# CHARGED-PARTICLE ACCELERATION BY INTENSE ELECTRON STREAMS*

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Accelerated protons and ions are observed when an intense relativistic electron stream is propagated through a gas-filled region. Several proton momentum peaks are observed for each stream pulse with a spread of $\leqslant 10\%$, consistent with our resolution. Proton energies are independent of the filling gas for $H_2$, $N_2$, and air. Total ion fluxes are $10^{13}$ to $10^{15}$ particles/stream pulse. Nitrogen-ion tracks were too short to determine the charge state and hence the energy, but estimated upper limits suggest +4 or +5, consistent with the energy-to-change ratio observed for protons.

Intense relativistic electron streams have been achieved in the past few years with the development of large pulsed power systems. A number of groups are now experimenting with ≈100-kA electron beams in the 100-keV to MeV region, and currently there is considerable interest in using these streams to accelerate charged particles, particularly as a route to less expensive accelerators and to higher energies. A large number of possible mechanisms which might be used to accelerate charged particles have been proposed, including the electron ring efforts at several laboratories.[1] Recently there has been some experimental effort toward a more direct utilization of the electron stream than in the ring approach. Plyutto et al.[2] report observing particles accelerated with a 200- to 300-keV vacuum-spark plasma; more recently, Graybill and Uglum[3] and Yonas et al.[4] observed the acceleration of positive-charged particles when propagating MeV electron streams through a gas-filled region. In these early efforts particle-energy measurements consisted of measuring the time of transit for positive pulses. Since there was some uncertainty as to the nature of the accelerated particles, and since the velocities measured by time of flight were pulse and not necessarily particle velocities, it became clear that both momentum and energy measurements for individual particles were needed. In this paper, we report on such an investigation.

Apparatus.—The particles accelerated by the electron stream were detected in two ways: current collectors and nuclear emulsion plates. We used two current collectors consisting of coarse copper screen disks placed directly in the positive beam 30 cm apart to provide time-of-flight information. Nuclear emulsion plates used in conjunction with a 3-kG magnet provided momentum, range, ionization, and multiple-scattering information for individual particles in the beam. In addition, the emulsion provided a direct measure of the flux. Ilford $K2$ plates were used in order to reduce sensitivity to the high bremsstrahlung and electron background.

Figure 1 shows the apparatus, consisting of (a) a field-emission diode, (b) the gas-filled drift region, (c) a differentially pumped region where electrons are removed, (d) a time-of-flight drift region for the positive accelerated particles, (e) two collimators defining $\pm\frac{1}{2}°$ solid angle, (f) the sweeping magnet, (g) a nuclear emulsion plate. The electron stream came from a Marx generator and coaxial transmission line system, which was coupled to the field-emission

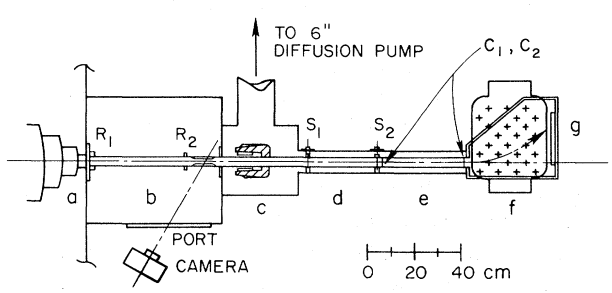


FIG. 1. Apparatus. (a) Field-emission diode with thin transmission anode (0.25-mil aluminized Mylar or 0.5-mil aluminum foil). (b) Gas-filled beam drift region with two Rogowski current probes, $R_1$ and $R_2$, to measure electron-stream current. (c) Evacuated region. Beam enters through graphite aperture. 1 kG ×5 cm magnet removes electrons. (d) Particle time-of-flight measurement; positive-charged particles collected on two screens, $S_1$ and $S_2$. (e) $\pm\frac{1}{2}°$ solid-angle collimator. (f) Sweeping magnet. (g) Nuclear-emulsion plate (100-$\mu$m Ilford $K2$ emulsion).

