Collective acceleration of carbon ions to 170 MeV

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The collective acceleration of carbon ions to a peak energy in the range 170–200 MeV has been achieved using a 6-MeV 190-kA 100-ns electron beam pulse generated by the Pulserad 1590 facility at Kirtland Air Force Base. Accelerated ions were detected using nuclear activation techniques.

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We would like to report the collective acceleration of carbon ions to energies in excess of 170 MeV using a 6-MeV 190-kA 100-ns electron-beam pulse. The use of the collective fields of dense electron clusters to accelerate ions to high energies was first suggested by Veksler in 1967.[1] Substantial interest has developed around the collective acceleration of protons and heavier ions in evacuated drift tubes using linear (nonrotating) electron beams since early work by Luce[2] demonstrated that protons with energies many times greater than the electron-beam energy are observed when an intense beam is fired through a small hole in a polyethylene dielectric anode. Studies at several laboratories[3-6] have substantially verified and expanded this work.

Several theoretical models have been proposed to explain this acceleration process. The formation of a vritual cathode downstream of the anode was predicted[7,8] to occur when the injected electron-beam current exceeds the limiting current for propagation of an electron beam of radius a in a grounded cylinder of radius R. This limiting current is given by

$$I_l = \frac{17\,000(\gamma_0^{2/3} - 1)^{3/2}}{[1 + 2\ln(R/a)](1 - f)} \quad \text{(A)},$$

where γ_0 is the relativistic mass factor for the electrons after acceleration in the anode cathode gap and $f = Zn_i/n_e$ is the fractional neutralization provided by ions. Hoeberling *et al.*[6] has demonstrated experimentally that effective collective acceleration is not observed in such system when the injected current is less than or comparable to this limiting value. The transient overshoot of the depth of the potential well associated with the virtual cathode to values of two to three times the peak diode voltage, and the subsequent collapse and movement of the virtual cathode when ions are introduced, have been used by Olson[9] to explain the collective accleration of ions in a neutral gas background. The ion energies observed in the evacuated systems, however, are too high to be explained solely on this basis, and several possible mechanisms have been advanced in an effort to explain the favorable experimental results. Destler *et al.*[10] have suggested that, in these systems, the early part of the electron beam

forms a dense plasma that is initially well confined to the anode region. The subsequent diffusion of this plasma into the downstream region shold allow a movement of the virtual cathode downstream, and enhanced acceleration may be expected of those ions that are trapped and accelerated by the electric fields associated with the moving potential well. Zucker *et al.*[11] have proposed that the dielectric anode acts as a cavity resonator and that ions are accelerated by resulting high electric field gradients in the anode hole. Luce *et al.*[12] have suggested that some of the acceleration effects may be attributable to dense plasma vortex filaments.

Although initial studies of collective ion acceleration in these systems have concentrated on proton acceleration, the greatest potential for collective acclerators lies in the acceleration of heavy ions. The experiments reported here indicate that heavy ions can be collectively accelerated to energies comparable to those achieved in conventional accelerators of moderate size, at particle current levels that are orders of magnitude greater than those achieved by conventional means.

The experiments reported here were performed using the Pulserad 1590 facility located at the Air Force Weapons Laboratory, Kirtland Air Foirce Base, Albuquerque, N.M. The PR1590 is a Marx/Blumlein type of electron accelerator and produces an intense beam of electrons (6 MeV, 190
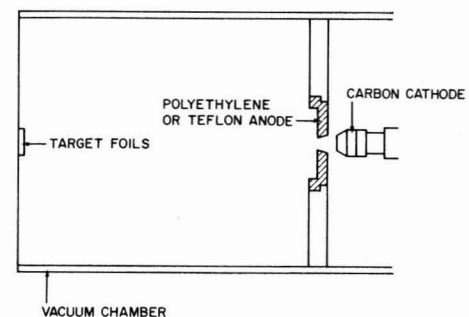

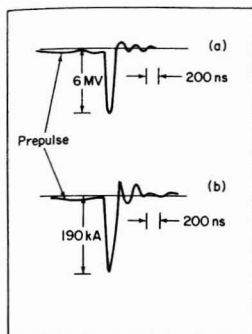FIG. 1. Typical geometry for collective ion acceleration.

