron-beam front velocities in hydrogen and mean proton velocities that places an upper limit on the length of the acceleration region and indicates that the net beam-current rise is preceded by the protons after particle acceleration. The apparent field strengths in the acceleration region are $\geq (3 \text{ to } 6)\times 10^7$ V/m.

In recent experiments particles, protons through argon ions, were observed to be accelerated to MeV energies by intense electron beams propagating through low-pressure gases.[1-3] The preliminary measurements were performed to diagnose the spectra and nature of the accelerated particles. In this article we report on experiments to observe the behavior of the electron beam under ion acceleration conditions in hydrogen. Measurements were made of the beam-front propagation in the drift region and these are compared with proton data taken under the same conditions.

A pulsed electron beam was injected into a gas-filled drift chamber. Ions formed and accelerated in the chamber were analyzed downstream with a sweeping magnet and nuclear emulsions.[4] The beam entered the drift chamber through a 0.25-mil aluminized Mylar anode. The chamber was a 7.6-cm-diam copper guide pipe, 58 cm long. Three Rogowski coil fast-current probes measured net current at 2, 12, and 54 cm downstream from the anode.[5] Two different electron beam conditions were used: 0.5 MeV, 160 kA, and 1.0 MeV, 110 kA (mean energy and peak current). Electron beam pulse widths were 50 nsec full width at half-maximum (FWHM). The experiments were performed in hydrogen gas over pressures from 34 to 960 μm Hg.

Figure 1 presents beam net current data for an electron beam in hydrogen with a mean energy at injection of 1 MeV. The net current profiles for 120 μm are shown in Fig. 1(a). The electron beam front as considered here is defined to be the onset of the large net current rise. The time of the beam front arrival at 2, 12, and 54 cm is shown at t_1, t_2, and t_3. Such a definition neglects possible low currents of fast electrons which may precede the "front." Figure 1(b) shows the position of the leading edge as a function of time for 50 and 120 μm Hg. Accelerated protons were observed at these pressures. Figure 1(b) also shows that the beam front moves slowly near the anode, then a short distance downstream undergoes a rapid acceleration and travels at uniform velocity to the end of the drift chamber. The final beam front velocity (v/c) is 0.061 ± 0.007, a value much lower than the v/c of 0.94 for the injected electrons.

Figure 2 presents the final beam front velocity as a function of pressure in hydrogen for both 0.5 and 1.0 MeV. Earlier measurements of Yonas et al.[6] above 1000 μm Hg are also presented to

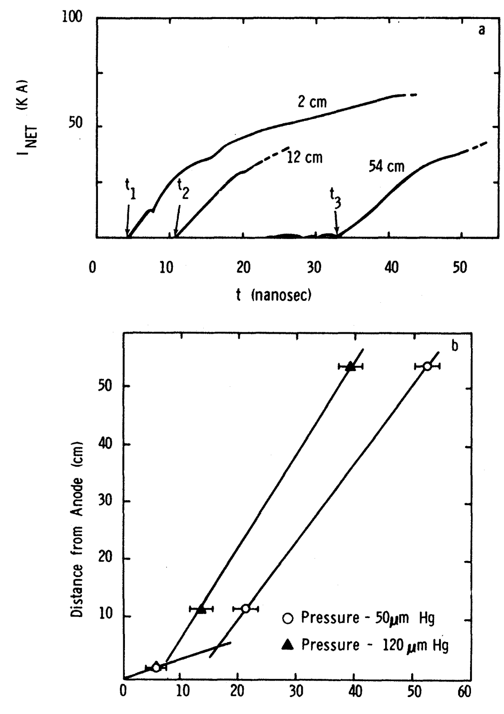

FIG. 1. Position of the electron beam front in hydrogen as a function of time after injection. (a) Net current profiles observed with Rogowski coils at 2, 12, and 54 cm downstream from the anode. Mean electron energy at injection is 1 MeV; drift-chamber pressure is 120 μm Hg. Beam front is defined here as the leading edge of the large net current rise: t_1, t_2, t_3. (b) 1-MeV data for pressures of 50 and 120 μm Hg; leading edge position as a function of time. Accelerated protons were observed at these pressures.

