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SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Enloe, C. L. (DFP, 333-2240), Amatucci, W. E. (Naval Research Labs, 202-404-1022)

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3. DISCUSSION. None

4. VIEWS OF OTHERS. N/A

5. RECOMMENDATION. Sign coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy.

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Tabs
1. Manuscript

Identifying and Mitigating Anomalous Transparency in Retarding Potential Analyzers

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Abstract

As an instrument for charged particle energy analysis, the often-employed gridded retarding potential analyzer is straightforward to construct and operate, but substantial error can arise in analyzing its output if the device's behavior deviates from the ideal. Interpreting the device's output as a charged particle energy distribution presumes that collected current is a monotonically decreasing function of the applied bias potential, but this is not the case in some configurations, in particular in applications where the device has been miniaturized; rather, in some regimes, an increasing current can be observed with increasing bias. This effect, which appears as a voltage-dependent transparency of the device, is readily explained in terms of individual particle trajectories. We present not only an explanation for the error, but also introduce an RPA geometry that eliminates it using a precision-fabricated, miniaturized structure in place of a traditional electrically-biased mesh or grid.

I. The Origin of Anomalous Transparency

In principle, the retarding potential analyzer (RPA) is one of the most reliable instruments that exist for analyzing the energy distribution of a population of charged particles. The theory of operation of an RPA is straightforward. As illustrated in Figure 1, a space potential V_R is established within the device, most commonly by biasing a conducting mesh or screen. Charged particles entering the device with kinetic energy $K_\parallel = mv_\parallel^2/2$ greater than the potential energy qV_R pass through the space potential region to be collected as a measurable current, while particles with kinetic energy less than this threshold are rejected. (Here, we make the distinction that the device affects particles' motion in the direction parallel

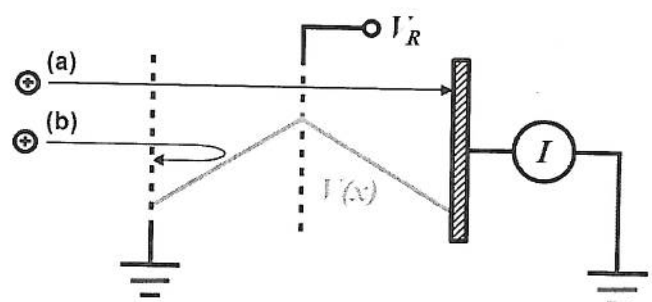

Figure 1. Schematic representation of an idealized retarding potential analyzer (RPA). Particles with sufficient energy (a) to surmount the retarding potential barrier V_R are collected as a measurable current, while particles with less energy (b) are rejected.

to the axis only, and so we adopt the term "parallel energy" even though energy is, of course, a scalar.) An RPA acts as a high-pass filter in energy, and the energy distribution $f(E)$ of the population of particles can be readily determined by varying the retarding potential V_R and taking the derivative of the collected current I with respect to V_R. This assumes that I is a monotonically-decreasing function with respect to V_R, as it would be for an ideal device. To construct an actual RPA, however, demands that one depart from the ideal. It is not feasible to construct a perfectly uniform potential in space and have that potential barrier be 100% transmissive. The most common construction method, using a biased mesh or screen, introduces two non-ideal characteristics: transmission $T < 1$, and a non-uniformity in the retarding potential.

The first characteristic of an actual device—finite transparency—should be trivial to account for: since some particles impact the wires or other metallization that make up the screen, simply compute the transmission from the open area of the screen and then divide the current I by the transmission T to determine the real particle flux incident on the device. This approach assumes that T is a constant based solely on the geometry of the screen. The second characteristic—non-uniform retarding potential—limits the energy resolution, $\Delta E / E$, of the device, but this, too, is an effect that can be deconvolved from the data. The trade-off between high transparency and high energy resolution (that is, low $\Delta E / E$) is one that the designer of an actual instrument must make. The relationship between screen geometry and the potential "sag" between the wires is well known[1-3] and, in particular, Goldan *et. al.* early on presented an analytical relationship (after Spangenberg[4]) for this variation $\Delta V_R / V_R$ in retarding potential,[2] which in the plane of the retarding grid reduces to