FIG. 2. (a) Typical voltage and (b) current waveforms.

FIG. 3. Activation of aluminum foils.

kA, 100 ns) when operated with the diode configuration shown in Fig. 1. The electron beam is emitted from an annular (2.5-cm diameter) carbon cathode positioned 5 cm from the back of a Teflon $[(CF_2)_x]$ or polyethylene (CH_2) anode. The electron-beam diagnostics include resistive and capacitive diode voltage monitors, an integrated $\dot{B}$ probe for measuring the diode current, and a calorimeter to measure the total beam energy propagating to a given axial position in the downstream drift chamber. Oscilloscope traces of the diode voltage and current waveforms are shown in Fig. 2 for a typical shot. These measurements indicate that the total energy in the electron-beam pulse in the diode is about 100 kJ. From calorimeter measurements, about 30 kJ of beam energy is observed to propagate to a position 30 cm downstream of the anode. The PR1590 prepulse, a result of capacitive coupling during the charging of the Blumlein pulse-forming network, is about 10% of the main pulse voltage and is of 1-μsec duration. The diameter of the downstream drift chamber is 60 cm. The calculated limiting current for these conditions is about 28 kA.

Accelerated carbon ions in these experiments were detected using nuclear activation techniques. A stack of 1-mil aluminum foils was exposed to the beam and the activation measured in each foil. NaI and germanium detector systems were used to identify the gamma spectrum and half-life of the various reaction products. Since protons and other ions are contaminants in the system, accelerated carbon ions were detected using the reactions $Al^{27}(C^{12},\alpha,n)Cl^{34m}$ and $Al^{27}(C^{12},C^{11})Al^{28}$. The isotopes Cl^{34m}, C^{11}, and Al^{28} were detected from both the gamma spectra and the product half-lives, and plots of the relative activation of each foil versus foil number are shown in Fig. 3. for experiments performed using both a Teflon and a polyethylene anode. For the plots shown in Fig. 3, a NaI coincidence counting system was used with the energy window centered around the 0.511-MeV gamma produced by electron-positron annihilation. The data taken with the polyethylene anode provides an opportunity to determine to what extent the aluminum foils and impurities within them (less than 0.05% Cu and lesser amounts of other contaminants) may be activated by the very high proton and neutron fluxes produced under these conditions.[13] In these experiments, using a Teflon anode, carbon-ion-induced reactions were detected in the fourteenth (1 mil)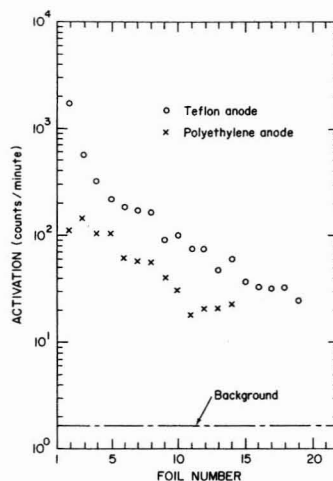 aluminum foil in a target foil stack. Cross section data for the production of Cl^{34m} and Al^{28} in an aluminum target as a function of incident carbon-ion energy are given in Ref. 14. The effective threshold energy for Cl^{34m} production is about 20 MeV, and for Al^{28} is about 75 MeV. The range and stopping power of carbon ions in aluminum are given in Ref. 15 and indicate that the carbon-ion energy necessary to penetrate through 13 (1 mil) aluminum foils (an effective range of 89.15 mg/cm^2) is about 153 MeV. To this value must be added the threshold energy for activation of the fourteenth foil, yielding a minimum of 173 MeV as the incident carbon ion energy. As a result of these calculations and the known counting efficiency of the detection systems, it is estimated that about 10^{10} carbon ions have been accelerated to energies in the range 170–200 MeV. This energy is substantially greater than that achieved in any other collective accelerator previously.

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