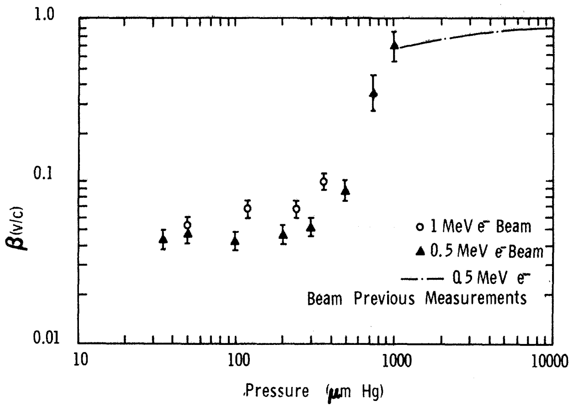

FIG. 2. Electron-beam front velocity measured between 12 and 54 cm downstream from the point of injection as a function of hydrogen pressure. Both 0.5- and 1.0-MeV data are shown. Also presented are earlier measurements of 0.5-MeV beam front velocity (see Ref. 6) that show the velocity trends at higher pressures.

show velocity trends at higher pressures. The present data show an apparent plateau in beam front velocity below 200 to 300 μm Hg, the pressure corresponding to the upper pressure cutoff for proton acceleration in hydrogen measured by Graybill and Uglum.[1]

Table I summarizes evidence for a relationship between the beam front velocity and accelerated proton velocity. The velocities of the beam front, between 30 and 250 μm Hg, and the accelerated-proton mean velocities are compared. The proton velocity appears to be the same as the beam front velocity, within experimental uncertainty. The proton data are an average of the mean velocity of the initial proton pulse taken from several experiments with the 7.6-cm-diam pipe both with and without the Rogowski probes.[7]

The rapid decrease in beam front velocity as the pressure is decreased below 1000 μm Hg appears to be related to the increase in breakdown times at low pressures where ionization is principally due to collisions. However, below 300 μm Hg, protons are accelerated and one might speculate that they, in addition to whatever precursor radiation[8] and electrons are available, provide sufficient ionization to allow the electron beam to propagate. In this view the beam front velocity would continue to decrease throughout this pressure region without accelerated protons. The proton pulse typically is well defined, being 3 to 5 nsec FWHM, containing approximately 10^{13} particles, with a momentum spread less than 10% FWHM.[1-3] Since the protons are presumably not accelerated when they are beyond the electron beam front, it seems reasonable to interpret the data of Fig. 1(b) also as an ion time history from the point that the beam velocity changes. This interpretation also allows an estimate to be made for the upper limit on the length of the acceleration region under our beam and drift chamber conditions. Using 3 to 7 cm as a maximum length from Fig. 1(b), the accelerating fields can be found from the mean energy per charge of 1.74 ± 0.18 MeV/Z for the accelerated protons. This gives accelerating fields of $\geqslant(3 \text{ to } 6)\times 10^7$ V/m.

Table I. Comparison of electron beam front velocity in hydrogen with mean proton velocity—averaged from 30 to 250 μm in Hg.

Electron beam energy (MeV)	Beam front velocity[a] (v/c)	Mean proton velocity[a] (v/c)
0.5	0.046 ± 0.005	0.045 ± 0.004
1.0	0.061 ± 0.007	0.061 ± 0.002

[a]Errors shown are statistical, ± one standard deviation.

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

[2]J. Rander, B. Ecker, G. Yonas, and D. J. Drickey, Phys. Rev. Lett. 24, 283 (1970).

[3]J. Rander, B. Ecker, and G. Yonas, Physics International Company Report No. PIIR-9-70, 1969 (unpublished).

[4]See Ref. 2 for a detailed description of the detection apparatus.

[5]Typical rise time for the 7.6-cm-diam Rogowski coils is 1 to 2 nsec. Tektronix 519 oscilloscopes were used to monitor the coils.

[6]G. Yonas, P. Spence, B. Ecker, and J. Rander, Physics International Company Report No. PIFR-106-2, 1969 (unpublished).

[7]Multiple proton pulses as described in Ref. 2 do not enter this consideration since the later pulses are separated in time from the first pulse and are lower in energy, and hence would not affect the beam front.

[8]Measurement of microwave emission of an electron beam was reported by J. A. Nation and W. L. Gardner, Laboratory of Plasma Studies, Cornell University, Report No. LPS 41, 1970 (unpublished).