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TARGET STEERING AND ELECTROSTATIC ACCELERATION FOR IFE

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Abstract—**We have demonstrated that in-flight electrostatic steering can substantially improve target placement accuracy. We optically track the motion of a charged target and feed back appropriate steering voltage to four steering electrodes. Target placement accuracy of falling ~1.8 mg shells with 0.5 m stand off from steering electrodes is improved from ~ 500 to 10 µm standard deviation in each transverse direction. It might be possible to replace current-day positioning systems for target shots with a system such as this, resulting in substantial debris reduction.**

We also completed fabrication and started testing an electrostatic accelerator that advances the electric field each time the charged target passes one of the 96 accelerating electrodes. Many of the accelerating electrodes are segmented to allow transverse position correction based on transverse position measurements during the acceleration process. The accelerator operation has now transitioned to vacuum acceleration of 1.8 mg hollow shells. Calculations indicate that this "first step" accelerator could achieve 10–15 m/s target velocity in 0.9 m with –0.5 nC target charge and ±4 kV accelerating voltage. Demonstrating this capability is still underway. Additional experimental work and updated acceleration results will be presented.

Keywords: Target injection; Electrostatic acceleration; Steering

I. INTRODUCTION

The Naval Research Laboratory (NRL) has proposed to develop a Fusion Test Facility (FTF) based on direct drive with a krypton-fluoride laser [1]. The FTF will ultimately be a high-repetition rate facility, but there will be a substantial period of time during which targets must be supplied at a low rate. If the targets can be positioned with sufficient accuracy at a given point in space, this eliminates the need to implement laser beam steering systems at this stage of the fusion development program. The requirements for the target positioning system during this initial testing are (a) rep-rate of once every five minutes, (b) placement accuracy of ± 20 µm at 50 m/s with a standoff distance of 50 cm. We are developing a target steering and acceleration system to meet these requirements and that will ultimately be applicable to improving placement accuracy of targets for Inertial Fusion Energy (IFE).

II. TARGET STEERING

Initial steering tests were conducted with 4 mm steel spheres in air as illustrated in Fig. 1. Targets were held in place by a transparent vacuum chuck, electrically charged by direct contact with a high voltage electrode, and dropped by releasing the vacuum. A laser beam was vertically positioned along the target's path.

The transverse position of the target was measured by calculating the center of the Poisson spot in the center of the target's shadow. Steering corrections were calculated based on these position measurements and were implemented by sending voltage corrections to the four cylindrical steering electrodes.

Transition to vacuum operation required installation of the system in a vacuum chamber with a high-voltage electrical feed through. An automatic target loading system was developed and the vacuum release mechanism was replaced with a solenoid release mechanism (Fig. 2).

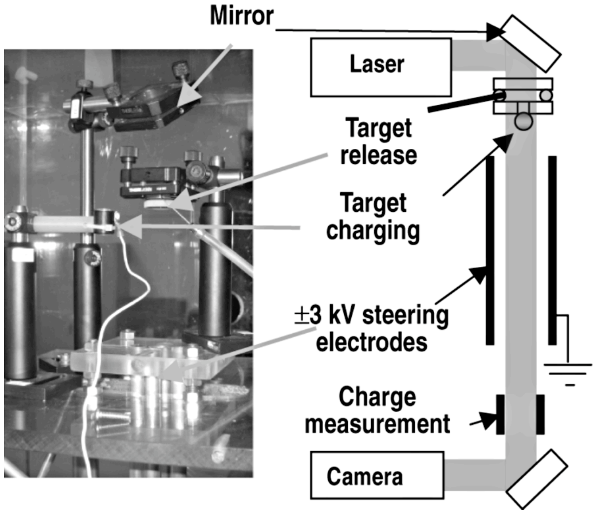

Figure 1. Configuration used for steering spheres in air. Two of the four steering electrodes that steer perpendicular to the page are not shown in the schematic view.

