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TARGET INJECTION PLACEMENT ACCURACY IMPROVEMENT WITH ELECTROSTATIC STEERING

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To achieve high gain in an Inertial Fusion Energy (IFE) power plant, driver beams must hit direct drive targets with ±20 μm accuracy. For driver beams to arrive at the target with sufficient simultaneity, the targets must be placed to ±5 mm from chamber center. Better placement accuracy simplifies driver beam steering by reducing the distance that steering mirrors must reposition the beam aim point in the last few ms. Current best target placement experimental accuracy is 0.22 mrad standard deviation which corresponds to 3 mm at 13 m. A factor of two improvement is required to achieve 3 σ accuracy in ±5 mm, and even greater accuracy is desired.

General Atomics has recently embarked on a program to improve target placement accuracy through electrostatic steering. Preliminary experiments have improved accuracy of falling charged spheres. We optically track the motion, and feed back appropriate voltage to steering electrodes. A steering algorithm was prepared to steer targets with placement accuracy limited primarily by rate and accuracy of target tracking. Substantial accuracy improvement is expected with higher-frequency tracking and voltage amplification equipment. The results will be reported.

I. INTRODUCTION

Driver beams must be steered to hit targets with an accuracy of 20 μm with a distance from the final optic of ~25 m and target speed of order 100 m/s. Improved accuracy in placement of these high-speed targets near chamber center will reduce the required steering distance for the large numbers of driver beams, thereby easing the slew rate and angular acceleration requirements for high-speed steering mirrors and improving the chance for successful target engagement. Improved placement accuracy also will also improve the centering of the target within the depth of focus of the driver beams. Electrostatic target steering to improve target-positioning accuracy was previously proposed.[1] General Atomics has a new program to improve target placement accuracy with electrostatic steering.

II. ELECTROSTATIC STEERING CONCEPTS

Electrostatic target steering requires the placement of a charged target in an electric field. There are two primary concepts for target steering. Discrete steering measures target trajectory prior to entry into the steering electrodes and then provides a constant steering field to correct this trajectory. Continuous steering frequently updates target position measurements during the steering process and corrects the steering field based on these measurements.

II.A. Discrete Steering

In the case of discrete steering, the target trajectory is measured prior to entering the steering electrodes. One method to measure the trajectory is to measure the target's transverse position at two points.[2] From those two points, one can extrapolate the remaining uncorrected target trajectory and calculate the required steering.

As indicated in Fig. 1, the target with charge q, mass m, and speed v passes between target steering electrodes with potential difference V, length L_s, and spacing Y_p. The electric field strength between the electrodes is approximately given by $E \approx V/Y_p$. The target subsequently travels an extra distance L_c toward the focal point near the reaction chamber center. The target steering displacement ΔY is given by

$$\begin{aligned}\Delta Y &= \int_0^{t_s+t_c} v_y(t)dt \\ &= \int_0^{t_s} at\,dt + \int_{t_s}^{t_s+t_c} at_s\,dt \\ &= \frac{Eq}{m}\left\{ \frac{t^2}{2}\bigg|_0^{\frac{L_s}{v}} + \frac{L_s t}{v}\bigg|_{\frac{L_s}{v}}^{\frac{L_s+L_c}{v}} \right\} \quad . \qquad (1) \\ &\approx \frac{Vq}{Y_p m v^2}\left\{ \frac{L_s^2}{2} + L_s L_c \right\}\end{aligned}$$

Steering in the two transverse directions can be done either sequentially with two sets of flat electrodes or simultaneously with a single set of four rods as shown in Fig. 2.

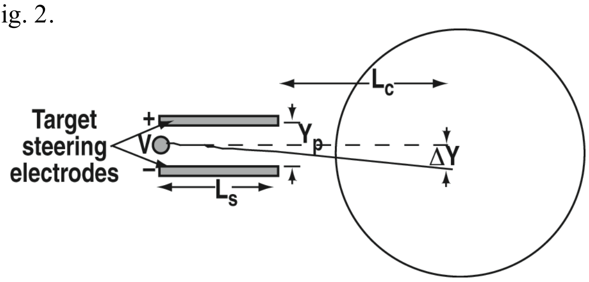

Fig. 1. The charged target is steered by an electric field between the target steering electrodes.

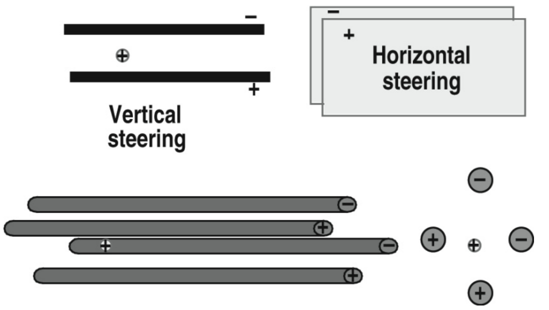

Fig. 2. Steering can be accomplished sequentially or simultaneously in the two transverse directions.