$$\frac{\Delta V_R}{V_R} = \frac{(2\pi d / a) - \ln(4)}{(2\pi d / a) - \ln(2)} \tag{1}$$

where a is the spacing between the wires in the screen and d is the distance between the biased retarding screen and the surrounding boundaries (screens or plates) assumed to be grounded. It is not particularly difficult, with the proper choice of screens and dimensions, to reduce the "sag" in the potential, and hence the inherent energy resolution of the device, to a few percent.

Unfortunately, this is not the only deviation from the ideal that an actual RPA, using an electrically biased screen, may exhibit. An actual RPA may exhibit a response that is *not* monotonically decreasing with increasing retarding potential; rather, with the device exposed to a monoenergetic stream of particles, the collected current may *increase* before the retarding potential reaching a threshold where the incident particles begin to be turned away. Unlike the issues of finite transparency or energy resolution, this effect is not easily accounted for in the analysis of the data from the device. Traditionally, the method of analysis of RPA current output, I, equates the distribution function in energy with the negative of the derivative of the current-voltage trace,

$$f(E) = -\frac{dI}{dV_R} \tag{2}$$

or, if the input distribution is assumed to be a drifted Maxwellian, the I-V trace may be fitted directly, using the function[5]

$$I(V_R) = \frac{I_0}{2}\left[1 - \mathrm{erf}\left(\frac{\sqrt{V_R} - \sqrt{V_0}}{\sqrt{kT/e}}\right)\right] \quad (3)$$

where I_0 is the unretarded current, V_0 is the voltage corresponding to the flow energy and kT/e is the voltage corresponding to the temperature of the Maxwellian distribution. In either case, trying to analyze an RPA response that does not decrease monotonically introduces substantial errors—and, in the case of taking a derivative, yields the non-physical result of a negative density of particles in some energy ranges.

One of the authors (CLE) has seen this effect in several instrument development efforts. In particular, this problem has arisen when designing spacecraft instruments, which benefit from being miniaturized. Most recently the authors have seen this effect in an instrument that needed to be mechanically robust in order to survive in use. Adapting the design for a "cone-in-a-can" RPA configuration[6] for use in analyzing a high-current, high-voltage (multi-milliamps at 2 kV) electron beam necessitated using a low-transmission screen in the device, with relatively thick wires compared to the spacing between them. The first iteration of the design yielded unacceptable results in calibration—shown in Figure 2—but these poor results provide a clear illustration of the phenomenon of "anomalous transparency" in retarding potential analyzers.

