Studies of Ion Acceleration in a One Meter Laser Controlled Collective Accelerator*

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I. Introduction

The basic concept behind the Laser Controlled Beamfront Experiment has been described in detail in previous reports.[1,2] In the experiment, control over the propagation of a virtual cathode at the front of an intense relativistic electron beam is achieved by a time-sequenced plasma channel produced by laser-target interactions (see Fig. 1). Ions are trapped and accelerated by the very strong electric fields (50–400 MV/m) at the virtual cathode.

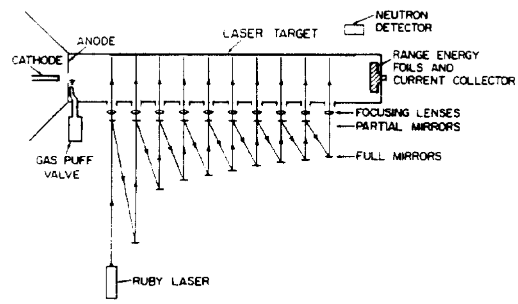

Figure 1: Schematic of the laser controlled beamfront accelerator.

II. Experiments

A. First Generation Laser-Controlled Beamfront Accelerator Experiments

During the past two years, we have completed our studies of the first generation Laser-Controlled Beamfront Accelerator experiment. In these experiments the injected electron beam pulse was 900 keV, 20 kA, 30 ns, and controlled beamfront motion and accompanying ion acceleration were attempted over a distance of 50 cm. The major conclusion of these studies are as follows[2]:

i) Effective control of a relativistic electron beamfront by a laser produced time-sequenced ionization channel has clearly been demonstrated for two different accelerating gradients (40 MV/m and 90 MV/m). In addition, beamfront motion without the laser-produced ionization channel is consistent with theoretical expectations, as is the rapid propagation observed when the ionization channel is produced well in advance of electron beam injection.

ii) Controlled collective acceleration of ions at a rate of 40 MV/m over a distance of 50 cm has also been demonstrated, but acceleration at the higher gradient (90 MV/m) over this distance has not been demonstrated to date. As discussed in the theoretical progress section of this report, both the successful acceleration of protons at the 40 MV/m gradient and the failure to accelerate ions at the higher gradient over the entire 50 cm distance are entirely consistent with numerical simulations of the beamfront accelerator and simple analytic theory. In the higher gradient experiments, it was simply not possible to maintain the required > 90 MV/m electric fields at the virtual cathode over the entire 50 cm accelerating distance.

iii) Approximately 10^9 protons/pulse were accelerated to a peak energy of 18 MeV in the 40 MV/m gradient experiments. Data from stacked foil measurements indicate that the spectrum has a strong peak at about 18 MeV.

B. Second Generation Laser-Controlled Beamfront Accelerator Experiments

A second generation Laser-Controlled Beamfront Accelerator has been designed with the aid of numerical simulations described in the theoretical section of this paper. The specific design parameters and objectives for the new experiment are discussed in the theoretical section. The second generation experiment is designed to accelerate protons over a 100 cm distance at gradients up to 60 MeV/m using electron beams with energies in the range 1.2–1.5 MeV. Construction of the new experiment was completed over the past year and initial experiments are currently underway.

Results of optical system tests are displayed in Table 1. This table details the actual partial reflecting mirror specifications, predicted laser energy at each spot, and actual experimental values achieved. Reductions in actual laser

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Table 1: Summary of optical system tests.

Channel	Axial Position (cm)	Partial Mirror Reflect-ivity	Theore-tical Laser Energy ($Joules$)	Experi-mental Laser Energy ($Joules$)
1	5	0.95	0.300	0.30
2	10	0.95	0.285	0.28
3	15	0.95	0.270	0.265
4	20	0.95	0.257	0.25
5	25	0.95	0.244	0.23
6	30	0.925	0.348	0.315
7	35	0.925	0.322	0.295
8	40	0.925	0.298	0.275
9	45	0.925	0.276	0.255
10	50	0.90	0.339	0.30
11	55	0.90	0.306	0.25
12	60	0.89	0.303	0.24
13	65	0.88	0.294	0.24
14	70	0.86	0.301	0.23
15	75	0.83	0.315	0.225
16	80	0.80	0.307	0.22
17	85	0.75	0.307	0.21
18	90	0.67	0.304	0.195
19	95	0.50	0.309	0.20
20	100	—	0.309	0.19

energy achieved over theoretical expectations are due to optical losses in the system.

