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# MAPPING OF ELECTRICAL POTENTIAL DISTRIBUTION WITH CHARGED PARTICLE BEAMS

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TABLE OF CONTENTS

# ABSTRACT

When ions are formed at some point of interest and they are accelerated toward a detector, their energies as measured by the detector are equivalent to the potential of the point where they were formed. Thus potentials can be measured by directing an ionizing beam through the point in the presence of neutrals. Measurements have been made using a beam of soft X-rays in air at $2 \times 10^{-5}$ Torr. Ions were detected by a continuous-dynode electron multiplier after they passed through a retarding field. Ultimate resolution depends upon the diameter of the X-ray beam which for this work was 3 mm. When the fields in the region of interest were such to disperse the ions only a small fraction were detected and the method of measurement was not very reliable. Yet reasonable data could be collected if the ions traveled in parallel paths toward the detector. Development should concentrate on increasing the aperture of the detector from the pinhole which was used to something measured in centimeters. Also increasing the strength of the source would provide a stronger signal and more reliable data. Measurements were made at an estimated ion current of $10^{-15}$A from a 10-cm length of the X-ray beam, this current being several orders of magnitude below what would have a perturbing effect on the region to be measured. Consequently the source strength can be increased and prospects for this method of measurement are good.

# INTRODUCTION

Work under Grant NSG-3166 has progressed simultaneously in several areas. This report deals primarily with the measurement of electric potentials by the use of an X-ray beam to produce ions at some point of interest. The ions are collected and their energies measured to determine the potential where they were formed. A report in preparation and to be issued separately describes methods of calculating potentials from data describing charged particle trajectories. A small effort was devoted to improving calculations of the response of an ion detector characterized by a small acceptance cone. Finally some preliminary design tests have been performed on an electron gun proposed for use in extensions of the current work.

In the work with particle trajectories, it has been shown that potentials within a region can be represented as a sum of potentials from singularities distributed around the region. Both dipoles and quadrupoles have been used. Though the iterative techniques for selecting the singularities do not lead to unique results, the errors are small if the singularities are not allowed too close to the boundary. The selection of singularities requires the simulation of particle trajectories in an estimated potential field and the adding of a singularity which will modify the potential and simultaneously modify the trajectories so that they more closely resemble experimental data obtained from the region being modeled.

A brief effort has been devoted to calculating the response of an ion sensor immersed in a thermal plasma and having the characteristic of sensing particles incident at near normal incidence. The restriction on angle of incidence leads to a simplification of the general solution. This work is not yet complete and will be reported separately.

An electron beam is needed for the proposed continuation of the work on this grant and some effort has been given to its development. It is required to have a ribbonlike shape with a cross section of a few millimeters by 0.1 mm. Yet current need be only 1 nA. A preliminary design has yielded a beam thickness of 0.3 mm using a collimating slit and no focussing. Some adjustments of that design should show improvement. Furthermore the measurement of thickness was made further downstream than the position where the 0.1-mm dimension is required. Consequently, the goal of 0.1 mm is seen to be quite reasonable.

# IONIZATION BY X-RAYS FOR POTENTIAL MEASUREMENT

If a low-energy ion is formed at some point of interest and it is then accelerated toward a detector, its kinetic energy at the detector is a measure of the potential where the ion was formed. The elements of such a system of measurement are a medium to be ionized, an ionizing source, and a detector. In this study, a collimated beam of soft X-rays ionized neutral gas at a pressure of $2 \times 10^{-5}$ Torr. Ions were accelerated toward a grounded plane having a pinhole which was the aperture of the detector. Ions entering the pinhole experienced a retarding field, which provided energy discrimination, before they struck the orifice of an electron multiplier.

An important requirement on the ionization process is that the ions be formed with an initial kinetic energy which is small compared with what they gain. The momentum of a photon is sufficiently small that essentially the ion and the liberated electron will gain equal and opposite momenta. Since velocities will vary inversely as masses, the particle energies will vary inversely as masses. If say a 100-eV photon ionizes an atom, the kinetic energy imparted to the ion will thus be less than 0.1 eV and it will be negligible if potentials of volts are to be measured. If electrons were to be used for measurements, the potentials being measured would need to exceed the energy imparted to the electrons by the ionizing process. All work reported here is for detection of ions.

An X-ray beam has advantages over an electron beam as the ionizing agent. It travels in a straight line which is unaffected by electric or magnetic fields as an electon beam would be. Furthermore the path followed by the X-ray beam does not contain any charge other than that produced from the neutral gas. However a disadvantage of X-rays is that focussing systems are bulky and expensive. Consequently, collimation has been used in this work to define the ionizating beam.

The ideal X-ray source projects as fine a beam as the application demands so that the region where ions form has a constant value of potential and so that the ions are monoenergetic. The ideal detector responds to all ions having energies greater than some set level and it ignores all ions having energies below that level. If some bias voltage applied to a grid inside the detector determines the energy level, then the output of the detector as a function of bias will be a step function. The location of the step is a direct measure of the potential where the ions were formed, yet in practice a step is not found and one must consider what features limit the resolution.

When potentials are to be measured, the system design must address several practical issues:

1. X-ray source strength as related to detector sensitivity and perturbations of the system being measured. Noise level.
2. Spacial resolution of both the ionizing beam the detector.
3. Mechanical degrees of freedom of the beam and detector.
4. Energy resolution of the detector.

In this report are described the various subsystems which have been built. Several examples of test data illustrate the use and limitations of these subsystems in terms of the issues listed above.

## System Description

The test system consisted of three structures, an X-ray source, a detector, and a biased electrode which produced the potential field to be measured. Actually the detector served a dual purpose. Not only did it detect ions but its face plate worked in conjunction with the biased electrode to establish a potential gradient. Two different biased electrodes were used to create two different test patterns.

The detector itself was mounted under a horizontal 15-cm disc which was grounded. Either a wedge-shaped structure or a flat plate was mounted above the disc and biased typically at 100 volts. Figure 1 shows the wedge-shaped configuration as well as the grounded box which contained the X-ray source. The apex of the wedge was 4 cm above the disc or face plate of the detector but when the horizontal plate was used instead of the wedge, it was mounted 3.4 cm above the detector.

The entire detector system and the disc on which it was mounted could be moved horizontally in the direction normal to the X-ray beam. This was so that the detector aperture could be centered on the stream of ions. However ions were formed along the length of the X-ray beam and they flowed in a vertical sheet from the beam to the disc supporting the detector. Since the disc admitted ions through a pinhole, only those ions from a point along the X-ray beam were detected. The X-ray source could be moved vertically and horizontally so that the beam could pass through any point of interest. Consequently the measurements were made on a two-dimensional system, the plane normal to the beam and passing through the aperture of the detector.

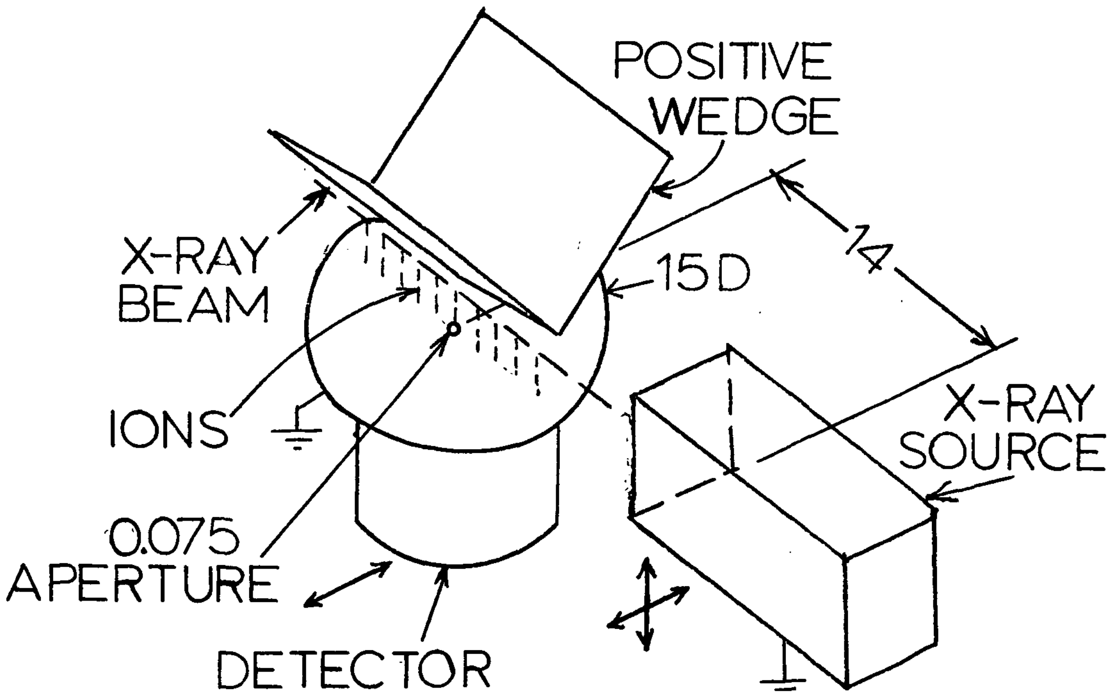


Figure 1. System configuration with dimensions in cm. The apex of the wedge was 4 cm above the detector. Arrows indicate allowed motions of the detector and source.

