Research toward an Electrostatic Microparticle Thruster based on Contact Charging

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Abstract: **This paper reports on our experiments aiming at an efficient technique for contact charging of microparticles, which could be applied for space propulsion. Photolithographically produced fine electrode structures create high electric field strengths at the particle surface when a conductive microparticle comes in contact with the high voltage electrode. Besides propulsion of space vehicles, terrestrial applications for surface treatment and as new particle source for hypervelocity experiments like simulation of micrometeorites appear possible.**

Nomenclature

A_i	= area of surface element i
C_{D}	= capacitance of the electrostatic particle detector
ΔU_{D}	= amplitude of the particle detector signal
d_1, d_2	= width and centre-to-center distance of conductive lines
σ_i	= surface charge density at particle surface element i
E_i	= electric field strength at particle surface element i
$E_{\mathrm{p\,max}}$	= upper limit of the electric field strength at the particle surface
e	= elementary charge
ϵ_0	= permittivity of free space
F	= electrical field force acting on a charged microparticle
i	= surface element i in a field simulation
m_{p}	= mass of a microparticle
q_{p}	= charge of a microparticle
r_{HV}	= radius of curvature of a high-voltage electrode
r_{p}	= radius of a microparticle
ρ_{p}	= mass density of a microparticle
U_{HV}	= high voltage
v_{p0}	= exhaust velocity of a microparticle

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I. Introduction

Since the early times of electric propulsion, the possibility of heavy particle thrusters has been discussed,[1] but their development has been slow, and no such engine has been flown successfully so far. Examples are droplet or colloid thrusters[2] and, more recently, nanoparticle field-extraction thrusters.[3] Recently, we proposed a thruster concept which is based on contact charging of microparticles by means of fine high-voltage electrodes.[4,5]

Our current research efforts are aiming at higher ejection rates. Therefore, we apply two novel ideas. One is the use of electrode configurations other than the typical needle-pinhole combination, in order to ensure that the microparticles always acquire the desired high charge. The other one is the miniaturization of electrode arrays as microelectromechanical systems (MEMS). In this contribution we give a report on so far investigated electrode assemblies and the applied diagnostics.

II. Contact Charging

Hypervelocity experiments for the simulation of micrometeorites and their impacts for example on the surface of the moon, space vehicles, space suits, solar panels, and instruments also use electrostatic acceleration of charged microparticles. A successful technique applied there allows charging close to the physical limits. The particles are brought in contact with very small spherical or needle-shaped surfaces at high voltage potentials. Shelton et al.[6] applied this technique using as charging electrode a small sphere with a diameter of 24 μm at the end of a tapered tungsten wire, which is maintained at a positive potential of $U_{\mathrm{HV}} = +20\,\mathrm{kV}$. If the charging electrode has the radius r_{HV}, and the much smaller particle has the radius $r_{\mathrm{p}} \ll r_{\mathrm{HV}}$, then the electrode potential U_{HV} yields a particle charge of $q_{\mathrm{p}} = 2/3\pi^3\epsilon_0(r_{\mathrm{p}}^2/r_{\mathrm{HV}})U_{\mathrm{HV}}$.

The charging electrode has not necessarily to be a sphere, any other geometry with fine structures which focuses the field lines on a small conductive area accomplishes the same purpose. For example, instead of a sphere at the end of a tapering wire, a needle can be used. Such needle dust sources, in combination with additional post-accelerators with potentials in the MV range,[7] are applied in today's dust accelerator facilities in Germany,[8] the United States,[9,10] and Japan.[11] Recently, a new facility has been constructed at the Colorado Center for Lunar Dust and Atmospheric Studies at the University of Colorado in Boulder.

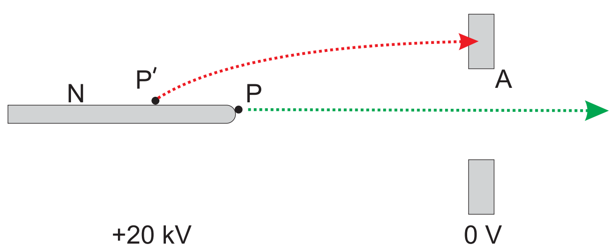

Figure 1. Schematic of particle charging and acceleration. The particle P is charged at the tip of needle N, is accelerated towards the aperture electrode A, and leaves the system through the latter. Particle P′ is charged laterally at the needle N and is charged less than particle P. Its acceleration has a component perpendicular to the needle, which makes it crash onto the counter electrode A.

