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GENERAL ENGINEERING LABORATORY

ELECTRON OPTICS PROGRAM FOR TALARIA

BY

S. P. NEWBERRY

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ELECTRON OPTICS DEVELOPMENT PROGRAM FOR TALARIA

INTRODUCTION AND SCOPE

This report covers the electron optics work done at the General Engineering Laboratory during 1960 and early 1961 on Project Talaria. The work was concentrated in the areas of electron gun development and electron mirror development.

As so often happens, this report encompassed a period of activity rather than a plateau of accomplishment. It therefore raises as many questions as it answers and does not tell a completed story. It does, however, report a necessary part of the progression toward more useful electron guns for picture display and report some important advances in the art of electron beam control.

OUTLINE OF WORK IN THE ELECTRON OPTICS AREA

From the work statement of June 28 and our quotation of July 11 the problems to be solved in the electron optics area and the hardware to be delivered were as follows:

1. Design and produce an electron gun for the Mark III equipment capable of giving the following performance at 7 to 10 kv:
   Spot 0.6 mil horz. by 1.0 mil vert.
   Current up to 10 microamperes.
   Working distance 3-1/2".
   Deflection 1" vert. by 1.5" horz.
   Deflection sensitivity better than present 1000 v. P-P.
   Deflection defocus goal less than 15% over raster.
   Neck length as short as possible.
   Goal for working model production 11-1-60.
2. Evaluate electron mirrors and/or prisms for non-linearities deflection sensitivity, etc: completion date 11-1-60.
3. Design an electron mirror system capable of writing a 1" by 1.5" raster without deteriorating the gun performance significantly. Mirror completion date 1-1-61.

At the outset of this program it was understood by all that these goals required extension of existing capabilities, that the time schedules were optimistic, and that some of the goals might prove to be unrealistic.

As the work progressed, it was agreed to make the following changes in the program:

1. Dates for gun changed to making design decision by 11-1-60 and working models (2) by 12-20-60.
2. Beam current up to 3 microamperes.*

*Our recommendation was to hold off on beam current specification until we could test writing on oil with a beam of known cross section because we suspected that the beam current has been used inefficiently in the past. This recommendation was not accepted but the beam current was lowered on the basis of further practical experience, to 3 microamperes. In the appendix it is shown that 10 microamperes is not a reasonable design goal. Since the current in the spot varies as the 8/3 power of the spot diameter, a 2:1 increase in spot size can mean a six-fold increase in possible beam current and of course the reverse is true.

3. Gun diameter to be limited to 1-1/2".

4. Increase working distance to 5".

5. Include work on pointed cathodes of Hibi type.

Recent work[1], reported at the annual meeting of the Electron Microscope Society at the end of August gave current density increases of 20 to 1 for the pointed cathode and demonstrated smaller source size. If we could find production of these points to be a practical matter, then the electron gun could be simplified to a single lens for the Talaria job.

The beam current specification change was very helpful, but we still advise that tests be conducted to determine whether considerable current reduction can be effected by use of small well-defined beams. This is highly important to the life ot the cathode, which is still the number one problem of the electron optics area.

The longer working distance was helpful for increasing the deflection sensitivity by 30%, but this advantage was more than offset by the increase in beam size and reduction of beam current which it brought about. The extra 1-1/2" added to the working distance also added approximately 3-1/2" to the overall gun length.

Perhaps the most questionable change at this stage of the program was the decrease of gun diameter from the 2" at which we had successful experience to the 1-1/2" diameter which was totally untested territory at that time. There is no theoretical reason why the smaller diameter cannot be made to work but because of the possible wall influences it may be necessary to throw in an extra pilot model to determine what lens constants must be changed to compensate for the wall effects. This change came late in the program and sufficient importance may not have been given to it.

The pointed cathode work was requested because development of a small electron source would permit construction of a very simple electron gun.

METHOD OF ATTACKING THE PROBLEM AREAS

It was decided to attack the gun improvement up to the point of the Mark III design by direct experimental development of components and systems on the electron optical benches. Following the results of these tests, two Mark III guns were built in our instrument shop and tested on one of the electron optical benches.

We tried to back up the experimental approach by pushing for rapid development of analytical methods of electron path and electric field plotting. However this analytical effort was intended primarily to be useful in the electron mirror work and in the even more difficult areas of Mark IV gun development. We must plead guilty to setting a grass fire in order to muster analytical forces in time to be of use for this later final task. We long ago learned that present problems must usually be solved by the techniques one already has in hand and that the techniques which one attempts to develop for present jobs are useful for the next job instead. This philosophy applies only to techniques which must be developed, it does not apply to use of well proven techniques which are borrowed from other people. In the present instance the setting up of a computer program to solve electron paths has been found to be extremely difficult and no record could be found of anyone solving either the general two-dimensional case or the unsymmetrical three-dimensional case which we must either solve or we as a Company must bow out of the modern race in the field of electron optical devices. We have found a workable method, as described in a later section, which with further development could probably replace trial and error experimentation altogeher except for final proof testing. However, it turned out, as we feared, that the breakthrough in computing techniques did not come in time and the electron mirror work also had to be done by intuition and trial and error experimentation. We were very fortunate that the method which appeared to us to be most promising was successful and looks very attractive for use in Talaria systems.

DETAILED REPORT OF FINDINGS

The detailed report of the program is separated into the following topics:

1. Descriptions of Equipment.
2. Electron Optical Bench Test of Gun Systems.
3. Electron Optical Bench Tests of Electron Mirrors.
4. Pointed Filament Development.
5. Gun Design, Manufacture, and Tests.
6. Development and Tests of Analytical Methods.
7. Summary.
8. Recommendations for Future Work.
9. Appendix.

1. Descriptions of Equipment

The electron optical benches used for these tests are demountable vacuum systems with unitized construction and strict standardization of dimensions so that by their use new electron optical systems may be stacked together and tested in a minimum of time.* A design of a typical unit of this stacked arrangement is shown in figure 1. The simple "O" ring seal permits metal to metal contact, for electrical and magnetic shielding, assures accurate parallelism of components, and provides for simple alignment adjustment under vacuum. Test setups are shown in a number of the later illustrations, e.g., figure 16.

There is one drawback to this type of test equipment. Because of the minimum thickness requirement for the "O" ring, it is difficult to make compact arrangements in the direction of the optic axis. In this program an attempt was made to get around this difficulty by use of a thin plastic ring with a large number of "feed throughs" for voltage connections, and a large number of interior abutments for positioning the elements. These units were not available until the closing days of the program, and therefore did not come in time to permit an exact mock-up of the Mark III gun before freezing the design. One of these

*Unfortunately the two benches were in process of being revised during the 1st half of the program. Nonetheless from August 22 through Dec. over 150 separate setups were tested.

compact units is shown in figure 2. In general the electron optical bench is a rapid, economical, and powerful tool for developing electron optical systems. The units at GEL are, to our knowledge, the best available in the Company.

There has been accumulated for them literally hundreds of interchangeable gun and lens parts and the stock of these parts continues to grow in number and diversity with time.

Measuring Instruments Used

Unless otherwise stated, the voltage measurements were made with torsion suspension electrostatic voltmeters, either G.E. or Electrostatic Instruments models. When a Keithley electrometer is mentioned, the model 200-B is implied. The total beam current was generally measured by a 3% D'Arsonval movement, but the writing current and all beam currents except the total were measured by an applied physics lab vibrating Reed Electrometer, model number 300.

Distances between lenses were measured from lens center to center by use of a simple steel scale on the outside of the stacked column. The distance from the source was measured from the front surface of the grid. All critical distances such as lens element spacings were measured by use of a depth micrometer from the surface of the vacuum housing using a hardened ground flat to support the micrometer at the flange level in the manner shown in figure 3.

Electron spot dimensions were measured by microscopic examination of a fine grain evaporated phosphor screen. The calibrated scale in the eyepiece was employed but was independently checked against the calculated calibration by use of a B&L stage micrometer, which is simply a piece of glass with accurately engraved divisions which are magnified by the microscope and compared with the eyepiece scale divisions. Because the objective sometimes had to be removed from the microscope and placed in the vacuum at non-standard distances, we also checked calibration by displacing the fluorescent screen a measured amount (which was read by dial indicator) and compared this shift to the image shift at the eyepiece scale.

All tests were thought to be carried out at lower than 10^{-4} mm. pressure. This conclusion is based on the fact that tests were not started until the ion gage at the entrance to the pumping system read on the 10^{-5} scale or better, and the fact that only one filament burn-out was encountered in the five months period of operation.

Choice of Approach to Gun Problem

The central core of the problem was in two parts. It required that we first find the optimum electron optical system for producing a scannable small spot with a clear working distance of approximately 5 inches, and then that methods be developed to fold and fit these optics in a useful package. As a practical expediency the investigation had to bring forth a "state of the art" model for the Mark III projectors.

At the outset certain things were obvious. One could not satisfy the requirements of Talaria by adaptation of existing electron guns such as the traditional cathode ray gun due to Malloff and Epstein[2]. Also one had no assurance that any startling new cathode developments would appear in time to simplify the gun problem. It was therefore decided to assume that a broad area cathode would have to be used, and to concentrate on development of lens systems of considerable demagnifying power, and of course with large deflection.

Because of interference with light optical components, for the present state of Talaria development at least, the electron optical component nearest the oil film must be at least 3-1/2" away. This requirement, coupled with the requirement of using a broad source of electrons, narrows the choice down to two possible systems.

The first of these is composed of a simple lens focusing electrons from a distant source to a point essentially at its principle focus. An improved version of this system using a lens composed of two line focus elements with one of the deflection plates between the two halves of the lens has been used on the Mark I and II projectors. The chief drawback to this type is the very long distance required from source to lens, and as we learned later in the program, the loss of intensity as the source is withdrawn. To bring this system to the point of meeting the work statement specifications would require development of a system for folding the electron optical path, and of perhaps developing a source of less divergence than now available. It appeared that these tasks were less certain of successful accomplishment and less attractive, even if accomplished, than the corresponding developments to perfect the second system discussed in the next paragraph.

This second choice is the use of a two-stage system in which a first very strong lens forms a highly demagnified image, at its principle focus, which is just outside the lens field, of a nearby source of electrons; followed by a second long focal length lens working essentially at unity magnification (or slight magnification) which relays the image to the oil film with plenty of room for the deflection plates. At the beginning of the program we referred to this sytem as the demagnification/magnification system, but because this is an awkward name we now refer to it simply as the relay system. The chief drawbacks to this system are the added complications of another lens and the requirement that they have very low spherical aberration if intensity is not to be lost.

