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MEASUREMENTS AND SIMULATION OF CONTROLLED BEAMFRONT MOTION IN THE LASER CONTROLLED COLLECTIVE ACCELERATOR*

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Abstract

In the Laser Controlled Collective Accelerator, an intense electron beam is injected at a current above the vacuum space charge limit into an initially evacuated drift tube. A plasma channel, produced by time-sequenced, multiple laser beam ionization of a solid target on the drift tube wall, provides the necessary neutralization to allow for effective beam propagation. By controlling the rate of production of the plasma channel as a function of time down the drift tube, control of the electron beamfront can be achieved. Recent experimental measurements of controlled beamfront motion in this configuration are presented, along with results of ion acceleration experiments conducted using two different accelerating gradients. These results are compared with numerical simulations of the system in which both controlled beamfront motion and ion acceleration is observed consistent with both design expectations and experimental results.

I. Introduction

The Laser Controlled Collective Accelerator concept[1-3] represents an attempt to extend the promising results from "naturally occurring" collective ion acceleration experiments to practical accelerators in which the accelerating gradient and distance can be systematically controlled. The concept is similar to that employed in the IFA-1 and IFA-2 experiments of Olson[4,5], although the actual experimental configuration is quite different. The basic concept behind the experiment is shown in Fig. 1. An intense relativistic electron beam is injected through a localized gas cloud into an evacuated drift tube at a current well above the vacuum space charge limit. A virtual cathode then forms immediately downstream of the injection point and ions produced within the localized gas cloud are accelerated to modest energies in a manner similar to more conventional collective accelerators. At this point, a channel of plasma is produced in a time sequenced manner down the drift tube by laser ionization of a CH_2 target strip located on the drift tube wall. The time sequencing of the plasma channel is achieved by dividing a Q-switched ruby laser pulse into ten approximately equal energy beams and using optical delays to ionize sequentially ten target spots equally spaced down the drift tube. In this manner, the virtual cathode at the beamfront can be carefully accelerated down the drift tube and ions trapped by the strong electric fields at the virtual cathode can be accelerated to high energies in a controlled manner.

In this paper we present in section II results of experiments in which controlled beamfront motion has been confirmed for two different accelerating gradients. Results of ion acceleration experiments are also presented. Numerical simulations of the experiments presented in section III confirm both controlled beamfront motion and the controlled acceleration of ions by the moving virtual cathode over significant distances. Conclusions are drawn in section IV.

II. Experiments

As shown in Fig. 1, an intense relativistic electron beam (900 keV, 20 kA, 30 ns) is emitted from a 4 mm diameter tungsten cathode located 1 cm upstream of a stainless steel anode. A 14 mm diameter hole in the anode plate on axis allows almost all of the beam current to pass into a downstream drift tube 10 cm in diameter. Seed protons for acceleration are provided by beam ionization of a localized gas cloud produced by a fast gas puff valve. The Q-switched ruby laser pulse (6 J, 15 ns) is divided into ten approximately equal energy beams and optically delayed to provide a time-sequenced source of ions down the 50 cm length of the drift tube. Design considerations for the experiment and results of tests of the optical system have been reported previously.[2,3]

Five current collecting wall probes were installed to measure beam current deflected to the drift tube wall at the beamfront as a function of time. These probes were located at axial positions 10, 20, 30, 40, and 50 cm downstream of the anode plane. Total current reaching the downstream end of the drift tube was measured using a Faraday cup, and accelerated ion energies were measured using stacked foil activation techniques. Titanium ($Ti^{47}(p,n)V^{47}$) and Copper ($Cu^{63}(p,n)Zn^{63}$) reactions were used having threshold energies of 3.7 and 4.2 MeV, respectively. A silver activation neutron counter recorded neutrons produced by these reactions and by accelerated protons striking the drift tube walls.

Experimental data has been obtained for two different accelerating gradients; one at 40 MeV/m over a 50 cm accelerating distance and one at 90 MeV/m over the same distance. Data from the five wall current probes for the smaller gradient are shown in Fig. 2 for a) the case when the laser is fired 200 ns in advance of the beam, b) the case where the laser is not fired at all, and c) the case where the laser timing is such that the plasma is produced by laser-target interactions at the same time as the beam is being injected (optimal timing). As can be readily seen from these results, good control over the beamfront motion has been achieved when the laser-beam timing is optimal. Measurements of the accelerated ion energy and propagated current, shown in Fig. 3, clearly show that protons can be accelerated up to the designed output energy when the laser -beam timing is such as to allow control of the beamfront.

Experimental data obtained at the higher accelerating gradient of 90 MV/m also indicate good control over the beamfront motion, but peak ion energies observed are actually less than those observed for the lower gradient experiments. This is undoubtedly due to a reduction in the electric field strength at the virtual cathode below 90 MV/m at some point in the acceleration process. The following results of numerical simulations of the experiments shed additional light on this result.