The test system was placed in a stainless steel bell jar equipped with electrical and mechanical feedthroughs. A base pressure below $10^{-6}$ Torr was obtained with a turbomolecular pump though a controlled leak could raise the pressure as desired. Pressure, as measured with a discharge gauge, was critical only as it affected the ion formation rate. It was typically set at $2 \times 10^{-5}$ Torr which was about the upper limit for low-noise operation of the detector. Both air and argon were used; little difference was noted. All data shown in this report are for air.

Outside the bell jar were the necessary electrical and mechanical systems to control and record events inside. Included were regulated power supplies, an oscilloscope, a pulse amplifier, a counter, meters, and position indicators.

## Detector Design

The ion detector was a critical part of the measuring system. It had to be highly sensitive so that the measurements could be made without significantly perturbing the potentials of interest. It had to be located outside of the region being measured. It was to view a fan-shaped region in the plane normal to the X-ray beam and it was to be movable so that it could intercept the particle flux from various regions in the plane.

The sensitivity was achieved through the use of a continuous-dynode electron multiplier CEM which generates a pulse in response to a single ion striking its collecting funnel. Though the actual response function depends upon many factors such as mass, accelerating voltage, and molecular form (1), the chosen mode of operation holds these variables relatively constant. It is estimated that with the sensitivity provided by the CEM, measurements were made with as little as $10^{-15}$A of current released over a 10-cm path of the X-ray beam.

The design described in the previous section shows how the detector is located away from the region of interest. This method of measurement requires that some boundary be established close to the region of interest so that ions formed by the X-ray beam can migrate through that boundary to the detector. To whatever extent possible one should incorporate the detector reference plane as a part of the system to be measured.

A design conflict arises between the need for precise energy discrimination and the desire to collect particles from different angles. Figure 2 illustrates this conflict in terms of simplified design drawings. If particles can enter the detector chamber from only one direction, then precise energy discrimination can be achieved by requiring them to pass through a biased screen or a saddle point if they are to strike the collecting funnel of the CEM. However when angles are permitted, those having oblique incidence require higher energy to pass through the screen than those with normal incidence. The use of curved screens overcomes this problem in principle but the question still remains whether or not the detection efficiency of the CEM depends upon the angle of incidence. The approach followed by Ross (2) was to allow only normal incidence and to tilt the detection system for maximum response. Finding the signal for a given X-ray position then required moving the detector horizontally and also tilting it. This process of finding the signal could be very tedious, though some data was taken (3). For collecting the data shown in this report, a system having a curved screen was built as shown in Figure 3. Incoming ions passed through a pinhole and then through a slot in the first curved surface. These grounded structures

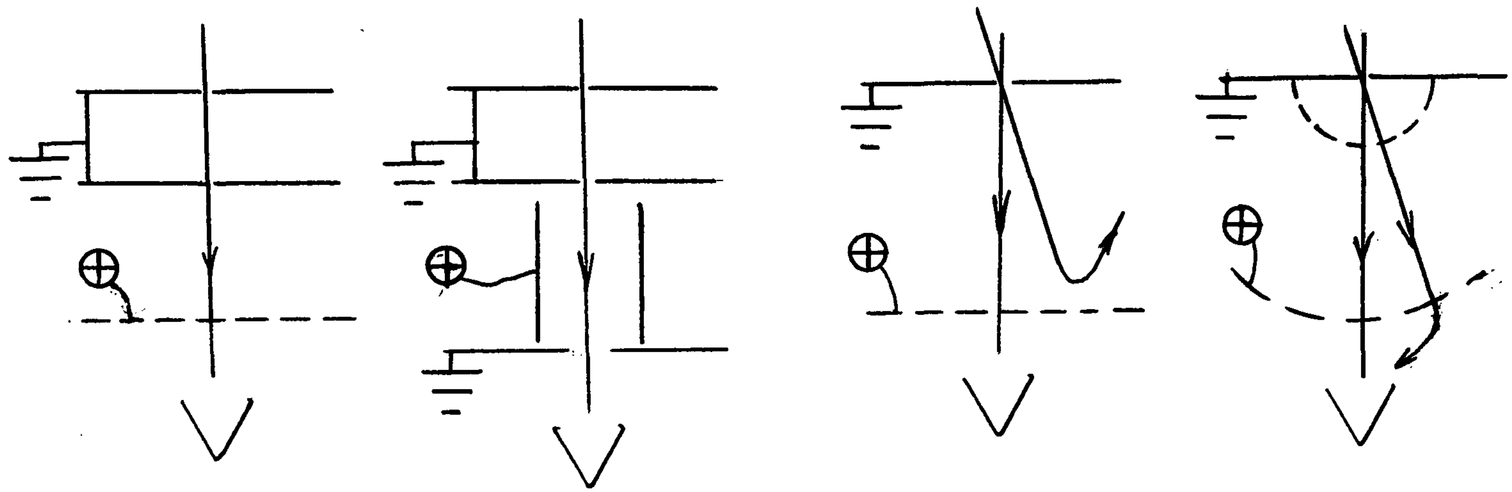

Figure 2. Various possible detector designs. The left two accept articles only from a narrow angle whereas the right two allow a broad angle. The curved screens force the field to be aligned with the particle trajectories.

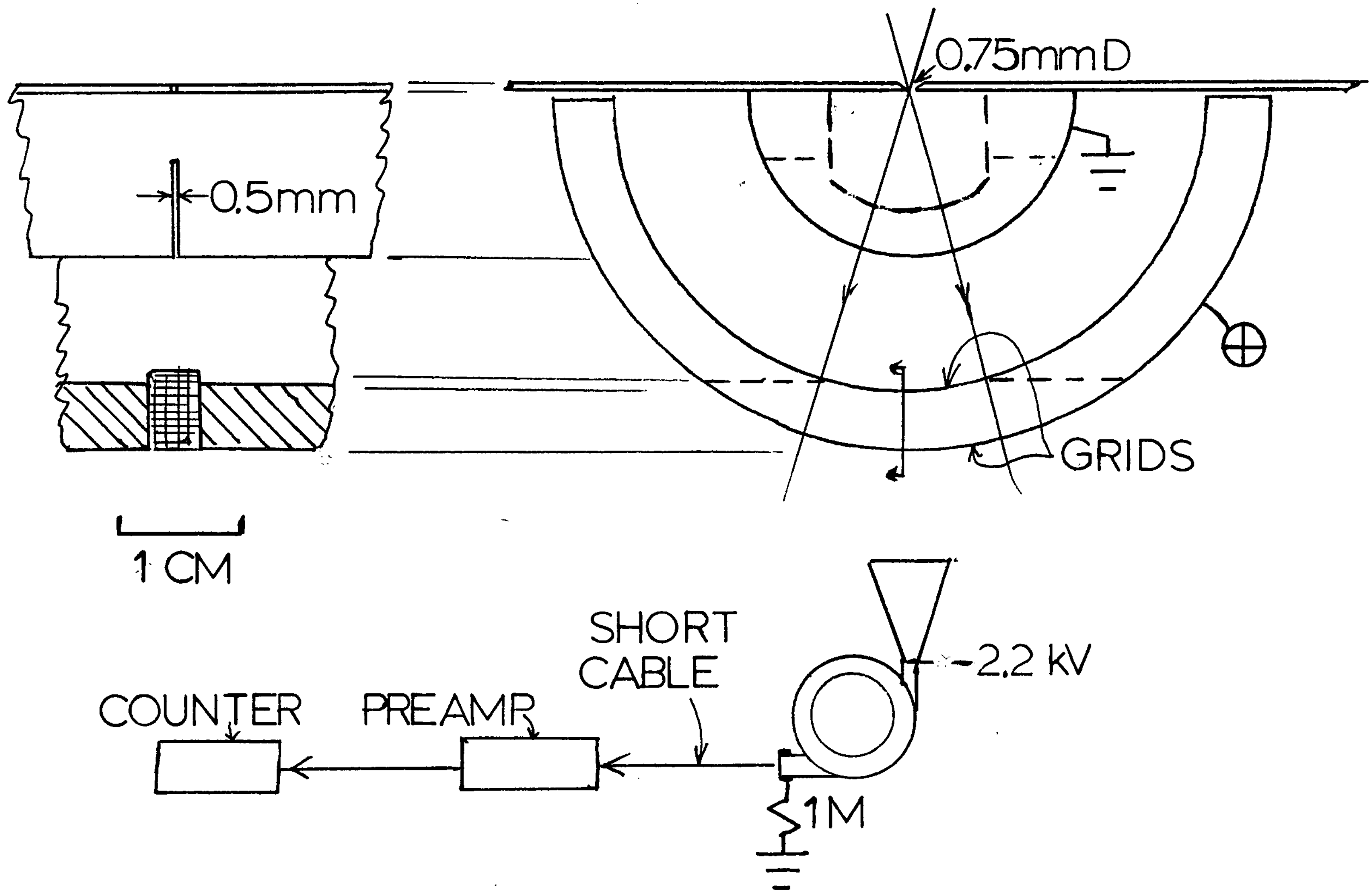


Figure 3. Design of the detector used in this report.

defined the region of space from which particles could come, a region which was fan-shaped. The particles then entered a decelerating region where the electric field was parallel to their velocity. Thus precise energy discrimination could be maintained.