Thinking in electric propulsion, the shortcoming of this technique is, that only a small portion of the particles gets in contact with the tip of the charging electrode, where they receive the highest electric charge and are extracted out of the source. Most particles touch the charging electrode laterally, where the field strength is much lower, and hence are charged much less (see Fig. 1). Moreover, those particles obtain a significant lateral momentum and will miss the electrode aperture. On their impact on the counter electrode, they are, depending on their speed, mechanically destroyed and contaminate or erode the inner of the particle source. The loss of particles and the imperfect charging can be acceptable for scientific impact experiments, where the "bad" particles can be sorted out,[8] but makes the technique unsuitable for a particle thruster or an application for industrial surface modification.

To avoid incomplete charging at the low field parts of the high-voltage electrode, we suggested lateral embedding of the electrode in a dielectric.[5] The dielectric does not qualitatively modify the field distribution around the needle, but assures that the particles get in electrical contact exclusively at the needle tip, where the field is highest. For a simple technical implementation, we filled a mold with a vertically clamped gold

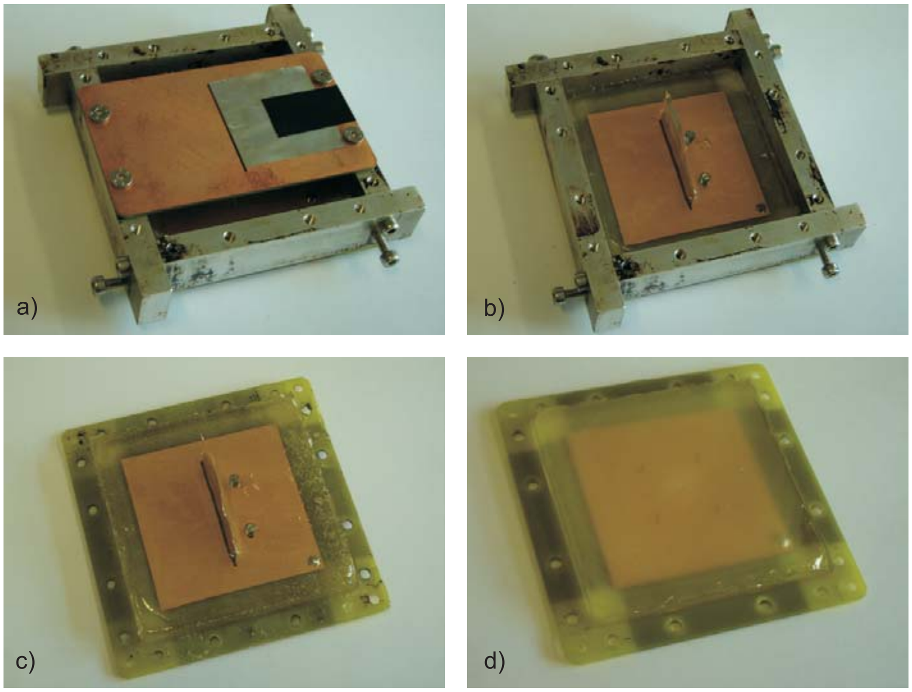

Figure 2. Resin casting of embedded electrodes. (a) Mold with a clamped aluminum foil, (b) mold after filling with liquid epoxy resin and hardening, (c) the electrode after removing of the mold. (d) Electrode array after milling and polishing of the surface (an array of fine gold wires and four stronger copper wires instead of a metal foil are used in this photograph).

wire (diam. 25 μm) with epoxy resin of very low viscosity, and milled and polished the surface after hardening (see Fig. 2). The truncated gold wire forms the needle with its tip at the surface. The wire can be replaced by a thin foil in order to increase the electrode surface, make it less delicate, and simplify the fabrication. A more detailed report on this experiment has been presented at the previous International Electric Propulsion Conference.[5]

III. MEMS Fabricated Electrode Structures

Microelectromechanical systems (MEMS) technology allows not only a more compacted, but also a much preciser fabrication of embedded electrodes than our epoxy resin technique described above. We produced small chips (22×27 mm^2) with thin d_1 wide gold lines on a glass wafer. The gaps between the lines with centre-to-center distance d_2 were coated with silicon dioxide. Figure 3 shows schematic side and top views of an electrode chip.