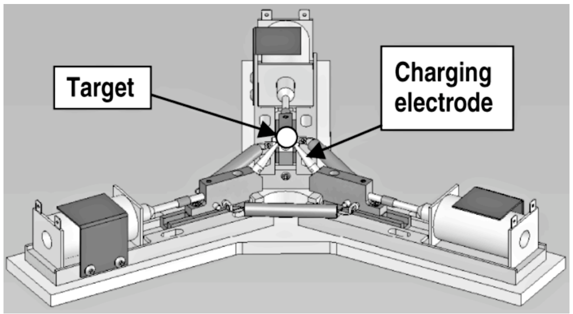

Figure 2. Three-solenoid target release mechanism with precision slides.

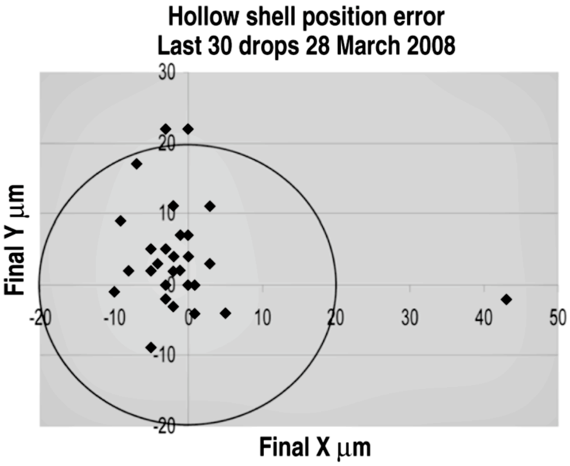

Figure 3. Standard deviation in X and Y are 9 and 7µm, respectively. Twenty-seven of 30 targets are within a 20 µm radius.

The release mechanism has three solenoids, each with one point of contact. The target charging electrodes are connected via a nonconductor (Delrin) and then to the solenoids via a precision slide assembly and a flexible coupling.

We achieved 9 and 7 µm standard deviation hollow shell steering repeatability in the two transverse directions with 30 consecutive targets (Fig. 3). Additional details regarding this steering system are provided in [2].

III. ELECTROSTATIC TARGET ACCELERATION

The FTF target positioning system will require an accelerator to increase injection velocity and also a clear path for target tracking. An electrostatic accelerator has been proposed to achieve this acceleration. An electrostatic accelerator has the advantage over other methods, such as mechanical injection, in that it can maintain a clear tracking path even during target acceleration.

We designed and built a test accelerator that uses a combination of split ring electrodes and solid electrodes as shown schematically in Fig. 4. The split electrodes allow for target steering during the acceleration process. For a negatively charged target, the electrode behind the target is charged negative to repel the target and the two electrodes in front of the target are charged positive to attract the target.

There are two components to the net radial electric force. First, the image force (which is shown as negative in Fig. 5) tends to pull the target off-center. The image force is proportional to the target charge squared. The larger the charge on the target, the less stable it becomes to radial position excursions. Second, the electric force created by the applied voltage to the electrodes is initially positive and later negative by a lesser amount and for a smaller distance. On average, the force from the applied voltage is positive and tends to center the target and mitigate the image force instability. ANSYS (a commercial finite-element code) calculations of the effective axial and the radial electric fields 1 mm off axis are shown on Fig. 6. The "image" is included in the net radial force.

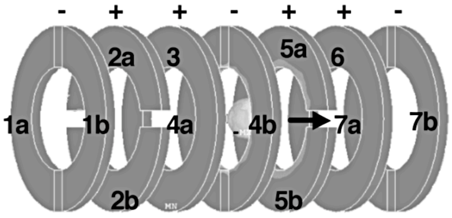

Figure 4. Electrostatic accelerator with split electrodes for electrostatic steering. Electrode configuration repeats each three electrodes. The target is shown between the fourth and fifth electrode.