III. Numerical Simulations

A particle-in-cell code was used to simulate the laser-controlled acceleration experiments. In the simulations, the electron beam is assumed to be focussed by an infinitely strong guide magnetic field so that the particles move only along the axis of

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the drift tube. The radius of the beam is also assumed to be much less than the radius of the drift tube so that the charge density, current density, and axial electrical field are approximately constant across the beam cross-section. Ionization of the neutral gas is modelled by keeping track of the amount of ionization produced by collisions with electrons and ions and introducing electrons and ions appropriately.

In the simulations, the laser-produced plasma is assumed to completely neutralize the space-charge on the axis of the drift tube once it reaches the electron beam from the wall. The time required for the laser-produced plasma to reach the electron beam from the wall is assumed to be given by the time required for a proton to fall through a logarithmic potential drop V_0 from $r = R_w$ to $r = R_b$, where V_0 is the electron beam voltage. R_w is the wall radius and R_b is the beam radius.

Results are shown for a 900-kV, 20-kA, 1-cm-radius electron beam which is injected into a 5-cm-radius, 50-cm-long drift tube with a 2-cm-wide, 100-mTorr hydrogen gas cloud located next to the anode plane. The front of the laser beam is assumed to travel down the drift tube at a velocity which increases linearly from $\beta_i = 0.04$ to $\beta_f = 0.2$ over a distance of 45 cm, corresponding to an accelerating gradient of 40 MeV/m.

Figure 4 shows the peak proton energy measured at 45 cm versus the time delay between the start of the laser pulse and the start of the beam pulse $\tau_L - \tau_B$. In plotting this data, we assumed that the laser requires 10 ns to produce plasma after striking the target on the wall. For a wide range of $\tau_L - \tau_B$, the peak proton energy which was measured actually exceeds the design value of 18.76 MeV.

Figure 5 shows the velocity versus position for an accelerated proton for $\tau_L - \tau_B = -8$ ns. Also shown in the figure is the velocity versus position for the front of the laser beam. The proton is accelerated relatively smoothly from an initial velocity of 0.04c to a final velocity of 0.2c.

In all runs the peak electric field E_z fell by an order of magnitude, e.g. from 3×10^8 V/m to 5×10^7 V/m, as the beam front moved downstream. Figure 6 shows the magnitude versus location of the peak E_z at a number of time steps approximately 2 ns apart for one run. The decrease in the strength of the peak electric field observed in the simulations is consistent with the experimental observation that the peak ion energy actually fell when a higher accelerating gradient was used.

IV. Conclusions

In conclusion, both experiments and numerical simulations now indicate that the laser-controlled collective accelerator concept is a promising one. Effective control over the propagation of a virtual cathode at the front of an intense relativistic electron beam has been achieved, and protons have been accelerated at a rate of 40 MV/m over a distance of about 50 cm. Furthermore, numerical simulations indicate that significantly higher ion energies can be achieved by either using longer accelerating distances (and consequently, longer injected electron beam pulse durations) and/or by injecting higher energy electron beams to maintain higher electric field strengths at the virtual cathode.

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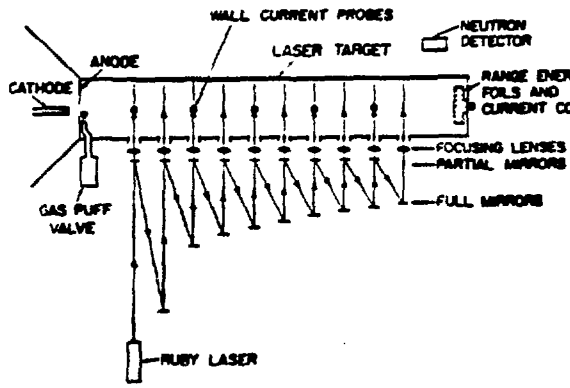

Fig. 1. Experimental Configuration.

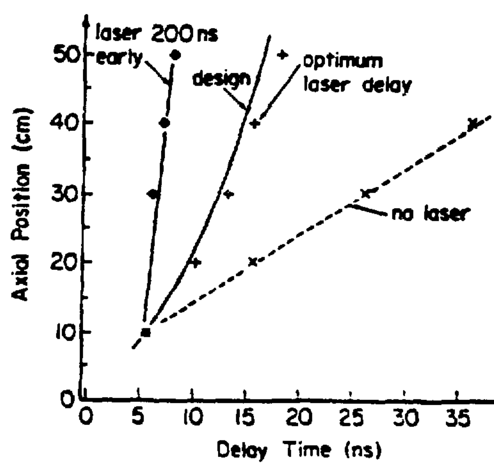

Fig. 2. Data from 5 axially spaced current collectors located on drift tube wall.