To understand the amount of target charge and electric field that will be required to steer a direct drive target, we consider an example. A 8 mg, 2 mm radius target with 0.44 nCoul charge corresponding to 2 kV moving 50 m/s is to be steered 10 mm by steering electrodes that are 50 cm long with 2 cm spacing a distance of 10 m from the chamber center. The required potential difference between the electrodes is given by:

$$\begin{aligned} V &= \frac{\Delta Y Y_p m v^2}{q\left[L_s^2/2 + L_s L_c\right]} \\ &= \frac{(0.01\ \mathrm{m})(0.02\ \mathrm{m})(8\times10^{-6}\ \mathrm{kg})(50\ \mathrm{m/s})^2}{(4.4\times10^{-10}\ \mathrm{Coul})\left[(0.5\ \mathrm{m})^2/2+(0.5\ \mathrm{m})(10\ \mathrm{m})\right]} = 1.77\ \mathrm{kV}. \end{aligned}$$

With a mechanical injector, it is possible to charge a target during the acceleration through a conductor in the pushrod (Fig. 3). The electrically grounded target will be forced into a negative potential sleeve in the gun barrel. Electrons will be repelled from the target as it enters the negative potential region. The exact amount of charge that will be transferred depends on the detailed geometry of the conducting surface near the target as well as the permittivity of the material in the front portion of the pushrod. The permittivity of the pushrod should increase the capacitance and therefore increase the charge. The conductor in contact with the target will deliver less charge to the extent that it encloses a portion of the target.

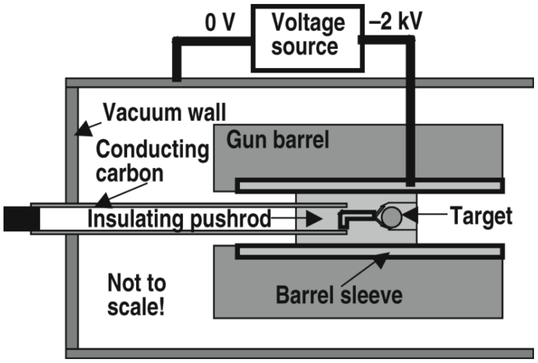

Fig. 3. Charge is induced onto the target through the grounded pushrod when the target enters the negative potential sleeve.

II.B. Continuous Steering

Continuous steering requires ongoing measurements of the target's transverse position. A laser beam continuously backlights the target and we measure transverse position with a camera on the opposite side of the reaction chamber as illustrated in Fig. 4. We are currently able to measure the targets' position once each 8 ms as it falls. Our transverse target tracking research is further described in Ref. 3 and 4.

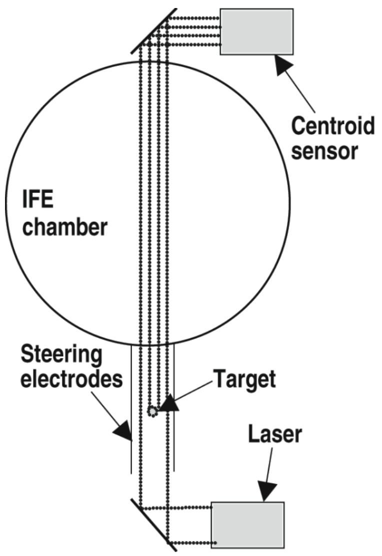

Fig. 4. Transverse tracking and steering layout.

II.B.1. One-Dimensional Continuous Steering

As a first step in the experimental program, we charged and dropped 4 mm steel spheres through a set of

parallel electrodes to steer in one direction only as shown in Fig. 5. The sphere is charged by direct contact with a retractable high-voltage electrode. The sphere is held in place by a transparent vacuum chuck and dropped by releasing the vacuum.

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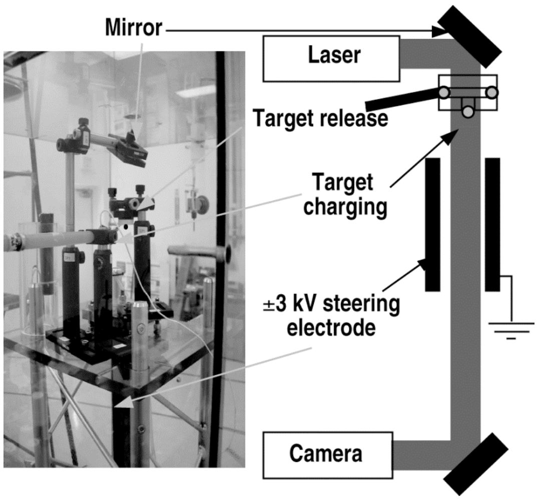

Fig. 5. One-dimensional steering of falling spheres.