diode (734 Pulserad). We operated at average electron energies of 200 keV and 1 MeV, with respective peak diode currents of 200 and 160 kA. The beam pulse was typically 80 nsec long and was transmitted into the gas-filled drift region through either a 0.000 25-in. aluminized Mylar or a 0.0005-in. aluminum-foil anode window. Electron-beam information was obtained with voltage and current monitors in the diode, two Rogowski coils in the drift region, and a time-integrated photograph of the region immediately upstream from the aperture of the evacuated region.[5] From the anode to the 1.9-cm-diam graphite aperture, the beam was transported in a 3.18-cm-diam copper pipe. $R_1$, the first Rogowski coil, typically measured currents inside the guide pipe of 40 to 60 kA at a position 1.7 cm downstream from the anode, while $R_2$, positioned 40 cm downstream from $R_1$, saw currents of 6 to 8 kA. The electrons were separated from the accelerated particles by both the unneutralized space-charge forces in the evacuated region and a 1-kG×5-cm permanent sweeping magnet. The accelerated particles were then transported through the time-of-flight region and on into the spectrometer.

Experimental procedure.—The experiment consisted of a number of separate electron-beam pulses. The thin anode window and the nuclear emulsions were changed for each pulse. We used four different gases in the drift region: hydrogen, helium, nitrogen, and air. Typical gas pressures were 200 $\mu$m Hg for hydrogen and helium, and 10 to 65 $\mu$m Hg for nitrogen and air. For one pulse the anode window was changed from aluminized Mylar to aluminum foil to investigate the possibility of substantial introduction of particles from the Mylar window. Average electron energies of 200 keV and 1 MeV were used.

Results and discussion.—The emulsion data indicate that both protons and slightly ionized gas atoms are accelerated by the electron stream on each pulse. The acceleration of protons on pulses where $H_2$ is not the filling gas is presumably due to vacuum-system impurities and outgassing from the nuclear-emulsion plate. The presence of protons on each pulse is of interest in understanding the acceleration process since they have a unique charge-to-mass ratio.

Figure 2 presents data from a typical pulse, 12 419, taken at a nominal electron energy of 1 MeV, propagating in air at 10 $\mu$m Hg. Figure 2(a) is the proton momentum spectrum measured