The factors which determine the performance of these two systems are quite complex in their effects, and while we have not seen a wholly satisfactory treatment of their interrelation and have none better to offer, a first order approximation is sufficient to demonstrate the wisdom of choosing the relay system as the first choice to test. The arguments are as follows:

The final spot size is due to the combination of the demagnified image plus the diffusion of each point in the image due to spherical aberration. It turns out that for optimum performance the errors must be nearly equal (ref. to Appendix - for amplification of this part). The aberration of the lens is a function of the focal conjugates chosen and it decreases as the source is removed toward infinity. Most of the gain is reached by the time the source is four focal lengths away however. This tells us that we should use a lens whose focal length is nearly equal to the working distance and that for reducing aberration alone we should have a gun length equal to 5X WD or 25". However since we want a spot only 1/2 mil wide from a 3 mil source, the geometrical requirements are even greater and thus dominate the design because with 6 fold geometrical reduction required the gun should be (6+1) 5" = 7 x 5" or 35" long for a clear resolution of 1/2 mil. Actually one may work to the 50% point of the beam, as explained in the appendix, and taking advantage of this one might reduce the gun length to (4+1) 5" = 5 x 5" or 25" total but with the need for much higher writing currents.

For the case of the relay system the demagnification requirement again dominates the design length. We can make up a simple formula to determine the total gun length as shown by inspection of the geometry of figure 4. Here one finds that the same performance can be obtained with a gun length of only 14" in the case of 2:1 magnification by the relay lens which is the case giving optimum brightness. We therefore conclude that the relay system looks more attractive for the Talaria application.

Prior to this program it had been established that ordinary axially symmetrical electrostatic lenses could not be used in a relay system because of their large aberration.* Furthermore it was known that the line focus einzel lenses were capable of giving highly demagnified spots without producing halo around the spots which suggests that their spherical aberration may be low enough. Attempts to relay these spots using ordinary einzel lenses as the relay were unsuccessful however and two sets of line focus elements were not available. When we tried to relay a line image from the strong lens, we obtained the butterfly pattern shown in figure 5. This demonstrated that spherical aberration was the cause of failure in the relay lens also showing that the einzel lens had far too much spherical aberration to relay any appreciable percentage of the energy from the small spot. Our experimental program started from this point on.

*Ref. MSVD Report (ref. 3)

2. Electron Optical Bench Tests of Gun Systems

In the description of experimental results which follows we give only the key results. More detailed results are given in the Appendix. The notebook references given here and in the Appendix give the complete experimental details. Copies of select pages may be obtained where not in conflict with the Company's best interest by contacting the author.

First Indication of Possible Success

Test lenses like those shown in figure 6 were made up and assembled into a relay system according to the schematic in figure 7. The first tests could not give spots below 10 mils diameter but would relay lines focused to less than one mil in one direction at a time. Our past experience with single lens systems had shown that if a fine line focus could be obtained in each direction independently, then with care a spot could be made which had dimensions equal to the respective line widths. This is a cardinal point in working with these line focus elements and has this time, as before, demonstrated the value of a system even though the experimental results of the combined focus looked like a miserable failure. With independent test of each direction of focus, for the demagnification lens alone as shown in figure 8, the following results were obtained:

Horizontal				Vertical			
D_1	D_2	Demag.	Line Focus	D_1	D_2	Demag.	Line Focus
5.5"	1.1"	5:1	12 microns	6"	0.6"	10:1	6 microns

Notebook ref. 8-24-60-1

For these tests the lines were focused in the opposite direction just enough (240 microns length) to bring them into the center of the field of view of the microscope so the quality of the line as it approached two-dimensional focus could be predicted. Past experience has indicated that the tungsten hairpin source is about 75 microns in diameter. On this assumption, one would predict line widths of 15 and 7 microns respectively if spherical aberration is small, in good agreement with the above data.

A Qualitative Test of Relaying with Line Focus Einzel Lenses

With the lenses arranged as shown in figure 7 obtained the following independent line foci:

Horizontal			Vertical		
Demag.	Mag.	Line Focus	Demag.	Mag.	Line Focus
10:1	2:1	18 microns	5:1	2:1	25 microns

Notebook ref. 8-22-60-3

Assuming as before that the tungsten hairpin source is approximately 75 microns in diameter, one would expect line widths of 30 and 15 microns respectively in the absence of spherical aberration limitations. The combined focus gave a tremendous star formation however.

Despite the blowup of the spot upon combined focusing we believed the good results for each independent focus to be sufficient evidence and proceeded to examine the individual components of the system to find out wherein the troubles lay.

A Test of the First Stage of the System

Returning to the setup of figure 8 we again looked at the demagnified image of the first stage. As first set up the combined focus was not good but good focus was obtained in separate directions giving the 6 x 12 micron line widths quoted above. This result is quite encouraging, it shows that the first stage can be crowded into a space of only 6" without spherical aberration becoming a problem. From the experience with the MSVD gun we can predict therefore that at least 10 microamps can be crowded into a spot 6 by 12 microns in this distance. If this could be relayed at even 2:1 magnification, it would meet specifications.

As can be seen in the detailed technical account in the Appendix, a long and difficult experimental trail lay between this point and a workable system. The following difficulties were encountered and overcome as described below.

Critical Adjustment of Lens Element Alignment

It was known that the two lens elements must be orthogonal to within a fraction of a degree else the line image will rotate several degrees at focus and the width will be the projected width rather than the actual width.[3] This image rotation can easily be as much as

30 degrees in a system which is thought to be orthogonal. The tests above were made with lenses which the shop had tried to assemble at right angles. It was finally shown that the simple method chosen for rapid interchangeability of experimental parts did not give adequate safeguard against tipping of elements, and that alignment must either be controlled by abutment against a machined surface or by measurement with optical instruments of sensitivity to a few seconds of arc. It was finally established that when the elements are mechanically right, they are electrically right. This is a very important point, because one might worry that incidental effects such as stray fields or dirt also affect alignment. The effects of dirt in the system could be plainly seen and it had no connection with image rotation. Only the normal design precautions were taken against stray fields yet the image rotation for a given lens was always the same until the elements were mechanically disturbed, therefore we do not blame stray fields. With simple mechanical rotation the image rotation responded in the reverse direction to the motion and in a reproducible fashion, therefore, the problem of image rotation can be controlled by manufacturing precision.

<u>Effect of Pincushion and Barrel Distortion</u>

If the lens does not have the same focal length all along the line image, it is then impossible to make a small spot, as shown in figure 9, unless the central part only is used and the rest discarded either by a physical aperture or by the small useful aperture of the next lens. An uncorrected line focus element shows extreme pincushion distortion but fortunately the negative action of the end effect stretches it out so far that only the central portion gets through to the next element. With elements corrected for the end effect, any pincushion distortion is very noticeable because the entire line is short enough to get through the next lens.

Pincushion and barrel distortion are affected by the thickness of the lens elements, by the spacing between elements and by the strength of the lens. Whereas "end effect" correction is controlled by the lens element radius and sagitta height. One can therefore correct the two independently.

The Effect of Dirt in System

The major effect comes from dirt on the apertures. In a line focus, dirt causes local change of focal length which has the same effect as pincushion distortion when the line is focused down to a point. In the case of the limiting aperture for the strong lens, this is not a serious problem because the beam keeps this aperture clean by heating it. The aperture for the relay lens is more difficult because it is not heated by the beam and because it is closer to the sources of contamination. The effect of dirt on the grid lens, developed later in the program, is not thoroughly known. Large chunks of dirt cause halo and distortion. No ill effects have yet been observed from hydrocarbon deposit although they obviously had formed early in the grid lens test.

Effect of Misalignment Between Relay and Strong Lens

This effect turns out to be small especially if the strong lens is focusing to a spot of roughly equal dimensions. When the strong focus is stigmatic, then the spot reduces to the projected width times the magnification instead of just the width times the magnification. This is a small increase unlike the case of the two line-focus elements within the same electric field, where there is magnification of the misalignment.

One must also be aware that the electron source has a weak cylinder lens in it because of the hairpin filament and that this lens must be lined up with one of the strong focus element lens so it may be compensated.

Depth of Focus of the Relay Lens

Intuitively one would not expect the depth of focus of the relay lens to be important since the depth of focus of the strong lens is expected to be small by comparison. However it is found that unless pains are taken to have the two directions of focus of the strong lens co-planar, a spot cannot be formed. Apparently what happens is that the greater depth of focus of the relay lens is a detriment because while accommodating both focal planes of the strong lens, it does so at different demagnifications which are a steep function of focus voltage.

If one attempts therefore to focus the relay system visually from scratch, he may either get a situation in which both elements of the strong lens are focusing the same way and no demagnification is obtained at right angles or, as more commonly happens, one makes the strong lens weaker and weaker until it finally becomes a weak correcting element for the relay lens and one has essentially a single lens system with a correspondently large spot. This therefore is another cardinal point. That is to focus a relay system one should first place the proper voltages on the strong element and then find focus by adjusting the relay lens. Once good focus is found, the strong lens can be made to give greater demagnification if desired. The system has too many degrees of freedom to permit any other method of setting up.

Loss of Intensity in the Relay Stage

As pointed out in the theoretical discussion, the beam divergence leaving the strong lens is greater than the divergence of the beam entering it by the ratio of the demagnification. It therefore takes a relay lens of very large aperture to utilize all of the beam from the strong lens. Our first tests were quite disappointing in this regard since only 10% of the beam current from the strong lens was getting through to the final screen. This was puzzling because it is known that the penalty for operating a lens at 1:1 magnification is only an increase of approximately 60% in spherical aberration over operation with parallel illumination. It was also puzzling because we could measure the aperture which was required to reduce aberration for parallel radiation and found that it was 160 mils compared with 375 mils for the beam cross section at 3" from the strong lens. Taking the distribution of energy into account, one should expect at least 25% of the current to get through the relay lens. The trouble lay in the presence of pincushion distortion and the fact that we were using aperture reduction to correct not only for spherical aberration but also for lack of orthogonalism in the relay lens.

In test #10-30-60-3 measuring these errors and including the current which caused them obtained 0.5 microamp at the target after going through both lenses with only 10 microamps total current to start. The system included an 80 mil limiting aperture for the relay lens and a 40 mil limiting aperture for the strong lens. We stopped at 0.5 microamp target current because the screen cannot take more without damage. However at 10 microamps total current the 40 mil aperture can only transmit from 1/4 to 2 microamps depending upon filament temperature thus the relay lens was transmitting at least 25-50% of the current coming to it. Going on the principle that if good line foci can be obtained, then a spot of the same dimension can also be produced, we can therefore conclude that relay lens systems with current efficiencies of 25-50% can be obtained using line focus einzel lenses.

At this point a decision had to be made on the basic design of the Mark III guns. Specific details could be worked out later during the design period. The program therefore continued as described below.

Image with Fully Corrected Elements

The first approach to a fully corrected system was the setting up of a lens with four elements. This gave sufficient degrees of freedom, as expected, to correct all errors simultaneously. In one, tests we obtained evidence of reducing spherical aberration according to the method of Scherzer[4]. However the elements could not be stacked in less than a 2" length so that the vertical direction could not demagnify more than 3:1. We therefore obtained very good quality images through the relay lens but they were large, 1-1/2 mils x 1 mil. (Ref. test #11-14-60-3).

In the second approach tested the effect of varying the radius of the line focus elements to eliminate the causes of low current as discussed above. Using a fixed sagitta height of 1/4" tested elements of 3/4", 1", and 1-1/2" radius, found that spot elongation upon focusing could be reduced from 30% to 15% vertical and 6% horizontal. (Ref. test #11-17-60-1&2).

