COLLECTIVE ION ACCELERATION VIA LASER CONTROLLED IONIZATION CHANNEL*

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Summary

Initial results from a successful laser-controlled collective ion acceleration experiment at the University of Maryland are presented. In the experiment, positive ions are trapped in the potential well at the head of an intense relativistic electron beam injected at current levels above the space charge limit. Seed ions for acceleration are provided by puff valve injection of a neutral gas cloud localized to within 3 cm of the injection point. Control over the acceleration of the well and the ions is then achieved by means of a laser-generated ionization channel produced by passing the light from a Q-switched ruby laser though a series of partially and fully reflecting mirrors in such a way as to provide time-sequenced laser ionization of a target located on the drift tube wall. Using this system, controlled acceleration of protons at a rate of approximately 40 MV/m has been demonstrated over a distance of about 50 cm.

Introduction

Interest in collective field accelerators has resulted from the relatively high electric fields (100-500 MV/m) that can be generated by intense relativistic electron beam systems, and considerable progress has been reported in the field over the last decade.[1-10] The goal of controlling these large fields over acceleration distances of more than a few centimeters, however, has been an elusive one. To date, the most encouraging results in this regard have come from the Ionization Front Accelerator (IFA-1 and IFA-2) experiments of Olson.[9,10] The experimental laser-controlled collective accelerator configuration under study at the University of Maryland is based on the same fundamental concepts as the IFA experiments, although the actual experimental configuration is quite different in both design and operation.

The conceptual design of the experiment is shown in Fig. 1. In Fig. 1(a), an intense relativistic electron beam (900 keV, 20 kA, 30 ns) is injected into an evacuated conducting drift tube at an injection current level several times the space charge limit, given approximately by

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

Here γ_o is the relativistic mass factor for the injected electrons, b is the drift tube radius, a is the radius of the electron beam at injection, and f represents any neutralization provided by positive ions. As shown in Fig. 1(a), a virtual cathode is formed at the injection point with a potential depth approximately equal to the anode cathode potential difference. The strong electric field associated with the virtual cathode can, in principle, be used for both ion trapping and acceleration.
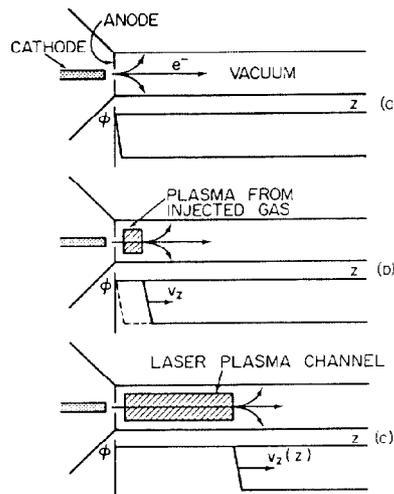

FIG. 1. Conceptual design of the laser-controlled collective accelerator.

If the beam is injected into a localized gas cloud, as shown in Fig. 1(b), electron impact ionization and ion-avalanche ionization processes can quickly build up sufficient ion density to neutralize the electron beam space charge, and the virtual cathode will move downstream to the edge of the gas cloud, accelerating a few ions to energies higher than that associated with the potential depth of the virtual cathode itself. In order to control the motion of the virtual cathode over distances longer than a few centimeters, however, a means of providing an ionization channel with time-varying axial extent is required [Fig. 1(c)].

In these experiments, shown schematically in Fig. 2, the ionization channel is generated by time-sequenced laser-target interaction. A Q-switched ruby laser (10 J, 15 ns) is separated into ten approximately equal energy beams which are then optically delayed over differing path lengths. The laser light is then directed onto a narrow polyethylene target located on the drift tube wall, and ions from the resultant plasma drawn into the beam by the electron space charge provide the desired time-sequenced ionization channel. Preliminary results from this experiment have been published previously.[11]

Design Considerations

The requirement that the injected beam current significantly exceed the space charge limiting current yields a lower bound for the drift tube radius of about 2 cm, assuming that the beam radius at injection is