The target is backlit by a 1 mW HeNe Gaussian laser beam expanded to ~14 mm. A Bassler A311f camera is used to measure the position of the Poisson spot in the center of the targets' shadow, thereby measuring the targets' position in the transverse dimensions. Our steering algorithm is given by

$$V_s = -\left(k_x x + k_v \Delta x\right) \quad ,$$

where V_s is the applied steering voltage, x is the distance from the last position measurement to the desired position, Δx is the change in x position over the last two position measurements, $k_x \sim$ 2.4 kV/mm and $k_v \sim$ 60 kV/mm are chosen constants of proportionality. Typical time between position measurements is ~8 ms. Typical target charging electrode voltage is –2.5 kV and the maximum steering correction voltage is ±3 kV. The targets drop 10 cm prior to the steering electrodes, 60 cm within the steering electrodes and 80 cm after leaving the steering electrodes.

The steering corrections resulted in reduction of the standard deviation in transverse measured final target position in the steered direction from 254 μm to 107 μm.

II.B.2. Two-Dimensional Continuous Steering

Having demonstrated effective steering in one-dimension, we are moving on to simultaneous steering in both transverse dimensions.

Four 1.27 cm diameter, 90 cm long cylindrical electrodes are held with 3.3 cm transverse spacing by brackets at the top, center and bottom as indicated in Fig. 6.

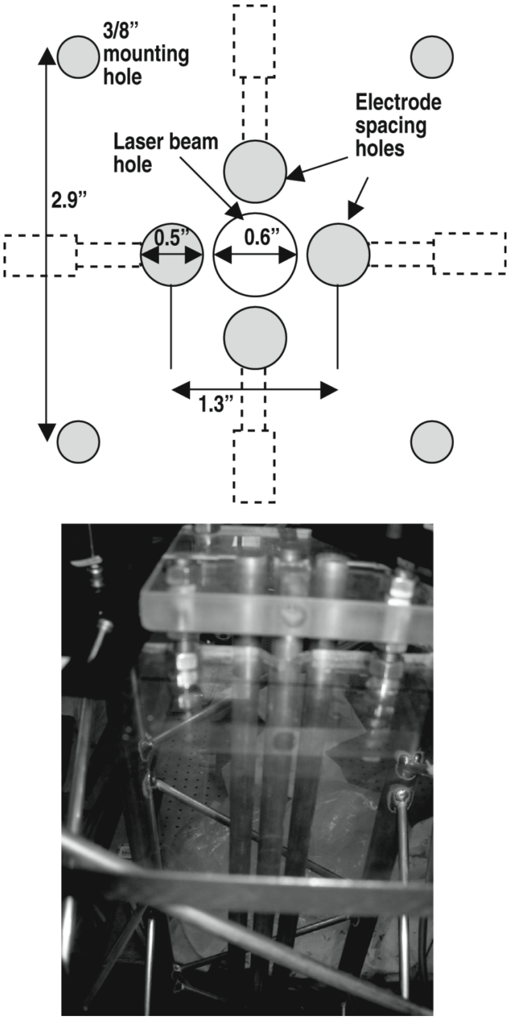

Fig. 6. Four steering electrodes provide steering in both transverse directions.

We calculated the potential and electric field strength between electrodes for the case the positive X electrode energized to 3 kV and the others at ground potential. The potential distribution between the electrodes is shown in Fig. 7(a). The potential within 4 mm of the center is graphed in 7(b). Near the center the electric field strength is approximately 100 kV/m in the –X direction as shown in Fig. 7(c). Off axis in the Y direction, there is also a significant electric field component in the Y direction, as shown in Fig. 7(d).