Electric circuitry for the detector is also shown in Figure 3. The details were conventional and were described by Ross (2). For practically all measurements, the number of counts in 10 seconds was recorded for each setting of the position indicators or bias voltages. The noise level was typically less than 1 count in 10 seconds though it would be much higher in a dirty system or if the pressure gauge were turned on.

A hot tungsten wire was used as a low-intensity ion source for checking the response of the detector. Ions are emitted from the surface of a glowing-red wire roughly in proportion to the pressure at $10^{-5}$ Torr. This effect has been observed for air but not for helium and the emitted current is too low for us to measure except by our CEM. The wire was located 10 cm above the aperture of the detector and biased at some positive voltage to provide a source of monoenergetic ions. The detector responded as a function of the voltage impressed on the curved screen as shown in Figure 4. Although the response is not as flat as might be desired for biases below the out-off point, it drops rapidly as the bias is increased above that point corresponding to the particle energy. The measurement of particle energy is precise to about 1 volt. Slight disagreements in the voltage scales for the source and the biased grid are within the accuracy of the meters used for the measurements.

Though the detector appears to function well, two cautionary remarks are in order. First, the source was not located directly over the aperture

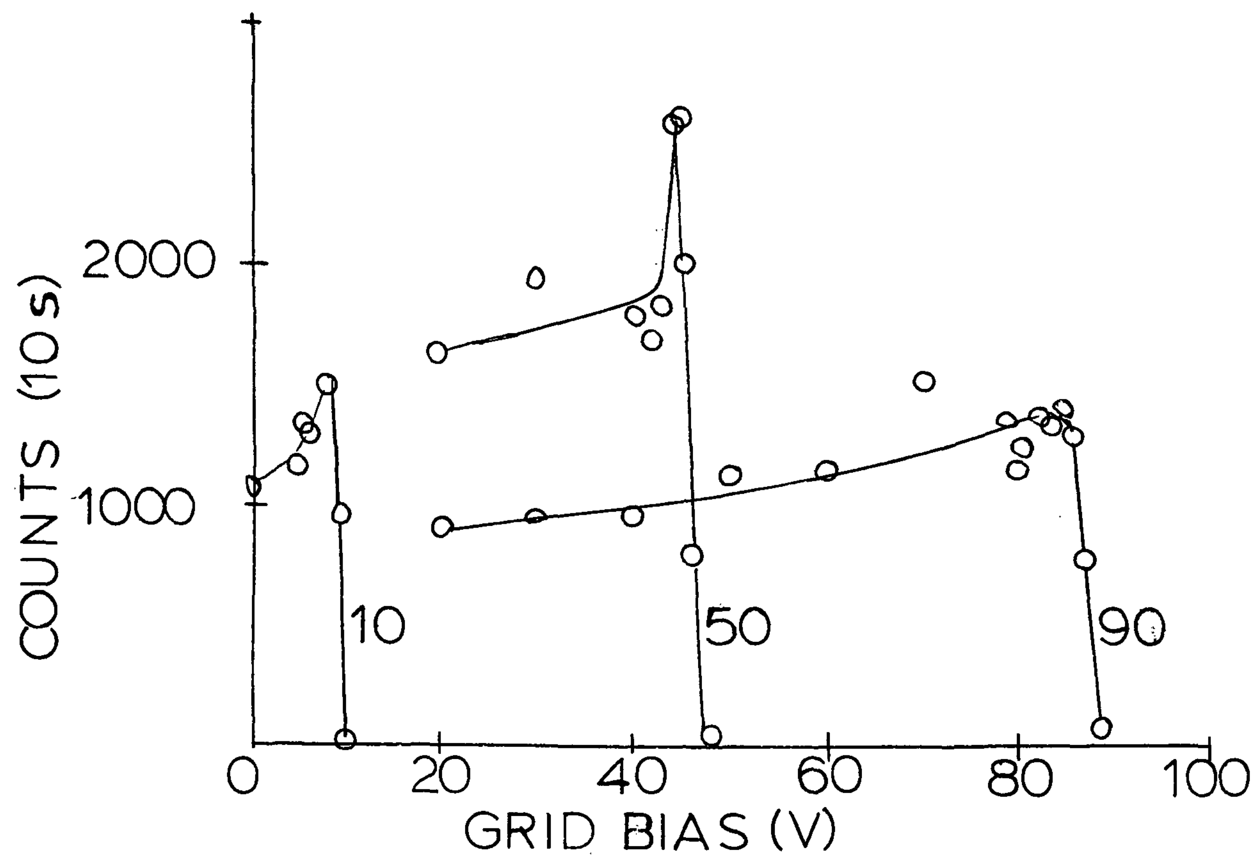


Figure 4. Response of the detector to monoenergetic ions emitted from a hot tungsten wire biased at 10, 50, and 90 volts.

but it was offset about 1 cm when maximum response occurred for 90-V ions. Also it is notable that response was not measured for different angles of incidence. In principle, the angle of incidence should be inconsequential, this being a desirable situation as particle trajectories can be difficult to predict. Yet some experimental data described later indicate that the angle is of importance. Certainly there exists a maximum deviation from normal incidence for which data can be obtained.

If the counting rate is 10 $s^{-1}$, as is typical, the the ion production rate can be estimated. For the simple case where ions follow parallel trajectories, an aperture having an effective area of 0.35 $mm^2$ collects ions from a column having the same area and having a length corresponding to the diameter of the X-ray beam, this typically being 3 mm. Thus the ionization rate is 10 $s^{-1}mm^{-3}$ and for an effective beam length of 10 cm, the rate is 7000 $s^{-1}$ or $10^{-15}$A.

## Ion Generation

Ions are produced by the binary interactions of photons with oxygen or nitrogen molecules. Other gases present in air may also be ionized. Cross sections for the photoionization process are found in the literature (4) and both have peaks of about 2 x $10^{-17}$ $cm^2$ near 650A. This wavelength corresponds to 20 eV. For a production rate of $10^4$ $cm^{-3}s^{-1}$ at a pressure of 2 x $10^{-5}$ Torr (7 x $10^{11}$ $cm^{-3}$), the photon beam intensity must be 7 x $10^8$ $cm^{-2}s^{-1}$ if the photons have 20 eV of energy. Typically a continuous spectrum of X-rays will be generated and a detailed calculation of ion production would require integration of the spectral function multiplied by the cross section.

## X-ray Source

The ionizing photons emanate from the tip of a steel needle and are collimated by a pinhole which defines a beam. The region from which ions are collected has been located 20 cm from the tip of the steel needle.

If the X-ray flux from the tip is distributed through $2\pi$ steradians and the intensity at the point of interest is $7 \times 10^{8}\ cm^{-2}s^{-1}$, then the source intensity can be estimated as $1.8 \times 10^{12}$ photons per second. The X-rays are generated by accelerating electrons toward the positively-biased steel pin which typically draws 1 mA at 1.5 kV. The current corresponds to $10^{16}$ electrons per second so that the efficiency of X-ray production is very poor. Nevertheless the power requirements for the X-ray source are modest. The X-ray production increases if either the voltage or the current to the pin is increased.

The design of the X-ray source is shown in Figure 5. Various sizes of pinhole were used and for some measurements the shield was not in place. Use of the shield and the smallest pinhole of 0.7 mm yielded an effective beam diameter of 3 mm. The other aperture prevented scattered photons from leaving the pinhole. The strength of the source was limited because the steel needle was heated by the electrons drawn to it and it melted at 10 W. The needle was mounted in a 1/4 in. rod which served as a heatsink; a more massive mount and a shorter needle could be used to increase the power limit.

Results of counting experiments were more easily interpreted when the X-ray source was operating at a high level. Consequently much of the data shown in later sections was taken near the thermal limit of the steel needle.

