

LA-UR- 96 - 2327

Title:

HYPERVELOCITY MICROPARTICLE
CHARACTERIZATION

CONF-960848-26

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Submitted to:

SPIE Meeting Denver Aug 4-9, 1996

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Hypervelocity microparticle characterization

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ABSTRACT

To protect spacecraft from orbital debris requires a basic understanding of the processes involved in hypervelocity impacts and characterization of detectors to measure the space environment. Both require a source of well characterized hypervelocity particles. Electrostatic acceleration of charged microspheres provides such a source. Techniques refined at the Los Alamos National Laboratory provided information on hypervelocity impacts of particles of known mass and velocity ranging from 20-1000 nm diameter and 1-100 km/s.

A Van De Graaff generator operating at 6 million volts was used to accelerate individual carbonyl iron microspheres produced by a specially designed particle source. Standard electrostatic lenses and steering were used to control the particles flight path. Charge sensitive pickoff tubes measured the particle charge and velocity in-flight without disturbing the particle. This information coupled with the measured Van De Graaff terminal voltage allowed calculation of the particle energy, mass, momentum, and using an assumed density the size. Particles with the desired parameters were then electrostatically directed to a target chamber.

Targets used in our experiments included cratering and foil puncture targets, microphone momentum enhancement detectors, triboluminescent detectors, and 'splash' charge detectors. In addition the system has been used to rapidly characterize size distributions of conductive plastic particles and potentially provide a method of easily sorting microscopic particles by size.

KEYWORDS: hypervelocity particles, hypervelocity impacts, hypervelocity detectors

2. INTRODUCTION

In the mid 1980s Los Alamos National Laboratory was tasked to provide information on particle impacts at higher velocities than previously attainable. Building on work originated by NASA for the space program in the early 1960s and continued abroad Los Alamos adapted its 6 million volt Van De Graaff nuclear physics machine to generate hypervelocity particles. Improvements to particle source designs, transport optics, and detector signal to noise ratio allowed particles with charges as small as 0.2 fC and velocities approaching 100 km/s to be detected¹. Although the facility has been abandoned for budgetary reasons the cratering data continues to be studied as more sophisticated hydrodynamic computer codes are developed. The techniques developed and described herein may also prove useful to future facility designers.

3. FUNDAMENTAL RELATIONS

An object with charge q accelerated through a voltage V_0 acquires kinetic energy:

$$K. E. = \frac{1}{2} mv^2 = qV_0 \quad (1)$$

As the relationship shows it is desirable to highly charge the sphere to obtain the highest velocities. However, if negatively charged the sphere will undergo cold cathode emission when its surface electric field reaches about 1 GV/m. If charged positively the field limit is ion emission which occurs at a field strengths around 10 GV/m². Our source generally charged spheres to a surface field between 0.5 and 10 GV/m. The sphere charge (q) is related to surface field strength (E_s) by:

$$q = 4\pi\epsilon_0 E_s r^2 \quad (2)$$

and the mass (m) of a solid sphere with density ρ and radius r is:

$$m = \rho \frac{4}{3} \pi r^3 \quad (3)$$

Assuming a given maximum surface field produced by a charging source and combining equations (1), (2), (3) one obtains the important relationship that particle velocity (v) is:

$$v = \sqrt{\frac{2}{3r} V_0 E_s \epsilon_0} \quad (4)$$

$$v \propto \sqrt{\frac{1}{r}}$$

Therefore the fastest particles are the smallest and for a given E_s they have smaller charges and so are more difficult to detect.