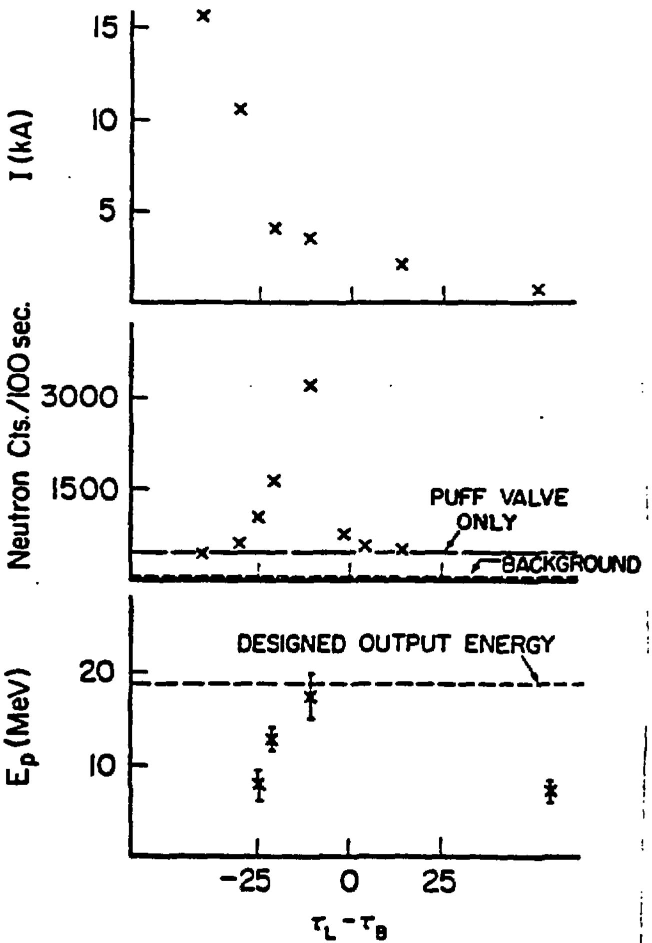

Fig. 3. Propagated current at 50 cm, neutron counts, and peak proton energy vs. beam-laser firing delay.

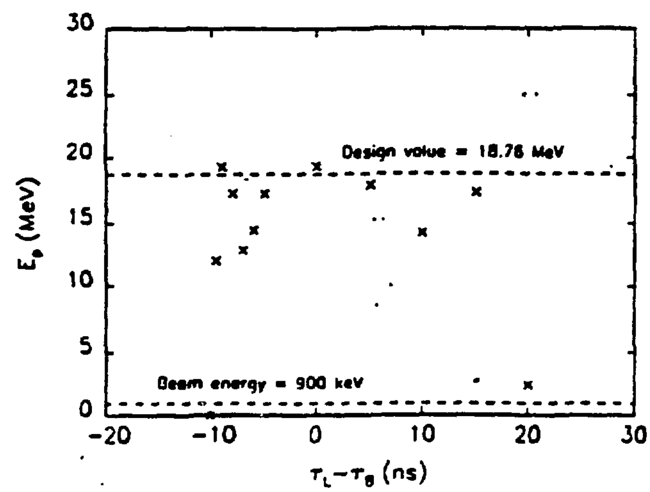

Fig. 4. Peak proton energy measured at 45 cm vs. time delay.

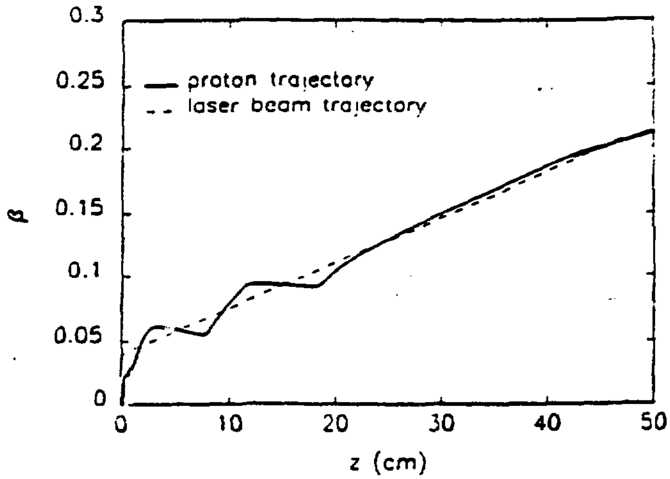

Fig. 5. Velocity vs. position for accelerated proton.

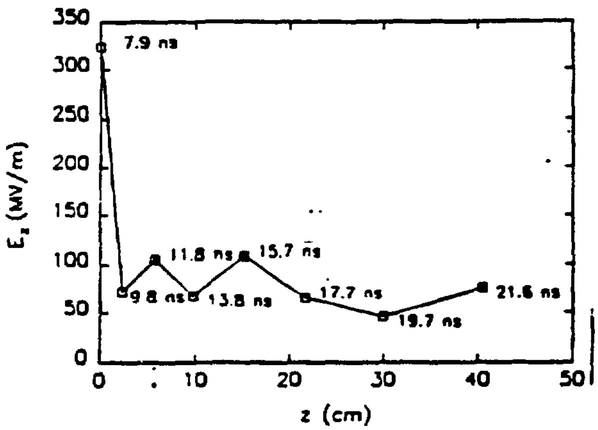

Fig. 6. Magnitude vs. location of peak electric field.