Chapter 2

The Dustbuster: A Compact Time-of-flight Mass Spectrometer for Cosmic Dust Analysis

2.1 Objectives in designing an improved cosmic dust mass spectrometer

Five goals defined my efforts to design an improved cosmic dust mass spectrometer. First, the instrument should have high mass resolution. Ideal resolution would be around 300 ($m/\Delta m$). This would allow for the identification of isotopes of any element even in less than ideal circumstances, assuming no interference. Second, the instrument should be lightweight, low-power, and otherwise physically suitable for inclusion on a spacecraft. Based on estimates from several proposed missions, our target mass was 1 kg or less, and target power was less than 3 W. Third, the instrument should have a large enough impact area that dust impacts would be reasonably frequent. A 50-cm^2 area sweeping out space at typical interplanetary cruising velocities would encounter interstellar dust at a rate of about one impact per week. For interstellar dust, and for interplanetary dust far away from its source, this impact area would be sufficient. Of course, for regions where dust is dense, such as a comet tail or planetary ring, a smaller impact plate is adequate. Finally, the instrument design should be adaptable to a variety of dust environments or proposed missions. It is a fact of life in dealing with the space program that missions are sometimes changed or cancelled. In addition, competition for scientific payload space is tight, so proposing an instrument for several missions increases the chances that the instrument will fly.

The original name of this improved cosmic dust mass spectrometer was the Advanced Space Particle Analysis System, but at the suggestion of another student, it was given the appellation “Dustbuster.” It was thought that a catchy name would make the instrument more memorable in presentations (especially to NASA mission planners). I beg the pardon of Black & Decker®, the makers of the Dustbuster™ portable vacuum cleaner, although I have been assured that trademark infringement is not an issue in this case.

The Dustbuster research was funded by NASA’s Planetary Instrument Definition and Development Program (PIDDP). As such it was not my intention to engineer and build a flight-ready, fully certified instrument, with all subsystems assembled and ready for launch. Rather I have developed the instrument through simulations and laboratory experiments, with the goal being the production of a workable design and a good understanding of the design’s potential. Hopefully the instrument design will find its eventual way into a flight proposal, then into the hands of capable engineers and machinists who will build it, and finally, off into space where it will sit and collect dust.

2.2 Early designs and obstacles

The original design concept was part of the original PIDDP proposal submitted to NASA in 1997. This design included a planar target plate, a reflectron, a drift tube with Einzel lens, and an ion detector, as shown in Figure 2.1. It was originally proposed that the mass spectrometer be combined with both laser scattering equipment and piezoelectric transducers to measure the trajectories and sizes of incoming particles. However, both the laser scattering and piezoelectric segments of instrument development were abandoned early on due to limited resources.

Several early designs I developed included two reflectrons, similar to what is shown in Figures 2.2a and 2.2b. These designs had the advantage that the ion detector was completely shielded from any incident particles or radiation, and from any secondary emissions or ejecta. A second advantage to these designs was that the out-of-reflectron path length was folded, and could be made sufficiently long without substantially lengthening the whole instrument. The first reflectron could occupy the length of the wide section of the instrument, while the rear reflectron could be very short, perhaps only a few millimeters (nothing more than an ion mirror). However, kinetic energy focusing for ions traveling through two consecutive reflectrons is more complex, and the ion beam spreads out more due to increased space-charge effects.

A number of my early designs used either a dual-stage reflectron (such as those in Figures 2.2b and 2.2c) or a quadratic reflectron. The idea behind these attempts was to minimize the ion drift region, again minimizing the size of the instrument. A limitation with some of these designs was that the ion detector was too exposed and susceptible to damage by incoming particles. In addition, generating a quadratic reflectron with such a large area is rather difficult unless several grids are used, and each grid reduces the total ion transmission and instrument sensitivity.