4. DUST SOURCE

The 'standard' projectiles chosen for our hypervelocity experiments were iron microspheres sold by GAF under the tradename Carbonyl Iron. The almost pure iron microspheres were produced by catalyzing iron pentacarbonyl gas causing a 'hailstorm' of spheres with a nominal 1-10 micron diameter³ although our experiments show a substantial number of much smaller particles. To optimally accelerate the sphere one must first isolate it from its neighbors and electrically charge it to a high value. A technique of charging and separating particles of dust was developed by Shelton⁴ and consisted of two oppositely biased parallel plates with a needle projecting from one of the plates positioned over a small hole in the other plate. When conducting spheres are placed on one plate the spheres will become charged. The charged spheres are accelerated by the electric field towards the opposite plate where they discharge and acquire an opposite charge and are then drawn back to the first plate. Eventually some of the spheres randomly bouncing between the plates are drawn to the high field region near the needle where the spheres acquire a very large charge. Some of these spheres will accelerate from the needle through the small hole positioned below the needle and can then be injected into an electrostatic accelerator. Friichtenicht^{5,6} coupled the Shelton source to a 2 megavolt Van De Graaff accelerator and performed a number of experiments with hypervelocity iron particles ranging from 2 - 10 km/s and 1- 0.15 μ radius. A major problem with previous source designs was the excessive amounts of conductive dust that escaped the source and entered the electrostatic accelerator. The dust degraded the accelerator performance so generally a dedicated accelerator was used for hypervelocity experiments.

Great effort has been expended to design Van De Graaff accelerators to maximize their accelerating voltage. Any dirt on the insulating surfaces in an accelerator can trigger an electrical breakdown which may cause irreparable harm to the insulator. Needless to say the proposal to deliberately introduce conductive dust into a 6 million volt accelerator was met with skepticism. In addition to damaging the machine the electrical discharges produce a shower of ions which cascade down the accelerator increasing the background electrical noise level thereby masking the small charges on the fast particles. An improved idea to trap the powder allowed our source to be used on the 6 million volt Van de Graaff without releasing large quantities of damaging dirt.

P. W. Keaton¹ the Principal Investigator for the Los Alamos hypervelocity project proposed a method of trapping dust by slowly increasing the gap between the electrodes towards the needle region as seen in Figure 1. The increased gap resulted in a bulging of the electric field lines towards the needle. A charged particle traveling along the field lines is centrifugally pushed towards the needle. The trapping effectiveness is enhanced by adding a 'dogleg' bend in the electrodes which requires an escaping particle to go around two corners before it can escape. A powder reservoir holds several grams of carbonyl iron which is injected into the needle cavity in a controlled fashion by applying a high voltage pulse to a metal 'tongue'. The pulse agitates the particles in the reservoir some of which leak through a small hole into the

needle cavity. By regulating the voltage and pulse width applied to the tongue the degree of agitation and therefore the number of injected particles can be accurately controlled.

The source design was so successful that the Van De Graaff actually performed better (more stable and higher achievable terminal voltages) after experimental runs with our source.

