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In-vacuum performance of a 3D-printed ion deflector

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ABSTRACT

Using conductive and non-conductive source materials, an ion deflector plate was fabricated by fused filament fabrication. The fully vacuum-compatible design was tested by measuring the voltage-dependent deflection of Rb^+ ions, and the results, which are ion energy dependent, are consistent with predicted kinematics for the ions. The results also compare well with a metal plate of similar dimensions and with an ion trajectory simulation.

1. Introduction

Additive manufacturing or 3D printing has opened up numerous avenues for small-scale and in-house prototyping and design. One of the most popular forms is fused filament fabrication (FFF) which utilizes thermoplastic feedstock and extrudes it onto a two-dimensional bed to build a part layer-by-layer [1]. When conductive parts are needed, other techniques, such as light polymerization and powder bed printing, are employed. These methods however require the use of solvents, or result in voids in the finished product, which inhibit the use in vacuum. With the advent of conductive filament feedstock it is now possible to fabricate non-metallic conductive parts using FFF and directly incorporate circuity such as printed thermometers and sensors [2,3].

We have investigated the in-vacuum application of conductive and non-conductive parts by fabricating an ion beam deflector assembly. The plate was tested for vacuum suitability and for its ability to divert ion beams as a function of their energy. The results were compared to both a metal plate and to a simulation. Similar efforts have looked at a 3D-printed ion funnel and an accelerator beam pipe [4,5]. The goal of these measurements is to determine whether the 3D printing of charged particle optics can provide a viable, i.e. functional and vacuum-compatible, path for rapid in-house prototyping of designs.

2. Materials and methods

For our measurements, all parts were fabricated using high impact polystyrene (HIPS) and polylactic acid (PLA) filaments in a Lulzbot TAZ 5 3D printer. Our designs utilized 3.00 mm HIPS for insulating components and 2.85 mm PLA for conductive components. The conductive PLA (Proto-pasta by ProtoPlant) contained a conductive carbon black additive and is quoted with a volume resistivity of 15 Ω-cm (unprinted) and 30 Ω-cm and 115 Ω-cm along and against the printed layers, respectively. A 16 x 16×0.68 mm^3 sample of conductive PLA was printed and measured via the four-point probe method to obtain a resistivity value of 11.5 Ω-cm, which is somewhat lower than the lowest quoted manufacturer's value and independent of the measurement direction.

The deflector design utilized two printed parts: a conductive PLA plate and an insulating HIPS mount for the plate (Fig. 1(a)). The deflector had attachment slots on the back to connect to the insulating mount. To attach connect an external voltage source to it a wire attachment was made onto the back by inserting a heated 0.5 mm Cu wire and then covering it with conductive PLA. The insulating mount was configured with mating slots for insertion of the plate and included additional space to accommodate the wire attachment. A second slot was included in the mount to secure it to a capillary plate in our system [6]. The configuration ensured that the deflector was 5–8 mm away from the primary beam axis.

All parts underwent vacuum compatibility testing utilizing a chamber that was configured for this purpose [7]. The chamber had a base pressure of 1×10^{-7} Torr and a working pressure between tests of 5×10^{-7} Torr. The HIPS and PLA parts were tested separately by inserting them and following the pumpdown curves for 24 h. The

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pressure at this point (P_{24h}) for the HIPS was $P_{24h} \approx 2 \times 10^{-6}$ Torr and for the PLA was $P_{24h} \approx 5 \times 10^{-6}$ Torr. The outgassing rates were measured to be 7×10^{-6} Torr L/(cm^2 s) and 3×10^{-6} Torr L/(cm^2 s) for the PLA and HIPS, respectively. These results, which were consistent with the results of others [5,7,8], indicate compatibility with our beamline and no significant outgassing was recorded upon their use in that setup.

Following the vacuum tests, the deflector and mount were placed into a CF six-way at the exit of our Colutron ion source [9]. The placement, which is illustrated in Fig. 1(b), put it directly in front of a metal capillary. Beyond the capillary and deflector assembly was mounted a Faraday cup for measuring ion beam currents. The beams utilized were Rb^+ generated from an aluminosilicate emitter which were accelerated to energies 500–1500 eV. Before deflection tests, a Rb^+ beam was tuned through the metallic capillary and into the Faraday cup with the deflector grounded. During a deflection test, a deflector voltage was applied and increased while monitoring the Faraday cup current. The voltage sweep continued until the measured beam current had dropped to less than 1% of its original value. The voltage was then swept back to zero to evaluate hysteresis effects. In practice, the initial applied deflector voltage for data collection was chosen by sweeping the voltage quickly up until the beam current was extinguished and noting the applied voltage at which the maximum beam current was recorded. The voltage was then lowered to ~50 V below this point and data collection was initiated. This procedure was repeated using a 316-stainless steel shim deflector.