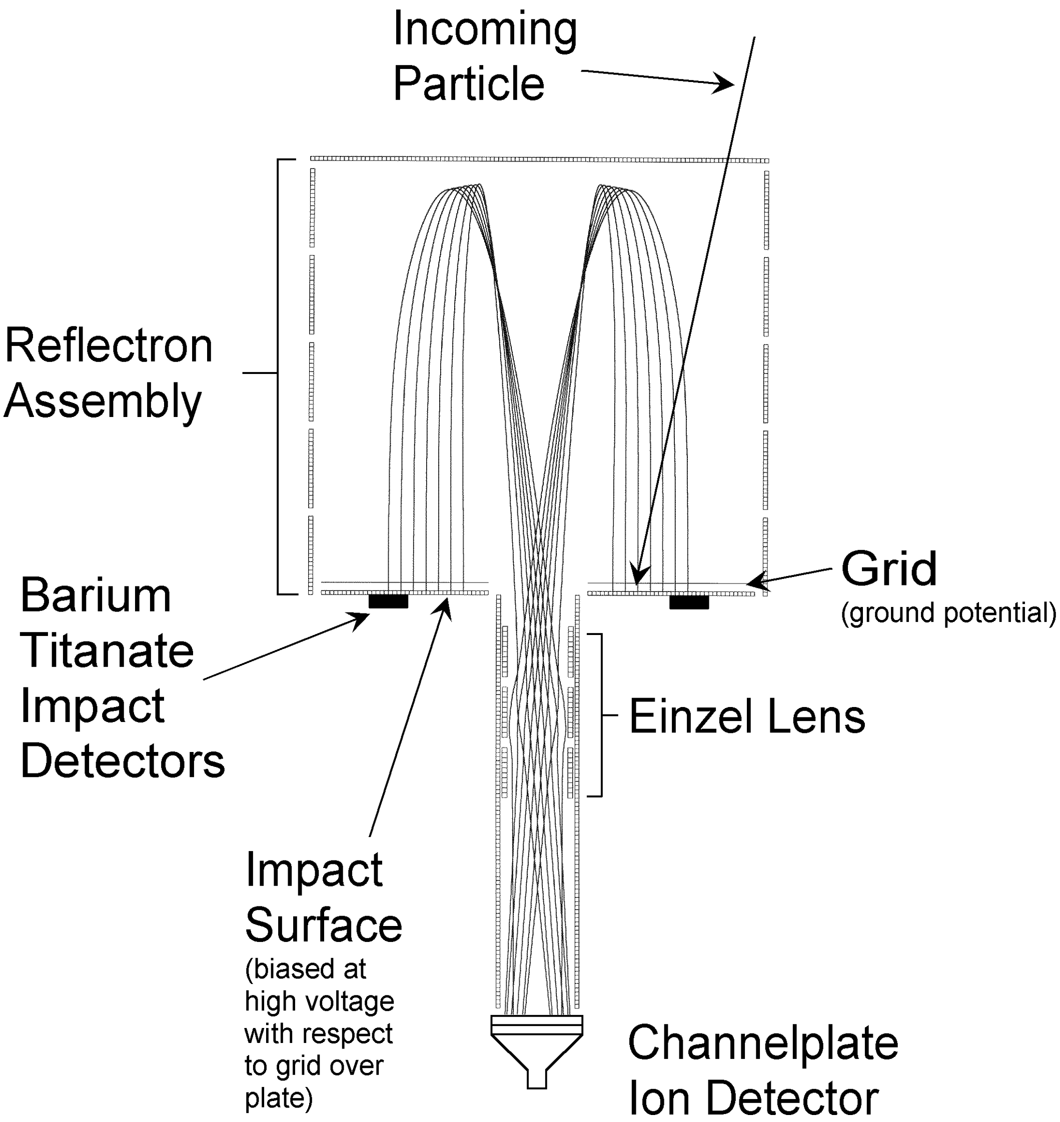

Figure 2.1. The original Dustbuster design (side view) as submitted to NASA in 1997 as part of the PIDDP proposal. Particles enter from the top and strike the biased impact surface. Ions formed by the impact are accelerated back down toward the front of the analyzer and redirected to the aperture in the center of the impact plate by appropriate potentials applied to the ring electrodes and entrance grid (which together comprise a reflectron). An Einzel lens near the entrance to the lower flight tube directs the ions to the channelplate detector.

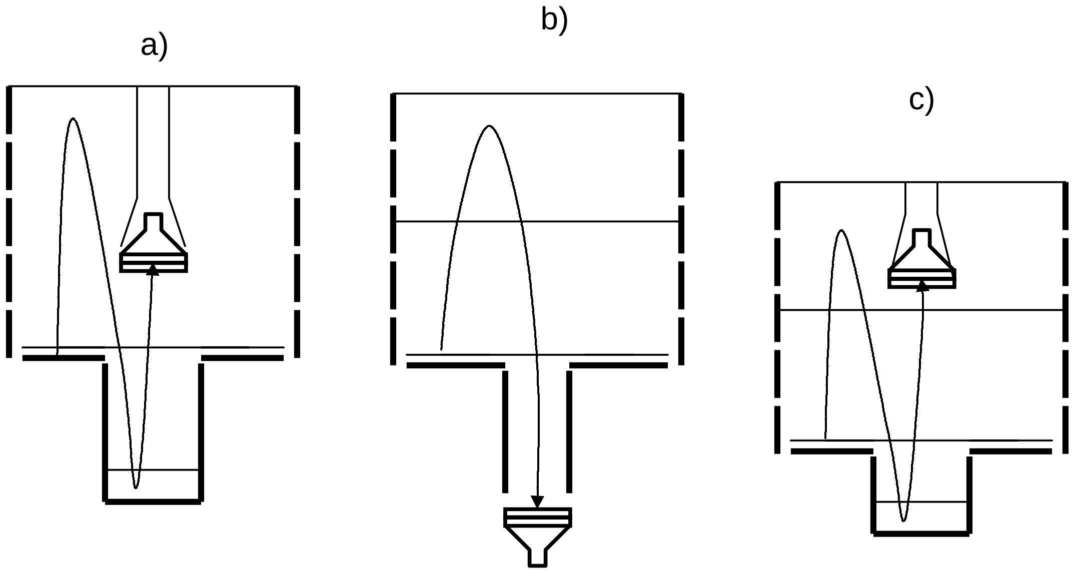

Figure 2.2. Several early Dustbuster designs: a) incorporating two reflectrons, b) with a dual-stage reflectron, and c) with both a dual-stage reflectron and second reflectron. General features are similar to those in Figures 2.1 and 2.3. Dust grains enter from the top of instrument in each case. Typical ion trajectories are shown.

These early designs revealed several limitations taken into consideration in later designs. One limitation is the difficulty of using a reflectron to focus ions originating from a large surface. Ion optics systems and methodologies typically use “point-like” ion sources, which are readily available for most laboratory experiments. In space, however, a large surface is needed to acquire a statistically significant number of dust impacts. Focusing ions from a large area is simple (for instance, the hemispherical impact plate of the Cassini Cosmic Dust Analyzer, in which all ions are focused into the center), but the simultaneous use of a reflectron introduces complications. However, because of the large initial kinetic energies of impact-generated ions, the reflectron is necessary in order to produce spectra with sufficient mass resolution to be useful.

A second limitation stems from the need to include a field-free drift region in a reflectron path. For a linear reflectron, the space-focus plane will be located approximately at the point in which ions will have spent equal amounts of time within and without the reflectron. Thus a drift region is essential to achieve high resolution in a linear reflectron system. For dual-stage and quadratic reflectrons, drift length requirements are different. Ions focused from a large area through a reflectron will retain transverse velocity through the drift tube. This transverse velocity component limits spatial focusing and makes difficult the use of both a small aperture at the reflectron exit and a small ion detector. An Einzel lens in the drift tube has limited power at resolving this problem. Einzel lenses are useful when ions originate at a point close to the optical axis, at some distance greater than the focal length of the lens. For close, off-axis ion sources, however, the aberrations of an Einzel lens become large, and transverse velocity components cannot be effectively corrected.

2.3 Working design

The instrument design which worked best in simulations, and which was constructed and used in subsequent experiments, is shown in Figure 2.3. The principal components are the impact plate, the reflectron region, the drift tube, and the ion detector.

Dust grains enter the instrument through the front grid, proceed through the extraction grid, and strike the impact plate, where they are partially ionized by the impact. The positive ions produced at the plate are accelerated to 4800 V by the grounded extraction grid, located 2-3 mm in front of the impact plate. Due to the close proximity of the extraction grid to the impact plate, the grid needs to have both high ion transmission and low field penetration in order to insure that most ions are extracted with minimum perturbation. At the same time, the grid needs to be sufficiently robust to withstand several dust impacts while retaining its shape or its tautness. Of course, ideal grids do not exist, but a grid suitable for laboratory experiments was a 70% transmission, 333 wire-per-inch electroformed nickel mesh manufactured by Buckbee-Mears St. Paul. A thicker, more expensive custom gold mesh may be more appropriate for a flight instrument.