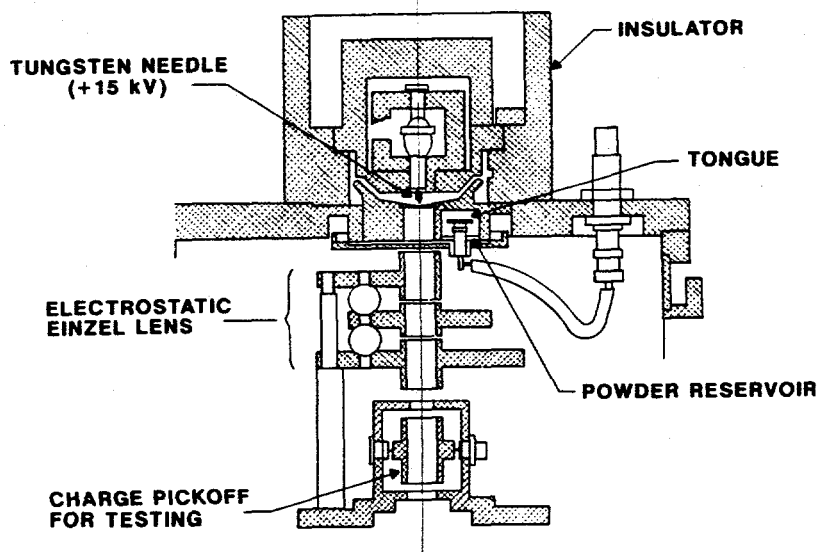


Figure 1. The charged particle source

5. PARTICLE TRANSPORT

Once a charged particle exits the source it immediately enters an Einzel lens which electrostatically focuses the diverging particle beam into a parallel beam for optimal coupling into the Van De Graaff accelerator. All focusing of the particle beam is accomplished using electrostatic lenses because unlike magnetic lenses the electrostatic focusing action is independent of the individual particle charge and mass. To calculate the transport trajectory a Van De Graaff ion beam optics code, OPTIC-II, was used optimize the lens settings and ensure the particle beam was not striking any apertures in the accelerator. The OPTIC-II v36.0 code is written in standard FORTRAN and runs on an IBM-PC platform. It was obtained from the current code 'caretaker' J. D. Larson of Independence, Missouri, the latest of many authors since the first versions of the code appeared in the 1960s. By calculating trajectories and presetting the accelerator optics potential accelerator damage and increased background electrical noise from a hypervelocity particle striking an electrode was minimized. To select a given class of particles for experiment an electrostatic 'kicker' was triggered to deflect the particles within a given charge and velocity range into an experiment chamber.

To verify the calculated accelerator optics we used a beam imaging device consisting of a thin layer of the triboluminescent material tetrakis (dibenzoylmethido) europium (III) ⁷. The europium compound emits light when its crystal structure is mechanically stressed. By observing the imager with a CCD camera that was integrated for one second we could visibly observe the effects of adjusting lenses, steerers, and Van De Graaff voltage.

6. IN-FLIGHT PARTICLE DETECTION

A series of hollow 'pick-off' tubes were used to measure particle charge and velocity. As the particle passes through the tube it induces an image charge on the walls of the tube. By measuring the induced charge one obtains the particle charge and therefore its kinetic energy if the Van De Graaff accelerating voltage is known (Eq. 1). By measuring the transit time between multiple pick-off tubes of known spacing the velocity can be calculated. From velocity and Equation 1, the mass can be deduced and if the density is known the particle radius and then electric surface field strength can be calculated. All this information is obtained without disturbing the in-flight particle parameters. If one desires the fastest particles then Equation 4, dictates that one must have extremely sensitive charge sensors and a high signal-to-noise ratio. The A-250 charge sensitive preamplifier from AMPTEK inc. headquartered in Bedford, MA satisfied the sensor requirement however the noise problem proved more difficult.

Because of the physical layout of Van De Graaff the pick-off tubes were located at the exit of the machine approximately six feet from the 50 horsepower high voltage terminal charging belt drive motor and a foot from the 50 kilovolt belt charging screen. To isolate the pick-off tubes from the vibration, magnetic, and electrical noise the tubes were individually shielded by aluminum tubes which were placed inside a mild steel outer tube. Signals were brought out through vacuum tight coaxial assemblies to a battery-powered A250. The entire assembly was shock-mounted using silicone rubber stoppers which had been vacuum baked at 250° C until their consistency resembled 'gum-drops'. Flexible stainless steel bellows vibrationally decoupled the vacuum feedthrough electrical connectors from the Van De Graaff. Concerns about radiation damage to the A250 when the Van De Graaff was operated with ion beams and the inaccessible location prevented closer coupling of the A250 and pick-off tubes which could have further reduced noise pick-up.

An added bonus using our sensitive pickoff electronics came during accelerator 'conditioning' to maximize accelerator operating voltage. In conditioning the accelerator voltage is slowly increased until signs of imminent breakdown are observed. Breakdown is signaled by small imperfections in the accelerator electrodes smoothing out the sharp points by emitting ions. Voltage is then held stable until the activity diminishes to where it is again safe to raise the voltage. If the operator raises voltage too rapidly a catastrophic spark occurs, pitting the electrodes and/or damaging the insulator structure, and the whole process must be started over. The pickoffs could detect the emitted ions long before the more conventional methods of observing vacuum increases or high voltage instability signaled breakdown conditions. As a result the accelerator could be safely conditioned to higher potentials.