1 cm. The upper bound for the drift tube radius is set by the requirement that ions created at the drift tube wall must be drawn into the beam in a time less than or equal to a few nanoseconds. Although calculations indicate that this places an upper bound to the drift tube radius of about 5-7 cm, the actual drift tube radius was chosen as a result of experiments described below.
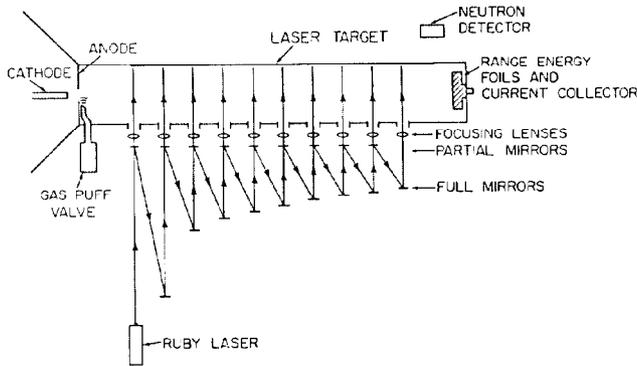
FIG. 2. Schematic of the experiment.

If the virtual cathode is to be accelerated continuously from an initial low velocity to a final higher one, ions can be contained within the potential well assuming that the relative velocity of the well and ions is less than a value given by

$$v_w - v_i < (2eV_o/m_i)^{1/2} , \qquad (2)$$

which for a 900 keV electron beam used for proton acceleration yields $v_w - v_i < 0.44 \ c$. To ensure that ions with very little initial velocity could be accelerated in the experiment, the initial ion channel sweep velocity was chosen to be 0.05 c. Clearly it is also desirable to have $v_w \cong v_i < eE/m_i$. Although the electric field strength at the virtual cathode can be as high as 100-500 MV/m at the injection point, a more conservative value of 40 MV/m was chosen for the initial experiments. Because of the finite duration of the injected electron beam pulse, the experiment was designed to accelerate ions over a distance of 50 cm.

In addition, to these theoretical constraints, the laser target geometry must be such that electron beam ionization of the laser target material does not occur to an extent that would influence beam propagation. Experiments to determine a suitable configuration are described below.

Experiments

To ensure that ions created by laser-target interaction could be drawn into the beam rapidly enough to control propagation, the beam was first injected into dielectric lined (a thin polyethylene sheet was used as the dielectric) drift tubes of various diameters. The current measured at the end of each 55 cm long drift tube was then measured using a fast Faraday cup current collector to determine if ions created by beam electrons striking the wall could allow beam propagation. Results, shown in Fig. 3, indicate that virtually the entire injected current could be successfully propagated down dielectric lined drift

tubes of radius 5 cm and under. The drift tube radius was therefore chosen at 5 cm.

Dielectric Lined Drift Tube
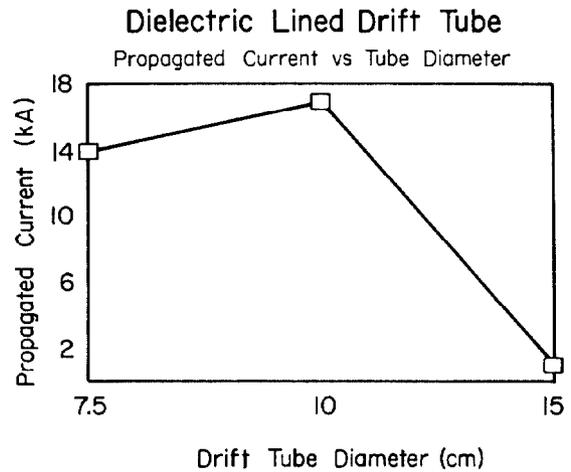### Propagated Current vs Tube Diameter

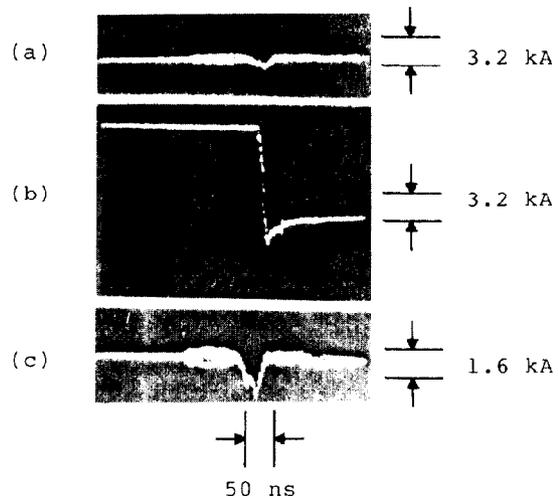FIG. 3. Current propagated in dielectric lined drift tubes as a function of drift tube radius.