From these tests concluded that for 1/4" sagitta height, the 3/4" radius is better than the 1" and 1-1/2" and that beyond 1" radius the properties of the lens change slowly with radius; also, that the strongest half of the lens should have an even shorter radius. On the basis of this experience chose for the Mark III the parameter shown in figure 10. Also started shop schedule to make an identical set for the electron optical bench in a compact holder so that we might eventually have the benefit of a fully corrected system.

The Use of Grids to Correct Spherical Aberration

Liebmann[10] has shown that placing a grid over the entrance of a weak einzel lens caused its spherical aberration, as measured by the convergence of bundles of rays coming to a focus, to decrease markedly to a value comparable with magnetic lenses of the same strength. He attributed the improvement to decrease of the diverging effect at the entrance and exit of the lens. He also warned that the grid had a detrimental "ground glass effect" which made them useless for electron microscope design. We thought that perhaps the ground glass effect would not be too objectionable for focusing to a small spot but were disappointed to find that the effect is quite large even with 750 mesh grids. While checking through the literature, we came upon some mention of grids in the plane of symmetry of tube lenses and some early work by Knoll and Weichardt[11] of placing a grid across the center of an einzel lens. Intuitively one would expect these lenses to have less spherical aberration so we assembled one using the 750 mesh grid, from an image tube, as shown in figure 11. It gave a nice focus about 3 mils in diameter of a hairpin source. Upon increasing the current the spot did not grow rapidly even up to 80 microamperes (momentarily). The fluorescent screen was damaged but the fine grid was not.

A large number of tests were then run with grid lenses. It was determined that each opening of the grid makes a small spot which almost coincides with the spots made by other openings but as the mesh size is increased, the spot is also increased. No gross effect of the 750 mesh screen could be detected but it did fuzz out the boundaries of the line focus spots it relayed and did produce a weak general haze in the background. It was found that as the action of the grid lens was made stronger, the effect of the grid openings became more pronounced. The grid lens is not suitable for the strong lens of the relay system. However, it can relay the spot with a 1" working distance and produce a final spot 3 x 5μ. This should form the basis for a useful electron gun for other projects even though it is of no present usefulness for Talaria.

It was at first thought that it must work in an accelerating system to pass high beam current. We later learned that when the power supply is stiff enough to maintain voltages, it will work either as an accelerating or an einzel lens, and that the two systems are about equally attractive. Klemperer[5] states that the grid einzel lens has the principle plane on the same side as the focus and therefore one should be able to obtain more defocus in a given gun length.

By this time the grid lens was beginning to look quite encouraging as a relay lens because of its simplicity combined with good performance. It had proven capable of transmitting large total currents (80 microamperes). Furthermore, measurements proved that the grid intercepts only a few microamperes even when very large currents are passing through it.

The grid lens has further attractive qualities. When used in a tube lens, it permits much stronger lens action for a given voltage ratio because it can suppress either the diverging or the converging action of the lens. This permits the use of a tube lens for the final lens without use of low voltages in the electron source where low voltage would decrease useful beam current.

A 2:1 voltage ratio in a tube grid lens is as good as a 7:1 ratio in an ordinary tube lens as shown in work reported by Klemperer[5] as follows:

		V'/V	1.5	2	3	7	10
Tube Grid Lens	Focal length/R		8.7	5.5	3.7		
	Midplane displacement/R		1.0	1.0	1.0		
Ordinary Tube Lens	Focal length/R			30.6	13.8	7.7	4.95
	Midplane displacement/R			5.0	3.6	2.8	2.62

When using a grid einzel lens, the principle plane is on the same side of the lens as the focus according to Klemperer[5]. This is of course the reverse of the usual electron lens. If so, it should give considerable advantage as a relay lens because it affords a shorter focal length for the same free space and thereby improves resolution and shortens gun length. Unfortunately this effect has not been realized by us yet. No attempt has been made to measure the position of the principle plane because of time shortage.

In our next test we stacked the grid lens with a three element strong lens in a manner as near to the Mark III design as was possible to put together at that time. The setup is shown in figure 12. Because of the long spacing and aberrations which were difficult to remove in the limited time available before the Mark III design would be frozen, we accepted a spot from the strong lens of one mil in diameter. The results of this test #11-3-60-2 were very encouraging. The laboratory record, dictated at the time of the test, reads as follows:

"The results of test no. 2 are quite encouraging. Find that a spot less than 2 mils in diameter can be made despite the fact that the strong lens is not properly centered or aligned and was giving a spot about a mil in diameter. Therefore, the spot 2 mils in diameter with 2 to 1 magnification is not surprising. The encouraging thing is that there doesn't seem to be any indication of screen structure or prismatic action by the screen and that the total beam current seems to come through the lens unattenuated and furthermore, that increasing the beam current by increasing the filament temperature does not seem to increase this spot size. Increasing beam current by increasing bias does affect it since the bias affects the focus of the first lens. The following voltages were used approximately:

Accelerating potential	5 kv
Bias	150 v
Potentiometer 1A	5.75 kv
Potentiometer #3	4.64 kv
Potentiometer #5	+3.17 kv
Potentiometer #6	+800 v

"This last spot remains stable. However, with several settings we had trouble with the current fading in and out as if there were some feedback from the positive lens to the bias."

This test still left the unanswered question of whether the grid would impose a limit on spot size if one should attempt to make a 1/2 mil spot. With this question in mind we continue to the next test.

Test #3

"Moved the screen down to the top of the 1/2" spacer which holds the exit aperture to the grid lens. The distance from the lens center to the fluorescent screen is 1 inch. Obtained the focused spot, with the combination of the strong lens and the relay lens working very close to its focal length, of less than 3 to 5 microns. The setup in this test could not be used to produce a practical Talaria gun because it does not have sufficient working distance. However, it is interesting to note that the lens is capable of making a very small image and is not overriden by prismatic effect of the screen openings."

3. Electron Optical Bench Tests of Electron Mirrors

There are many ways in which electron mirrors and/or electron prisms might be used to simplify the design of a Talaria projector depending upon the basic system chosen. They might be used to:

1. Fold the long distance from source to lens.
2. To bend the electron optical axis to fit a package.
3. To increase deflection sensitivity.
4. To break up the interference between electron and light optical paths.

The basic notion of these applications is shown in figure 13.

The fourth application of an electron mirror would have an obvious and immediate beneficial effect upon the progress of Talaria, and was therefore given the first attention.

The ideal way to break up this interference without completely redesigning one or other system is to separate the two axes by a large angle and then swing the electron beam into line with the optical axis by use of optically transparent devices. (The converse need not be considered since any optical bending device would be opaque to electrons.) It is equally obvious that the bending field must be in the space through which the optic axis passes. One could use a large exterior coil to form a magnetic prism. This is a reasonable solution as shown by the simple calculation in the Appendix. It would also be desirable to provide the designer with an all electrostatic solution. This is more difficult because the field forming means, for practical reasons, must cross the light optical path. Some investigators, as in the Aiken patent[6] attempt to get around the light absorption of the field forming means by making it physically small but in so doing introduce severe non-linearity. Others use a series of wires or a gauze, both of which would be very objectionable in a Schlieren system. An example is the mirror shown in figure 14 which was used by RCA[7]. It requires transmission through the screen twice. They make the following comment. "With available high transmission screens, this loss might be reduced to about 50%."

It would appear much more hopeful to use a transparent conducting plane at a high negative potential, because this would have least electron optical aberration, fit into a space not occupied by the light optical components, and have little or no effect upon the Schlieren system. It could be supported upon a thin optical quality glass plate and it would be at a forty-five degree angle thus avoiding reflections.

The first tests were made on the bench in the manner shown in figure 15. By this arrangement, one could easily compare the undeviated beam performance with the performance through the mirror. The first mirror was made "free hand" by bending a sheet of brass to an estimated 45 degrees. The electron source was a hairpin filament of the usual variety. The focusing lens was a "condenser lens quality" einzel lens operating at approximately 2:1 magnification. The spot was therefore expected to be large but adequate for testing the mirror performance for sweep linearity and first order spot defocus.

A simple, battery powered, spot deflection system with wire-wound potentiometers and 1% accuracy voltmeters was used to deflect the spot to a number of positions over the proposed raster area and a composite photograph was taken showing the spot at each of these positions (fig. 16). The voltages from right to left and from top to bottom were made symmetrical. Horizontal deflection was obtained by plates immediately following the lens and vertical deflection by mirror potential changes. However, deflection by plates in the vertical direction had been previously checked by rotating the plates 90 degrees. Deflection without the mirror had also been checked at the same voltage. With the plates in the vertical direction at 7.3 kv, the deflection sensitivity through the mirror was 5 mils per volt compared with 3.7 mils per volt without the mirror.

Deflection by mirror potential is less sensitive (0.57 mil/v. at 5 kv) and is non-linear (20% greater average deflection in bottom half of sweep). At 5 kv the horizontal deflection sensitivity is 8.7 mils per volt compared with 5.4 mils per volt without the mirror. Adjusting to a common base we find therefore that the mirror increases deflection sensitivity by 1.35X vertically and 1.6X horizontally. It is suspected that these ratios are a function of geometry and are diminished by lack of equal path length with and without the mirror. As nearly as we could measure, the path lengths were 6" without the mirror and 4-1/2" - 5" with the mirror. It is interesting that 1.6 x 6/4.75 = 2.03 approximately and gives one cause to wonder whether the mirror does not fundamentally double the deflection sensitivity.

An extra set of plates was made up and a television raster displayed through the mirror. At low beam current the spot was small enough to resolve the picture. Figure 17 shows a snapshot of the screen taken close up on 35 mm. film. The camera wasn't quite in focus or the image moved, because the screen looked better than shown here.

Although no keystoning is shown in the test with static deflection voltages carefully measured, we did obtain some keystoning on the television images which was only discernible when the border could be seen. This may have been the fault of the deflection currents. At any rate it was decided to test the effect of changing the outline of the mirror to see what distortions (and therefore corrections) might be introduced. Four such mirrors were made up as follows:

#1 Carefully machined square 2" x 2" to replace the hand bent original.

#2 Square aspect ratio as seen by beam (2" x 1.4").

#3 Tall slender mirror (1" x 2").

#4 Broad short mirror (2" x 1").

These mirrors, shown in figure 18, have not yet been studied systematically but #2 and #3 have been compared qualitatively.

Three effects were noted in comparing the square aspect mirror as the beam sees it with the square (2" x 2") mirror.

1. The picture on the screen was larger with the square aspect ratio mirror for the same height and width settings of the deflection circuit.
2. The overall bending of the image required less voltage on the mirror.
3. There was no startling difference in keystoning of the image.

From the change of sensitivity with mirror area, one can predict that a keystone-shaped mirror can correct for image keystoning.

This is all of the progress made thus far with mirrors. Considerable effort was expended, without visible return in 1960, on trying to obtain an analytical approach to the solution of simultaneous deflection and mirror action. Such a system could conceivably increase deflection sensitivity greatly. The problem is to produce linear deflection in a mirror. The analytical attempts are reported in Section 6. The mirror deflection problem is discussed further under Recommendations for Future Work.