The MEMS electrodes differ from the above described electrodes (sphere, needle, embedded wire and embedded foil) in the following aspect. The high voltage is not provided from behind, but from the side, and the electrode width $d_1 \geq 10$ μm is greater than its height of approximately 600 nm, which is the thin film thickness. Even though this geometry is very different from the previous geometries, the principle to produce high electric field strengths where the particles are charged remains the same. We showed this with the help of an electrostatic field computation with the finite element method.[5]

The field solution includes the electric field strengths E_i at the surface elements A_i, from which the surface charge densities $\sigma_i = \epsilon_0 E_i$ can be derived. The simulated particle shown in Fig. 3(c) has a diameter of $2r_\mathrm{p} = 3$ μm and was charged close to the border of the $d_1 = 10$ μm wide line electrode. Most of the charges are located on the upper hemisphere of the particle yielding a maximum electric field strength of $E_\mathrm{max} = 1.0 \times 10^9$ Vm^{-1}. This value is still an order of magnitude smaller than the critical value for field evaporation.[12] The sum

$$q_\mathrm{p} = \sum_i \sigma_i A_i \qquad (1)$$

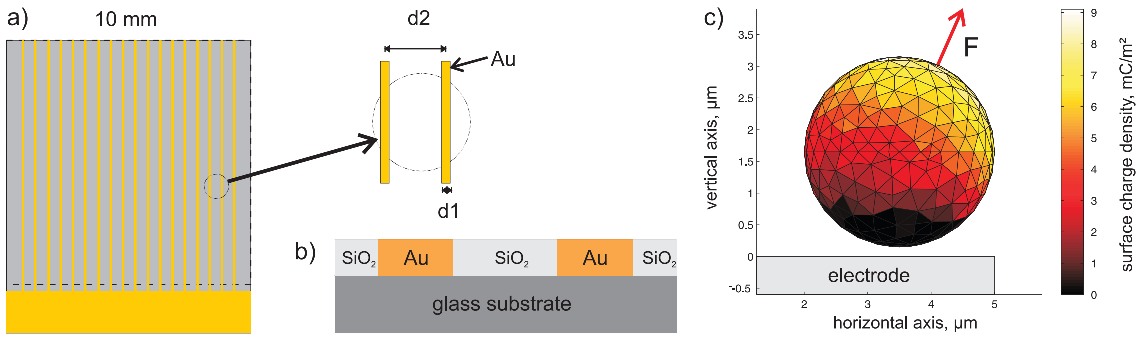

Figure 3. Schematic of the MEMS design. (a) The top view shows the conductive lines embedded in silicon dioxide. (b) The profile shows the thin film on the glass substrate. (c) Simulated surface charge density on the particle when it detaches from the electrode. The red arrow indicates the direction of the total force.

for all particle's surface elements i is the particle charge, in case of the example is $q_{\mathrm{p}} = +6.6 \times 10^5 e$. An isolated particle with this charge, i.e. after ejection and before its neutralization, would have a surface potential of $q_{\mathrm{p}}/(4\pi\epsilon_0 r_{\mathrm{p}}) \approx +635$ V. Also the electric field force acting on the particle

$$\vec{F} = \sum_i \frac{1}{2}\sigma_i \vec{E}_i \cdot \vec{A}_i \frac{\vec{A}_i}{|\vec{A}_i|} \tag{2}$$

can be obtained, which is approximately $F = 18\,\mu$N for the moment of detachment from the electrode. The kinetic energy that the particle gains in the 20 kV acceleration potential is $q_{\mathrm{p}} U_{\mathrm{HV}}$ and corresponds to an exhaust velocity of $v_{\mathrm{p0}} = 445\ \mathrm{m\,s^{-1}}$ for a gold-coated melamine particle ($\rho_{\mathrm{p}} = 1510\ \mathrm{kg\,m^{-3}}$).

Figure 4(a) shows a 6-inch glass substrate with 20 electrode chips. Each chip has a size of 22×27 mm [Fig. 4(b)]. In Figs. 4(c) and 4(d), a chip is mounted in a frame, which is used in the particle source that also contains the counter electrode.[5]

IV. First Experiments with Chip Electrodes

A. Experimental Setup

The experiments have to be performed in vacuum in order to avoid ionization phenomena like arcing or glow discharges due to the high voltage and correspondingly high electric field strengths. The vacuum chamber is basically a DN 250 ISO-K stainless steel cross piece with four 250-mm apertures. The turbo molecular pump is mounted at the lower flange and provides pressures below 4×10^{-5} Pa. The three other flanges are closed by covers with small flanges for the pressure gauge and electrical feedthroughs for the high-voltage supply, the electrostatic particle detector, and the microscope camera. Figure 5(a) shows a view into the opened vacuum chamber.