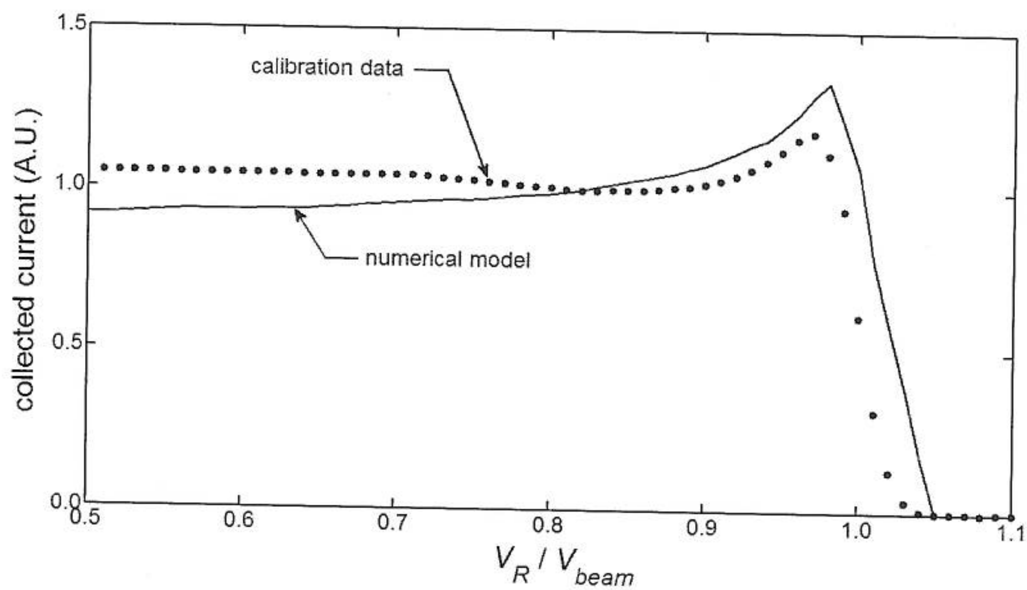

Figure 2. A retarding potential analyzer with a low-transmission screen exhibits severely non-ideal behavior when calibrated against a nominally monoenergetic electron beam (points). A numerical model (line) explains the behavior as a case of "anomalous transparency" in the screen.

Numerical analysis of the as-built device provides an explanation for the observed behavior. The screen on the retarding structure in the first iteration of the analyzer was particularly coarse: the wire diameter was 0.40 mm while the wires were spaced 1.27 mm apart. This resulted in an optical transparency of 47%, the same transparency that particles would see if $V_R = 0$. The grounded, collecting plate in the analyzer was 9.0 mm from the back of the retarding structure. Equation (1) predicts a variation of 1.6% in the retarding potential across the screen. (Equation (1) strictly applies to a symmetric, planar configuration, but we apply it here as an approximation.) Using the electric field solver and particle trajectory packages in COMSOL Multiphysics, we track particles incident on one of the square openings in the screen.

We track two populations of particles separately and then combine them proportionally to model the response of the as-built device. Particle trajectories for particles initially aimed at the opening between the wires are shown in Figure 3(a). Here we see the effects of the non-uniform potential between the wires. Although the potential V_{RPA} applied to the wires should be more than sufficient to turn around the incident particles, the reduced potential in between the wires is not sufficient to reject them, so some make it through the potential barrier to be measured as current. This effect itself presents no difficulty in analysis—it simply means that the device has a finite energy resolution.