The target plate itself is a 75-cm^2 disk which has an active area of 65 cm^2 for dust analysis. The target must be made out of a material with high density and high melting point in order to maximize the number of ions produced in a given dust impact event [1, 2]. Because a portion of the target plate is also ionized when a dust grain

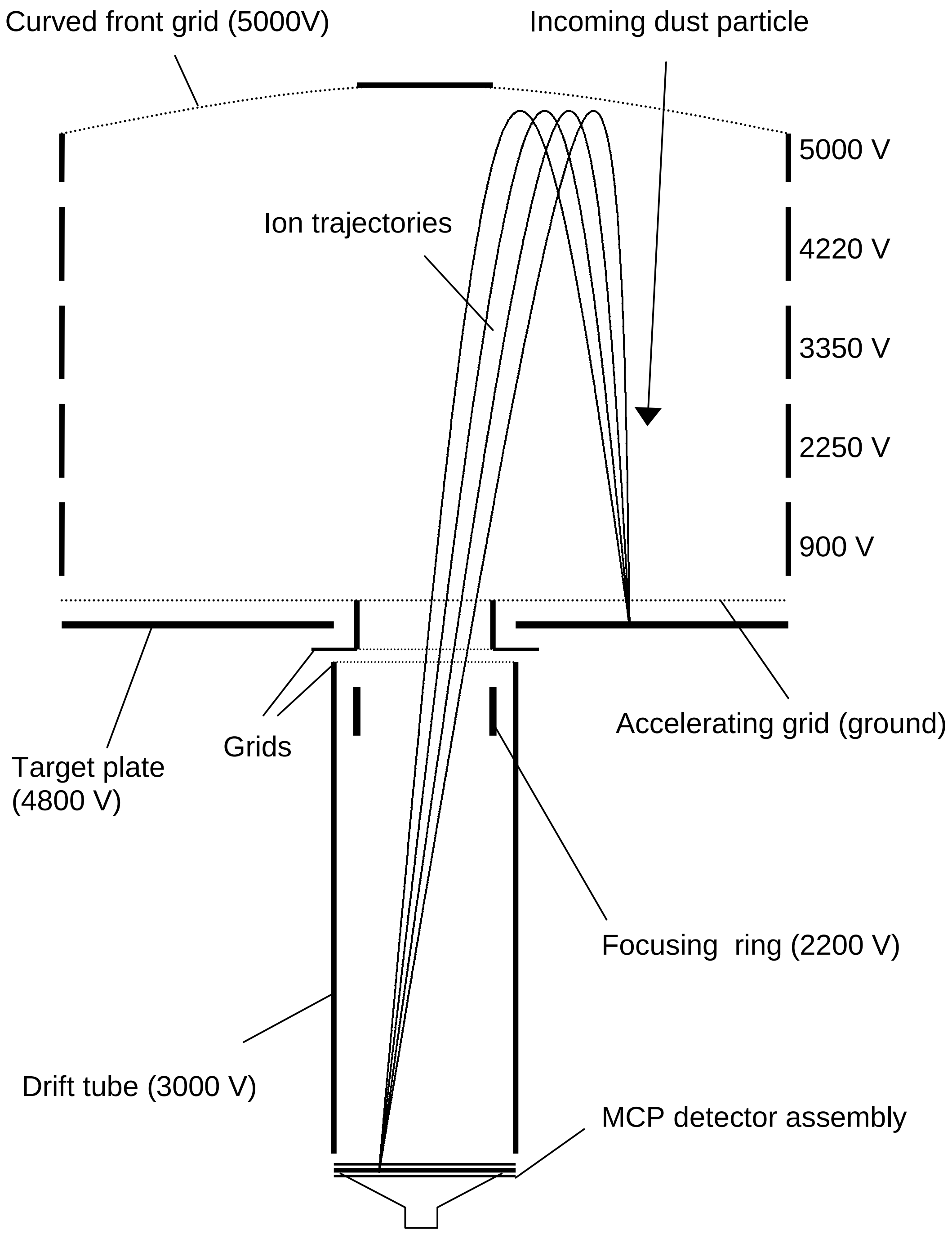

Figure 2.3. Design of the “working” version of the Dustbuster. Typical ion trajectories are shown. Particles partially ionize upon impact with the target plate. Ions are accelerated into the reflectron, then focused onto the microchannel plate detector at the bottom of the figure.

impacts, the target plate must be made out of a material with low cosmic abundance to avoid interference with the dust composition. Rhodium and silver [3, 4] have been used for target plates in previous instruments, and tantalum or gold would also likely work [5]. A copper plate was used in laser ionization experiments, and a tantalum plate was used for microparticle impact studies, both of which will be described in a later section. A target containing two metals might work best for a flight instrument since the mass spectra could be calibrated using ions of both elements from the target plate.

The reflectron region consists of five ring electrodes with voltages (with respect to the accelerator grid) of 5000 V, 4220 V, 3350 V, 2250 V, and 900 V, as shown in Figure 2.3. In a previous publication [6] the ring voltages were reported as 5000 V, 3710 V, 2950 V, 2160 V, and 960 V. The latter are the voltages used in preliminary experiments, and they produce similar results to the former set of voltages. Varying the voltages on the other rings can easily compensate for a 5% variation in the voltage of any one ring, so many possible combinations of ring voltages can work equally well. These reflectron rings provide a longitudinal potential gradient, just as a standard reflectron does, in order to compensate for the initial kinetic energies of the ions. The rings also provide a small radial (transverse) gradient, pushing the ions toward the center of the instrument. Ions originating from approximately 65 cm^2 of the target plate will be focused into the drift tube and onto the MCP detector. This modified reflectron design makes it possible simultaneously to optimize spatial focusing and energy focusing. In addition, any neutrals, liquid droplets, or solid ejecta fragments that might be produced [4, 7] during the impact will not reach the detector, simplifying spectra and preserving the life of the microchannel plates.

The front grid defines the end of the reflectron field. A result of the transverse potential gradient in the reflectron is that ions with initial velocity outward have a longer path through the reflectron than do ions with initial velocity inward. Curvature of the front grid compensates for this problem. The front grid curvature is actually one of the most crucial factors affecting mass resolution. Ion packets reaching the detector may be completely coplanar, but if the ion packet is not parallel to the ion detector, signals are significantly broadened. The angle of the front grid largely defines the angle of the ion packet at every subsequent point, and can be optimized to match the ion packet angle with the detector surface at that point. The front grid, which is kept at 5000 V, may have less than ideal field penetration, but should have high transmission in order to minimize blockage of incoming dust grains. With a difference of 200 V between the potential at which ions are formed and the front grid, ions will typically penetrate to within a few mm of the grid. This distance is far enough that small field inhomogeneities will not be important.

Ions leave the reflectron through the center of the instrument, pass through several grids, and enter the drift region. The intervening grids provide uniform electric fields in this area, although they are not strictly essential. Although drift tubes are normally grounded, the Dustbuster drift tube is kept at a high potential (3000 V). In general, when a time-of-flight mass spectrometer uses a reflectron, ions with different initial kinetic energies will reach the same plane or focal point after the ions have spent approximately equal amounts of time inside and out of the reflectron [8]. In this case, a grounded drift tube would need to be quite long, about three times the length of the reflectron. Increasing the potential of the drift tube moves the space-focus plane of the reflectron closer. A high-potential drift tube considerably shortens and lightens the instrument, while sacrificing resolution only minimally. In simulations, resolution is limited mainly by other factors, so the shortened drift tube has little effect on the overall mass resolution. The Dustbuster drift tube is not completely field-free. A small ring electrode (2200 V) at the entrance of the drift tube aids in directing the ions toward the detector. The difference between the voltages of the focusing ring and the drift tube is crucial to obtaining high mass resolution. Just as the curvature of the front grid affects the angle at which ion packets strike the detector, the field imposed by the focusing ring also affects the ion packet angle. Thus it is possible to optimize this angle regardless of the curvature of the front grid, simply by varying the ring voltage. However, significant variations of the voltage of the focusing ring can affect the number of ions that reach the ion detector.