7. DATA ACQUISITION ELECTRONICS

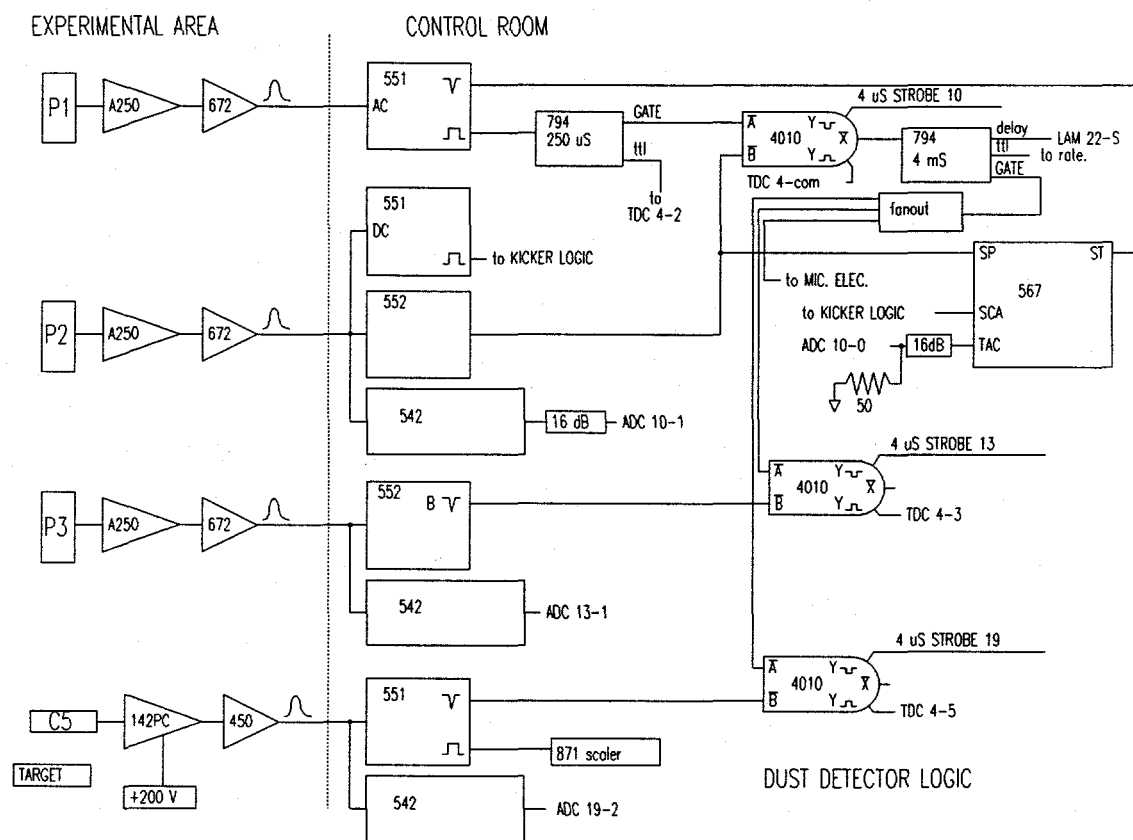
The data acquisition hardware used standard NIM electronics for analog signal conditioning and decision making, CAMAC modules for digitizing the analog signals and interfacing to the data acquisition/display computer, and an IBM PC/AT-class personal computer.

Figure 2 shows the data acquisition hardware configuration for a typical target cratering experiment. Three pickoffs (P1, P2, P3) detect the charged particles passing through them and C5 detects the ion cloud produced when a hypervelocity particle impacts a target. The A-250 pre-amplifiers use an external low noise 2SK152 JFET input stage which provides a sensitivity of approximately 1 mV/fC with preamplifier noise rating of about 100 electrons rms at room temperature. Every effort was made to eliminate ground loops and to shield the pickoffs from extraneous noise sources. As a result of these efforts the noise level had been reduced enough to enable detection of induced charges as small as 0.2 fC (~1250 electron charges).

From the pre-amplifier a short (15 cm) length of coaxial cable enclosed in an additional shield braid coupled the signal to an ORTEC model 672 shaping amplifier located in a NIM bin positioned as close as feasible to the preamplifier. The NIM rack served as a common ground point for the pickoffs. Electrical power was supplied to the rack through an electrostatically shielded power isolation transformer. The output of the shaping amplifier (gain = 1500, shaping time = 2 μ s) was a 'high level' signal of roughly 1.5 V/fC and was sent approximately 75 meters to the control room instrumentation rack.