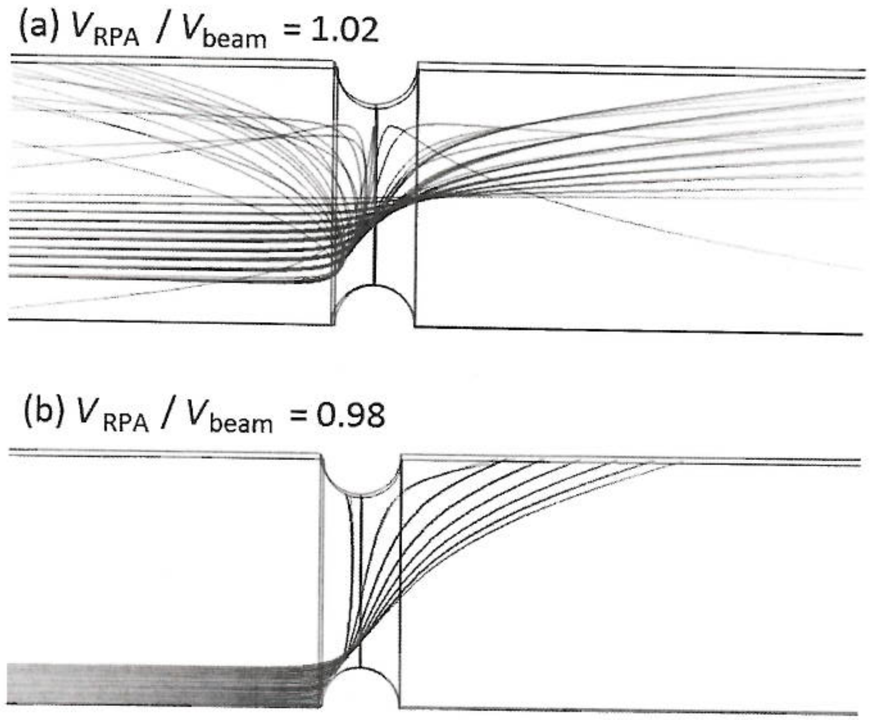

Figure 3. (a) Particles aimed at the open space in the retarding screen see a different maximum potential depending on their trajectories, leading to a broadened energy response. (b) Particles aimed at the wires in the screen can be deflected into the open space between the wires by potentials close to, but not equal to, that required to reject them, leading to an anomalous increase in the transparency of the screen.

Particle trajectories for particles initially aimed at the wires, on the other hand (as shown in Figure 3(b)), are a different matter. At retarding potentials just below what is necessary to reject particles, a substantial fraction of the particles that were aimed at the wires are deflected into the region between the wires, where the space potential is reduced (so-called potential "sag") and the particles have enough energy to overcome the potential barrier. These particles cause an increase in the collected current, and as the consolidated results shown in Figure 2 demonstrate, the effect is most pronounced right before the incident particles are rejected. This is the cause of anomalous transparency in RPAs: effectively, the transparency of the retarding screen increases with applied retarding potential until a sufficient potential is applied to reject all incident particles.

II. Mitigating Anomalous Transparency

The problem of anomalous transparency becomes worse as the overall transparency of the retarding grid in an RPA decreases. Unfortunately, grid transparency tends to decrease as the overall physical size of an RPA device decreases, for the simple reason that the wires or other metallization of a miniaturized grid tend to take up a larger fraction of the grid's area merely to maintain mechanical integrity. On the other hand, if the retarding grid (or equivalent retarding element) could have 100% transparency to begin with, there would be no anomalous transparency at all.

In this paper, we present a gridless RPA configuration that, indeed, does have 100% transparency in the retarding structure even for zero applied potential, while maintaining high energy resolution (that is, high uniformity due to low potential "sag"). Such a device is illustrated schematically in Figure 4.

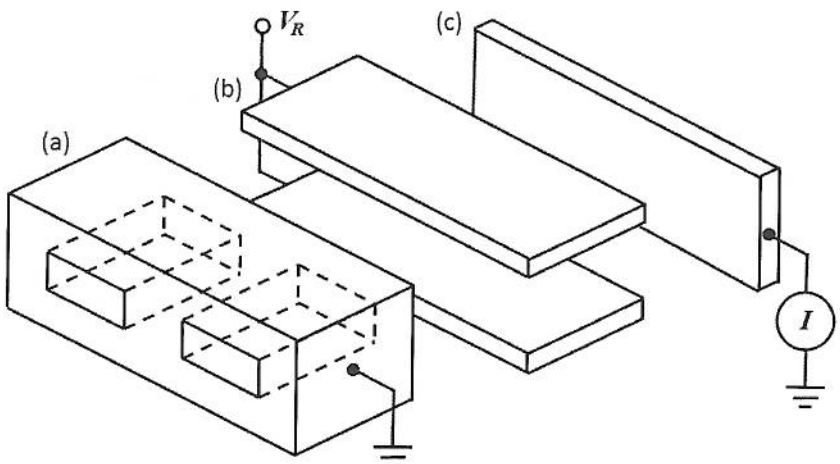

Figure 4. Schematic representation of an RPA configuration that eliminates anomalous transparency.

The device consists of a series of well-defined, grounded apertures (Figure 4a) that are aligned carefully with a slot in an electrically-biased retarding structure (Figure 4b), Behind the retarding structure is a collecting plate (Figure 4c) that is held at ground potential by the current-measuring circuitry. Figure 4 shows two separate apertures of the device, but as manufactured the actual device contains 715 apertures (13 rows of 55 apertures each) arranged on a 4.0 cm × 2.5 cm plate, as shown in Figure 5. A cross-sectional schematic of the device, with as-built dimensions, is shown in Figure 6.