As ions leave the drift tube they are detected using the microchannel plate (MCP) detector. The MCP signal is then amplified and recorded. Despite the popularity and widespread use of MCPs in time-of-flight mass spectrometry, they are not the best detectors for the Dustbuster. Microsphere plate detectors or continuous dynode detectors would be more suitable for a flight instrument, and perhaps also for laboratory prototypes. These other detectors operate at higher pressures, are more robust, and may eliminate the need to have the whole instrument maintained in a sealed vacuum system before and during launch.

Figure 2.4 shows typical trajectories of ions originating from various locations on the target plate. Ions of a given *m/z* from a single dust impact will all have the same flight time, but the time will be slightly different from the flight time of ions of the same

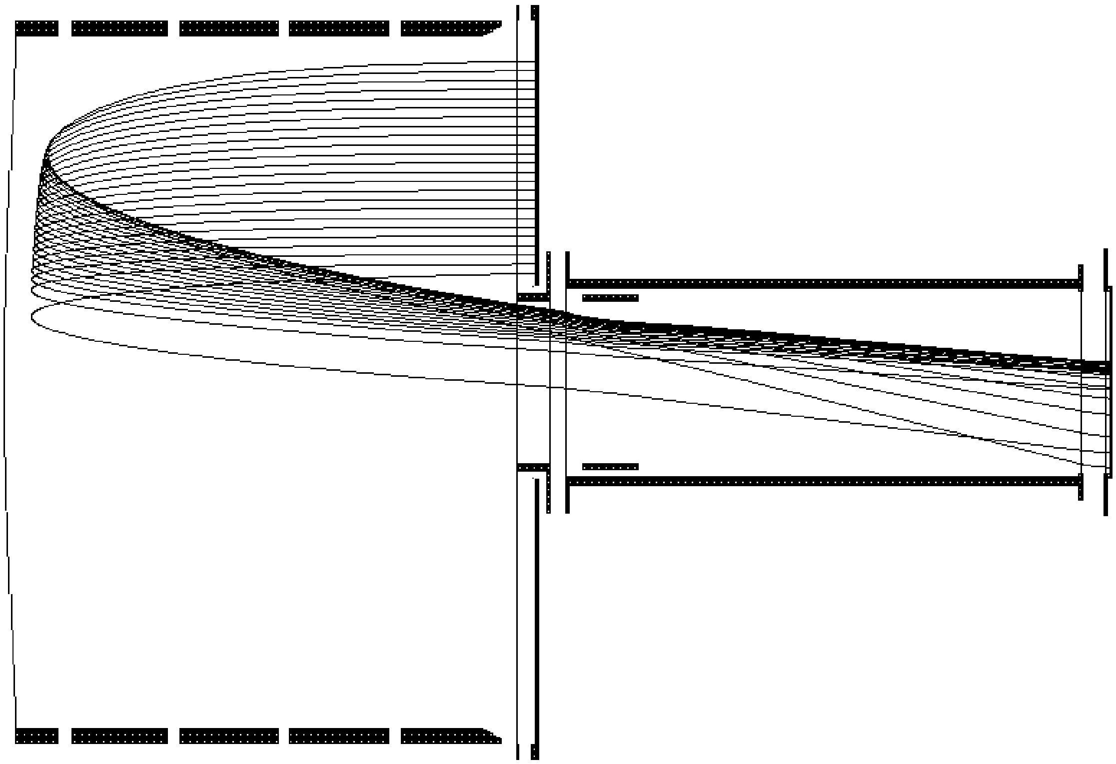

Figure 2.4. Simulation showing trajectories of ions originating from various locations on the Dustbuster target plate. Ions have initial kinetic energy of 40 eV normal to target plate.

m/z from a dust impact elsewhere on the target plate. This variation of flight times with location of dust impact will not present a problem because only one dust grain will strike the instrument at a time. However, the spectrum from each dust impact must be calibrated to compensate for this variation in flight time.

The voltages given in Figure 2.3 are for extraction and detection of positive ions produced during a particle impact. In theory, detection of negative species would simply involve changing the signs of all the voltages (and perhaps floating the detector). However, according to two studies, hypervelocity impacts of metal microparticles typically do not produce a useful abundance of negative ions [5, 9], although impacts of minerals may produce negative ions. If negative ions are produced, the large number of free electrons produced in the impact will interfere with the detection of the negative species unless the detector is able to recharge quickly, or unless the electrons are pulsed out of the way at some point along the flight path.

2.4 Computer simulations of Dustbuster performance

SIMION ion trajectory software [10], versions 6.0 and 7.0, were used extensively both in testing possible designs and in evaluating the working design. Although there is no satisfactory substitute for a good experiment, changing the shape of an electrode is much easier on the computer than in the machine shop.

In order to make full use of SIMION’s capabilities, I wrote a spreadsheet to simulate the properties of positive ions emerging from an impact-generated plasma. Ions were assumed to originate from within a hemisphere of given radius corresponding either to the dust particle size, or to the point in the plasma expansion at which ion-ion collisions dropped to a certain frequency. The center of the hemisphere was located on or slightly above the impact plate surface in each case. Ions were defined individually with randomly distributed positions within the hemisphere, and randomly distributed initial kinetic energies within a specified range. The number of ions in each simulation could be specified from 1 to 50,000. For most performance simulations, groups of 500 ions were defined to have initial kinetic energies with a Gaussian distribution centered at 40 ± 25 eV. Ion groups were designed to have an overall spatial distribution (particle density function) of isotopic, $\cos\theta$, or $\cos^2\theta$ about the normal to the target plate. These represent the energy and angular distributions of ions reported by Ratcliff and Alladhadi [11] for a 94 km/s impact, and have been used for simulations by other researchers in this field [12]. Impacts at lower velocities will produce ions with lower energies [13]. A variety of ion mass-to-charge ratios were used. The details of the ion definition spreadsheet are given in Appendix B.

In simulations with 40 eV ions, mass resolution ($m/\Delta m$) ranged from 100 to 400, with higher resolution for impacts closer to the axis of the instrument. Ion collection efficiency ranged from 15-35%, with most ion losses caused by the grids through which the ions passed. Also, many ions in simulations were unable to pass through the entrance to the drift tube, which also contributed significantly to the overall collection efficiency. Note that SIMION treats grids as having 100% transmission. Space-charge effects, other than those included in the ion definition spreadsheet, were not used in the trajectory calculations.

Figures 2.5, 2.6, and 2.7 show the trajectories of singly charged ^{56}Fe ions, with initial kinetic energy of 25 ± 7 eV and $\cos\theta$ angular distribution. In Figure 2.5, the particle impact was located toward the center of the target plate (small radial distance from instrument axis). In Figure 2.6, the particle impact was located at an intermediate radial distance. In Figure 2.7 the particle impact was located toward the outside of the target plate. Ion packets are shown at various time intervals chosen for clarity and illustrative effect.