In the control room the amplifier output signals were sent to ORTEC 551 and 552 Constant Fraction Discriminators (CFD) set just above the signal noise level in order to see the fastest particles. When the P1 CFD accepted a pulse it started the ORTEC 567 Time to Amplitude Converter (TAC) and also triggered a Phillips Scientific 794 Gate/Delay generator which output a 250 μ s wide enabling pulse to an ORTEC

The CAMAC crate was interfaced to an IBM PC/AT-class computer via a DSP Technology Inc. model 6002 crate controller and interface card. A custom 'C' language program named MPI, for MicroParticle Impacts, configured the digitizers, read the digitizers, calculated user selected parameters, displayed and stored the data. The data were analyzed and displayed in real time at steady state rates of up to 30 events per second with faster burst rates.



The in-flight data was used to select which particles are allowed to hit the target. The Single Channel Analyzer (SCA) output from the P1-P2 TAC was used to select a particle transit time window (Δt) for particle to be deflected (kicked) into our experimental chamber. A particle charge window (Δq) was set using an additional 551 CFD on the P2 pickoff. These signals were logically ANDed together to form the

kicker initiate signal. The kicker signal started an adjustable delay generator which triggered an adjustable gate generator. The gate output is transmitted back to the Van de Graaff area where it grounded one of the parallel plates in the kicker thus deflecting the selected particle onto the target. The kicker delay and gate widths were adjusted to correspond to the range set on the Δt discriminator, the distance from P2 to the kicker deflector plates, and the length of the plates. While accuracy was not critical, a reasonable setting was necessary to have the one kicker plate grounded while the particle is passing through the kicker, and to have full voltage on the plates when other particles ahead of or following the selected particle pass through the selector. The kicker circuit had a voltage fall time of <5 ms and a rise time of about 50 ms. Particle frequency was set by pulsing the dust source tongue (Fig. 1.) for approximately 100 ms each second which extracted between ten and one hundred particles. This gave an average interparticle spacing of a few milliseconds. Thus, a kicker pulse window with 100 ms leading and trailing margins gave a high probability that only the desired particle were deflected onto the target. Smaller margins were used for faster particles. If the particle was successful kicked onto the experiment target an impact splash detector (C5) measured the magnitude of ion cloud produced and provided an additional timing signal

9. PARTICLE EVENT ANALYSIS

The event analysis is based on measuring particle charge and time of flight in order to calculate the various parameters of interest. Particle velocity is determined from times of flight between the P1, P2, P3 and C5 detectors. The parameters of interest include the mass, size, energy, and momentum of the particle. Also of interest is the surface electric field because of its relation to the operation of the cosmic dust source. Table 1. shows some of the measured and calculated parameters for Carbonyl Iron ($\rho = 7.86$ gm/cm³) and polypyrrole (PPY, $\rho = 1.5$ gm/cm³) particles accelerated on the Van De Graaff (5 MV) and our test stand (60 kV).

Composition	iron	iron	iron	iron	PPY
Accelerating voltage (MV)	5.00	5.00	5.00	0.06	0.06
Charge (fC)	2.98	1.036	0.528	3.58	0.293
Velocity (km/s)	10.1	37.8	70.6	9.15	2.38
Energy (pJ)	14.8	5.11	2.58	17.55	215.
Momentum (fNs)	2.92	0.27	0.073	3.84	180.2
Mass (fg)	289.	7.155	1.036	0.419	75.5
Radius (nm)	206.	60.	32.	41.	132.
Surface field (GV/m)	0.6	2.58	4.77	1.6	1.85

Table 1. Parameters for typical particles.

A feature of the MPI data acquisition system was the ease with which additional data channels and calculated event parameters could be added. The entire setup for an experiment was specified in a user-editable text file. This file allowed the user to specify the number and type of CAMAC modules being used, the names and scalings of the data, and the number and formulas for the calculations to be performed. The user could also change most of these parameters interactively from within the MPI program. Any changes made to these parameters were stored upon program exit. The MPI program also recorded the state of the displays at exit so that the program remained set-up from one run to the next. With each particle event the CAMAC crate generated an interrupt to the computer which read the counts from the ADCs and TDCs. These counts were converted into times and charges using calibration factors for the appropriate channel. These calibration factors were calculated using a precision delay generator for the time-of-flight channels, and a precision voltage pulse source into a precision capacitor for the charge channels. Typical conversion factors were 0.05 volts/ms and 1 volt/fC with ADCs having a 2048

counts/10 volts full scale input. This gave a resolution of 0.1 ms/count and 0.005 fC/count. The MPI program included a least squares fitting procedure to calculate the slope and intercept values for a signal from a set of events of known time-of-flight or charge.