3. Results and discussion

Our voltage-dependent deflection measurements for Rb^+ ions with energies of 500–1500 eV are shown in Fig. 2. The first feature to note is that the voltage required to significantly deflect the ions and extinguish the beam current increases with the beam energy. From a kinematic analysis one obtains an expression for the voltage required to deflect ions of charge state q and incident energy E_{inc} through a deflection distance Δ as

$$V\text{deflect} = \frac{4\Delta \text{d}}{ql^2} E\text{inc}$$

where l is the plate length and h is the nominal distance from the plate at which the ions experience the deflecting field. For Rb^+ ions over our energy range and expected minimum plate separation distance ($d = 5$ mm) we find reasonable agreement for a deflection equivalent to the size of our capillary, i.e. $\Delta = 2.3$ mm, with these values shown as the vertical lines in Fig. 2. To compare these data to a simulation of the deflector, the derivative (dI/dV) was determined for each incident energy and the location of the peak value was assigned as the experimental cutoff voltage (Fig. 3).

The ion optics simulation SIMION was used to model the dynamics of our setup [10]. For the simulation, a 1.6×10^8 point grid was configured to contain a capillary and deflector (Fig. 1(b)). The deflector was placed a distance d from the beam axis and x from the capillary entrance, with both values treated as variables. A simulated Rb^+ beam was generated 75 mm from the capillary entrance distributed in a circular profile (0.25 mm radius) about the beam axis. A 4° angular divergence was assumed for the beam and accounted for in the direction towards the deflector. The energy and angular spreads were set to be Gaussian with FWHM of 15 eV and 0.8°, respectively.

To determine the deflection voltage for ions of a fixed E_{inc} (V_{cutoff}), 10^4 ion flights were used and the number of ions passing through the capillary was recorded as the deflector voltage was varied. This was repeated for all experimental E_{inc} values and for fixed combinations of the spacing (d, x) of the plate. The simulated data was numerically differentiated with respect to the deflector voltage to reproduce the experimental method.

In Fig. 3, the voltages corresponding to the peak of the simulated and experimental $\frac{dI}{dV}$ curves are shown. Three simulation runs with different combinations of the d and x offsets are shown. In both the experiment and simulation a linear dependence in V_{cutoff} with respect to the energy is obtained, which is expected based on the expression for V_{deflect}. For the PLA deflector and metal plate, best-fit lines show that we obtain a non-zero intercept, which is not reproduced by the simulation. This arises from the fact that our beams are not straight, parallel beams but instead were focused to maximize current through the capillary and into the Faraday cup. The overall offset between the PLA and metal plate results can be attributed to small differences in placement of the deflectors (d and x) relative to the capillary. As the simulations show, small changes in these values can shift the absolute voltage required for deflection significantly.