The particle source consists basically of the electrode chip and a 100×100-mm grounded counter electrode with apertures a few millimeters above the electrode surface. The chip is mounted in a frame of the same size as the counter electrode [Fig. 4(d)], which has a clamp connection for the high voltage supply. Frame and counter electrode are stacked, but separated by a 3-mm acrylic glass plate with cut-out where the chip is [see Fig. 5(b)].

The particle diagnostic is done by a direct observation of the chip surface with a microscope camera. The camera itself is operated under atmospheric pressure conditions in a 40-mm tube and looks at the chip through a glass window from below.

The electrostatic particle detector shown in Fig. 5(a) is mounted above the particle source assembly. It follows the example of the detectors used in devices for the simulation of micrometeorites, which make use of electrostatic induction.[6–8] Our detector was described in an earlier report.[5] When a particle with charge q_{p} flies through the inner one of two cylinders, which form a capacitor, it produces a trapezoid-like voltage signal with steep edges, which allows a time-of-flight measurement of the particle speed. The amplitude ΔU_{D} together with the detector capacitance C_{D} yield the particle charge $q_{\mathrm{p}} = C_{\mathrm{D}} \Delta U_{\mathrm{D}}$.

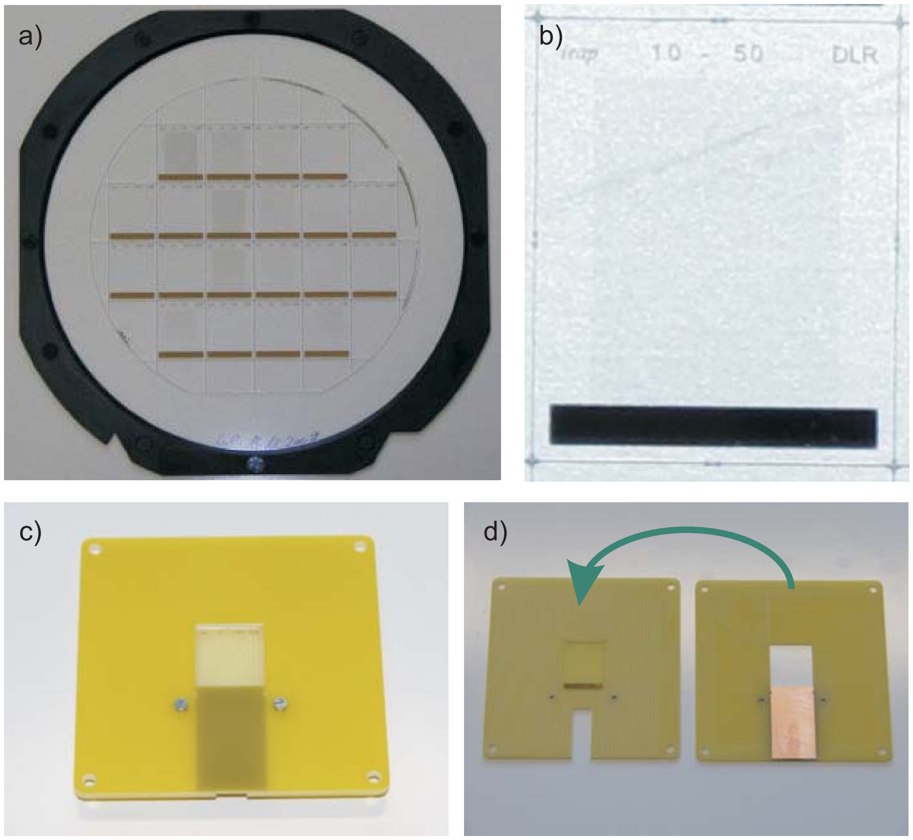

Figure 4. MEMS electrodes. (a) A 6-inch wafer in its transport frame and (b) a single electrode chip with a size of 22 × 27 mm. (c) Chip frame used in the electrode assembly and (d) the opened frame.