In order to monitor beamfront propagation down the drift tube, four wall current probes were inserted at four axial positions downstream of the injection point to measure beam current density at the drift tube wall. Typical oscilloscope waveforms from beamfront propagation measurements are shown in Fig. 2. These waveforms exhibit characteristics consistent with a picture of the beam propagating in a well focused manner to the end of the ionization channel, and then rapidly exploding to the drift tube wall at the position of the virtual cathode. In fact, it is encouraging to see that the wall probe current drops off quite rapidly as the beamfront passes by the probe position.

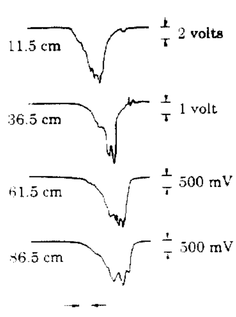

Figure 2: Typical traces from the current probes used to measure the beamfront propagation velocity.

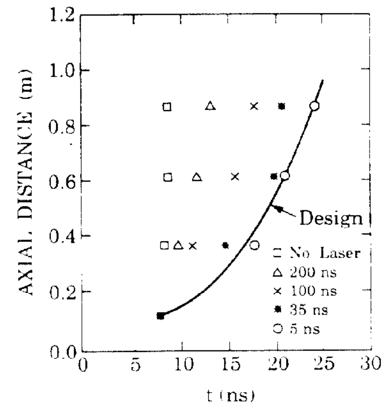

Figure 3: Wall probe measurements of beamfront propagation versus time for different laser firing delay times and without the laser ("two-part" gradient).

Plots of beamfront propagation distance vs time in the drift tube obtained from these waveforms are shown in Fig. 3 for various delay times between the firing of the laser and electron beam injection. It is easily seen that the designed beamfront control can be achieved if, as expected, the laser is fired immediately before the beam pulse. If the laser is fired too early, a plasma channel simply fills the drift tube in advance of beam injection and beam propagation occurs quite rapidly down the tube.

Ion acceleration experiments are currently underway.

III. Theoretical Studies

A. Model, Ion Production, and Initial Ion Acceleration Phase

In the simulations, an electron beam of voltage V_0, current I_0, and radius R_b is injected into a grounded cylindrical drift tube of length d and radius R_w along the axis of the drift tube. The region of the drift tube extending from the anode to a distance z_0 downstream is filled by hydrogen gas at a constant pressure p_0. The electron beam is assumed to be focussed by an infinitely strong guide magnetic field, so that particles in the simulation move only along the axis of the drift tube. The beam radius is also assumed to be much smaller than the wall radius so that the charge and current density and the axial electric field are approximately uniform across the beam cross-section. Ionization of the neutral gas is modeled by dividing the gas region into grid cells and monitoring the amount of ionization in each grid cell which is produced by impact ionization. Other details of the simulation appear in Ref. 3.

The time required for the laser beam to create plasma after striking the target on the cylindrical wall and the time required for the plasma to reach the electron beam, are assumed to be constant quantities. The front of the laser-produced plasma is assumed to sweep smoothly from one end of the drift tube to the other and the only effect of the plasma in the simulation is to completely neutralize any space-charge in the drift tube behind the plasma front. Details of this part of the simulation appear in Ref. 4.