An attempt to detect the X-rays directly was made by aiming the beam at a metal plate which was grounded through an electrometer. Switching the

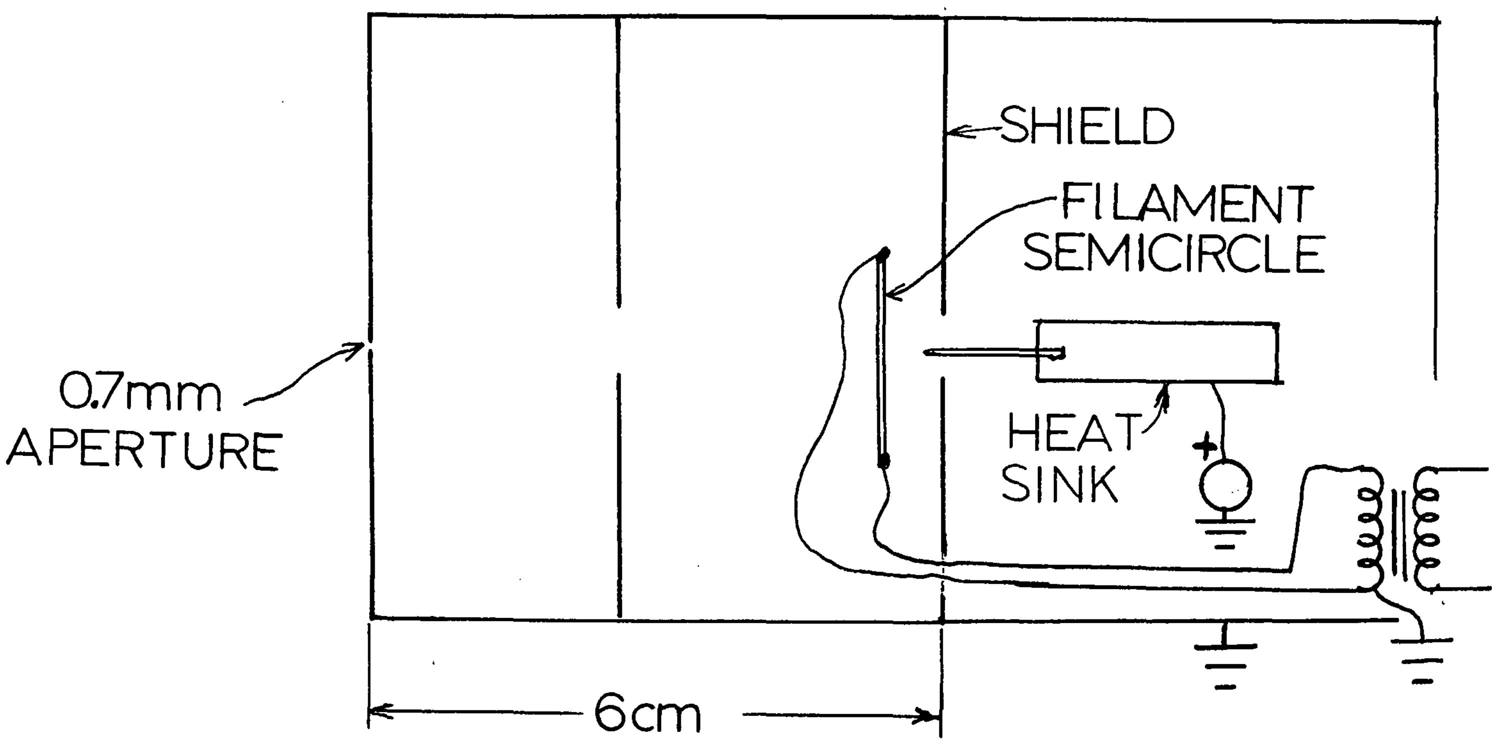


Figure 5. Design of the X-ray source. The filament and positively biased pin were housed in an enclosed aluminum box having a pinhole which collimated the X-rays.

beam on and off caused no change in the electrometer indication for a scale of $10^{-13}$A. Yet when the pin was grounded and the filament was negatively biased, an electron beam was clearly detected by the plate and electrometer.

## Spacial Resolution

The critical parameter for resolving measurements is the diameter of the X-ray beam, but also of interest is the resolution provided by the detector. Since the detector aperture for this work was 0.75 mm and the typical beam diameter was 3 mm, the detector sampled a fraction of the ions produced by the X-ray beam.

The greater resolution provided by the detector was in fact undesirable as will be demonstrated. Because no attempt was made to calculate particle trajectories, the resolution provided by the detector served no purpose; better would have been a system that collected all of the ions from the beam instead of sampling a portion. This comment of course refers to sampling on a cross section of the beam; longitudinal resolution is of little consequence.

For the test geometry consisting of two parallel plates and having a uniform electric field, the beam resolution was measured by moving the detector through the pattern of ions striking the face plate of the detector. Resolution was also measured by moving the X-ray source. The results are comparable and independent of X-ray beam height as shown in Figure 6. However the magnitude of response is a function of ion energy. These measurements were made for the 0.7-mm orifice on the X-ray source. Though these measurements show resolution only in the horizontal direction, the vertical resolution was assumed to be similar because the critical elements in determining resolution were a needle point and a circular orifice. A check on vertical

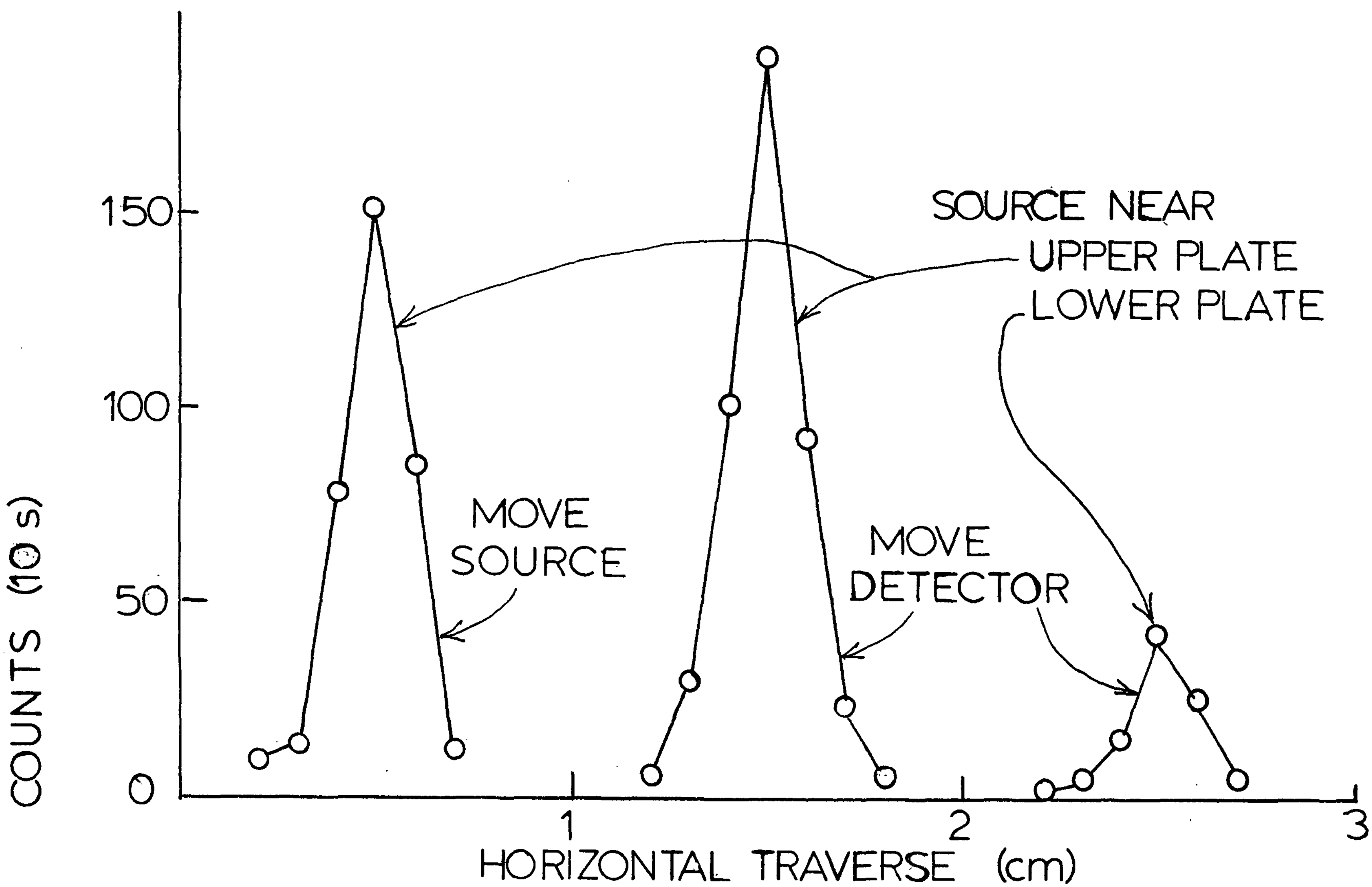


Figure 6. Measurements in a uniform electric field of X-ray beam resolution. The patterns displayed above are offset along the abscissa for clarity.

resolution was made by placing a 2.5-mm horizontal slit at the edge of the region of interest and passing the beam through the slit. Addition of the slit had no significant effect.

When the field is not uniform the ions do not follow parallel paths to the detector. As shown in Figure 7, the fields near the apex of the wedge dispersed the ions and complicated the detection problem. In fact one finds that maximum signal occurs at different detector positions for different values of the bias applied to the screen inside the detector. In such a case the resolution provided by the detector is not desirable and one would like to detect all particles ionized by the X-ray beam without moving the detector. The orifice would then necessarily be quite large, perhaps several centimeters. Such a requirement would be in direct conflict with the need for a precise measurement of ion energies. Improvements in detector design should emphasize maintaining energy discrimination with an increased aperture size.