The gridless RPA achieves 100% transparency in the retarding grid by careful choice of dimensions. As Figure 6a shows, un-retarded particles pass through the opening in the retarding structure even at the most extreme entrance angles allowed. The aspect ratio (thickness:height) of the slot in the retarding structure is sufficient to establish a highly uniform potential barrier in the middle of the slot. Figure 7 shows a contour plot of the calculated electric potential inside the slot. As the figure shows, the variation in the potential in the center of the slot is less than 1%.

Because of the uniformity of the electric potential in the middle of the slot, the transition between particles' being transmitted and being turned back is quite sharp (at least for particles in the plane of the paper) as shown in Figures 6b and 6c. Importantly, under no conditions do incident particles strike the walls of the retarding structure.

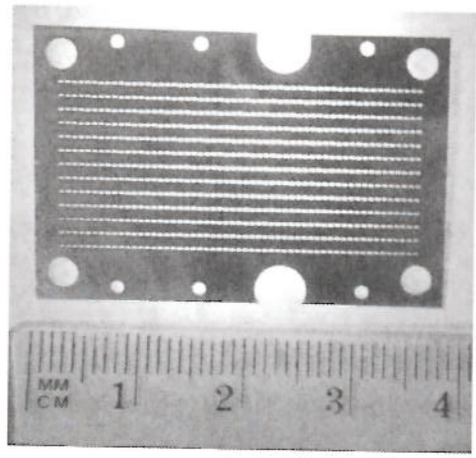

Figure 5. Arrangement of 715 individual entrance apertures on the front plate of the gridless RPA.