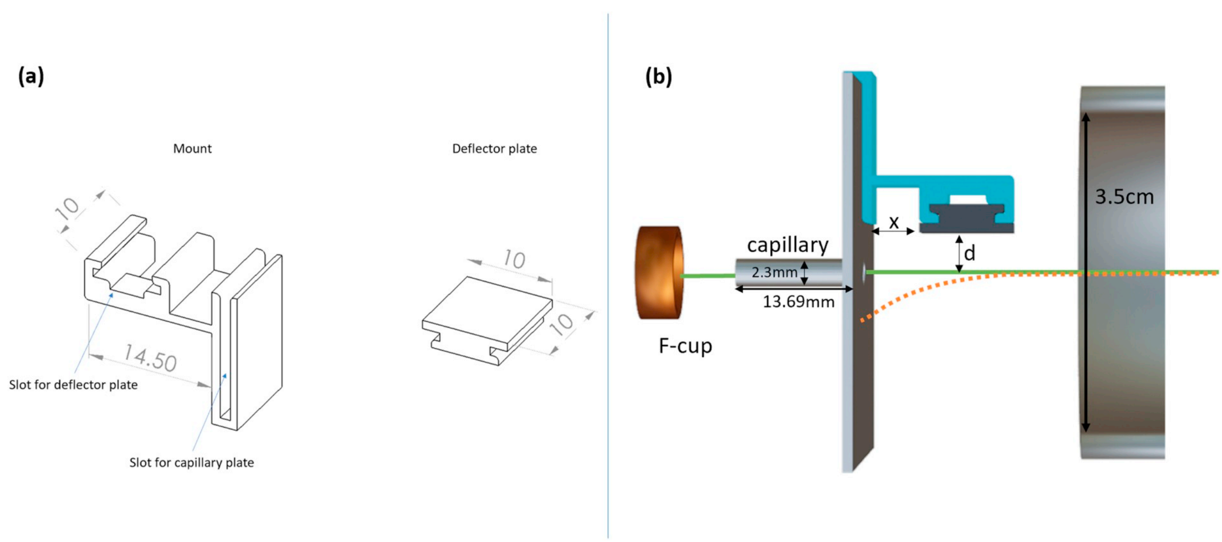

Fig. 1. Schematics showing (a) the HIPS mount and PLA deflector (dimensions in mm) and (b) the setup of the deflector (black) and metallic capillary, where the deflector is aligned distances x and d from the capillary front and beam axis, respectively. The 3.5 cm opening corresponds to the inner diameter of the CF six-way that housed the setup. The solid green line shows the path when the deflector is grounded, and the orange dotted line shows the path with a voltage applied. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

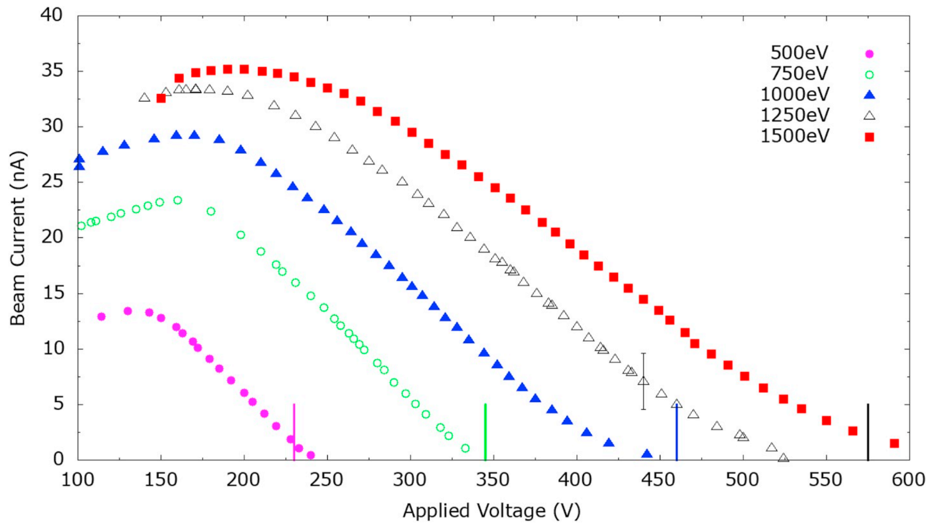

Fig. 2. Measurements of the transported beam current for Rb^+ ions as a function of the voltage applied to the 3D-printed deflector for different E_{inc}. The four vertical lines along the voltage axis correspond to the deflection voltage values ($V_{deflect}$) calculated from a kinematic analysis. A representative error bar for the data is shown and was obtained from a hysteresis measurement.

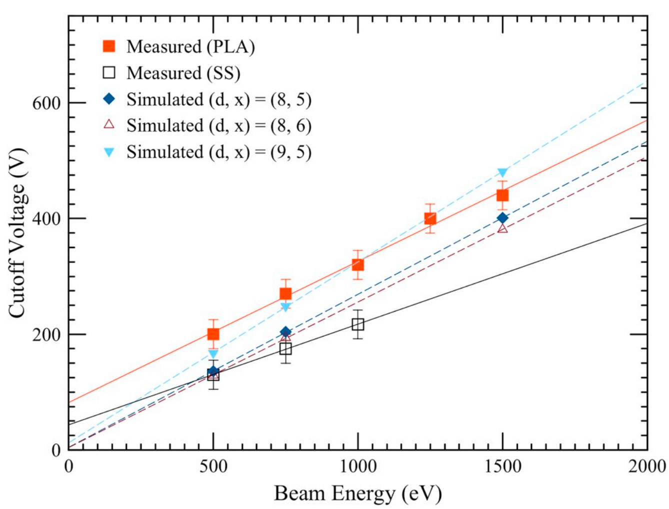

Fig. 3. Measured and simulated (SIMION) cutoff voltages for Rb^+ as a function of the beam energy. The experimental data were obtained from deflection measurements, with the voltages assigned from dI/dV peak positions. The simulated data are shown for 3 d and x combinations as defined in Fig. 1(b).

4. Conclusion

Our results indicate that 3D-printed PLA components are vacuum compatible and can be utilized for charged particle deflection. The linear energy-dependence obtained for the deflection of ions is consistent with what is expected based on simple kinematics. In addition, both simulations and metal deflector data give similar results, as the slope of the cutoff voltages show good agreement, indicating that conductive PLA could serve as a rapid prototyping component or straight-up replacement for charged particle-facing components in vacuum applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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