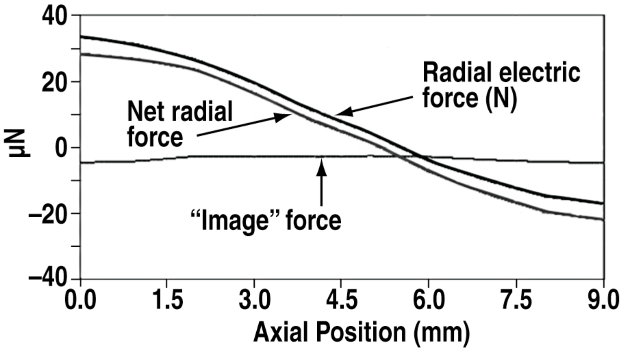

Figure 5. ANSYS calculations of the axial dependence of radial electric force that affects the target with a charge of –0.5 nC in an electrostatic accelerator. Radial displacement is 1 mm.

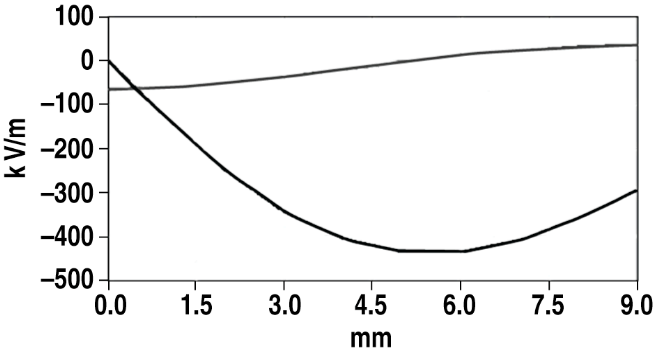

Figure 6. ANSYS calculations of the electric field distribution along the Z-axis between electrodes in an electrostatic accelerator with steering. Target charge is –0.5 nC. The applied voltage between electrodes is 8 kV.

The average axial electric field magnitude is –307 kV/m. For our 1.8 mg, –0.5 nC sphere, the resulting acceleration is 85 m/s^2 or 95 m/s^2 when added to gravity. Thus, with perfect timing of the accelerator voltage and a stable target trajectory, we could achieve 13 m/s velocity.

We designed circuit boards (PCBs) with the accelerator electrodes printed on them. These boards are stacked with every third board connected in parallel. The 96 accelerating electrodes are spaced 9 mm apart, giving the accelerator an overall length of 0.9 m as pictured in Fig. 7. We installed five Trek Inc. ±5 kV high voltage amplifiers to provide steering in two directions and acceleration orthogonal to the plane of steering.

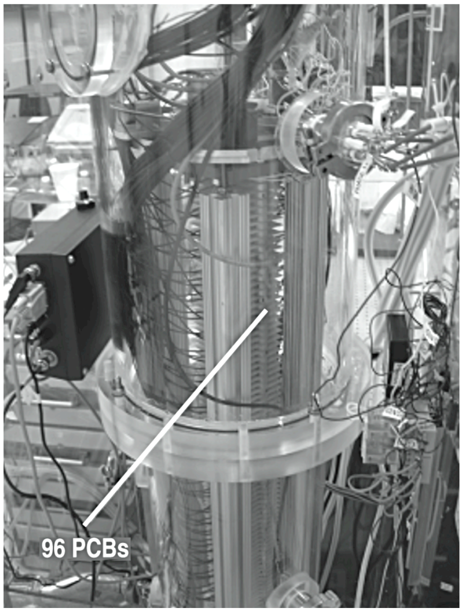

Figure 7. Ninety-six PCBs installed in vacuum chamber.

Timing the electrode voltage changes is a challenging part of operating the electrostatic accelerator. Optical sensors utilizing fiber optics to direct the light across the target's path indicate when targets approach each electrode in the accelerator. Photologic detectors give a high TTL output when light reaches the detector and low TTL when the target blocks the light. NAND and OR chips combine the signals to give a positive TTL signal when any of the 32 photo detectors in a phase are blocked. There are three of these signals, one for each of the three phases. These signals are directed to our timing electronics as the target is being accelerated and are shown in Fig. 8. After a delay time calculated to allow the target to pass through the center of the accelerating electrode, acceleration control voltage signals are generated by the timing electronics. These control voltage signals are amplified by the HV amplifiers, thus charging PCB boards above and below the target to push and pull the charged target along its trajectory, resulting in an overall acceleration in addition to gravity. As the target moves, its transverse position is measured. Steering is then achieved by varying the voltage and thus the electric field across each PCB board.