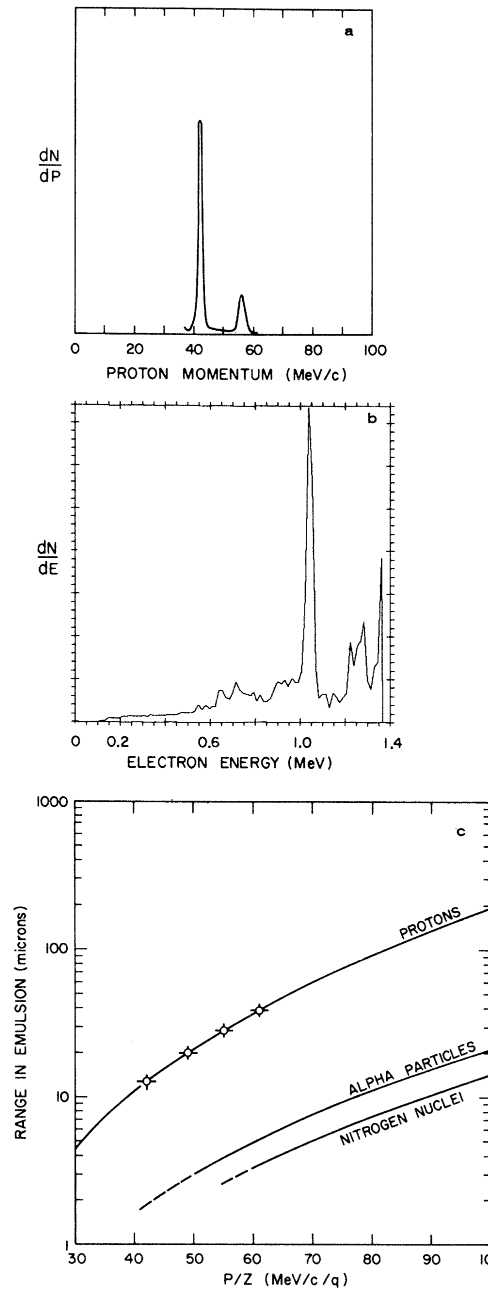


FIG. 2. Data for pulse 12 419. (a) Observed proton momentum spectrum. The peak width is consistent with the collimator resolution. (b) Typical electron energy spectrum at 1-MeV nominal voltage. (c) Particle ranges in emulsion versus momentum per charge. The solid lines are known values for different particles. The data points are measured ranges for each momentum. Error bars represent spectrometer resolution and emulsion range scatter. In addition to the tracks displayed there were a number of short tracks $\leq 2.5$ $\mu$m long which are interpreted as slightly stripped gas ions. These begin to appear above 40 (MeV/$c$)/$z$ on pulse 12 419.

with the emulsion spectrometer; the widths of the peaks are consistent with the resolution of the collimator. Figure 2(b) shows a typical 1-MeV electron-stream energy spectrum.

It should be noted that there is a striking resemblance between the electron energy spectrum [Fig. 2(b)] and the observed proton momentum spectrum [Fig. 2(a)]. However, if one looks at the 200-keV data where the maximum electron energy is ≈280 keV, proton momenta of 40 MeV/$c$ are observed, so that no simple relation seems to exist between electron energy and proton momentum.

Figure 2(c) is a plot of particle range measured in the emulsion for this pulse as a function of momentum per charge. The solid lines represent different particles; the data points are particles sampled from pulse 12 419. In addition to the proton tracks shown on Fig. 2(c), there were a number of very short tracks, essentially dots on the emulsion surface. Scanning across the plate axis it was possible to resolve the collimator spread in dot densities; it seems reasonable then to interpret these dots as particle tracks. An upper limit on the track ranges is $\leq 2.5\ \mu$m. We observe them on both $N_2$ and air pulses, but not with $H_2$ or He. Assuming that these tracks were made by nitrogen and oxygen ions we can use the upper limit on the range to determine a maximum ionization state. Using the measured momentum/charge ($p/z$) of the low-momentum peak in the ion spectrum we find an upper limit of +4 or +5 for the degree of ionization.

At 1 MeV, the $p/z$ spectrum for $N_2$ and air is very broad and lacks the narrow peaks of the proton data. Typically the ion spectra rise from a sharp cutoff at 40 to 60 (MeV/$c$)/$z$ to a peak at 50 to 80 (MeV/$c$)/$z$; the spectra then slowly drop three orders of magnitude to the spectrometer cutoff at 900 MeV/$c$/$z$. Because the resolution at 900 (MeV/$c$)/$z$ is ±250 (MeV/$c$)/$z$, there is considerable uncertainty in particle momenta. The track lengths in this region are $\leq 2.5\ \mu$m, so they must be due to singly ionized molecules. In addition to the decreasing resolution at high $p/z$, the lack of narrow peaks in the ion spectra can be explained by the existence of accelerated ions with a number of different charge states. Further broadening of the ion spectra might be due to the substantially lower ion velocities when compared with protons; this low velocity would make them more subject to beam variations over time.

Table I is a summary of the pulses using nuclear-emulsion plates. All the pulses presented in the table used the aluminized Mylar anode except No. 12 418, where aluminum foil was used. There was some concern that the narrow proton momentum widths were due to protons accelerated out of the Mylar and so aluminum foil was substituted for the usual anode material. No significant change was observed.

The observed flux into the collimator varied from $10^{12}$ to $10^{14}$ ions/cm$^2$ sr over all momenta, and from $10^{12}$ to $10^{13}$ protons/cm$^2$ sr per proton momentum peak. If we assume that the particles are produced approximately into a steradian and from a 10-cm$^2$ source (the approximate area of the electron stream), each momentum peak would represent total proton fluxes of $10^{13}$ to $10^{14}$ protons, with corresponding total ion flux of $10^{13}$ to $10^{15}$.

