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CONTROLLED COLLECTIVE FIELD PROPAGATION FOR ION ACCELERATION USING A SLOW WAVE STRUCTURE*

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Summary

Acceleration of ions by intense relativistic electron beams in a vacuum has been investigated using the injector of the Maryland ERA project. Proton energies above 16 MeV and proton beam currents above 10 kA have been obtained. Carbon ions have been accelerated to energies above 20 MeV using the same facility. The propagation of the beam in the accelerating region has been investigated, and the effects of different conducting boundaries studied. A helical slow wave structure to control the propagation of the collective acceleration field is proposed, and preliminary experimental considerations are presented.

I. Introduction

In recent years, much interest has developed around the possibility of using the collective fields of dense electron clusters to accelerate ions to high energies. The use of rotating electron rings for this purpose is currently being investigated at Maryland, Dubna, Garching, and Japan, but to date the highest accelerated ion currents and energies have been obtained in linear beam (non-rotating) systems. Linear beam acceleration of ions by the interaction of an intense electron beam with a neutral gas background was first reported by Graybill et al.[1] Experimental and theoretical work in this area has continued at several laboratories. The acceleration of ions in vacuum, where the positive ions are provided by an insulating anode material, was first reported by Luce.[2] In this work, protons and heavier ions have been accelerated to energies in excess of 20 times the electron beam energy, with peak proton energies reported up to 45 MeV. Investigations of this acceleration process are currently underway at Cornell,[3] Kirtland Air Force Base,[4] and Maryland.[5]

Although the experimental results achieved using the Luce-type diodes for linear beam acceleration of ions in vacuum have been very encouraging, the actual acceleration process seems to be more complicated than in the gas-filled drift chamber. The limiting current phenomena and the formation of a virtual cathode behind the anode may be the same as in the case of acceleration in a gas-filled chamber, but in a Luce-type diode, the charge neutralization of the electron beam is obtained only by diffusion of positive ions from the diode plasma. The diode plasma conditions are, in turn, dictated by the diode geometry and other factors, such as preionization in the diode region produced by the injector prepulse. In this paper, experiments which have been performed to investigate this acceleration process are reported in section II. Also presented in section II are results of preliminary heavy ion experiments in which carbon ions have been accelerated to energies in excess of 20 MeV. In section III, a proposal to control the propagation of the accelerating collective field using a helical slow wave structure is discussed. Conclusions are drawn in section IV.

II. Studies of the Acceleration Process

The general experimental configuration is shown in Fig. 1. The electron beam injector used for these experiments is the facility used for the Maryland ERA experiments described in another paper at this conference. An intense relativistic electron beam (1-2 MeV, 20-40 kA) is emitted from a needle cathode located 6-7 mm in front of the anode plane. The pulse duration of the beam on the diode side is about 30 ns (FWHM), and the voltage and current risetimes may be controlled by adjusting a prepulse switch gap in series with the injector output. The insulating anode, containing the material to be accelerated, has an 11 mm hole bored through it on axis to allow most of the electron beam to pass through the anode plane into the acceleration region. Outer conducting boundaries of different diameters may be inserted in the region downstream of the diode, and beam propagation characteristics in the various configurations have been investigated using a series of integrated $\dot{B}$ loops located at various axial positions in each drift tube, as shown in Fig. 1. A system of floating electrodes, discussed previously,[5] may also be inserted in the post-diode region. A Faraday cup measures the total current reaching the end of the drift tube. Accelerated ions are detected by foil activation techniques, and stacked copper or aluminum foils are used to determine the ion energy spectra. Neutron producing reactions are detected by two Geiger-Mueller tubes located at 0° and 90° from the system axis. An axial magnetic field of up to three kilogauss may be applied using the external field coils used for the ERA experiments.

A. Proton Acceleration Studies

In these experiments, the insulating insert was made of high density polyethylene, and accelerated protons were detected using copper foil activation ($Cu^{63}(p,n)Zn^{63}$, $Cu^{65}(p,n)Zn^{65}$). Previous experiments performed under similar conditions[5] have resulted in maximum proton energies of about 16 MeV and maximum proton beam currents of 12 kA. The pulse width of the proton beam was about 5 ns. An applied magnetic field of 1.8 kilogauss was used and the diameter of the proton beam was determined to be less than 1 cm. The maximum neutron yield from the copper foil was 6×10^9, which corresponds to a total of 1×10^{13} protons accelerated to an energy in excess of 2.16 MeV. In the current experiments, reproducible proton acceleration with peak energies of about 11 MeV has been obtained using four different conducting tube diameters (3.2 cm, 6.4 cm, 10.2 cm, and 25 cm) and an applied axial magnetic field of two kilogauss. The maximum total power delivered to the diode was about two kilojoules. By varying the injector charging voltage and carefully monitoring the diode current and voltage, a measurement of the neutron flux measured by the Geiger-Mueller tubes as a function of the total electron beam power at the diode has been obtained. Results are plotted in Fig. 2 and show clearly the strong dependence of the neutron flux (and thus the proton current and energy) on the total electron beam power.