4. Pointed Filament Development

As mentioned above, the pointed cathode was first reported by Hibi[8] in 1954 and later by Maruse and Sakaki[9] in 1956. It was essentially a thermionic source of small size and lower divergence constructed as shown in figure 19. A brightness gain of 2:1 and later 10:1 was reported but most workers were skeptical of the 1954 report. In late August of 1960 Frandez-Moran[1] of Mass. General Hospital showed conclusive proof of higher brightness, smaller source size and equal life compared with tungsten cathode - operating in a Siemens electron microscope. His application was identical to our own except for the use of 60 to 100 kilovolts acceleration. Frendez-Moran showed moving pictures taken at 200,000 times whereas with the hairpin cathode the screen would be just readable by the dark-adapted eye.

We attempted to reproduce his results but due to misunderstanding of his work, spent an undue amount of time in developing the welding procedure for the pointed cathode. One of the key points to his improved performance of pointed cathodes was symmetry of the point at the junction to the hairpin. We thought he had butt-welded the point onto the hairpin in the plane of the hairpin. It turns out that this cannot be done by any known welding methods. It further turned out that Frandez-Moran had deformed the hairpin tip to make a cradle for the tip so that the tip could lie in the hairpin plane and yet produce the weld by crossing the wires not butting them together. At the end of the time span summarized by this report, the etching was just beginning to get under control. The tip radius is too large as shown by figure 20 which is a photograph of our tip radius compared with the required radius. We did however try a tip with the electron mirror and found it less bright for a given filament temperature than the ordinary hairpin and little or no difference in spot size. This result is not surprising; the tests were only made to make sure that the further reduction of tip radius is necessary.

5. Gun Design, Manufacture, and Tests

The philosophy behind the Mark III guns was to make them an improvement over the Mark II in size, deflection sensitivity, stability, spot size, etc.; but not to attempt to achieve low manufacturing costs. Since it was doubtful that all the improvements would be achieved in the first go around, and since more than one source of electron guns would be tried on the Mark III equipment, we decided to design the housing so that the gun could be interchanged with modifications or with other designs of the same size. This interchangeable feature considerably increased the machining complications and the cost of the guns. The basic geometry of the Mark III system is shown in figure 21. At first it was hoped that the gun could be flanged at the housing at the point "F", but the close spacing between electron optics and light optics made this impossible. We then turned to the next best alternative which was to place the flange in the housing. The point "G" was chosen and the gun tube was provided with a flanged platform upon which interchangeable lens packages could be supported. The electron source was supported from the end of the gun tube.

It was decided that the best electron optical system to use at the then current knowledge, would be the line focus einzel lens followed by a grid relay lens. The reasons for choosing the relay system are explained in previous sections. The reasons for choosing this combination of lenses were first that the line focus lenses are the only ones which have produced a spot which can be relayed, so they had to be used for the strong lens. Secondly, in the crowded space available, the placement of a second larger aperture line focus set in the relay lens position was providing a great many problems and was expected to prolong the delivery date of the guns excessively. By contrast the grid lens had given good performance, required less diameter, was shorter, and required only one voltage to focus it. The grid lenses drawbacks are the need for a positive voltage below ground (or two stages of acceleration), its inability to correct faults in the strong lens action, its tendency to catch and hold solid particles of dirt, and its slight diffusion of the image.

Our knowledge of the behaviour of relay systems was still marginal at the time when decision on the Mark III design could no longer be put off. We had produced relay images which contained more than 25% of the energy from the strong lens and with spot sizes which apparently followed the demagnification rules. However we had not had compact lens package available so the demagnification could be reduced sufficiently in both directions. Similarly we had used grid lenses as relay lenses but without the benefit of sufficient demagnification in the initial stage. We had also produced a spot by use of a grid relay lens of 3 x 5μ at 1" working distance. Nonetheless we had not been able to test a complete system capable of producing 1 x .6 mil spot at 5" working distance and were therefore on an uncertain foundation at the outset of the Mark III design. (The wisdom of the choice of a grid relay lens is still undetermined.)

The basic design parameters were chosen as follows:

1. Source to strong lens center = 6".
2. Strong lens center to relay lens center = 2".
3. Relay lens to screen = 5".
4. Source 4 mil hairpin filament in .031" grid.
5. Anode .250" at .420 from grid.
6. Limiting aperture preceding strong lens .040".
7. " " " relay lens .080".

The design was executed in the manner shown in drawing #421D114. In this design the 750 mesh copper grid was to be replaced by nickel. The supplier sent 250 mesh nickel instead. A quick check showed no visual difference between the spots formed by the two grids. The 250 mesh grid was more rugged and trapped less dirt so we decided to use it in the first model of the Mark III design.

Upon assembly of the guns certain difficulties were encountered. These included an instability due to spark breakdown which was cured by flowing nitrocellulose solution over the junction between two epoxy insulators. The nitrocellulose can be dissolved away easily for disassembly. Another difficulty arose because the lens package, which is held together by tie rods, was not coming to rest on the lens elements but striking the opposite insulator instead. As a result the end plates of the lens were floating electrically. Metal shims were inserted in the package thus placing the load on the lens elements and solving the problem.

After the minor difficulties were removed, we encountered a major difficulty. The spot was several mils in diameter and did not behave as if it were an image of the demagnified spot. That is, it did not form line foci when slightly out of focus. Instead it went from a bulging square image at focus into an expanding circle away from focus.

Finding out the cause of this difficulty consumed considerable time and the path was not direct. However by setting up an exact replica of the Mark III gun on the electron optical bench we were able to duplicate the behaviour of the Mark III and to eliminate the causes of trouble and alleviate suspicions one by one. By dissecting the system we proved that the fundamental cause was that the relay lens when only 2" from the strong lens could not focus from the object to the image plane. An increase in the spacing from the grid lens entrance aperture to the grid was sufficient to make the difference and bring the spot down to the neighborhood of 1-2 mils.

The beam currents could be made very high (up to 12μ amps) without increasing beam size and raster lines were well resolved at 4 microamps.

Improvement beyond this point was not spectacular and the lack of further progress has not been satisfactorily explained. We did not attain as good performance on the Mark III as the electron optical bench work indicated we should obtain and the beam size appeared to be unresponsive to improvement by aperture reduction, to screen mesh fineness, or to demagnification changes. It is possible that in the rushed atmosphere we failed to get the right combination of aperture size, demagnification, etc. We are inclined to believe that something more fundamental is in control because the spot size is nearly always the same. It may be, for example, that we are limited by the aberrations in the cathode region and in fact this is at present our best guess.

The best operating conditions and operating directions for the Mark III gun are given in the Appendix.

6. Development and Tests of Analytical Methods

The need for analytical assistance in this program has already been pointed out in earlier sections. A two-pronged approach was taken toward obtaining analytical help.

First, a scaled model of the lenses employed was tested in an electrolytic trough already available in the laboratory. It turned out that the paths of the electrons in these line focus elements do not stay in one plane and therefore one would have to plot them in three dimensions. It was finally decided that this is not a practical thing to do. An attempt was made to circumvent this problem by use of measurements in two planes at right angles. This could be accomplished by rotating the model 90° and making another plot on the liquid surface. The general relation between the field at any point and the field distribution in the two planes was developed by Poritsky and the analysis of the precision required was done by Farr. Their analysis (given in the Appendix) reveals that in order to get 1% accuracy of the field at intermediate points, one would need five place accuracy in the field plots in the two planes. A letter report by Klotz (also in the Appendix) points out that our electrolytic trough sometimes gives error in the second decimal place and that the very best that has ever been accomplished in an electrolytic trough is three place accuracy. Therefore it was decided to relegate the electrolytic trough to approximate solutions of axially symmetrical problem.

Our second approach to obtaining analytical help was to have a search made by the GEL computer group to see what computer programs were available for computing electric field distributions and/or electron trajectories directly. It was found that no general solution to Possion's or Laplace's equation is on record. Some computer programs were found both inside GE and externally but these were limited to axially symmetrical problems. To solve the electron paths of lens systems which have only bilateral symmetry with respect to the optic axis is considerably more complex. This requires solution of electron trajectories which do not stay in one plane and which may make multiple crossings of the axis before leaving the lens. It also requires that the method used be well adapted to calculations of potential fields in open-ended regions.

A method employing a configuration of surface charges was suggested by Dr. Poritsky and proved to be very effective for our needs. As a result, we now have available a general purpose program for the calculation of electron or ion trajectories in electrostatic fields.

The surface charge technique replaces the surface of the electrode by an equivalent distribution of surface charge whose electrostatic field is the same as that which would be produced by the electrode configuration. This charge distribution is then used in an elementary fashion to calculate the forces acting on the ion or the electron.

The program treats the surface charge as though it were uniformly distributed over a planar surface area element. This is accomplished by modifying the potential field of a set of lumped point charges by a series expansion in order to approximate the potential due to charges uniformly distributed over rectangular elements. For the purposes of the present calculation only the first two terms of this series have been used. However additional terms have been worked out and can be programmed if desirable. Therefore, in effect, this analysis may be visualized as replacing the actual surface charge, which is distributed in a continuous fashion, by a stepped charge distribution. It may be seen that as a result of this approach the lumping approximation is only made at the surface of the electrodes. To a certain extent the effects of this lumping are smoothed out at the location of the moving ion or electron. In contrast the traditional method of trajectory computation evaluates the potential field at discrete mesh points and obtains the force field by a process of numerical differentiation and interpolation. This process, therefore, also requires that the physical problem is lumped at its most sensitive point mainly the current positions of these electrons.

In order to realize the full potential of this program, it is desired to reprogram it for an IBM 704 computer. At the present time the program requires approximately three hours of computation time on the IBM 650 computer at a cost of $150 for the calculation of a single electron trajectory. It is estimated that a 50-1 reduction can be effected in time and a more than 10-1 reduction in cost by developing a similar program for the 704 computer. This will be necessary in order that the program can be used as a design tool to calculate trajectories for a large number of lens configurations. Trajectory calculations made with the present program have used 40 charge subdivision. By using the existing 704 Matrix Inversion programs up to 140 charge subdivisions could be employed with a concomitant increase in resolutions.

Additional analysis is recommended to exploit the natural advantages of this program for the calculation of trajectories in the presence of space charges and of magnetic fields.

As the program now stands, it is too slow and costly to be used during the rush days of the Talaria program covered by this report.*

7. Summary

The electron optics program for Talaria development described above has explored the possible electron gun systems for writing on oil with a resolution of 1 mil x .6 mil on a 1 x 1.5" raster approximately. A first attack to the problem was chosen, based on acceptance of the tungsten hairpin cathode in a triode gun and attempting to demagnify the image sufficiently by use of a relay lens system such as has been successful with magnetic optics. During the course of the work, frequent experimental comparison was made with single lens system and standard lenses.

Compact focusing elements were not available until the close of the program, thus it has not been determined whether electrostatic

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*It should be noted that while the first search for computer method was supported by the present program and the importance of the Talaria project helped to enlist support for development of this computer program, the funds for it continued support were derived from general Company funds and not charged to the project.

systems based on line focus elements can successfully operate as a relay system or not.