Table I. Nuclear emulsion plate data summary. Peak 1 and peak 2 refer to the first two proton momentum peaks observed on the emulsion plate.

| Pulse No. | Nominal electron energy (MeV) | Gas | Pressure ($\mu$m) | Proton data: Mean momentum (MeV/$c$) Peak 1 | Peak 2 | Approx. flux ($10^{12}$ protons/cm$^2$ sr) Peak 1 | Peak 2 | Heavy ions approx. total flux ($10^{12}$ ions/cm$^2$ sr) |
|---|---|---|---|---|---|---|---|---|
| 12 383 | 1 | Air | 65 | 57.5 ± 2.9 | <36.0 | 1.1 | ··· | a |
| 12 418 | 1 | $N_2$ | 25 | 52.0 ± 2.6 | 46.1 ± 2.3 | 1.3 | 12.6 | 1.8 |
| 12 419 | 1 | Air | 10 | 56.2 ± 2.8 | 42.5 ± 2.1 | 0.8 | 4.2 | 54.0 |
| 12 420 | 0.2 | $H_2$ | 200 | 39.6 ± 2.0 | <36.0 | 5.1 | ··· | ··· |
| 12 421 | 1 | $H_2$ | 200 | 55.0 ± 2.8 | <36.0 | 0.3 | ··· | ··· |
| 12 423 | 0.2 | He | 200 | <36.0 | <36.0 | ··· | ··· | ··· |

[a]Stainless-steel foil was placed over the emulsion on this pulse with an equivalent range of 13.5 $\mu$m of emulsion. Observed ion ranges were $\leq 2.5\ \mu$m on uncovered plates; so this plate was insensitive to heavy ions.

In addition to emulsion data, we also measured time of flight with the current collector screens. We generally observe two large positive pulses 5 to 8 nsec wide and 10 nsec apart. The first pulse is generally lower in current than the second by a factor of 4. The $\beta$ of these pulses correspond to the proton peaks in the spectrometer, with the $\beta$ of second pulse lower than the first. With gases other than hydrogen in the drift region, the pulses are followed by a positive tail 60 to 80 nsec long. Presumably the tail contains accelerated gas ions. If the particles in the first pulse are assumed to be accelerated near the anode, then we can relate the time of acceleration of the first proton pulse to the arrival of the electron stream at the first Rogowski coil. Delays of 35 $\pm 5$ nsec for air at 10 $\mu$m and $5 \pm 5$ nsec for hydrogen at 200 $\mu$m are found, consistent with the time required for force neutralization of the electron beam as also observed by Graybill and Uglum.[3]

In summary, we observe that protons and gas ions are accelerated when a relativistic electron stream is propagated through a gas-filled region; the protons are accelerated in multiple pulses, with momentum spreads $\leq 10\%$; the proton momentum is the same for $N_2$ and $H_2$ filling gases; the proton momentum but not flux is reproducible from pulse to pulse within 10%, with total accelerated ion fluxes of $10^{13}$ to $10^{15}$ ions/electron stream pulse. If the nitrogen ions comprising the low-momentum peak are +4 or +5, which is consistent with our upper limit on track length, then it appears that they have the same energy-to-change ratio as the lowest proton momentum peak observed with the spectrometer, consistent with the time-of-flight data of Graybill and Uglum.[3] It would appear that this dependence upon $z$ and the narrow proton momentum spectrum place severe constraints on an ion acceleration model.

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# DUALITY, QUARKS, AND INELASTIC ELECTRON-HADRON SCATTERING*

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A model for high-energy hadron reactions is proposed, incorporating ideas borrowed from the duality scheme of strong interactions and from the quark version of the parton model for inelastic electron-hadron scattering. Experimental tests of the model are discussed.

Some time ago we proposed a simple model[1] for inelastic electron-hadron scattering, in which we applied ideas borrowed from strong interaction dynamics[2] to the absorption of virtual photons by hadrons. The model suggested that (i) the Pomeranchuk singularity dominates high-energy photoabsorption cross sections; (ii) the $q^2$ dependence of the Pomeranchukon contribution is different from that of the other trajectories; and (iii) as $q^2$ increases, contributions of $s$-channel resonances or (equivalently) "ordinary" $t$-channel exchanges decrease very rapidly, leaving the Pomeranchukon term as the only important term even at relatively low energies.

A different model was developed by Bjorken and Paschos.[3,4] These authors view high-energy