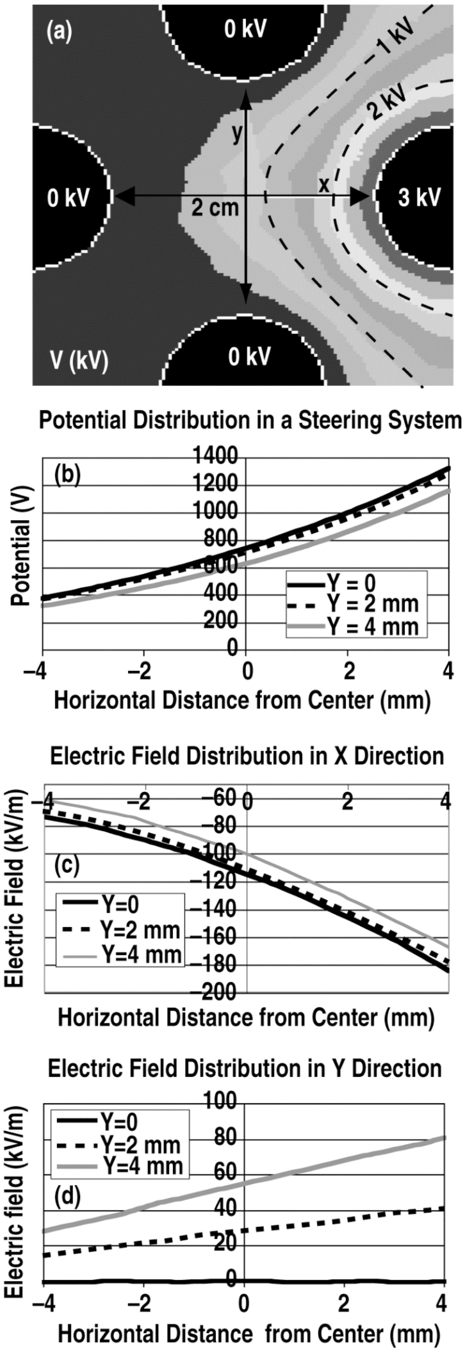

Fig. 7. ANSYS calculations of (a,b) electrostatic potential (c) X electric field, and (d) Y electric field between our target steering electrodes.

We indirectly measure the charge on the falling targets by passing them through a conducting tube that is connected to the 1 MΩ resistance of an oscilloscope (Fig. 8). The charge on the target is approximately equal to the charge induced on the tube and therefore is given by

$$q \approx \int I dt = \int \frac{V dt}{R}.$$

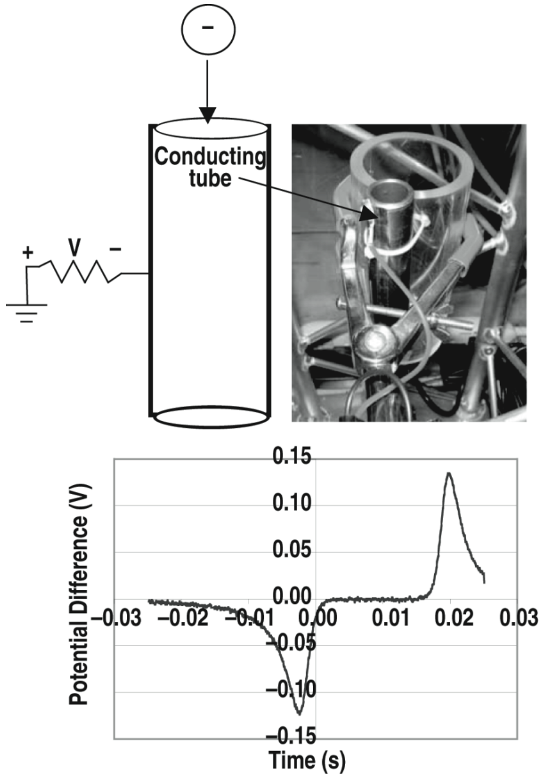

Fig. 8. The negatively charged falling target attracts charge onto the conducting tube causing a negative voltage pulse as it enters and a positive pulse as it leaves.

The calculated charge on the target based on data from Fig. 8 is –0.74 nC which corresponds to –3.3 kV on a 2 mm radius sphere. The charging electrode potential was –5 kV. The standard deviation in sphere charge for a constant charging electrode voltage is approximately 12%.

The targets drop 0.1 m prior to entering the steering electrodes, 0.9 m in the steering electrodes, and 0.5 m after exiting the steering electrodes. Preliminary data indicates that the standard deviation in transverse measured final target position is approximately 60 microns in each of the transverse directions.

III. CONCLUSIONS AND FUTURE PLANS

Our work on target steering is just beginning. We have thus far developed a method for tracking the targets' position, charging a target in air and have achieved substantial improvement in the trajectory of falling solid spheres. We have demonstrated a method of measuring the charge on the spheres as they fall.

Future work includes further improving position measurement accuracy and doing this at higher rates. This will enable us optimize our steering of solid spheres in air and then move on to steering hollow targets in vacuum. Our current method of launching targets with a vacuum chuck must be replaced prior to the vacuum testing. We anticipate launching targets vertically off of a grounded retractable shutter by briefly pulsing a transparent electrode above the target.

Following successful steering of falling targets, we intend to introduce electrostatic acceleration to achieve higher injection speed followed by continuous electrostatic steering. These test are expected to provide the scientific basis for design of a target positioning system for the Fusion Test Facility and later IFE power plants.

ACKNOWLEDGMENTS

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