Because any resolution obtained by using the detector requires a knowledge of particle trajectories for its interpretation, resolution should be specified in terms of the diameter of the X-ray beam. The product of the beam diameter and the electric field yields the uncertainty in measurements of potential. Yet in a practical system the requirements for accurate measurements can be expressed in terms of a characteristic length $\lambda$ defined in the region of interest as a function of electric field:

$$\lambda = |E| / |\partial E/\partial x|$$

If the X-ray beam has a diameter which is small compared with $\lambda$ then the ions will follow nearly parallel trajectories and they can be detected with relative ease. When the diameter is comparable with $\lambda$ the ions will be dispersed such that they strike the detector plane over a wide region. Measurements in

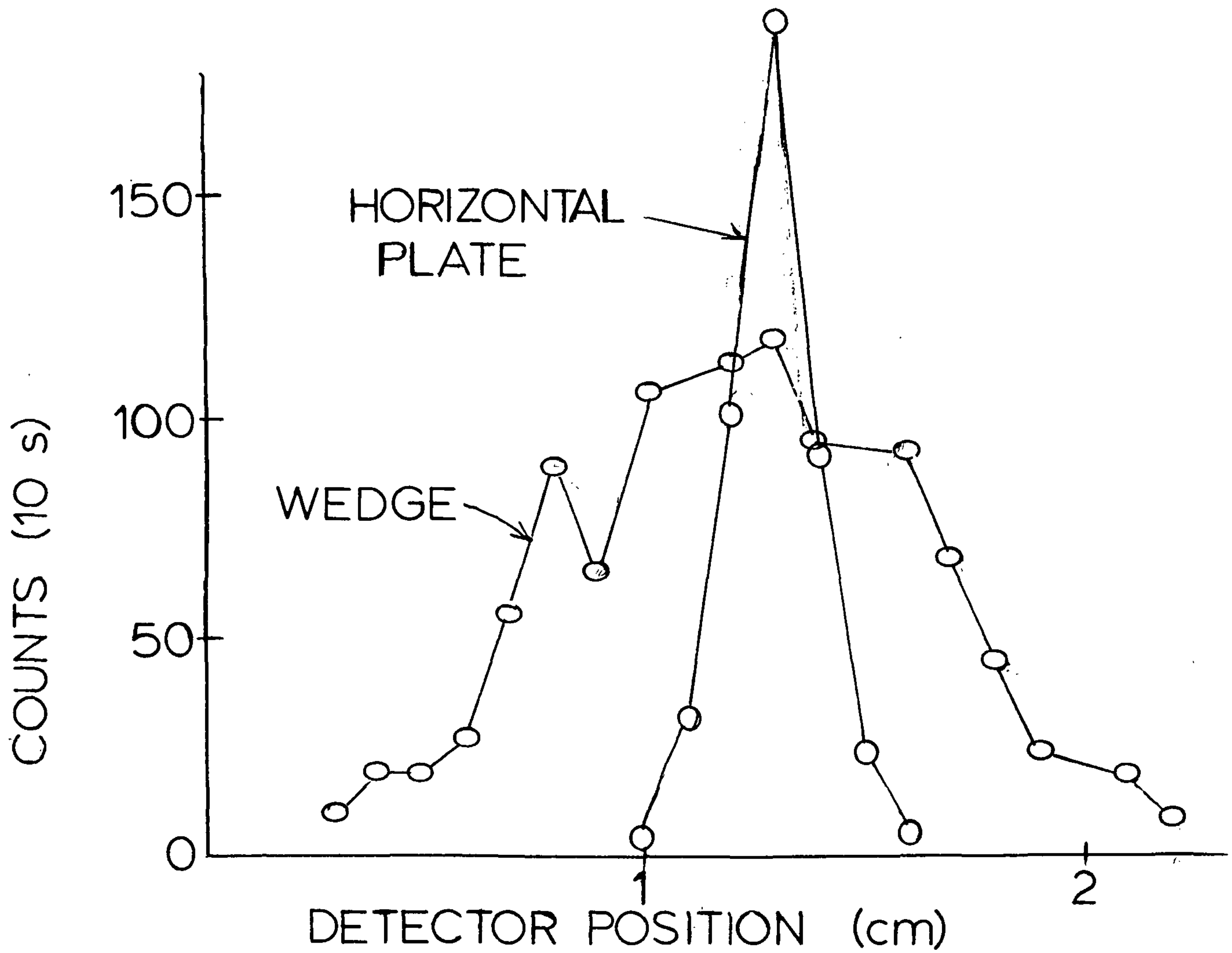


Figure 7. Response of the detector as a function of position for two cases. The horizontal plate creates a uniform field which does not disperse the ions. However ions released near the apex of the wedge are scattered.

such a situation are difficult because an otherwise adequate detector orifice would collect only a small fraction of the ions. The difficulties encountered are illustrated with measurements near the wedge-shaped electrode as shown in a later section.

## Measurements In A Uniform Field

Measurements have been recorded in a uniform field where potential varies linearly with height. A potential of 100 V was placed upon the upper horizontal plate which was 3.4 cm above the lower. Thus the field strength was 30 V/cm. When the X-ray beam has an effective diameter of 3 mm, the resolution in potential should then be approximately 10 V. This has indeed been found. Results depend somwhat on beam intensity and the angle at which particles strike the detector.

The measuring procedure was as follows:

1. Activate the X-ray source and set it at the desired height.
2. With zero bias on the detector grid, move the source or detector horizontally until maximum counting rate is observed.
3. Record counts in 10 seconds for several values of detector-grid voltage, taking data at close intervals where the counting rate is a sensitive function of bias.

The records for several cases are summarized in Figures 8 and 9, one having a log scale and one linear. Also shown are marks indicating the expected potentials which were calculated from the vertical displacement of the X-ray source. Since the vertical scale had no precisely defined reference point, a 10 volt translation was imposed on all raw data points to force agreement at the 9-V point. Some of the discrepancies associated with the

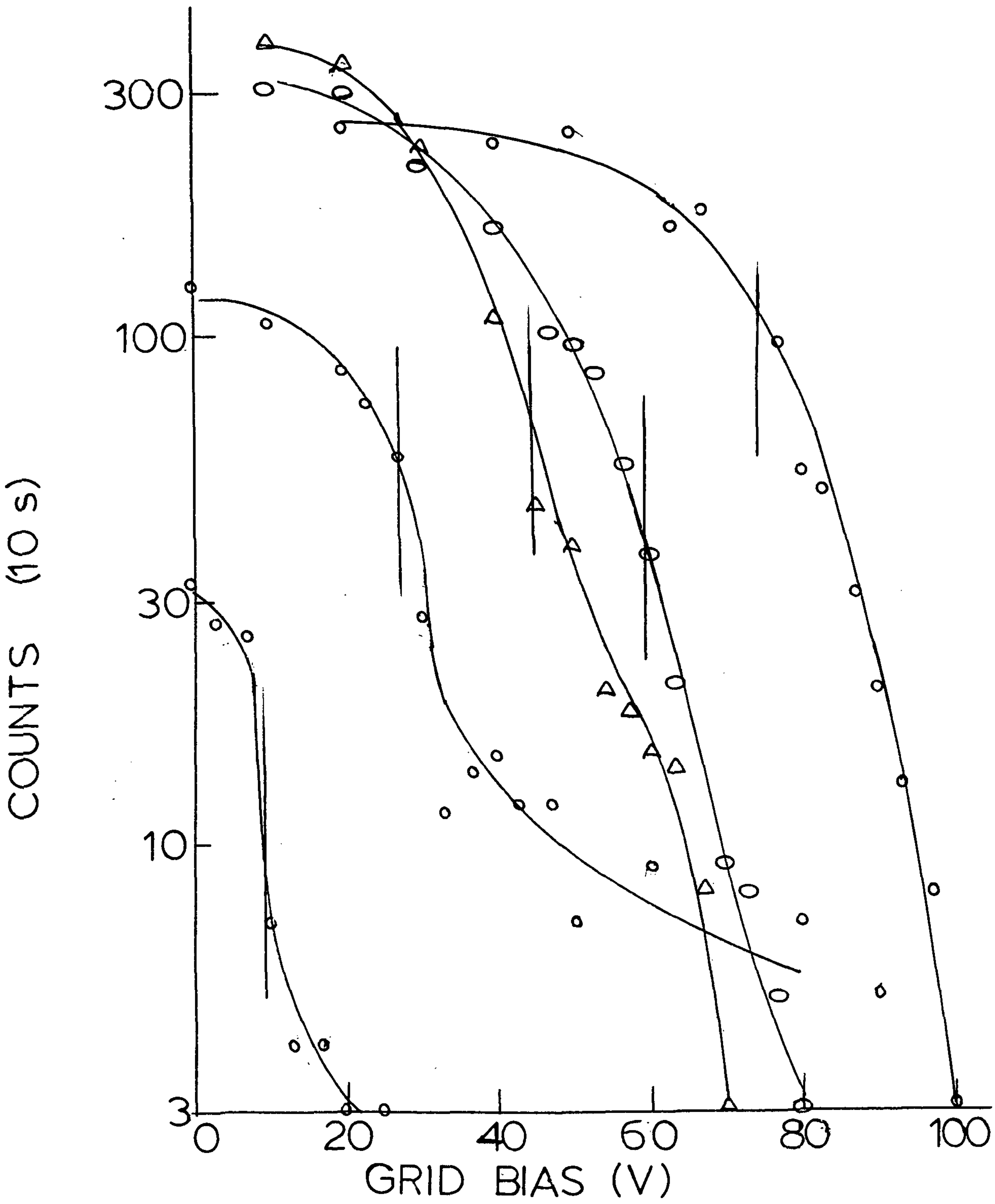


Figure 8. Detector response as a function of grid bias for various positions of the X-ray source. The vertical lines indicate the value of ion energy (eV) calculated from the source position.