A Mark III gun was designed and built incorporating the best knowledge available last November. In this design an attempt was made to use the promising results with grid lenses. The results were comparable with previous gun except for their improved sized reduction but did not give the improvement hoped for in beam resolution. They gave 10 microampere spots of approximately 1 mil diameter to the 50% point but gave essentially no improvement in spot size at reduced current. This gun is designed so that improvements can be readily substituted for existing components.

However it should be clearly understood that the position of the Talaria gun development is unsatisfactory at the present time and that considerably more work will probably be required to accomplish the goals. About 1/3 of the originally estimated development cost for an electron gun system has been expended.

8. Recommendations for Future Work

Whatever else may be done, the cathode should be improved as an electron optical device. The fact that the aperture size has little effect upon spot size and that all lens systems seem to reach the same limit of 5 amps/cm^2 for a 1" wide display and half a mil resolution points strongly to the cathode spherical aberration as the fundamental limitation. We have found in the past that in a multi-element system, the aberrations of the first elements are much more critical because they are magnified by succeeding elements. The most promising cathode development today is the pointed cathode. It works in a relatively poor vacuum, has very high brightness, and a very small size which makes possible a reduction in grid diameter with a possible decrease in aberration. The pointed cathode work should be pushed ahead vigorously until it is either accomplished or found undesirable. If the pointed cathode works out, then almost any simple single lens system will solve the Talaria problem when used to image this cathode at about one to one magnification or even greater.

If the small cathode doesn't work out, then Talaria must have either a folded electron optical path or a relay system (multi-lens system). Since magnetic optics have been successful in producing relay systems and since the unsymmetrical lenses have given strong evidence that they are capable of producing relay systems, the relay system should be explored next including the possibility of a permanent magnet lens system for relaying.

If the pointed cathode makes the relay lens system unnecessary for Talaria, then an effort should be made to find other support for the relay lens development because it will be an essential part of the development of information writing and reading guns as the information storage density is pushed higher and higher.

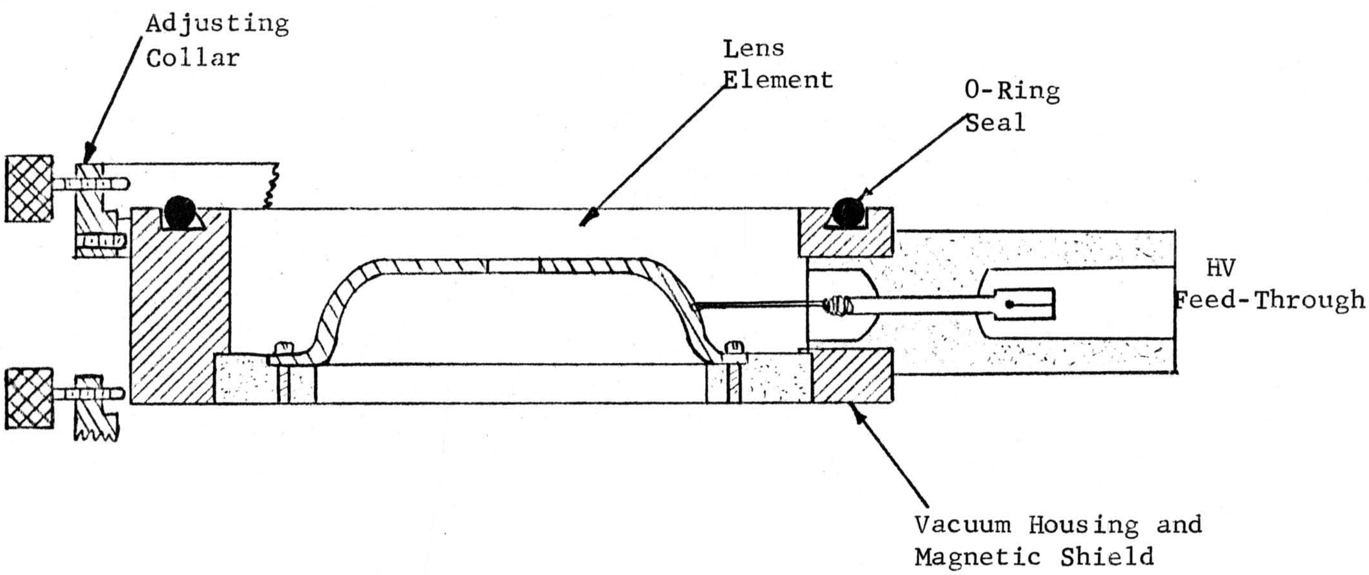
We recommend that the folding and trimming down of a single lens system be the last resort for the Talaria application to be employed only if the other two fail.

Concurrently with this work a study should be made, under microscopic observation, of oil writing to determine what beam current and distribution is really best.

These recommendations are confined to the area of electron optics. They do not take into account the need for complete changes in the concept of Talaria nor the possible changes in electron optical requirement which these changes may bring about.

This is as far as we can recommend that work be done on Talaria electron optics until a product is established. A considerable more imaginative approach will be warranted as the product matures.

LIST OF FIGURES



A TYPICAL UNIT OF THE STACKED
COLUMN OF AN ELECTRON OPTICAL BENCH

Figure 1

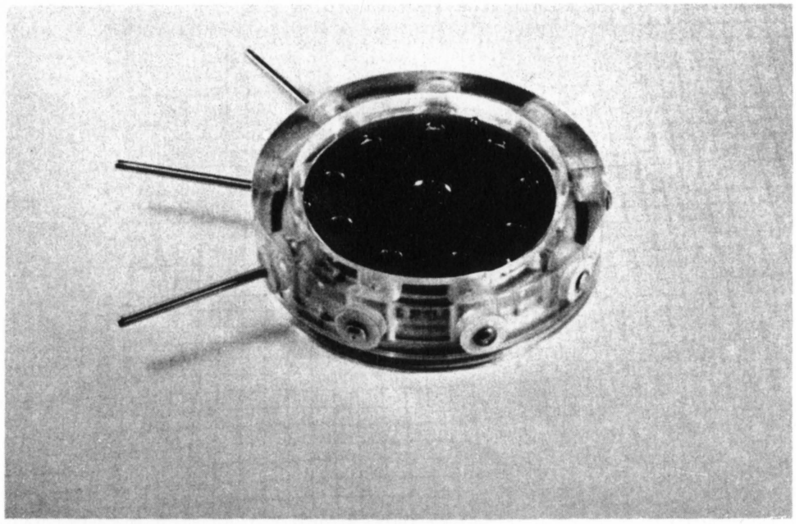


Fig. 2. One of the compact lens units capable of supporting six independent electrodes in a 1" length.

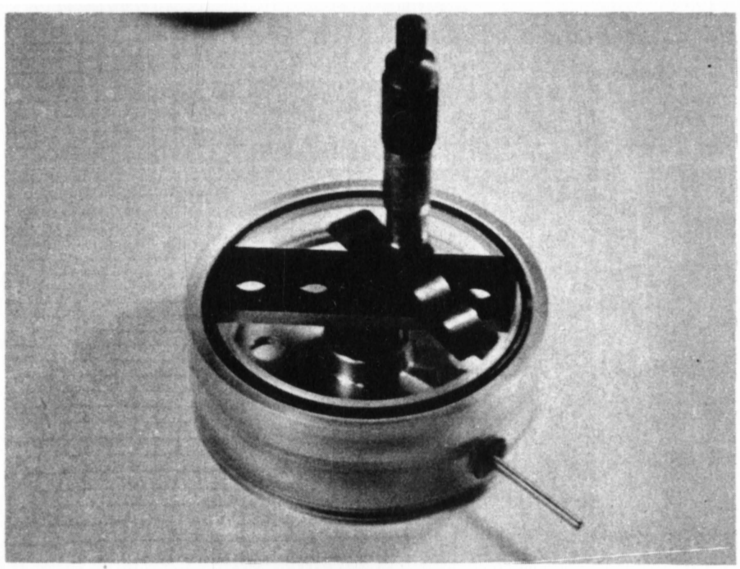
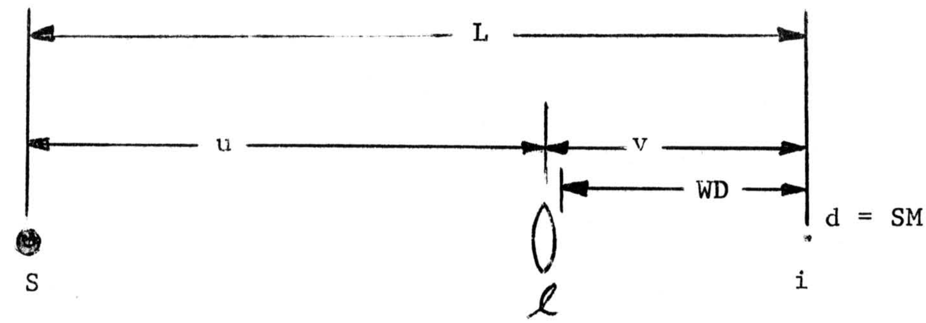


Fig. 3. Depth measurement of axial position of electrodes using the vacuum housing flange as a reference.