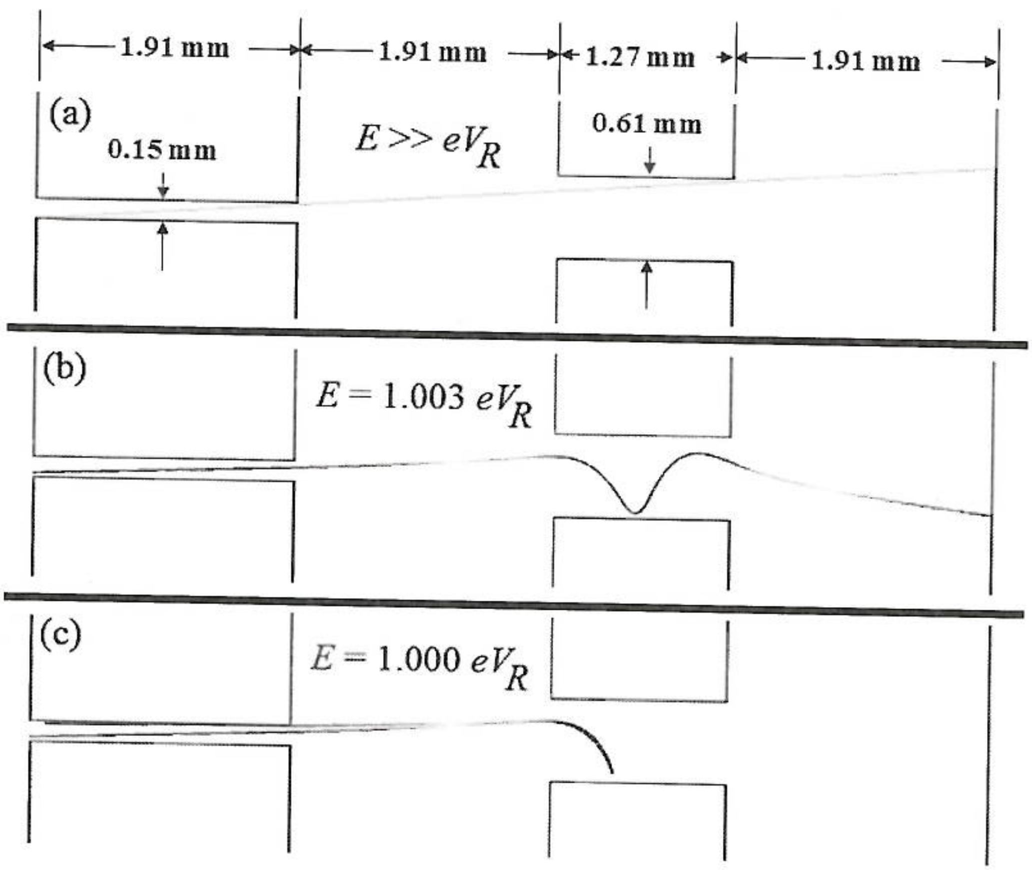

Figure 6. Cross-section of the gridless RPA with particle trajectories.

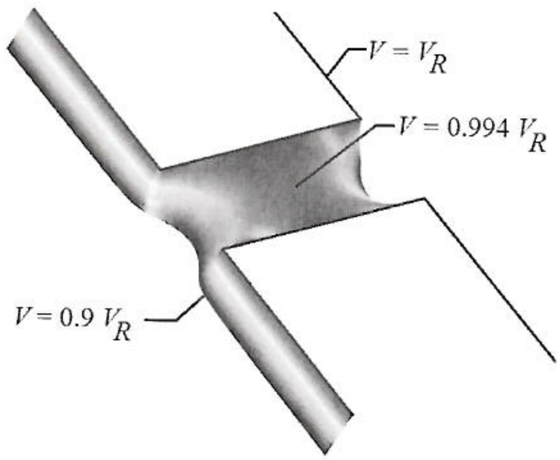

Figure 7. Calculated electric potentials inside the slot in the retarding structure.

Figure 8 shows the performance of the gridless RPA placed in a nominally monoenergetic electron beam. Consistent with its design, the current-voltage trace (Figure 8a) is monotonically decreasing, so that determining the particle distribution function in energy by a derivative of the current-voltage curve gives a straightforward result (Figure 8b).

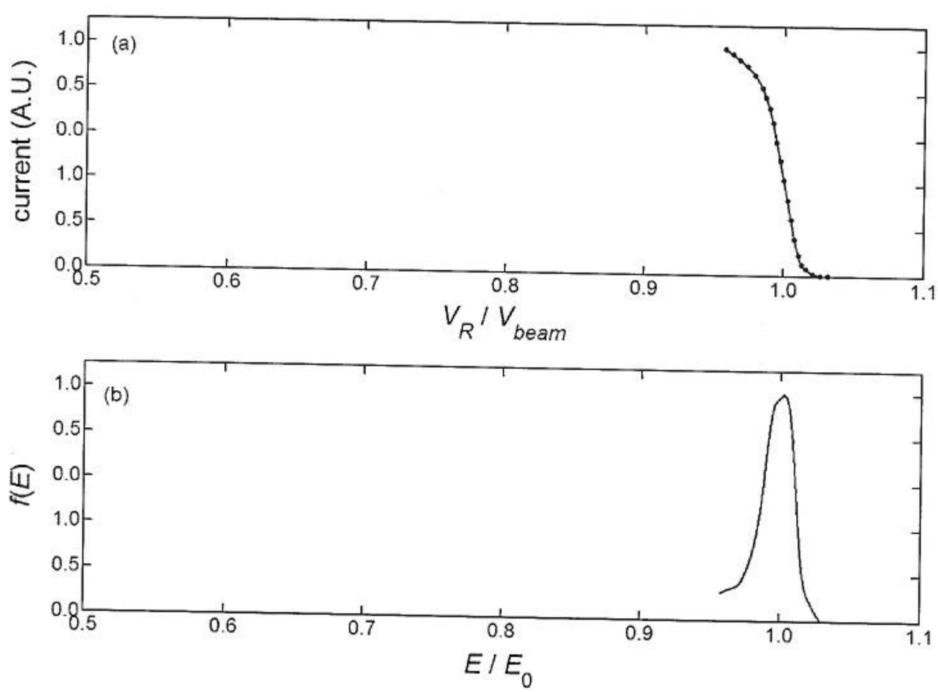

Figure 8. Calibration results for the gridless retarding potential analyzer.