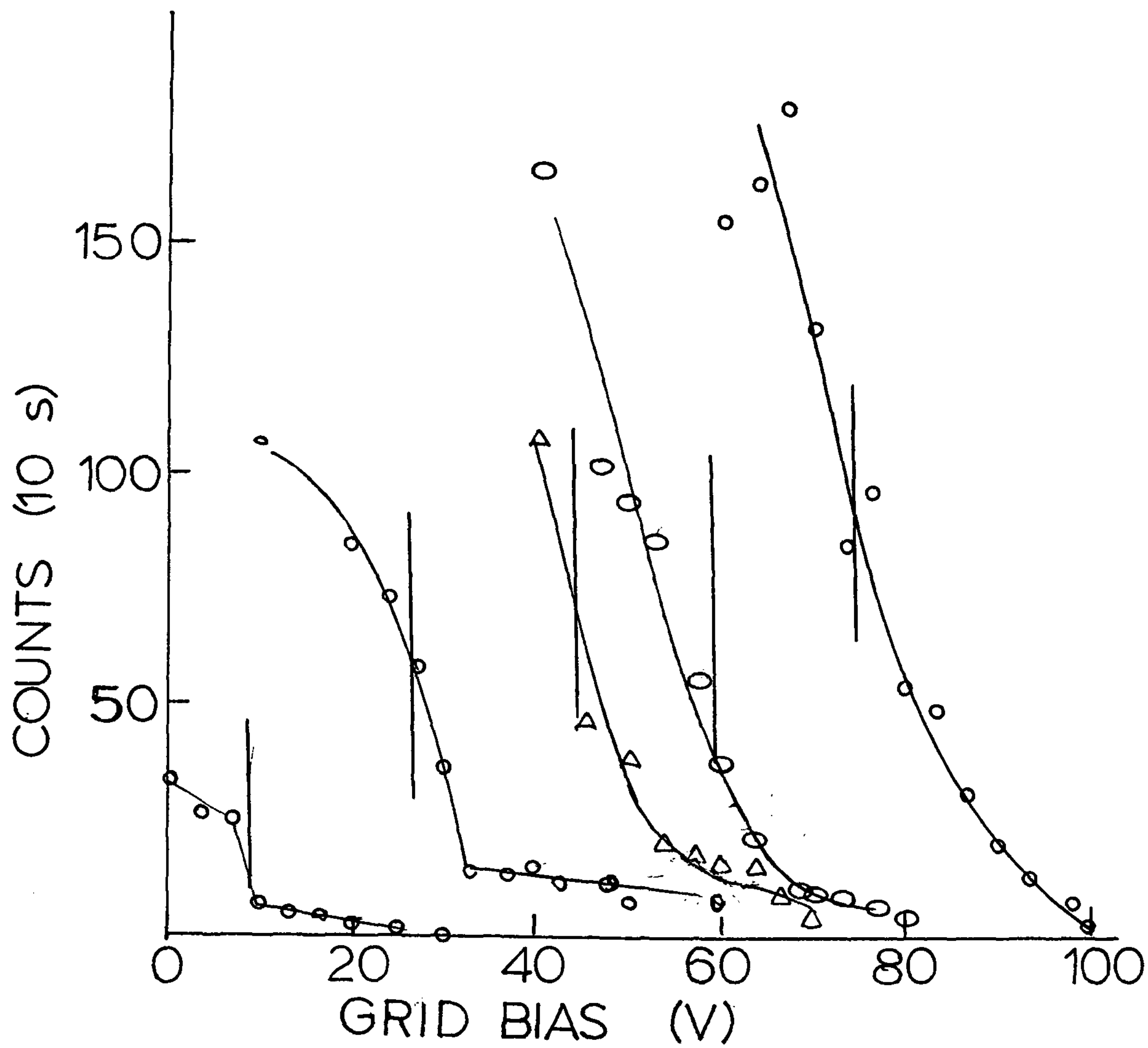


Figure 9. Same data as in Figure 8 on a linear scale.

vertical scale are probably associated with a wobble which was noticable in the vertical drive mechanism.

Several features of the data are worth noting. The figures quite clearly show the progression of energies as the X-ray source is raised. Of more critical interest is the resolution in potential which is attained. If the potential at the center of the beam is identified with the point of maximum slope on the linear scale, then this potential can be identified to about the same precision as is associated with the beam diameter. However a disappointing feature of the data is that the transitions are not more abrupt. The count should not depend upon grid bias up to within say 10 volts of the point of maximum slope. The shape of the curves is in sharp contrast with the shape of the detector response shown in Figure 4. This unexplained contradiction, apparent here, becomes even more severe when wedge data is viewed. Finally note that the counts are higher as the ionizing beam is raised. This factor in itself should not influence the measurement except as noise becomes important at low count rates.

When the ionizing beam is not strong enough, the measured potential can be much in error as illustrated by the data shown in Figure 10. The two curves shown there were recorded for the same mechanical positions of the source and detector but for different X-ray intensities. The curve showing the abrupt transition at 70 V is what would be expected for the source position. The other curve at a counting rate lower by 10 does in fact show the same transition near 70 V but it is nearly obscured by noise and it is likely to be missed. The apparent broad transition at 30 V might be chosen instead of the correct one.

When the ions are formed at a point just below the edge of the upper plate instead of being formed near the center, the ions strike the detector