Figure 2.8 illustrates the effect of grid curvature on the orientation of the ion packet prior to impact on the ion detector. Figure 2.8a and Figure 2.8b show ions resulting from front grid curvatures of 0.8 m and 1.3 m radii, respectively. Figure 2.8c shows the result from a planar front grid. Figure 2.8d shows the result from an optimized grid curvature, although optimization of the ion packet angle can come from either grid curvature or from the voltage on the focusing ring.

2.5 Other instrument issues

One issue not yet addressed is that of detector protection. MCP detectors and other ion detectors are sensitive both to UV light and to impacts by dust grains (although the latter has not been tested). It is essential that the Dustbuster detector be protected from both. One obvious solution is to include a solid disk at the center of the front grid. Although this may eliminate most direct light and impacting particles, in order to completely block all direct paths to the detector the disk would need to be quite large. The resulting obstruction would significantly reduce the effective surface area of the

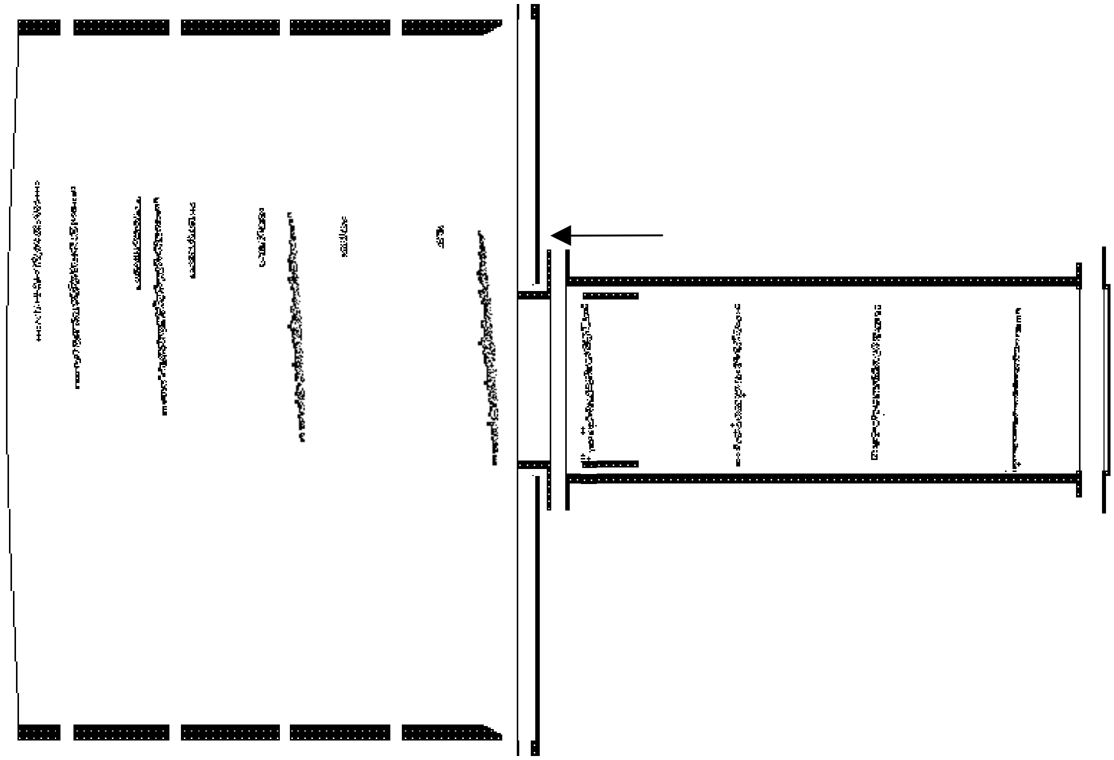

Figure 2.5. Trajectories of ions resulting from an impact near the center of the target plate (indicated with arrow). Simulated ions have initial kinetic energy of 25 +/- 7 eV with a cos θ distribution about the normal. Locations of ions at various time intervals are shown.

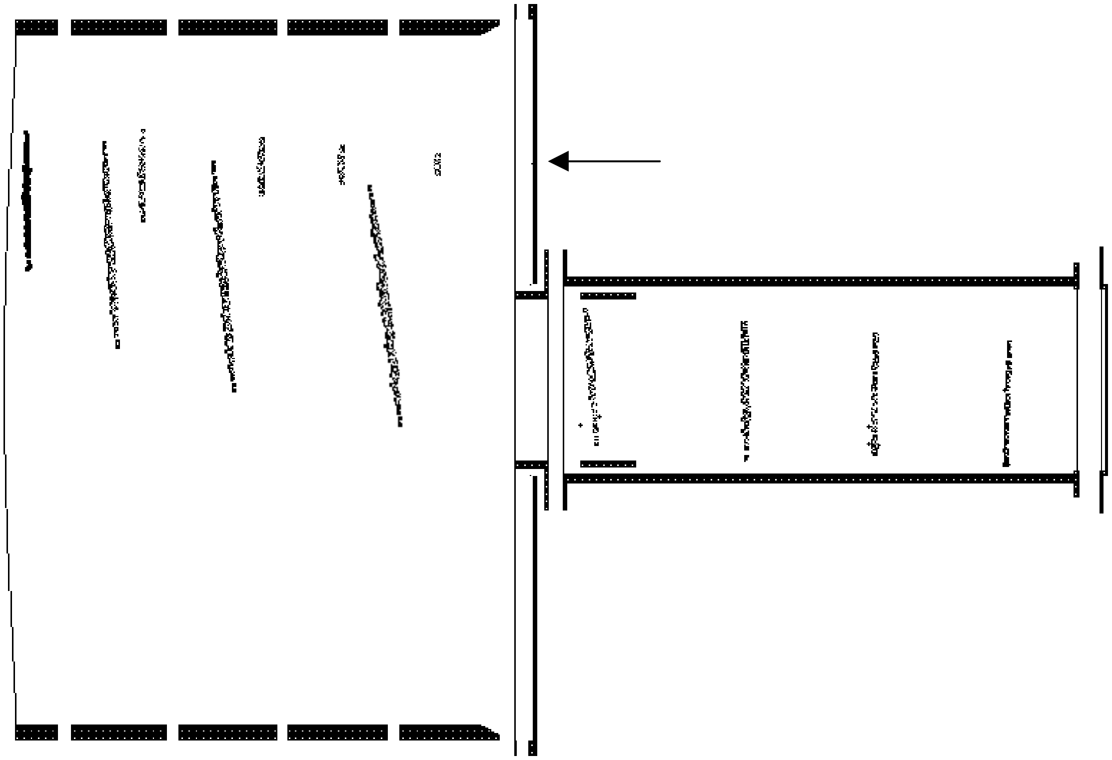

Figure 2.6. Trajectories of ions resulting from an impact at an intermediate radial distance on the target plate (indicated with arrow). Simulated ions have initial kinetic energy of 25 +/- 7 eV with a cos θ distribution about the normal. Locations of ions at various time intervals are shown.