While no clear scaling of the peak proton energy with conducting tube diameter was observed, the propagation of the electron beam was dependent on the tube diameter. Fast integrated $\dot{B}$ probes were located at various axial positions near the inside wall of each tube, as shown in Fig. 1, and were carefully timed to provide an indication of the time of flight of the electron beam between the probes. Results of these studied are shown in Fig. 3, and it is evident that the mean electron beam front propagation velocity is faster for the larger diameter conducting tubes. This result may be related to the mean proton velocity necessary to neutralize the electron space charge. It is possible that this mean proton velocity may be higher with a larger diameter drift tube because of a change in the position of the virtual cathode formed behind the anode. It is interesting to note that this result is also in agreement with predictions for the beam front velocity in a neutral gas given by Olson.[6]

To date, the highest proton energies in these experiments have been observed when the two floating electrodes were used in the post-diode region, as discussed in a previous paper.[5] Reproducibility of these results is much poorer than for the results obtained with no floating electrodes, and the acceleration process is critically dependent on the setting of the prepulse switch gap, an indication that some preionization in the diode region may be essential in achieving high proton energies under these conditions. Typical proton energy spectra are shown in Fig. 4 for both the case where two floating electrodes are used and for the case where a simple conducting boundary is present.

B. Heavy Ion Acceleration

The same facility may be used to accelerate heavy ions by simply changing the anode insert material. The initial heavy ion experiments reported here involved the identical geometry described previously, and used the 6.4 cm diameter conducting drift tube downstream of the diode. No attempt was made to use the floating electrodes to maximize ion current and energy. Acceleration of carbon ions has been detected using aluminum target foils. Significant neutron fluxes have been observed from these targets and are possibly attributable to the reaction $Al^{27}(C^{12},C^{12}n)Al^{26}$, which has a threshold of about 19 MeV. In addition, the reaction $Al^{27}(C^{12},C^{11})Al^{28}$ has been detected from both the gamma ray energies and the product halflives. From considerations of both the Coulomb barrier and the cross section for this reaction, the probable carbon ion energy is estimated to be at least 20 MeV.

III. Control of Collective Field Propagation

The possibility of controlling the collective field propagation has been briefly discussed in a previous paper. The acceleration of ions by intense electron beams is usually explained in terms of the formation of a virtual cathode behind the anode plane and the trapping of positive ions in the potential well of this virtual cathode. If one could control the velocity of the collective field propagation in synchronization with the positive ion velocity, the large collective fields of such a system (about 1 MV/cm, typically) would make possible the construction of an economically competitive ion accelerator. For this reason, we are investigating the possible use of a helical slow wave structure to control the collective field propagation velocity.

The limiting current in a grounded cylinder of radius a is given by

$$I_\ell = \frac{17000(\gamma_o^{2/3}-1)^{3/2}}{(1+2\ln a/r_b)(1-f)} \qquad (1)$$

where

$$\gamma_o = 1 + \frac{eV_o}{m_o c^2} .$$

Here r_b is the radius of the electron beam, v_o is the diode voltage, and f is the ratio of the ion density to the electron density. In a gas-filled chamber, the limiting current may be changed by changing the fractional neutralization f, as in the proposed ionization front accelerator.[7] In collective ion acceleration in vacuum, one can control the limiting current by changing the electron kinetic energy. If a cylinder is biased with a nonzero voltage $\phi(z,t)$, γ_o in equation (1) must be replaced by

$$\gamma = \gamma_o - \frac{e\phi(z,t)}{m_o c^2} . \qquad (2)$$

If we now consider a given cylindrical tube and ground the upstream end of the tube while applying a high negative voltage to the downstream end, a given electron beam might propagate easily in the grounded portion of the tube where $I < I_\ell$ and fail to propagate in the biased portion of the tube where $I > I_\ell$. Thus, a virtual cathode would form at the entrance of the biased part of the cylinder. The propagation of the virtual cathode can be controlled by dictating the bias voltage propagation in the cylinder with a slow wave structure. A proposed conceptual scheme is shown in Fig. 5. In this scheme, the electron beam would charge up the helical slow wave structure during the early part of the pulse. During this period, initial collective ion acceleration would occur in the diode region, and when the initial positive ions reach the entrance of the helical slow wave structure, the upstream end of the helix would be grounded using a spark gap switch. If the phase velocity of the helix at the entrance point is matched to the ion velocity, controlled collective ion acceleration may be achieved by varying the pitch of the helix to achieve the desired collective field propagation velocity.