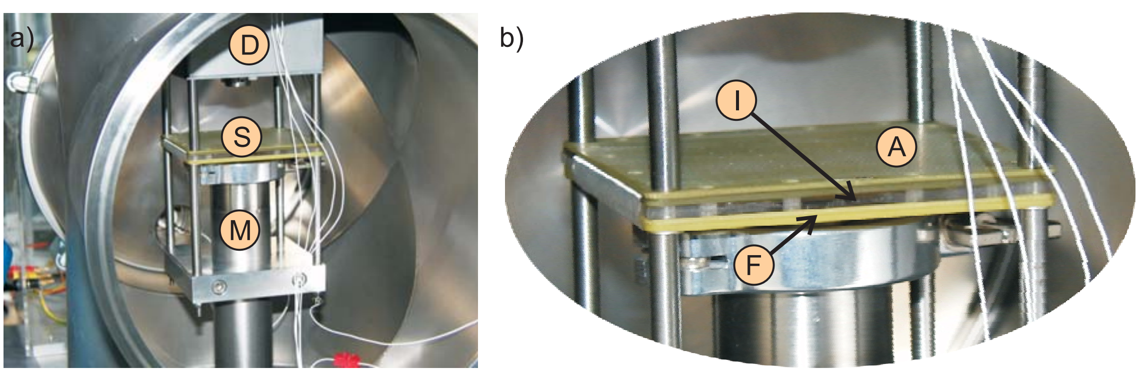

Figure 5. (a) View into the vacuum chamber. Four thread rods hold the particle source S. The upward ejected particles fly through the detector D above the source. The microscope M resides in a tube with window and observes the chip surface from below. (b) The particle source consists of an electrode chip in its frame F, the counter electrode with apertures A, and an insulating separator I in between.

B. "One Shot Operation"

The procedure described in this section was used in our experiments so far, but we are working already on a device which drops single particles onto the electrode chip.

Before a "shot", the electrode surface is coated with a thin layer of particles. For this purpose, the surface is covered with a suspension of gold or aluminum coated microspheres in isopropanol. The alcohol evaporates within a few seconds and the particles remain firmly on the surface due to adhesive forces.

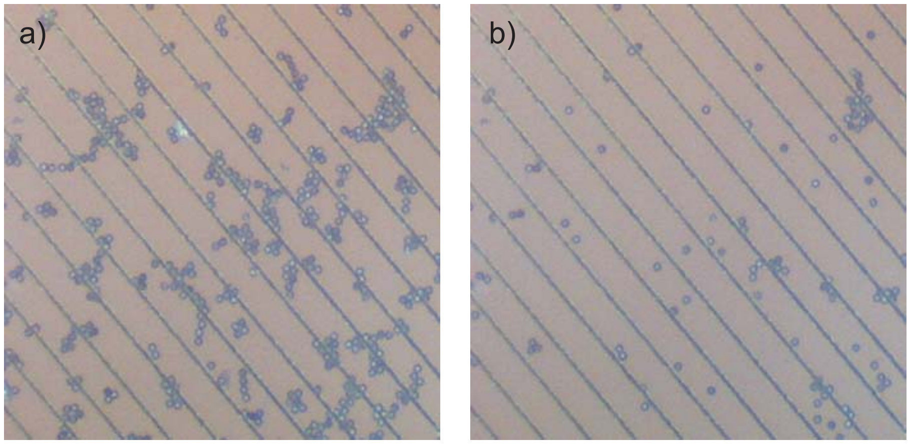

Figure 6. (a) Before and (b) after application of a 20-kV high-voltage pulse. The 10-μm particles had been coated with aluminum. ($d_1 = 10\,\mu$m, $d_2 = 50\,\mu$m.)

After pumping down, the high voltage is switched on. Immediately and during a very short time, many particles are ejected through the apertures in the grounded electrode. The two photographs in Fig. 6 were taken by the microscope mounted below the glass chip. It looks through the 1 mm strong glass and is focused on the conductive lines at the upper surface. The time elapsed between the two consecutive video images is 1/25 s. This is not fast enough for an observation of the particle movement, but the video confirms that the majority of the particles is charged and leaves the chip.

Even particles which were not in direct or indirect contact with the high voltage left the surface. This can be explained by the high electric field strength in the vicinity of the electrode inducing a dipole in the conductive particle, which in turn feels the dipole force in direction of the gradient of the field, i.e. toward the next electrode line.

The ejected particles can be collected with a glue strip above the opening in the grounded electrode. This simple method was used as a direct proof that the particles left the electrode assembly through the aperture. A more sophisticated diagnostic, which allows to determine charge and speed of single particles, is the electrostatic particle detector. However, due to the "one shot operation", which always releases hundreds of particles at the same time, it has not been possible to detect a single particle event.