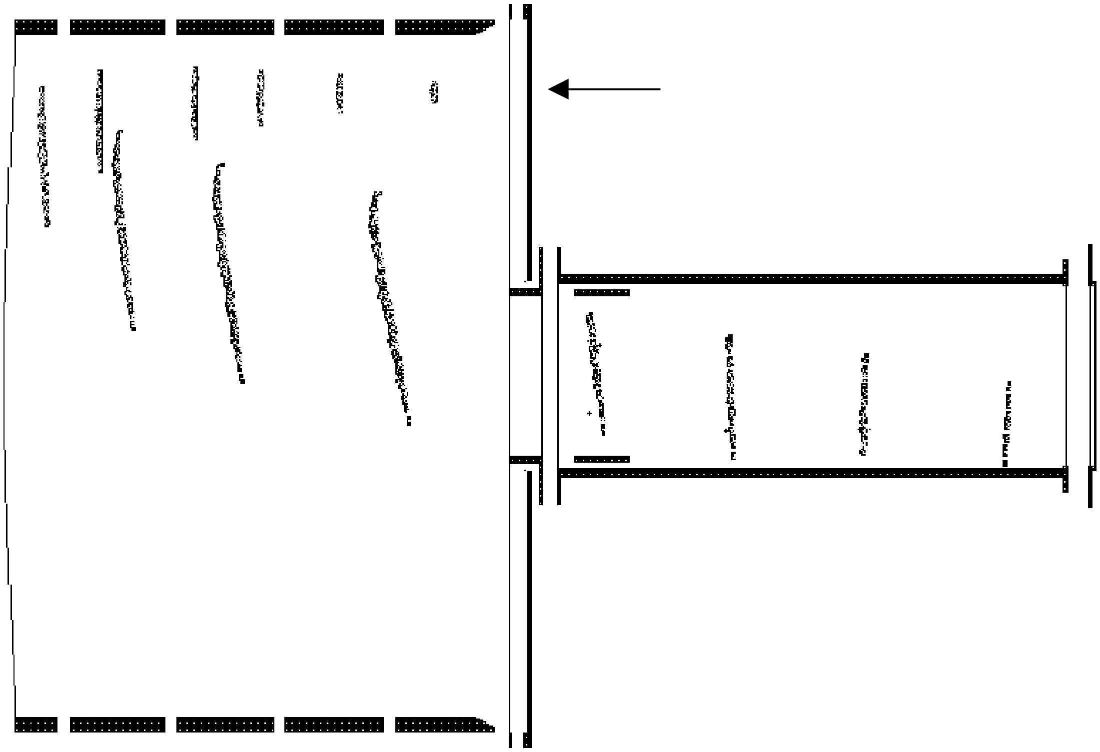

Figure 2.7. Trajectories of ions resulting from an impact near the outside of the target plate (indicated with arrow). Simulated ions have initial kinetic energy of 25 +/- 7 eV with a cos θ distribution about the normal. Locations of ions at various time intervals are shown.

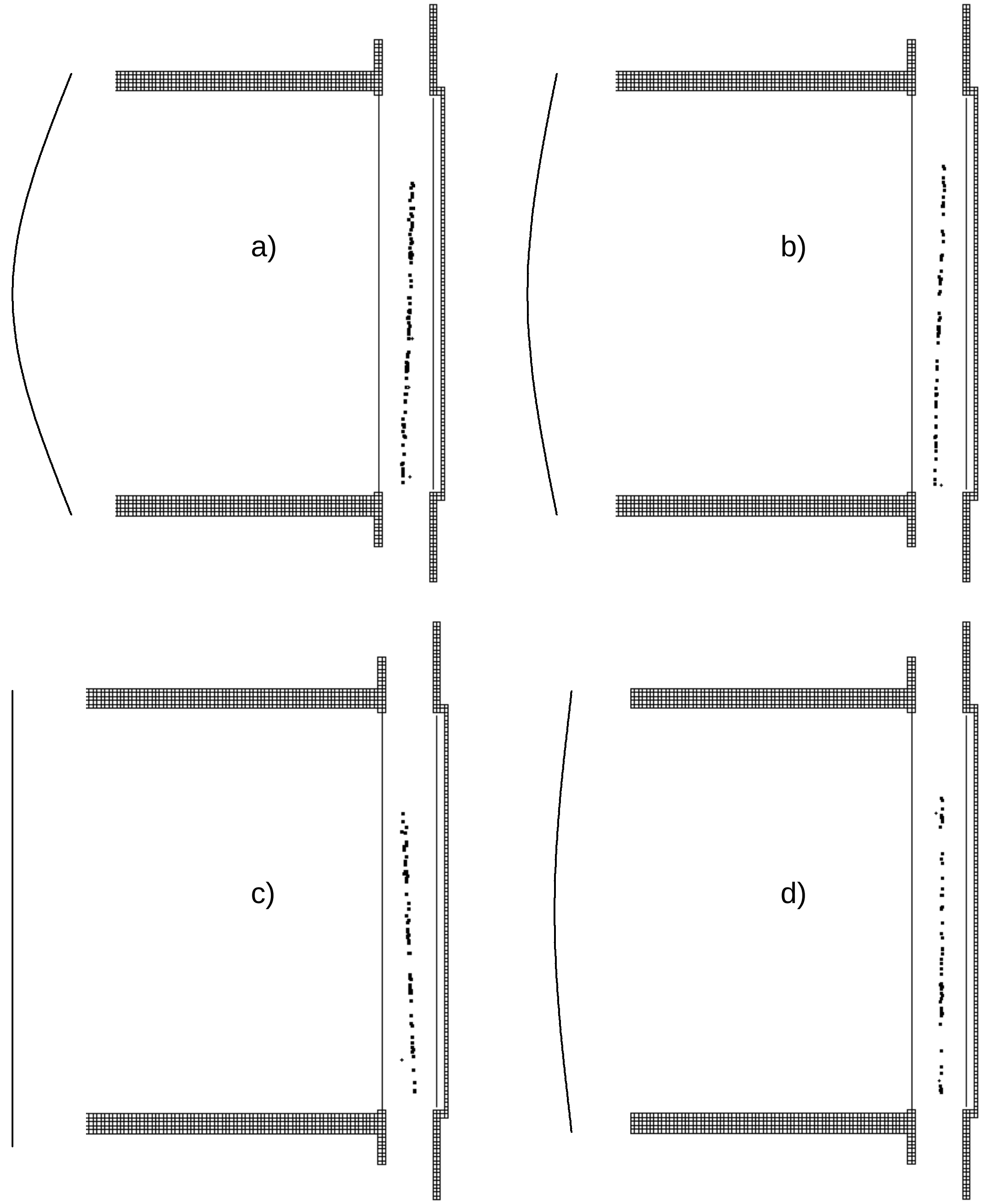

Figure 2.8. The effect of the curvature of the front grid on the mass resolution. Each frame shows simulations of typical ions reaching the detector. In a), b), and c), front grid curvatures are r = 0.8 m, r = 1.3 m, and r = ∞, respectively, and resulting ion packets are not parallel to ion detector. In d) curvature is optimized so that ion packet is parallel to ion detector, maximizing mass resolution.

impact target. Another method for protecting the detector is to use a narrower drift tube, or to include smaller apertures at both ends of the drift tube. The complication with this is that ions from the outer regions of the impact plate will have significant components of velocity perpendicular to the axis of the drift tube, and will tend to crash. This can be remedied somewhat with the ring electrode within the drift tube, which, depending on its voltage, can straighten out or scatter the ion trajectories. In any case, further work is needed on the question of detector protection.