$M = \frac{v}{u} < 1$

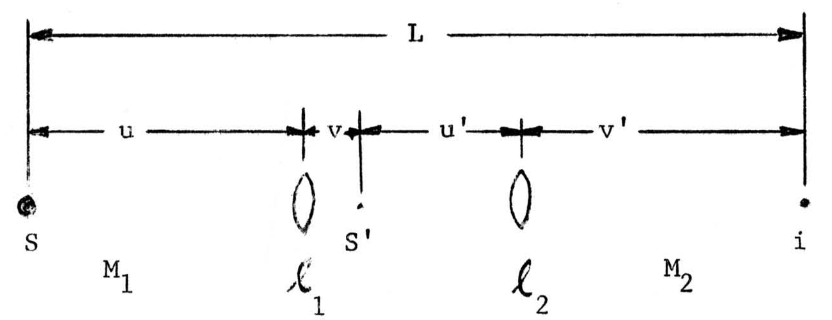
for $v = 5''$, $M = 1/6$

also $v < WD$

$L = u + v = \frac{v}{M} + v$

$L = 7 \times 5 = 35''$

a) For Single Lens Case



$M_1 = 1/12$

$L = u + \frac{u}{M_1} + \frac{v'}{M_2} + v'$

$M_2 = 2$

We find $u = 6''$, $v' = 5''$

$\therefore L = 6 + 1/2 + 2\ 1/2 + 5 = 14''$

b) For Relay System

GEOMETRICAL CONSIDERATIONS IN ELECTRON GUNS

Figure 4

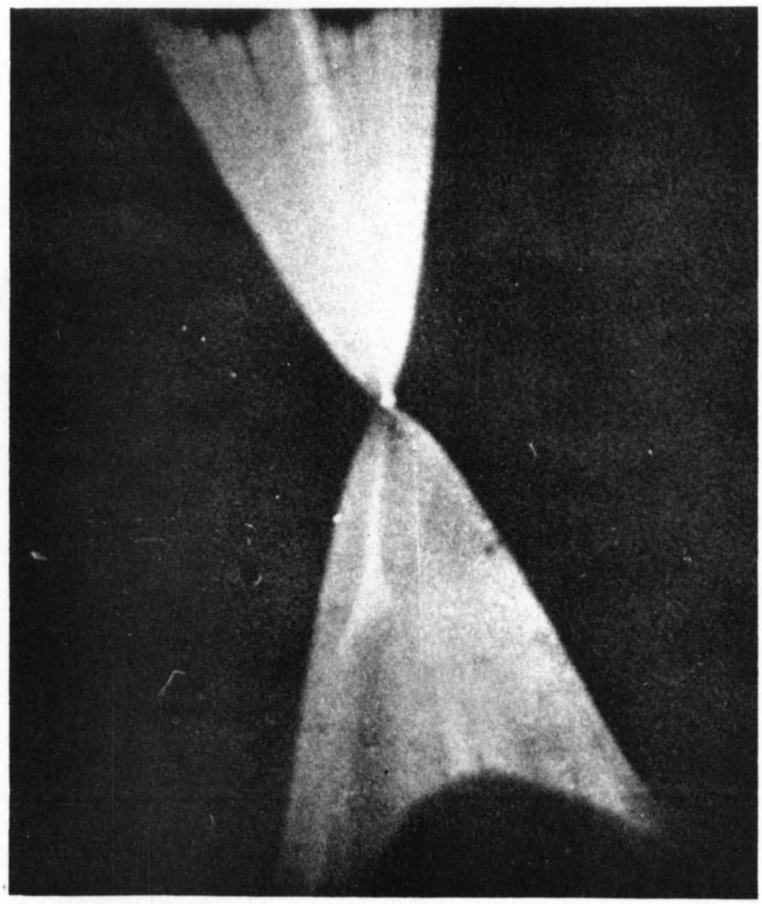


Fig. 5.

"Butterfly pattern" produced by spherical aberration in relay lens when trying to relay line focus.

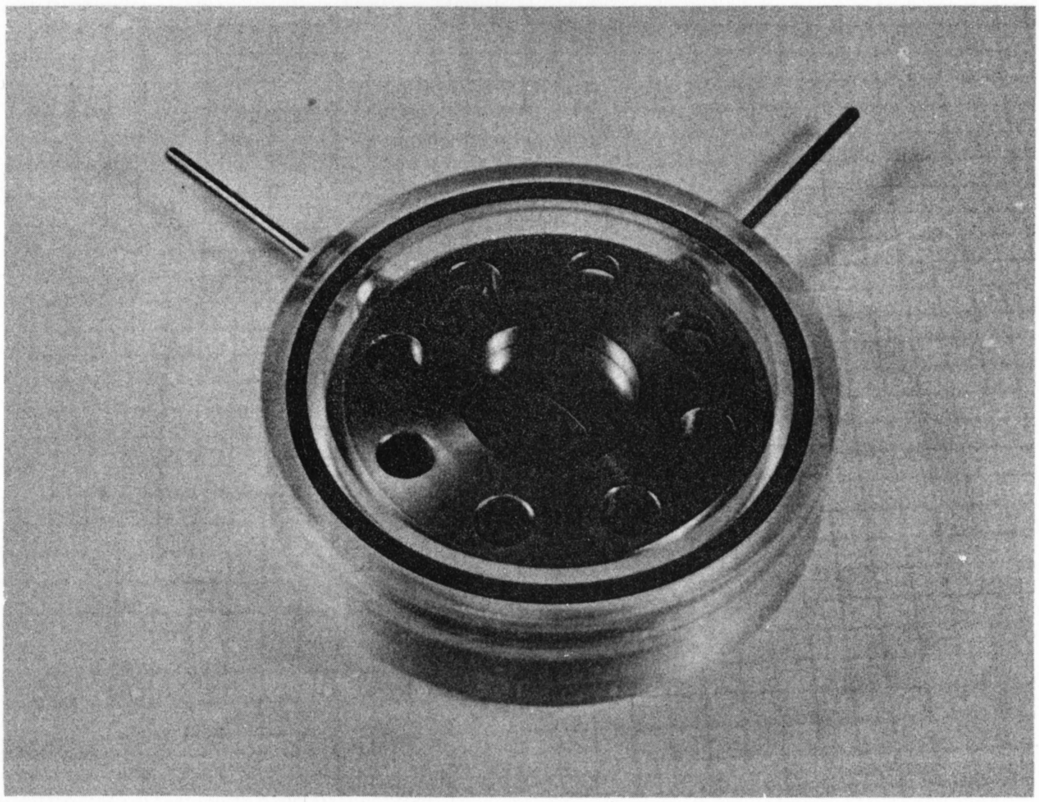
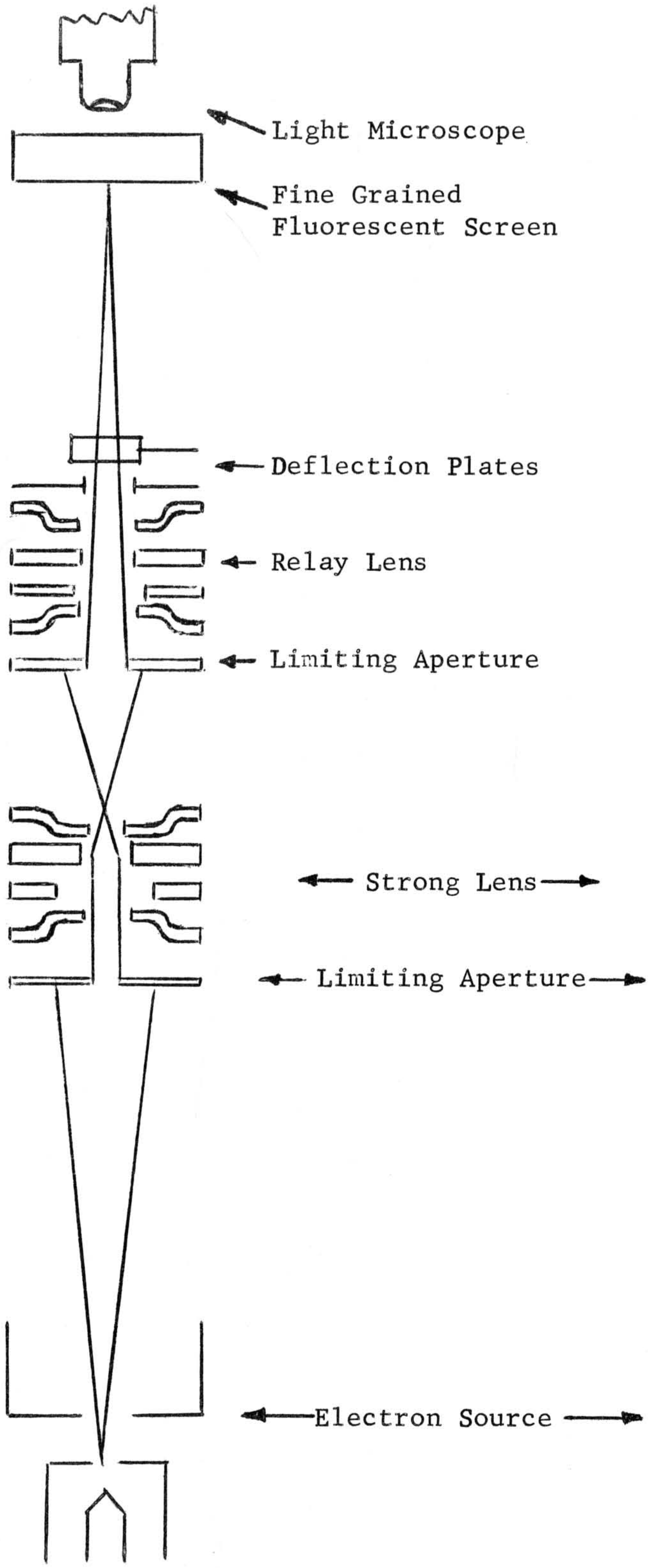
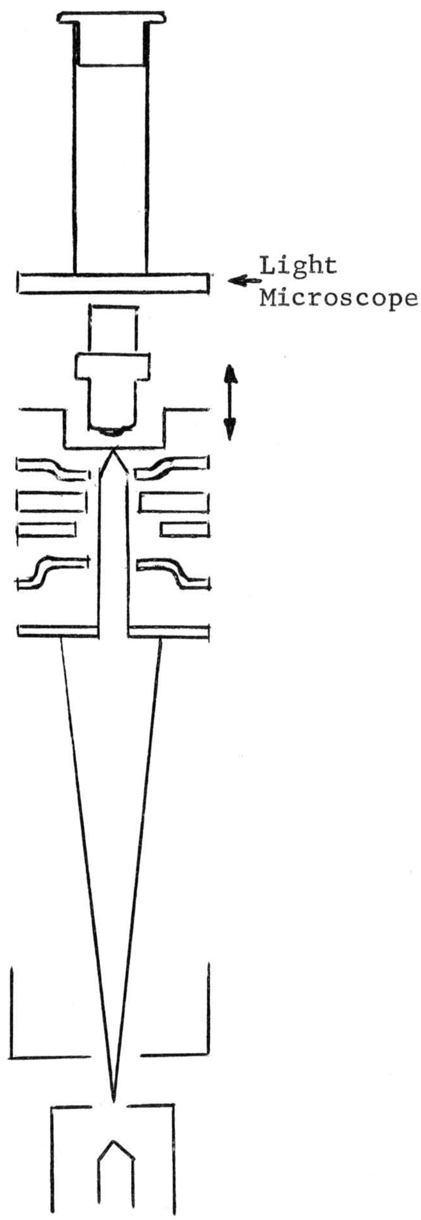


Fig. 6. Line focus test lenses used for these first tests.