Several pickoffs were used to provide consistency checks on charge and timing data. Times of flight were measured between P1 and P2, P2 and P3, and P2 and C5. Particle charge was measured at P2 and P3. This redundant data proved very useful in distinguishing real particle events from those with one or more signals caused by noise. The most sensitive measure was the time of flight correlation. Figure 3 shows typical data taken on the 5 MV Van De Graaff with the velocity calculated from time of flight between pickoffs P1 and P3 plotted against the P1 to P2 calculated velocity. The noticeable line is caused by the real particle events that display the proper time ratio. The points off the line are events where one or more of the discriminators fired on noise.

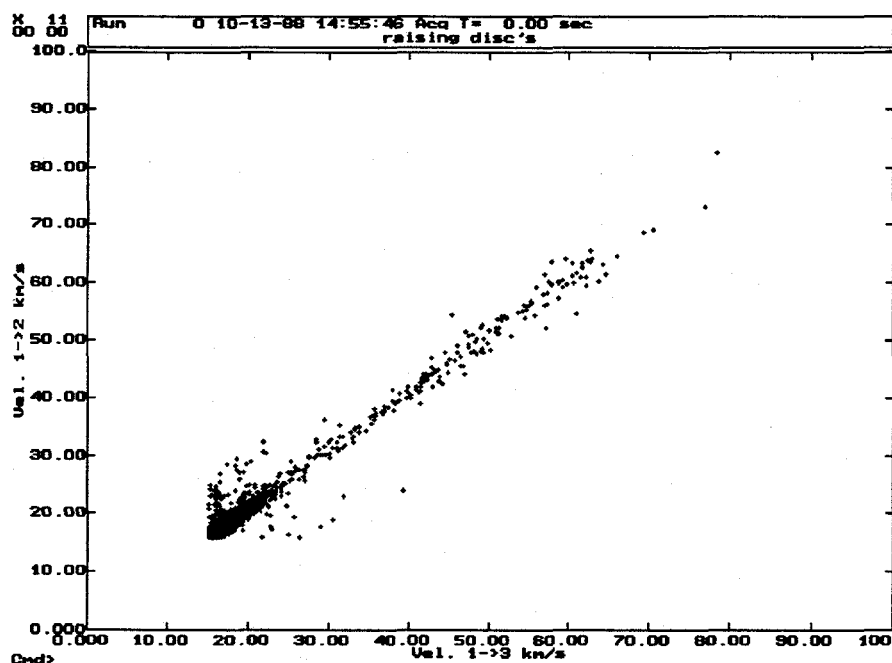


Figure 3. Calculated velocity correlation between multiple pickoffs.

Our source tended to produce particles with about the same surface electric field independent of particle size in agreement with Friichtenicht's measurements^{5,6} except for the smallest particles. Keaton¹ has speculated an 'arcing' mechanism to account for the larger observed surface fields on the smallest particles. Even with higher fields and therefore greater than 'normal' charge these fastest particles are near the ~ 0.15 fC detection limit of the A250 amplifier systems caused by residual thermal and electrical noise. Thus the percent uncertainty of the charge measurement increases for the smallest particles. Fortunately as seen by combining Equations 1 and 3 the radius varies only as the cube root of the charge value so a 30% uncertainty in charge results in only a 10% uncertainty in radius.

The data acquisition system computer stored the raw data and calibration values on disk for later playback and more detailed analysis. This included comparing one run with another, or filtering the data to remove unwanted events. Filtering was used to remove events which did not trigger all the discriminators, or those with uncorrelated timing signals. The operator could also highlight (display in a different color/symbol) a sub-set of the events meeting a compound criterion such as: "all particles with radius between 10 nm and 50 nm and velocity greater than 50 km/s".