Fig. 4. Typical oscilloscope waveforms of the current measured at the end of the drift tube for a) a beam injected into the 5 cm radius stainless steel drift tube without any source of ions, b) a beam injected into the same tube with the polyethylene liner, and c) a beam injected into the same tube with the narrow laser target strip installed but no laser ionization of the target.

The laser target geometry was tested to ensure that beam ionization of the CH_2 target was not in itself sufficient to influence beam propagation. The final target geometry consisted of a 0.200" strip of 0.030" polyethylene sheet mounted in a stainless steel bracket that allowed for axial movement of the target if necessary to provide a fresh target for the laser pulse. Figure 4 shows typical oscilloscope waveforms of the current measured at the end of the drift tube for a) a beam injected into the 5 cm radius stainless steel drift tube without any source of ions, b) a beam injected into the same tube with the polyethylene

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liner, and c) a beam injected into the same tube with the narrow laser target strip installed but no laser ionization of the target. As can be easily seen, beam ionization of the laser target does not appear to produce sufficient ions to influence propagation significantly.

Tests of the laser system are summarized in Table I. Although the transmittivity of the partially reflecting mirrors was chosen to split the laser beam into ten equal energy beams, tests indicate that optical losses are not negligible especially for the last few target spots. Some systematic error in these results is present due to the fact that only one laser calorimeter was available and the data had to be obtained over ten consecutive shots. The laser energy was approximately 6 J, and the laser spot size at each target point was less than 1 mm in diameter.

TABLE I. Summary of optical system tests.

Spot No.	Axial Position (cm)	Partial Mirror Reflectivity	Theoretical Laser Energy at Spot (J)	Experimental Laser Energy at Spot (J)
1	5	0.90	0.60	0.55
2	10	0.89	0.59	0.52
3	15	0.88	0.58	0.50
4	20	0.86	0.59	0.53
5	25	0.83	0.62	0.48
6	30	0.80	0.61	0.38
7	35	0.75	0.60	0.42
8	40	0.67	0.60	0.40
9	45	0.50	0.60	0.34
10	50	--	0.60	0.32

Results of collective ion acceleration experiments on the system are shown in Fig. 5. Plotted in the figure as a function of the relative firing delay between the laser and the beam are a) the current reaching the downstream end of the drift tube, b) fast neutron counts produced by a silver-activation neutron detector measuring neutrons produced by accelerated protons striking the current collector and the drift tube wall, and c) the peak proton energy measured at the current collector using stacked-foil nuclear activation techniques. Both copper and titanium foils were used employing the reactions $Ti^{47}(p,n)V^{47}$ and $Cu^{63}(p,n)Zn^{63}$.

As is evident from the data, firing the laser well in advance of the electron beam pulse allows for most of the injected beam current to propagate to the end of the drift tube, as expected from the dielectric-lined propagation experiments. Firing the laser after the electron beam pulse is equivalent to not firing the laser at all, and little beam propagation is observed. The transition between these two regimes of operation clearly defines the experimental parameter regime where controlled collective acceleration should be observed. As the data clearly show, the accelerated ion energy rises to a value consistent with design calculations and accompanying neutron production also peaks in precisely this transition region.
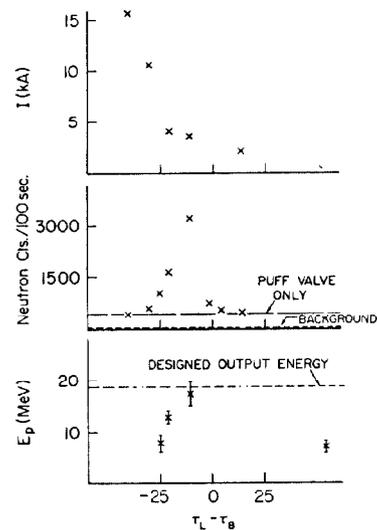

FIG. 5. a) Current reaching the downstream end of the drift tube, b) fast neutron counts all plotted as a function of laser-beam delay time, and c) peak proton energy.

Conclusions

The controlled collective acceleration of ions over significant distances using this simple laser-controlled ionization channel technique has been demonstrated, and results appear to be very close to design values. Future experiments are planned to determine both the potential and limits of this new collective accelerator configuration. These experiments will attempt to determine the maximum accelerating gradient, resultant ion beam emittance characteristics, and the extent to which this concept can be scaled to significantly longer accelerating distances and higher ion energies.

Acknowledgments

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