In order to minimize dispersion of the voltage wave, it is desirable to have an outer conducting cylinder close to the helix. The phase velocity of waves propagating in such a system at high frequencies is given by

$$v_{ph} = c \sin\psi \qquad (ka \gg 1)$$

where ψ is the pitch angle of the helix. At low frequencies, the phase velocity is given by

$$v_{ph} = c \frac{\sin\psi}{\left[1+\left(\frac{1-a^2/b^2}{2\ln b/a} -1\right)\cos^2\psi\right]^{1/2}} .$$

In order to achieve controlled acceleration by this method, the electron beam and the downstream structure must be carefully matched by tailoring the electron beam energy and current to the desired values. Initial experiments were performed using 3.2 cm diameter helical slow wave structure inside a 6.4 cm diameter conducting drift tube, and the pitch of the helix was varied along its length in such a way that the predicted phase velocity at the input of the helix corresponded to a proton energy of about 5 MeV and at the output corresponded to an energy of about 20 MeV. No spark gap switch was employed, although the input end of the helix was floated with respect to the potential of the outer conducting tube in such a way that electrical breakdown between the helix and the tube was possible. An axial magnetic field of 3 kilogauss was applied. Preliminary experiments have not produced substantially higher ion energies using the slow wave structure system. This result is attributed to our inability to tailor the electron beam such that the beam current is below the limiting current given by the helix radius. Attempts to lower the beam current and increase the electron energy by increasing the anode-cathode gap have resulted in the destruction of the anode insert due to a spreading of the electron beam cross section in the AK gap.

Future plans include the construction of a pulsed magnetic field system capable of applying 10 kilogauss in the diode-acceleration region. This system should provide sufficient confinement of the beam electrons to protect the anode insert. A diode parameter search will then be conducted to find operating conditions suitable to the slow wave structure experiments.

IV. Conclusions

The acceleration of protons and heavier ions in vacuum using linear electron beams has been studied under a variety of experimental conditions. The neutron flux produced by accelerated protons striking copper targets has been found to be a strong function of total electron beam power delivered to the diode, and the propagation velocity of the electron beam front has been observed to increase as the conducting drift tube diameter is increased. In these experiments, protons have been accelerated to energies in excess of 16 MeV, and carbon ions to energies in excess of 20 MeV. The possible control of the collective field propagation using a helical slow wave structure is currently being investigated.

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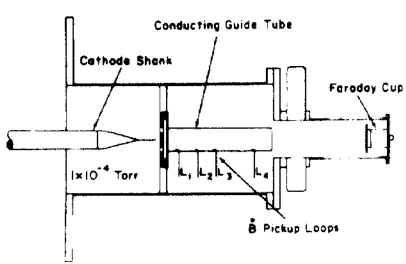

Fig. 1. General experimental configuration.

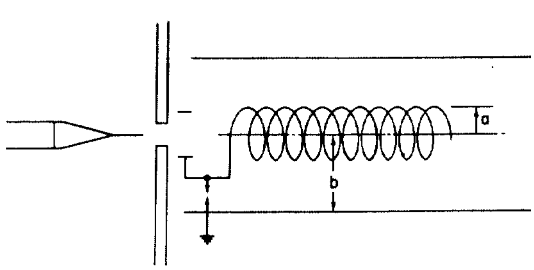

Fig. 5. Slow wave helix experiment.

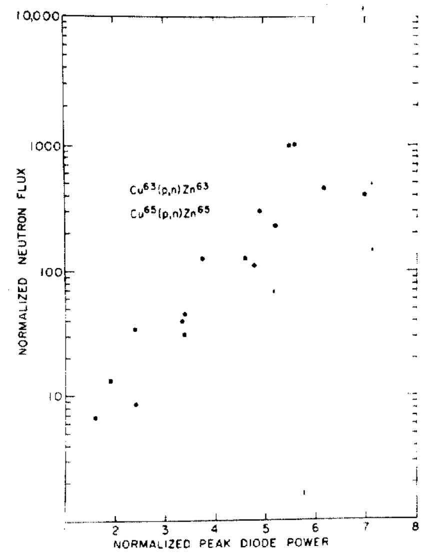

Fig. 2. Neutron flux vs. peak delivered power to the diode.

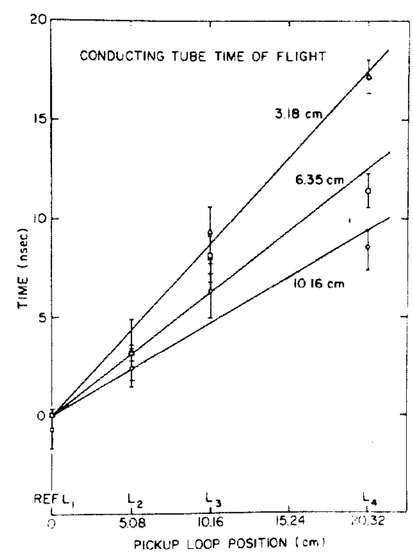

Fig. 3. Beam time of flight vs. Ḃ loop position.

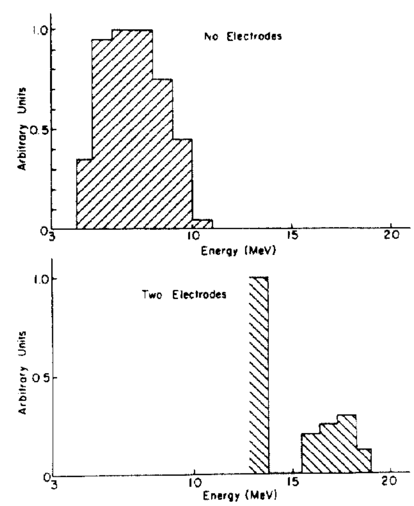

Fig. 4. Proton energy spectra with and without floating electrodes.