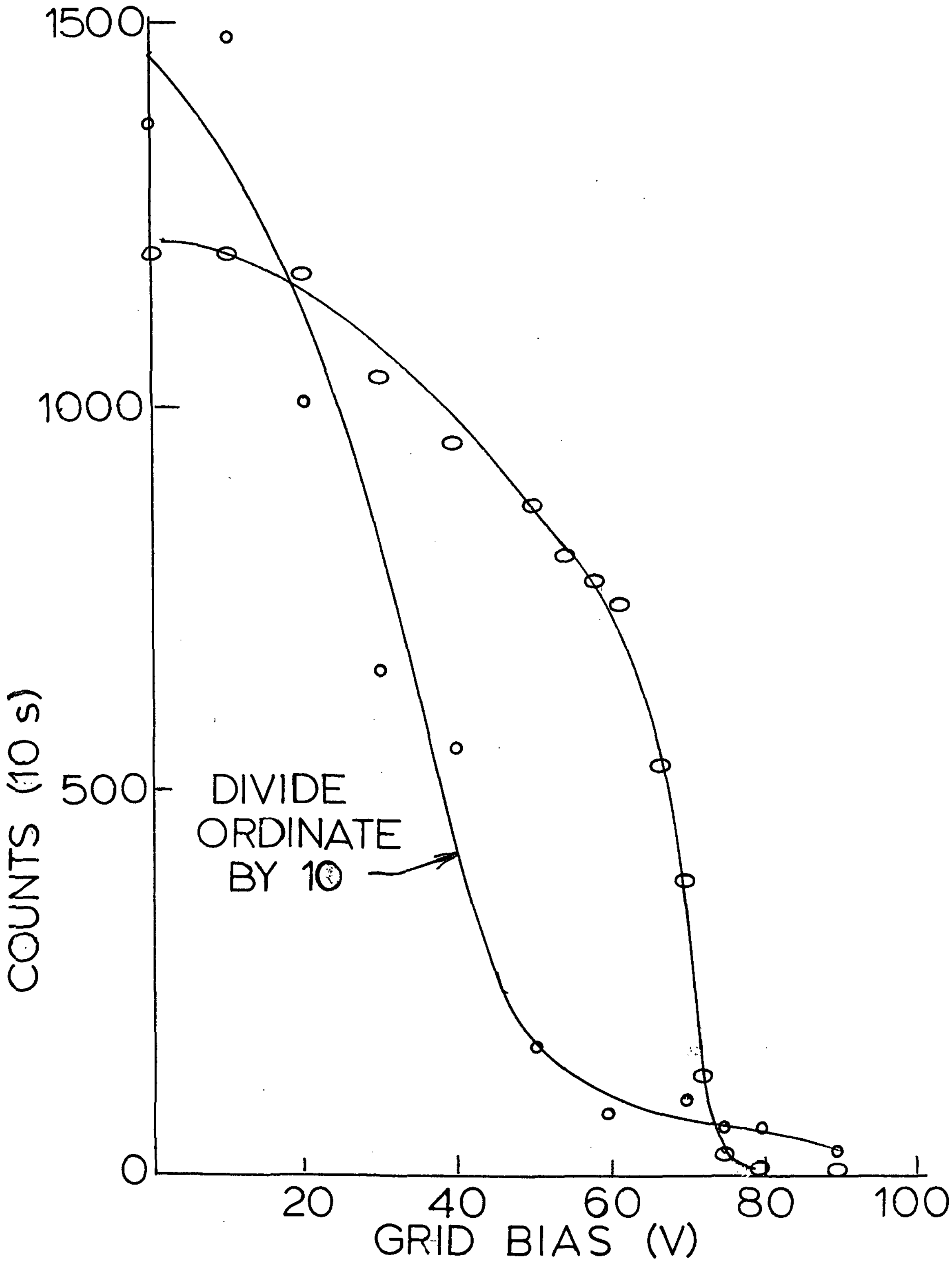


Figure 10. Effect of X-ray source intensity on response characteristics. The source position corresponded to 70 eV ions.

plane at an oblique angle and the counting rate is less. This reduction can obscure the signal as can a reduction in X-ray beam strength. The effect of oblique angles to reduce signal strength has also been demonstrated by tilting the detector system as a whole, though no calibrated measurements of tilt were made.

## Measurements Near The Wedge

Near the apex of the wedge, ions are dispersed in many directions so that the counting rate of the detector is much lower than it would be for a uniform field. Consequently errors related to low intensity are more likely to occur than for the uniform field. This problem is well illustrated by many attempts to measure potentials near the apex. Many curves which have been obtained resemble the poor illustration shown in Figure 10 though the upper tail of interest has been completely lost.

Another problem has been identified through measurements with the wedge system. The detector position for maximum counting rate depends upon the detector grid bias. Though this behavior should not be, it nevertheless occurs and it is somewhat responsible for the loss of sensitivity. Figure 11 illustrates this problem. When the detector grid was biased at zero and the source was positioned for maximum counting rate, then the curve shown in the top part of the figure followed. This corresponds to the marked reference line in the bottom part. Yet if the bias was held constant and the detector was repositioned, a larger signal could be obtained. Specific points entered on the upper graph show a corrected version of the original curve. Though the corrected version is more nearly what is expected, the potential to be measured in this case is estimated to be 75 V.

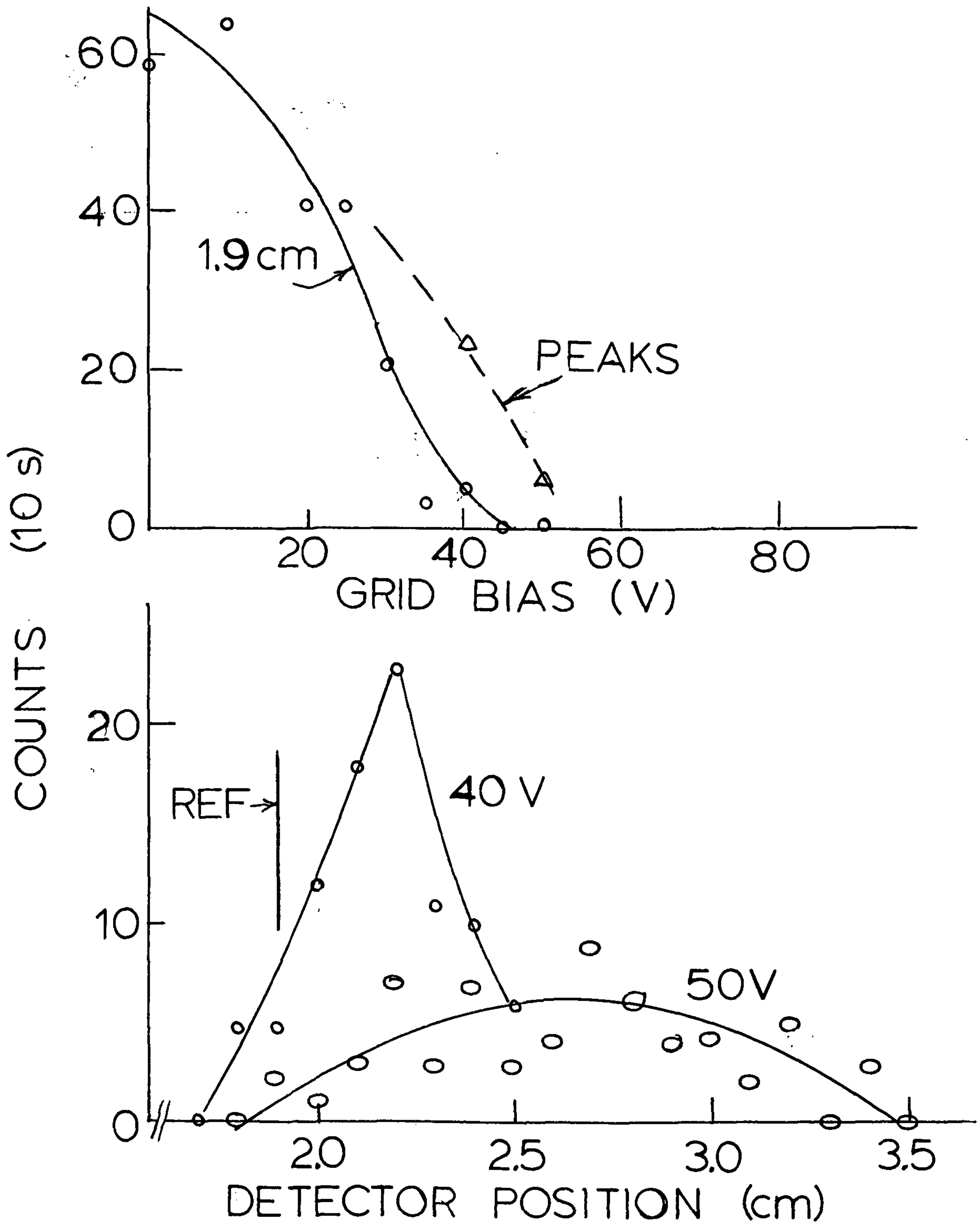


Figure 11. Data illustrating the relationship between optimum detector position and detector grid bias. Initially the source was positioned for maximum detector response with zero bias and a position of 1.9 cm.

A deliberate and patient hunt for high energy ions has yielding settings of the source and detector for which the curves of Figure 12 were obtained. In both cases particles corresponding to about 80% of the wedge voltage were detected. Of course the counting rate was small because of the dispersion near the wedge.

## Discussion

Quite clearly the concept of measuring potential with an ionizing beam of X-rays has been shown to be viable. Yet a practical implementation of the technique requires a careful analysis of the limits of resolution and sensitivity.

Spacial resolution is certainly no better than the diameter of the ionizing beam and accuracy depends upon the aiming mechanism. The relatively simple system used in this work provided a beam diameter of 3 mm and an aiming error of about the same magnitude. Yet the use of X-ray optics (5) and precision-drive mechanisms should allow an improvement of at least a factor of 10.

The ionization rate of the X-ray beam was near the lower limit of practical measurements and in several situations, the signal was not strong enough to give reliable data. Signal strength was limited because the anode of the X-ray source, a needle, would melt at higher intensities. Yet redesign of the source with better heatsinking of the needle (or use of a focussed source) could extend the usefulness of the system. Certainly the effect of the X-rays on the environment was negligible and the beam strength could have been increased by several orders of magnitude without perturbing the potentials to be measured.