When the laser is not used, our particle-in-cell code finds that the majority of the ions produced achieve energies of the order of the beam energy. There are a few ions that are accelerated to energies several times the electron beam energy by the coherent motion of the ions and the intense virtual cathode electric fields. For the parameter regimes investigated, peak ion energies of 5–6 times the electron beam energy have been observed in the numerous simulations.[3]

B. Laser Controlled Beam Front

The first set of results[4] using the laser was obtained for a 900 keV, 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 cloud of hydrogen gas located next to the injection plane. These parameters are those associated with the successful first generation laser-controlled beamfront accelerator experiments. As in the experiment, the front of the laser-produced plasma is assumed to travel down the drift tube at a velocity which increases linearly from 0.04c to 0.2c over a distance of 45 cm. Peak proton energies measured 45 cm downstream from the injection plane as a function of the time delay between the start of the beam pulse and the start of the laser pulse show that the design energy of 18.8 MeV is attained over a broad range of time delays. If one compares the phase-space trajectory of the peak-energy proton macroparticle and the phase-space trajectory of the laser-produced plasma front, we find for this design that the accelerated proton tracks the laser beam trajectory closely.

When the length of the drift tube is doubled from 50 cm to 100 cm (with all other system parameters the same) and the same velocity gradient is used, the peak proton energy measured at the end of the drift tube falls short of the design value, i.e., the original velocity gradient cannot be extended to longer distances. The reason the original velocity gradient cannot be scaled to longer distances can be seen as follows. The equation of motion of a proton which is being accelerated by an electric field E_z is $dv/dt = (e/m)E_z$, which can be rewritten as $E_z = (mc^2/e)v dv/dz$. If the velocity gradient dv/dz used in the above runs is substituted into the preceding expression, we find that the electric field needed to accelerate the proton at the desired velocity gradient is approximately $E_z = 334\,\beta$ MV/m, where $\beta = v/c$, e.g., for $\beta = 0.3$, an electric field of more than 100 MV/m is needed. In our simulations for a 100 cm long drift tube, we find that as the beam front moves downstream, the peak electric field tends to fall until it is no longer large enough to continue accelerating the proton at a constant velocity gradient.

The tendency of the peak electric field to fall as the beam front moves downstream suggests that it may be better to accelerate the protons with a steep velocity gradient at the start and then taper the gradient as the beam front moves downstream. In the second series of simulations, we therefore chose to do a set of runs in which the beam front velocity increases linearly with distance (i.e, dv/dz = constant) until it reaches a transition point, after which the beam front velocity increases linearly with time (i.e., dv/dt = constant). The plasma front velocity at the anode plane was chosen to be 0.04c, the plasma front velocity at the downstream end of the drift tube was chosen to be 0.4c, and the velocity $\beta_t c$ at the transition point z_t was varied. Figure 4 shows the peak proton energy measured at 90 cm as a function of β_t for three different values of z_t. Note that $V_0 = 1.5$ MV in this run. The figure shows that by adjusting β_t, energies in excess of the design energy of 60.7 MeV can be achieved. It should be noted that, as might be expected, the peak proton energy depends strongly on the beam energy, since the peak electric field increases with increasing beam energy. Although the code only approximately models the experiment, it has been able to reproduce some of the experimental results and appears useful as a design tool.

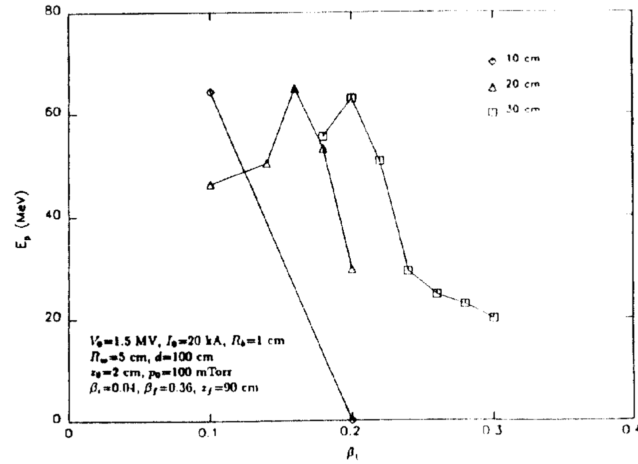

Figure 4: Peak proton energy measured at 90 cm versus transition velocity β_t.

IV. References

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