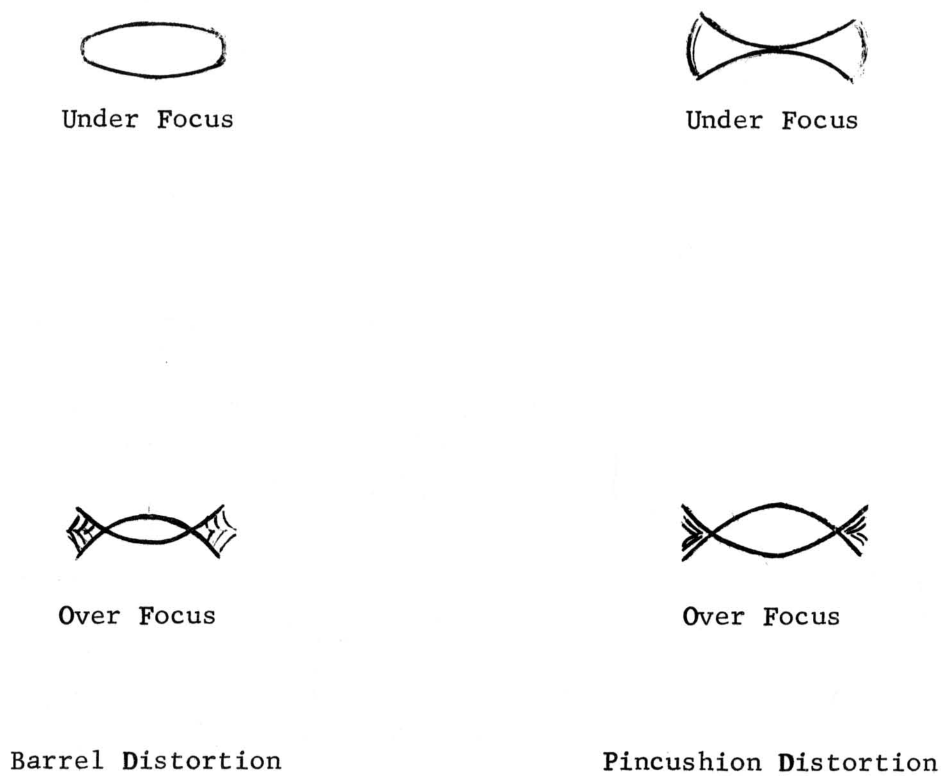
SCHEMATIC VIEW OF SYSTEM
USED TO TEST THE RELAY IDEA

Figure 7



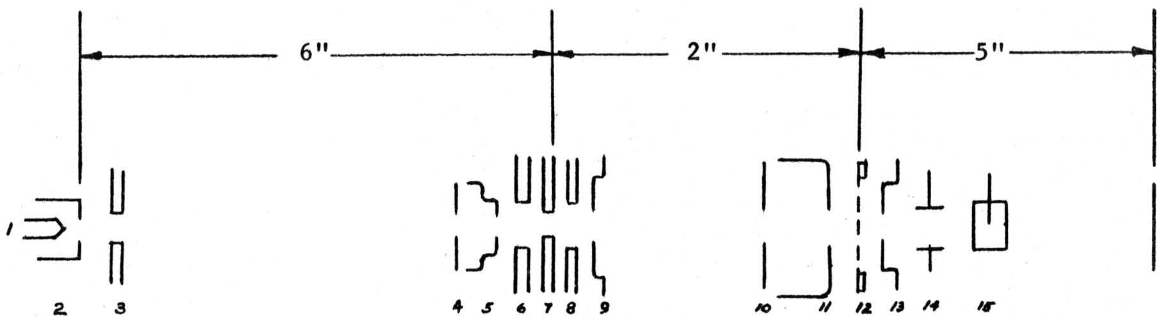
THE METHOD OF VIEWING THE
DEMAGNIFIED IMAGE FORMED
BY THE STRONG LENS

Figure 8



THE EFFECT OF PINCUSHION AND BARREL DISTORTION

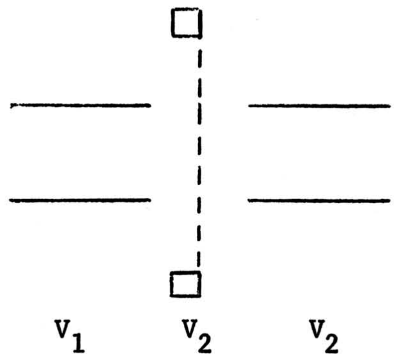
Figure 9



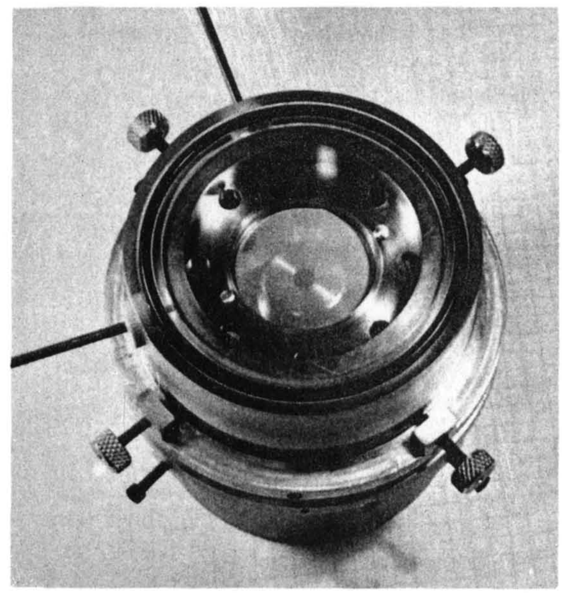
Item #	Name	Essential Dimensions	Material
1	filament	4 mils 7/16" long	tungsten
2	grid	10 mils thick, 31 mils dia.	molybdenum
3	anode	125 mils dia., 240 mils from grid	304 stainless steel
4	aperture	32 mils dia., 10 mils thick	molybdenum
5	lens cap	250 mils, 28 mils thick	304 stainless steel
6	correcting lens	829 mils long x 750 mils radius-57 mils thick	304 stainless steel
7	lens line focus	545 mils long x 545 mils radius-57 mils thick	304 stainless steel
8	lens line focus	484 mils long x 500 mils radius-57 mils thick	304 stainless steel
9	lens cap	62 mils dia., 28 mils thick, 104 mils from lens	304 stainless steel
10	aperture	80 mils thick, 10 mils thick	molybdenum
11	lens cap	250 mils dia., 28 mils thick	304 stainless steel
12	grid lens	250 mils mesh, 80% trans.	nickel
13	ground plane	250 mils dia., 28 mils thick	304 stainless steel
14	deflection	5/8"x 15/16"	304 stainless steel
15	deflection	7/8" x 15/16"	304 stainless steel

PARAMETERS FOR MARK III DESIGN

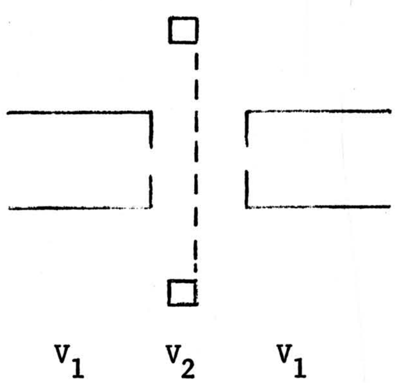
Figure 10



Tube Grid Lens



Grid Lens



Grid Einzel Lens

Fig. 11. Grid lens.

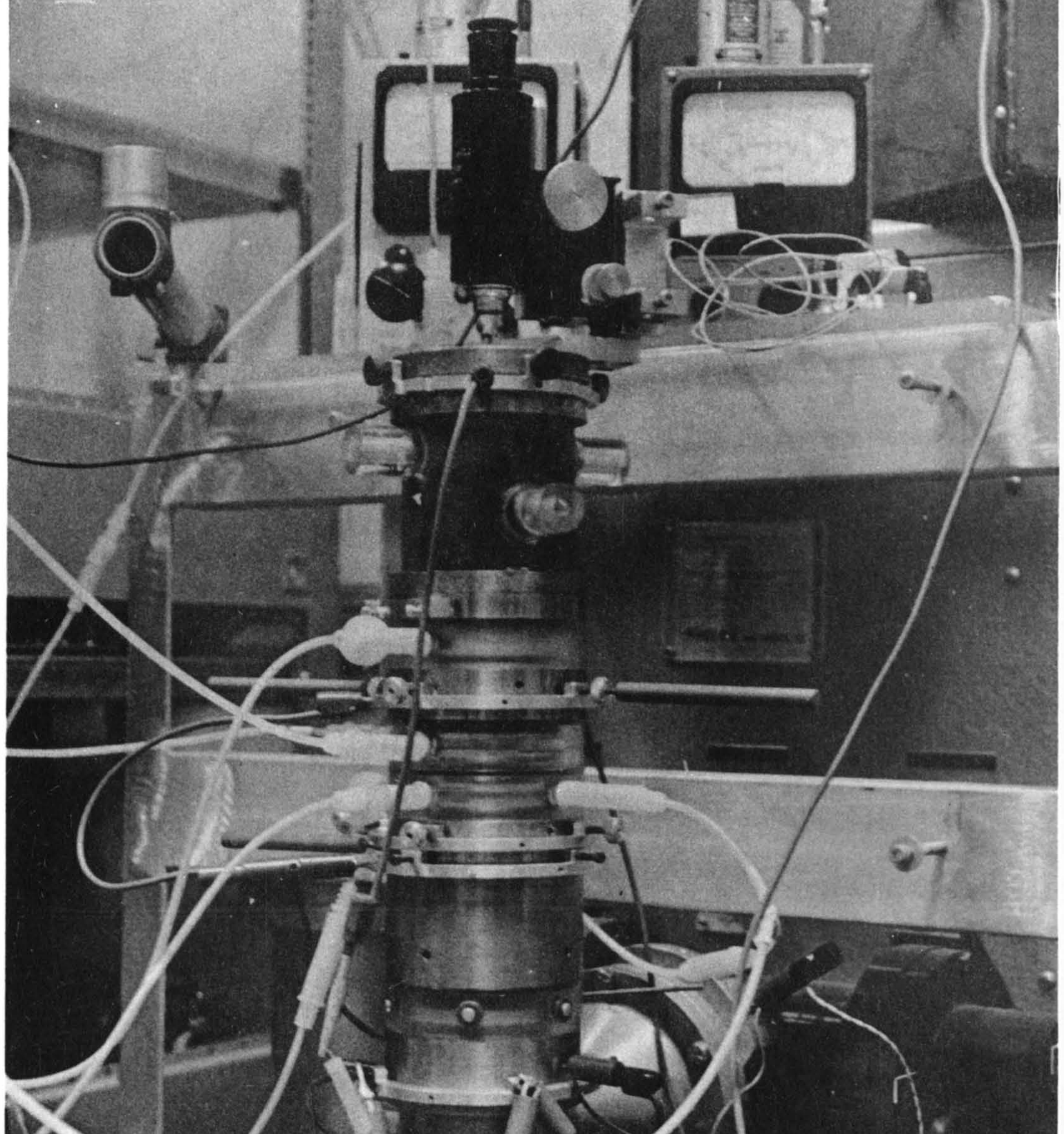
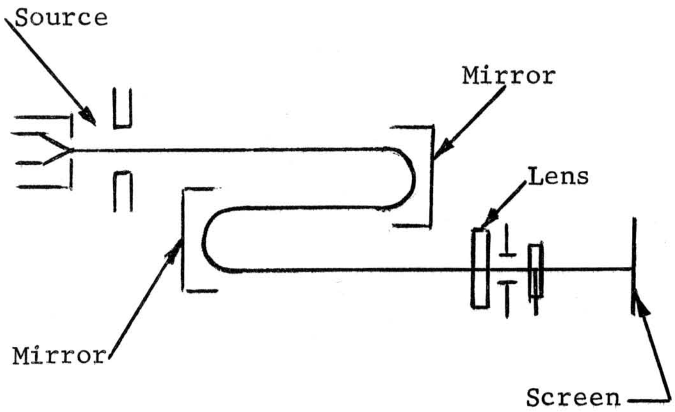
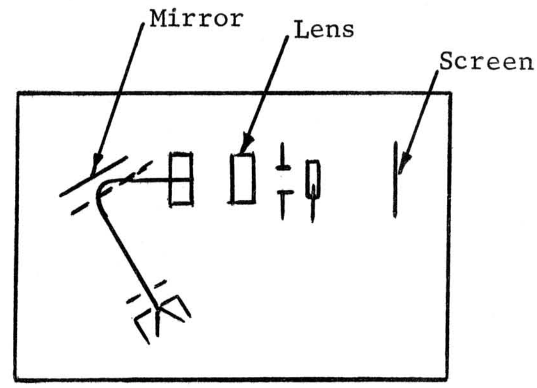


Fig. 12. Mark III mock-up.