10. PARTICLE IMPACT ANALYSIS

Additional diagnostic channels were used to record signals produced by particle impacts for a specific type of experiment. In impact cratering experiments a 'splash' detector, C5 in Fig. 2, was used to verify that a selected particle was kicked onto the target material. When a hypervelocity particle impacts a surface an ionized cloud of material is ejected. The amount of charge ejected is a function of the impactor mass and velocity² and the signal timing provides a velocity correlation. Counting the events provided the number of craters expected on a given target when it was subsequently scanned by electron microscope.

The ejected cloud imparts additional momentum to the target in addition to impactors momentum. By using a microphone diaphragm as the target the momentum enhancement could be measured. Our diagnostic is described in Stradling⁸ and consisted of a precision calibrated microphone mounted in an inertial damper constructed of several large masses suspended via springs.

Cratering data have been analyzed by Walsh⁹ to determine material strength at the high strain rates (10^8 /sec) achievable with hypervelocity particles.

11. PARTICLE SIZING

Another use for the technology developed at Los Alamos was measuring the mass distribution of a conductive powder sample. Armes and Gill^{10,11} have used our test stand to measure the sizes of conductive polymer particles that they fabricated. Previous to using the test stand the particle size distributions were determined by manually measuring a sample of powder magnified by a Transmission Electron Microscope (TEM). From the apparent radius, masses were determined using an assumed density. The TEM process was extremely laborious requiring a number of guesses when particles appeared to be merged together and usually took about one day per sample. On the other hand the test stand could process thousands of particles in twenty minutes and because it measured mass not radius clumped particles were not a problem.

12. PARTICLE SORTING

In our quest for the highest velocities we had discovered that standard commercial grade Carbonyl Iron of nominal 1 micron radius contained a number of particles in the 20 nm range. It would have been desirable to accelerate only the small particles to reduce the electronics dead time caused by larger particles triggering the system. Several attempts were made to sort the iron using conventional materials science techniques of air columns, water columns, etc. but none were very successful. The problem apparently is that particles less than about 1 micron tend to stick together thereby defeating the sorting scheme. It occurred to our team that the dust source would separate the particles as they bounced between the source high voltage plates. If a source was made without a needle then the charge on each particle would roughly equal the particles projected area times the surface charge density on the plates. The velocities obtained by the particles as they bounced between the plates would be inversely proportional to their radius. If such a source had a 2000 volt bias, 1 cm plate spacing, and ejected iron particles at 45° from vertical then a 1 micron radius would travel 5.5 cm horizontally whereas a 0.1 micron particle travels 68 cm. A system could be constructed to enrich the number of specifically sized particles by placing a catching container the appropriate distance from the ejecting source.

13. CONCLUSIONS

A versatile Hypervelocity-Microparticle-Impact laboratory was operated at the Ion Beam Facility at Los Alamos National Laboratory. A variety of conducting microparticles with sizes ranging from 20 nm radius to 1 μ m radius made of iron, nickel, and conducting polymers have been accelerated to velocities from 1 to 100 km/s. A 'clean' particle source with well characterized optical properties allowed sharing the 6 MV Van De Graaff with nuclear physics users. Low noise high sensitivity detectors observed particles with charges as small as 0.15 fC. The HMI facility featured non-destructive particle diagnostics and in-flight particle selection. Although the Van De Graaff accelerator and the specialized equipment built for generating hypervelocity particles have been abandoned it is hoped the techniques described within may assist future experimenters.

13. ACKNOWLEDGMENTS

The Hypervelocity Microparticle Impact project at Los Alamos National Laboratory was the result of the dedicated efforts of many people. I specifically wish to acknowledge the Principal Investigator, P. W. Keaton and his successor Gary Stradling, the Ion Beam Facility group headed by Larry Rowton which operated the Van De Graaff accelerator, Anna Hopkins-Blossom from EG&G energy measurements corporation, Science Applications International Corporation employees Mike Collopy, Hal Curling, Jr., and Dave McColl, and our machinist Roger Persons all of whom were critical to the success of the program. This work was performed under DOE contract W-7405-ENG-36.

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