As with any analytical instrument, sensitivity is an issue. Improvements in sensitivity can come from two directions: increasing the number of ions produced upon impact, and increasing the number of produced ions that reach the detector. Increasing ion yield of an impact can be achieved using a high-density material for the impact plate. Increasing the number of ions reaching the detector is a bit more complicated. Factors affecting total ion detection include the transmission of all grids through which the ions pass, truncation of the ion beam with apertures at the ends of the drift tube, and the general ion focusing ability of the system. However, increasing sensitivity brings benefit only to a certain point. Dust grain masses vary over several orders of magnitude. The instrument sensitivity is limited by the dynamic range, which is limited by the ion detector and electronics and centered on the range of signals produced from particles of interest. Thus the ideal sensitivity may be different depending on the range of dust particle sizes and impact velocities for a given type of dust.

2.6 Suitability for various missions

The Dusbtuster was originally designed with the hope that it would be included on the Pluto-Kuiper Express, a NASA mission to the outer solar system that was later cancelled. As such, the design was optimized with the mission objectives and limitations of the Pluto mission. Because of the severe power and mass limitations on such a spaceflight, particular attention was paid to minimizing these two properties of the Dustbuster. The low dust flux for this mission made the large impact plate essential. Also, little work was done on developing a system to protect the ion detector, since it was thought that there was relatively low risk of damaging particles and radiation based on the projected mission trajectory. Although information about the charges, masses, and velocities of particles encountered on the Pluto mission would be important, these parts of the Dustbuster had not yet been developed.

After the Pluto mission was cancelled, the engineering group and Project Manager for Deep Impact became interested in the Dustbuster. This NASA mission involved a comet rendezvous, ablation of the comet surface by a large projectile, and analysis of the resulting debris. This mission, in many respects, represented the exact opposite environment of Pluto: dust flux would be much higher, the potential for damage would be higher, and instrument mass and power were much less of a concern. The use of a low-transmission entrance grid (plate) solved these obstacles. Dust flux was reduced, but still high enough to obtain numerous samples in the few minutes the comet debris would pass by the spacecraft. The entrance plate could be designed in such a way that particles and light could be completely excluded from the detector, and no one would complain about an instrument being lighter and lower-power than the payload limits. Measurements of particle velocity and trajectory would not be needed for the cometary debris, since the origin of particles would be known. Due to the lack of funding and other factors, the Dustbuster was not selected for Deep Impact. Interestingly, the Deep Impact spacecraft in its final form has no instrument designed to directly sample and measure the composition of the comet material, although this was identified as an important scientific objective.

We have considered trying to get the Dustbuster accepted on other missions, including Hew Horizons (the replacement Pluto mission), Solar Probe, and the recently proposed earth-orbiting dust observation satellite [14]. In terms of instrument design, minor modifications make the Dustbuster suitable for the different conditions of each mission.

2.7 Future design improvements

I have worked out several improvements to the Dustbuster subsequent to the most recent laboratory performance testing and publications. Foremost among these is a method to measure the mass and trajectory of incoming particles. In addition, small changes in the basic design geometry improve mass resolution.

The instrument originally proposed to NASA included systems to measure the velocity, angle, mass, and size of incoming dust grains. As the particle passed through several light "sheets," the scattered light would be detected by a series of high-speed photodiodes. This information would provide the velocity and angle of the particle, and perhaps also the size. Upon impact, piezoelectric transducers measured the impact energy, which would be used, together with the impact velocity, to determine the size of the particle. Other instruments, such as the Cassini Cosmic Dust Analyzer, uses a series of charge-sensitive grids to measure the charge and location of a particle [4]. From this information, the CDA determines the velocity and angle of the particle. The Dustbuster, as reported in recent publications, is not a standalone instrument: no method for measuring particle parameters was given. However, the Dustbuster can be outfitted with a set of components that will provide all this information and minimize instrument mass and size.

Passing a particle through a series of parallel grids wastes a great deal of space, and, depending on the geometry, reduces ion transmission. All essential information can be gathered using only two measurements of position and charge separated by sufficient time and space. However, both of these measurements do not necessarily have to be prior to impact, nor do they have to be the same type of measurement. For the Dustbuster, before the incoming particle passes through the front grid, five wires, arranged in a star, record the image current produced by the particle. The differences between the induced currents on the wires provide both the charge of the incoming particle and its location as it enters the Dustbuster. Although three wires are the minimum needed to specify unambiguously both magnitude and location of any charged particle in a plane, five wires increase the precision of the measurement. In addition, five wires provide a high level of redundancy: if one or two of the wires break or otherwise fail, the remaining three will still provide all the essential information about the particle. This provides the first set of measurements.

Upon impact of a particle with the target plate, a flash of light is given off, the intensity of which is proportional to the impact kinetic energy [15-17]. Surrounding the target plate are four photodiodes with wide-angle lenses. Similar to the charge-sensitive wires, these optical sensors provide the location and energy of the impact. Combining charge and optical data yields both the velocity and angular trajectory of the incident particle. Particle mass is calculated from velocity and kinetic energy. In addition, the light flash provides the zero point for the time-of-flight mass spectrum. The photodiodes are placed in a location that shields them from direct light that enters the instrument, although small amounts of scattered light may reach the detectors and limit sensitivity. Figure 2.9 shows the arrangement of the charge-sensitive wires and the photodiodes on the instrument, and Figure 2.10 shows an example of the signals that might be detected by this arrangement. This type of detection system does not markedly increase the size or mass of the instrument.

A second improvement is the use of a curved impact plate. A curved plate was examined as a possibility early on, but simulations of its performance proved difficult. Because of its discrete nature, SIMION is not able to realistically simulate the electric fields immediately above curved surfaces, even at the highest possible resolution. In addition, individually defining ions to originate at various locations on a “discrete-curved” surface is much more labor-intensive than individually defining them on a planar surface. Nevertheless, a concave impact surface will likely improve the instrument performance, if it is possible to mount a curved extraction grid above it. It is possible, however, that a curved impact plate will increase the risk of secondary impacts and secondary ionization.