Given the small variation in the calculated potentials shown in Figure 7, the experimental results shown in Figure 8 appear to be something of a disappointment, with a 2.8% full width at half maximum (FWHM). Approximately 1% of that variation is inherent in the calibration source itself, a filamentary electron source, however, the remainder of the energy spread is related to the fact, noted in the first section, that planar RPAs discriminate against the parallel energy of particles only. For a particle coming in off-axis by an angle θ, its parallel energy, $K_{\parallel}$, compared to its total energy, K, is

$$K_{\parallel} = K \cos^2 \theta \quad . \tag{4}$$

This is why the entrance apertures for the gridless RPA are rectangular and arranged in a line, rather than being a single, long, and narrow slit—to try to preserve the inherent accuracy of the design while allowing a reasonable angular field of view. Each aperture is 0.5 mm wide (in and out of the page in Figure 6) with limits the azimuthal angle at which the particles may enter to ± 15°. This introduces an error in the energy of the most extreme particles of 7%, by Equation (4). Fortunately, these most extreme particles comprise a vanishingly small portion of the incoming population, so that an energy resolution of approximately half this value (consistent with the measured response) is achievable. We also note that the gridless RPA has, as a consequence of its design, a small field of view in elevation. Figure 9 shows the measured angular response of the device in elevation (in the plane of the page in Figure 6) and this response is essentially the geometry of tilting the entrance aperture, shown as a dashed line in the figure.

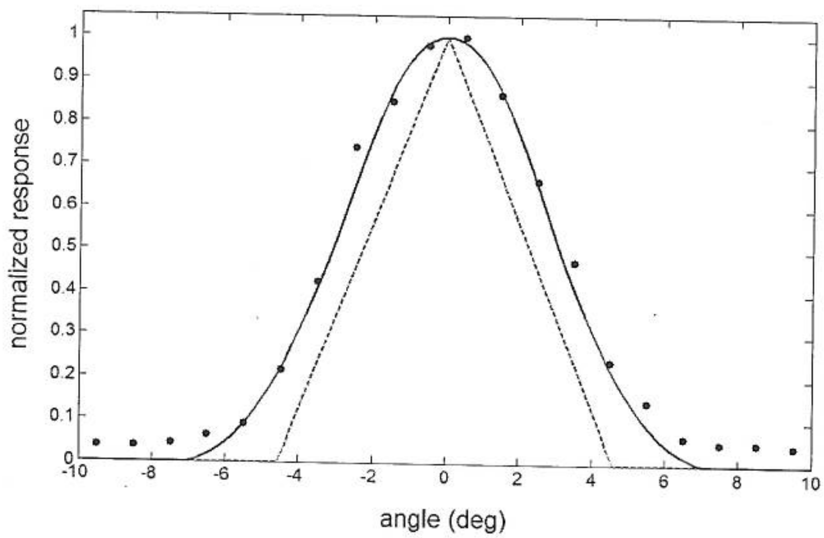

Figure 9. The measured angular response of the gridless RPA in elevation (points) is consistent with the geometry of tilting the entrance aperture (dashed line).

III. Conclusion

We have shown that the phenomenon of "anomalous transparency" in gridded retarding potential analyzers—the steering of particles away from the grid wires into the transparent portion of the grid—is a sufficient explanation for the non-monotonic response with increasing retarding potential observed in some RPAs, especially those that use relatively coarse, low-transparency grids to achieve miniaturization. We have demonstrated a design that eliminates this undesirable phenomenon by eliminating the retarding grid, substituting instead a precision high-aspect-ratio retarding structure, achieving an energy resolution of a few percent with a 100% transparent potential barrier.

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