V. Conclusion

In this paper, we reported on our current work on contact charging of solid metal or conductively coated dielectric microparticles and their electrostatic acceleration. The research aims at a novel electrostatic microparticle thruster. Starting from a well known technique applied in experiments for the simulation of micrometeorites,[6,7] improvements with regard to a reliable and high particle charging and a high mass flow rate were proposed and first experiments were presented. Three key features of our improvements are lateral dielectrical embedding of the fine electrodes, arrangement of many fine electrodes on a surface, and miniaturization. We implemented these features by means of MEMS technology and reported on first experiments.

A challenge in our experiments is the desire of charging and accelerating only a single particle in order to measure specific charge and speed of an individual particle. In our first experiments, usually many particles were accelerated at the same time, and the particle diagnostic captured data of rather a particle avalanche than of an individual particle. To overcome this difficulty, we are currently developing a particle conveyor which releases single particles close to the high voltage electrodes.

This will be an important step toward an electrostatic microparticle thruster and not only during its development. Since a thruster will be operated under microgravity conditions, the released particles have to be delivered to the charging electrode. In our concept, this will be achieved by the dipole forces acting on the induced electric dipole produced by the strong electric field around the fine electrodes.

Potential applications besides an electrostatic microparticle thruster for space flights are terrestrial utilizations like a refined sand blasting or fast deposition of particles on surfaces. The dielectrically embedded electrodes could also replace the currently used needle particle sources in dust accelerators for the simulation of micrometeorites.

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References

[1] Jahn, R. G., *Physics of Electric Propulsion*, McGraw-Hill, 1968.

[2] Smith, K. L., Stark, J. P. W., Krpoun, R., and Shea, H., "Performance of a micro-fabricated Colloid thruster system," *31th International Electric Propulsion Conference, Ann-Arbor, Michigan, USA*, 2009, pp. IEPC–2009–189.

[3] Liu, T. M., Wagner, G. L., Gallimore, A. D., Gilchrist, B. E., and Peterson, P. Y., "Mapping the Feasible Design Space of the Nanoparticle Field Extraction Thruster," *31th International Electric Propulsion Conference, Ann-Arbor, Michigan, USA*, 2009, pp. IEPC–2009–004.

[4] Trottenberg, T., Kersten, H., and Neumann, H., "Feasibility of electrostatic microparticle propulsion," *New J. Phys.*, Vol. 10, 2008, pp. 063012.

[5] Trottenberg, T., Schneider, V., and Kersten, H., "Experiments on Contact Charging for an Electrostatic Microparticle Thruster," *31th International Electric Propulsion Conference, Ann-Arbor, Michigan, USA*, 2009, pp. IEPC–2009–010.

[6] Shelton, H., Hendricks Jr., C. D., and Wuerker, R. F., "Electrostatic Acceleration of Microparticles to Hypervelocities," *J. Appl. Phys.*, Vol. 31, 1960, pp. 1243–1246.

[7] Friichtenicht, J., "Two-Million-Volt Electrostatic Accelerator for Hypervelocity Research," *Rev. Sci. Instrum.*, Vol. 33, 1962, pp. 209–212.

[8] Stübig, M., Schäfer, G., Ho, T.-M., Srama, R., and Grün, E., "Laboratory simulation improvements for hypervelocity micrometeorite impacts with a new dust particle source," *Planet. Space Sci.*, Vol. 49, 2001, pp. 853–858.

[9] Keaton, P., Idzorek, G., Rowton Sr., L., Seagrave, J., Stradling, G., Bergeson, S., Collopy, M., Curling Jr., H., McColl, D., and Smith, J., "A hypervelocity - microparticle - impacts laboratory with 100-km/s projectiles," *International Journal of Impact Engineering Volume 10, Issues 1-4, 1990, Pages 295-308*, Vol. 10, 1990, pp. 295–308.

[10] Manning, H. L. and Gregoire, J. M., "An upgraded high-velocity dust particle accelerator at Concordia College in Moorhead, Minnesota," *International Journal of Impact Engineering*, Vol. 33, 2006, pp. 402–409.

[11] Hasegawa, S., Hamabe, Y., Fujiwara, A., Yano, H., Sasaki, S., Ohashi, H., Kawamura, T., Nogami, K.-I., Kobayashi, K., Iwai, T., and Shibata, H., "Microparticle acceleration for hypervelocity experiments by a 3.75 MV van de Graaff accelerator and a 100KV electrostatic accelerator in Japan," *International Journal of Impact Engineering*, Vol. 26, 2001, pp. 299–308.

[12] Müller, E. W., "Field Desorption," *Phys. Rev.*, Vol. 102, No. 3, May 1956, pp. 618–624.