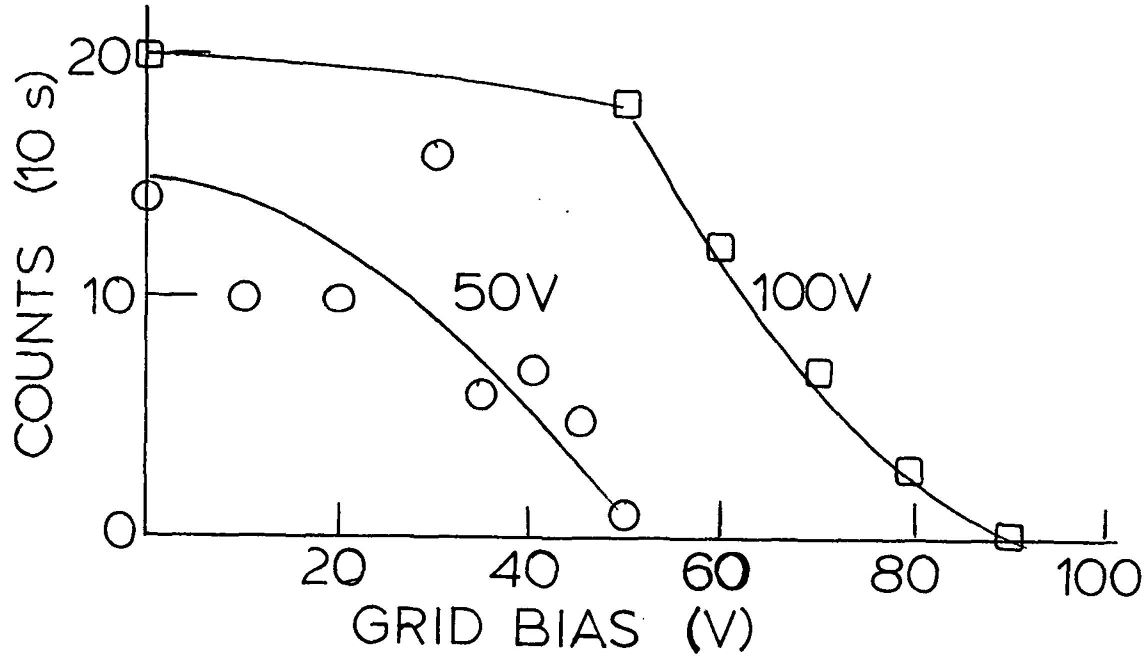


Figure 12. Response of the detector when the wedge was biased at 50 and 100 V. The source was raised sufficiently high that the X-ray beam struck the biased wedge.

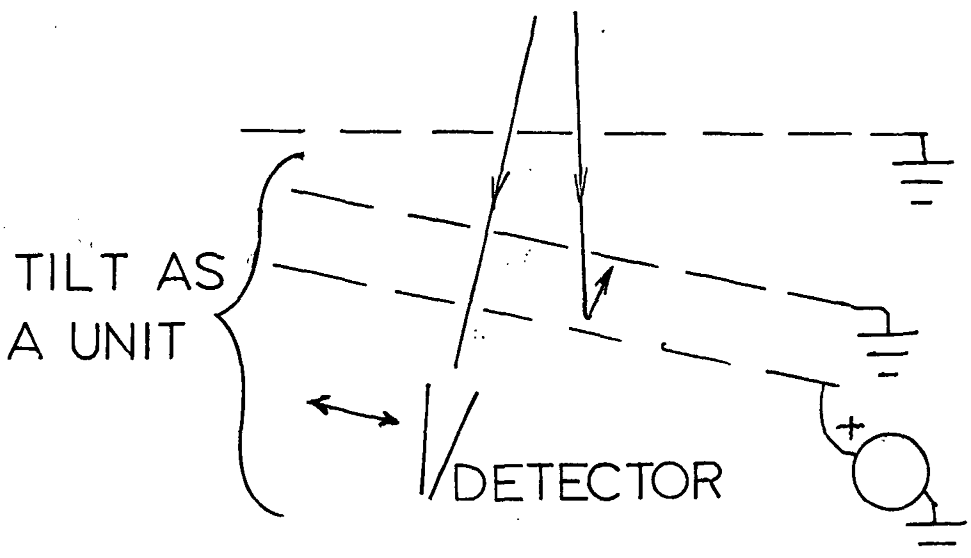


Figure 13. Schematic diagram of a possible detector configuration.

If charged dielectric surfaces are present they will probably set the upper limit upon X-ray intensity. The X-ray beam releases charges of both polarities, one type migrating to the detector and the other type to the charged surfaces of interest. The current to the surface will discharge it. Either the rate should be low enough that little discharge occurs during the measuring time or else the environment must act to restore the lost charge while the measurements are being made. In the latter case the environment might create a noise level that would obscure the signal. Certainly the upper limit will be a complicated function of the system's geometry and it is best to determine by experiment if that limit is being surpassed in any given situation.

Two problems come from raising the pressure higher than about $2 \times 10^{-5}$ Torr. If any dielectric surfaces are involved in the system being measured, their surface charges are rapidly lost at $10^{-3}$ Torr so that pressure should be kept well below that level. A more critical problem is that the ion detector becomes noisy as the pressure is raised above the specified limit. Any increase in signal strength should come from redesign of the source or the detector but not from raising the pressure.

The most difficult aspect of this scheme of measurement is probably designing the detector. The need to collect particles dispersed over a wide region conflicts with the need to resolve particle energies precisely. The detector described in this paper was designed to provide energy resolution without a large collecting aperture and its performance was not satisfactory. In tests with a monoenergetic ion source the detector showed a spurious peak for grid biases slightly below the cutoff point, but this was not a problem. However the detector's response was a function of the angle of incidence and it probably should have had a built-in tilting mechanism. The small aperture was required to provide the energy resolution yet it sampled only a small portion of the ion flux to the detector face plate. Maximizing the ion flux at one bias value did not guarantee a maximum at other bias values. As a result of various problems the response of the detector vs. bias voltage was a monotonically decreasing, poorly-resolved function which often obscured the desired data.

It was assumed in the preceding paragraph that the ion flux to the detector's face plate was not monotonic but at least bounded in energy. The measurements would imply that the energies of the ions covered a broader spectrum centered much lower than what would be associated with the X-ray beam orientation. It is possible of course that because of some undetermined mechanism the ion energies were actually lower than they were thought to be. However the arguments against this possibility are well established. The pressure was sufficiently low that particles had mean free paths greatly exceeding the dimensions of the test chamber. The only collisional process of interest is the ionizing collision of an X-ray photon with a neutral particle, and the mean-free-path for this process is about $10^5$ cm. Currents collected by structures are too small to measure and certainly to small to be associated with space-charge perturbations of the potential. The X-ray beam terminated on the wall of the vacuum chamber and any scattered radiation would be orders of magnitude less intense than the primary beam. Consequently one might assume that the ion energies are as they should be and that the faults lie with the detection system which can be criticized in several ways.

Since the energy discrimination of the detector is performed on particles which have already entered the aperture, the relation between the bias voltage on the detector grid and the optimum location of the aperture would imply that the detector is seeing a broad spectrum of particle energies which correspond to different trajectories from their points of origin to the face plate of the detector. This point of view is in conflict with that of the previous paragraph and the issue has not been resolved.

The extension of the measuring concepts to systems having larger dimensions depends primarily upon being able to collect the ions and measure the energies. Again the design of the detector is critical.

The limits on potential being measured are very broad, ranging from a low of about 0.1 V associated with the thermal energy of the neutral particle to high values limited by the design of the energy discriminator in the detector. Further limitations at the low end can come from contact potentials associated with the detector's materials. As discussed before, sensitivity is important and it apparently is more difficult to attain at low particle energies.

One design for a detector might use a set of three meshes, one representing the face plate and the others representing the energy discrimination feature as shown in Figure 13. The face plate or grid never moves as it represents one of the boundaries of the system being measured. The second grid encountered by an ion is at the same potential as the face grid but it can be tilted along with the third, biased grid. Particles having the highest energy can be measured by tilting the pair of grids so that they are normal to the trajectories of those particles and then biasing the third grid to stop those particles. The measuring procedure would be one of iteratively increasing the bias voltage and then tilting through the available angles to determine if any particles have energies above that level. It might also be necessary to move the CEM to the spot where the ions are emerging or else to build an ion collecting system that would focus ions onto the funnel of the CEM.

# CONCLUSIONS

Work on Grant NSG-3166 has progressed on several fronts, the one stressed in this report being the measurement of potential by use of an X-ray beam which ionizes background gas. Ions formed at some point of interest are detected at a remote location and their energies are measured to provide an indication of the potential where they were formed. This system of measurement has been shown to be feasible though susceptible to errors if the signal strength is too small or if the detector does not collect a sufficient number of the ions which are produced. Several observations are summarized here.

1. The ultimate spacial resolution depends upon the diameter of the ionizing X-ray beam, which in this was 3 mm but could be made smaller by a factor of 10.

2. Using the detector to provide resolution is not recommended as the response of the detector is hard to interpret when it samples only a small fraction of the ions which are formed.

3. The lower limit of measurable potential by this method is about 0.1 V as set by thermal energies and energies imparted by the ionizing process. However the practical lower limit may be fixed by contact potentials or by loss of sensitivity at the low energy levels.

4. This method of measurement has little influence on the system being measured, to the extent that a much stronger signal could have been used. The current produced by the X-ray beam was estimated to be $10^{-15}$A.

5. At the signal levels used in this work, many of the desired measurements were lost below the noise level of the counting system. Yet some of the data showed the method to be feasible.

6. The most difficult aspect of designing such a measuring system appears to be the planning of the detector. The ideal detector would accept particles scattered over a wide area and having different angles of incidence. Nevetheless it would provide precise energy discrimination. These goals are incompatible yet they can be compromised to some extent. The finer the X-ray beam the less stringint the requirements on the detector.
7. Choice of neutral gas is not critical, both argon and air having been used. However the pressure should not be allowed to rise above that level which affects the operation of the electron multiplier.

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