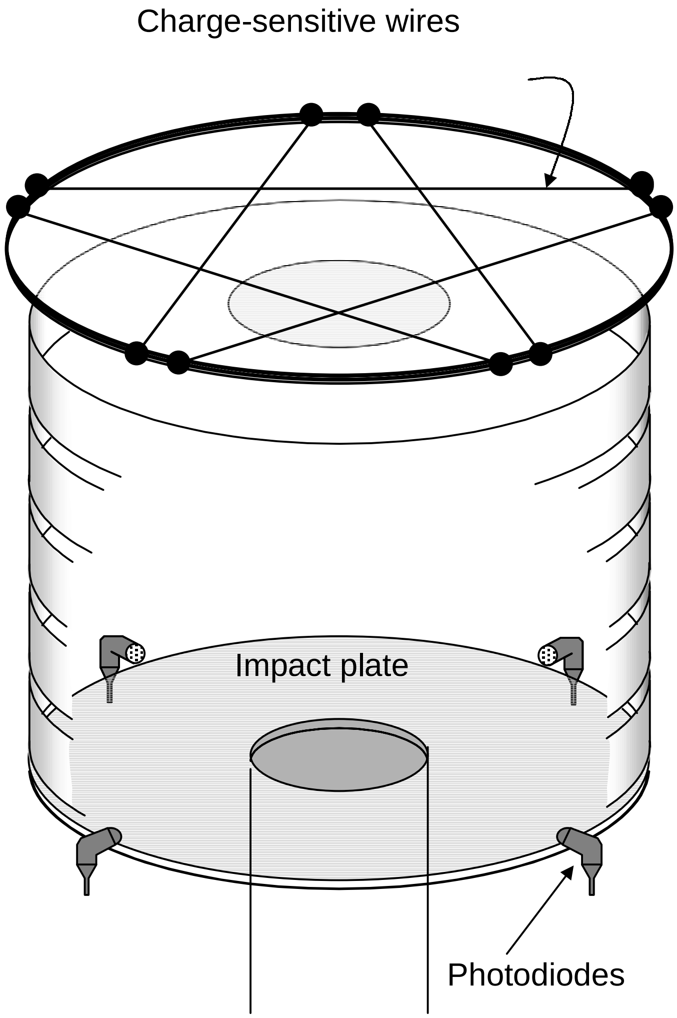

Figure 2.9. Charge-sensitive wires and photodiodes for determination of mass, velocity, charge, and trajectory of particles as they enter the Dustbuster.

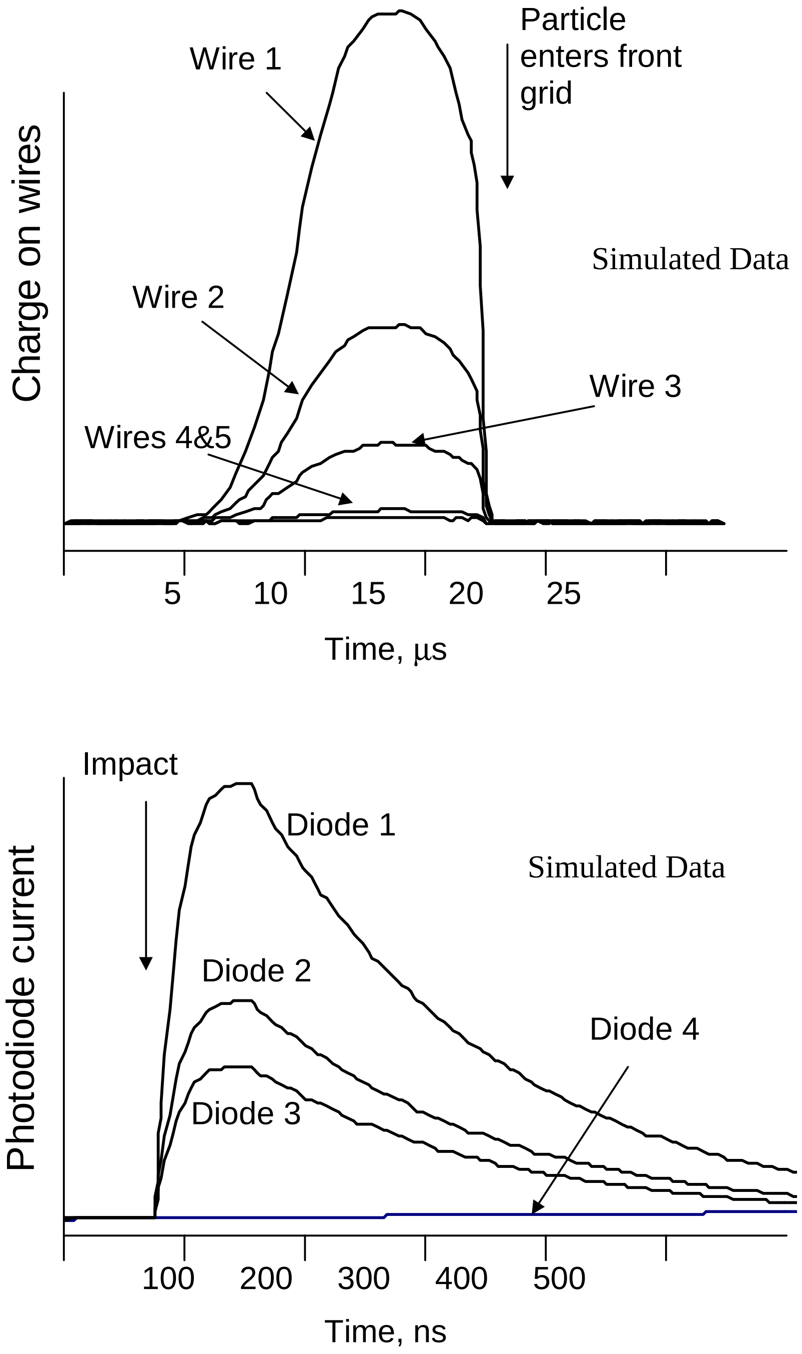

Figure 2.10. Simulated signals on charge-sensitive wires and photodiodes. Differences in signal amplitudes constrain particle location at each event. Timing between events constrains particle velocity. Signals also yield particle charge and impact kinetic energy.

In order to reduce the exposure of the ion detector, an ion reflector could be placed at the rear of the drift tube. Ions would then be deflected 90° onto the detector. The detector would thus be completely shielded from stray microparticles and incident radiation. Simulations on this possibility were not performed. Ion focusing could be an issue, and this will need to be explored in the future.

Finally, the spacing between the impact plate and extraction grid should be somewhat larger than originally designed. A distance of 4 mm seems to reduce plasma shielding, which can create a spread in the apparent times-of-birth of the ions, as well as increase the spread in the kinetic energy of the ions after extraction.

2.8 References

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