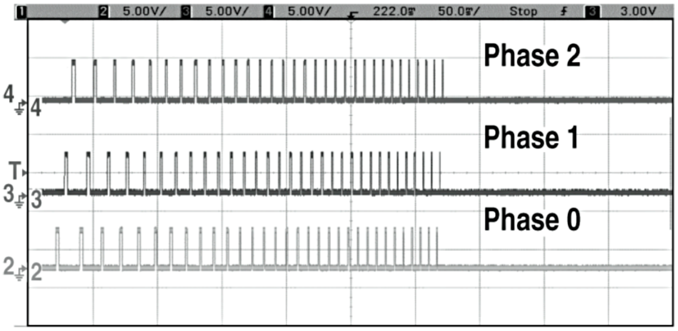

Figure 8. Signals given by phases 0, 1, and 2 which are sent to timing electronics. A TTL high is shown when a target blocks a photodetector.

High-voltage arcing damaged many of the system electronic components. A ground plane was installed above the high voltage components to protect the electronics in the upper chamber. Resistors and diodes were added to the system to prevent excessive voltage from reaching sensitive electronic components outside of the vacuum chamber.

Acceleration with steering has been achieved in vacuum on hollow, metallic-coated, 1.8 mg plastic targets. The greatest acceleration to date was achieved with –1.5 kV charging voltage applied to the target and ±2 kV on the electrodes. The target acceleration increased from 9.8 to 22 m/s^2.

The measured charge on spheres with a –1.5 kV electrode charge is ≃0.15 nC. With 150 kV/m average electric field, the average acceleration increase for a 1.8 mg sphere is 12.5 m/s^2 (12 m/s^2 above gravity was achieved). Larger charging voltage on the electrodes has resulted in unstable target behavior to date. The electrodes can hold off the full ±5kV from the amplifiers with steady dc voltage. However, attempts to increase the acceleration voltage above ±2 kV in addition to ±500 V across the steering electrodes resulted in electrical breakdown during the high frequency voltage oscillations required for target acceleration. Improving the vacuum from about 1 mTorr to less than 0.1 mTorr has not, to date, resulted in significant improvement in voltage holding in the system.

To achieve the higher velocity of 50 to 100 m/s, as is needed in an IFE power plant, would require a longer accelerator with still higher target charge and accelerator voltage. These results indicate that a much higher charge on the target will probably require a different charging method. Charging the targets by passing them through an energetic ion beam has been proposed. A longer accelerator has greater capacitance and higher velocity will require faster acceleration voltage changes. Both of these will necessitate voltage amplifiers with greater current and faster slew rate. Vertical injection will still be beneficial since it simplifies transverse position control of the target. It also allows the target to maintain a relatively straight trajectory after leaving the accelerator thereby reducing the field of view requirements for the tracking system. Since the target is not in contact with the accelerator, and the acceleration takes place in a vacuum, the accelerator electrodes need not be operated at cryogenic temperature.

IV. CONCLUSONS

Target steering has been demonstrated with excellent results of <10 μm standard deviation in each transverse direction with 0.5 m standoff from the steering electrodes. This system could be useful in reducing debris and shrapnel in current day single-shot experiments by replacing target holders and positioners that are destroyed by a shot.

The electrostatic target accelerator has been designed and built. Initial testing has demonstrated modest acceleration (12 m/s^2 above gravity) of lightweight plastic targets in vacuum. Substantial additional improvement will require an alternative target charging method, such as with an ion beam, and an improved design for high-voltage holding.

ACKNOWLEDGMENT

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