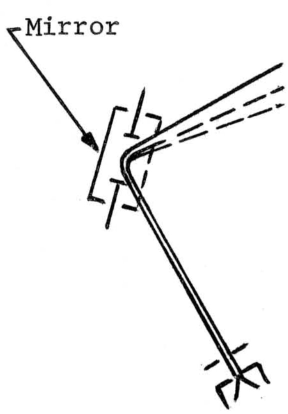
a) Folding Long Distance from Lens to Source



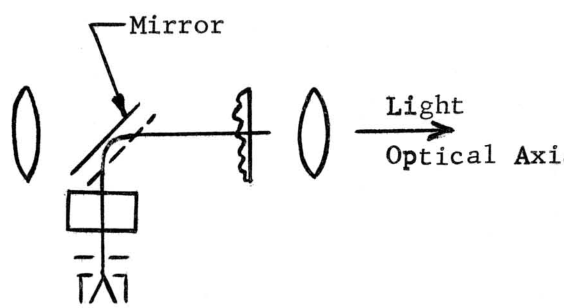
b) To Bend the Electron Optical Axis to Fit a Package



c) To Increase Deflection Sensitivity

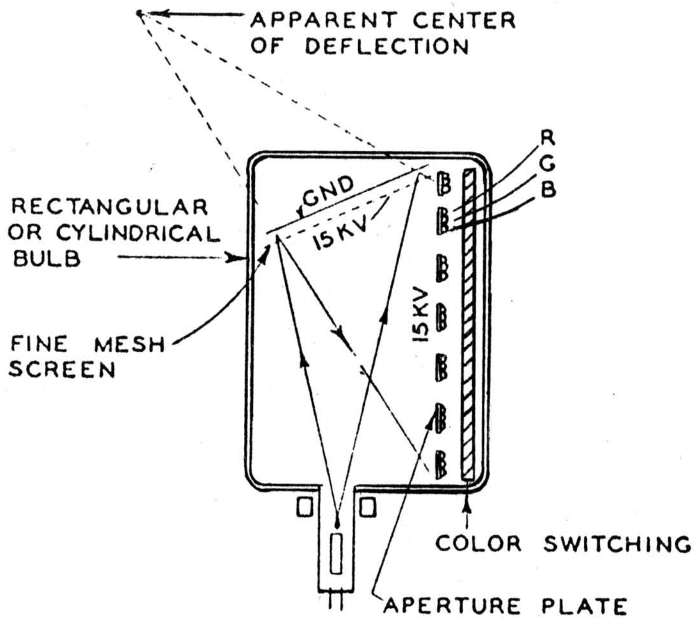


d) To Break Up the Interference Between Electron and Light Optical Paths



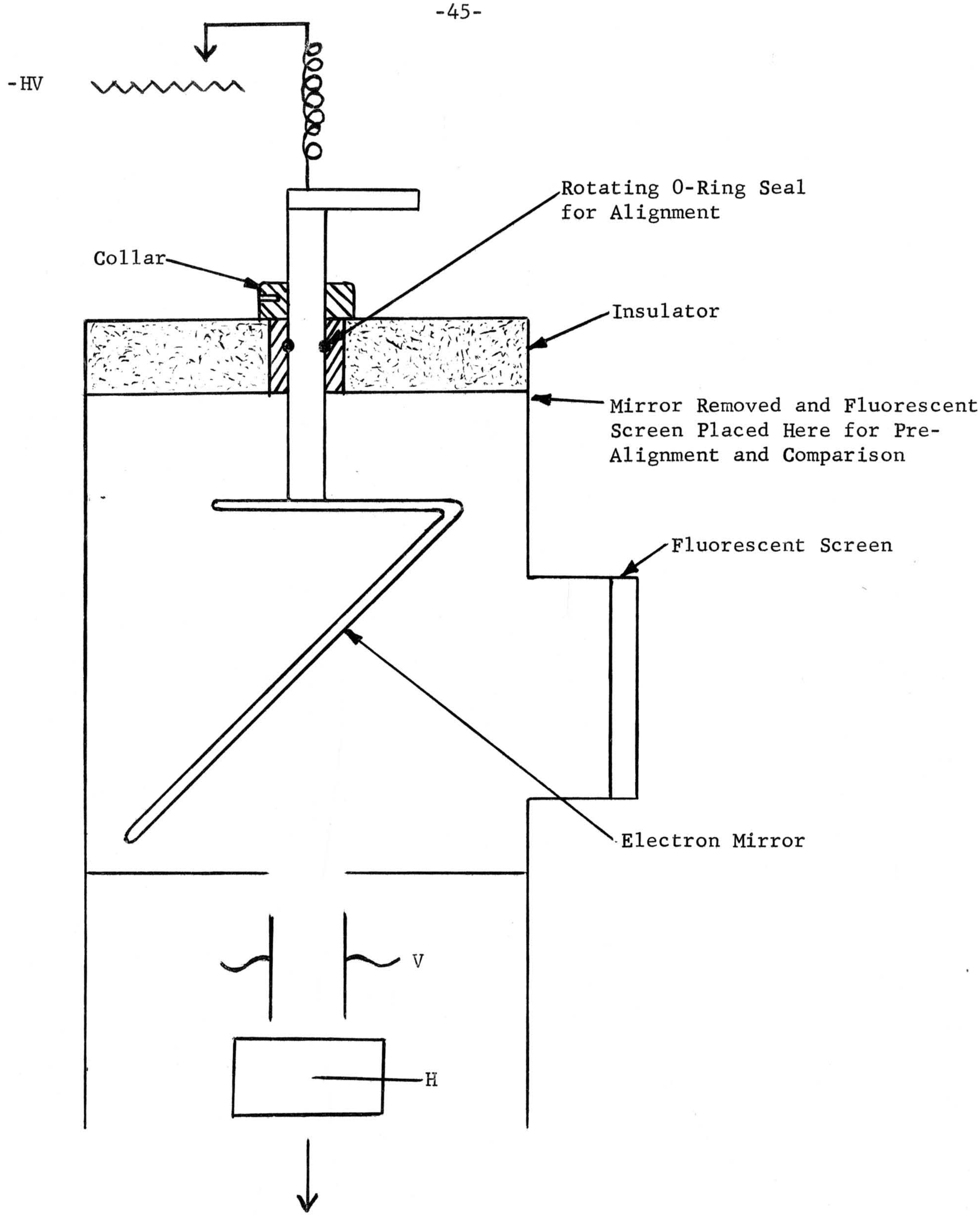
BASIC METHODS FOR USING ELECTRON MIRRORS

Figure 13



RCA ELECTRON MIRROR EMPLOYING
GRID AND CONDUCTING PLANE

Figure 14



ELECTRON MIRROR TEST ARRANGEMENT

Figure 15

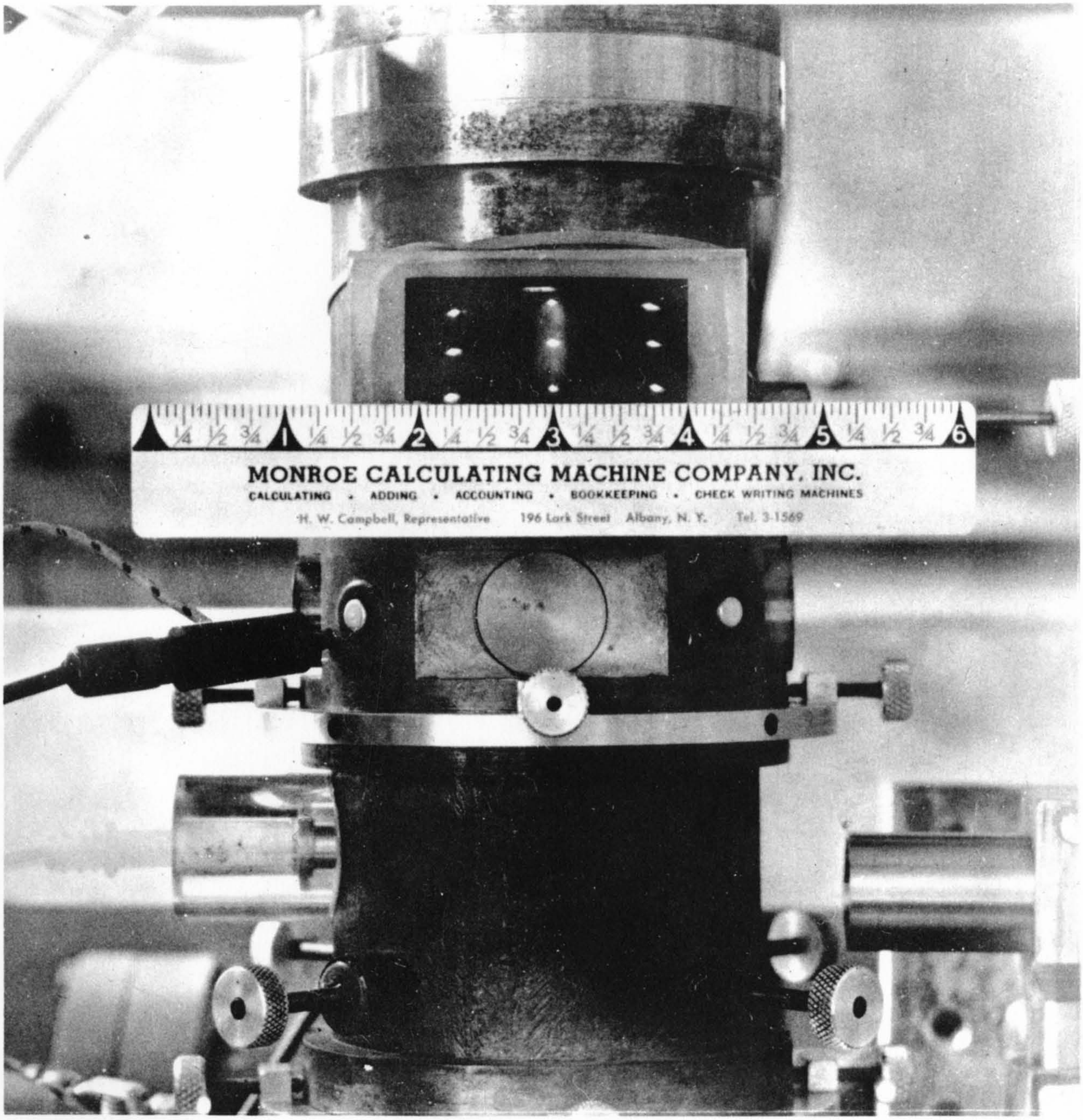
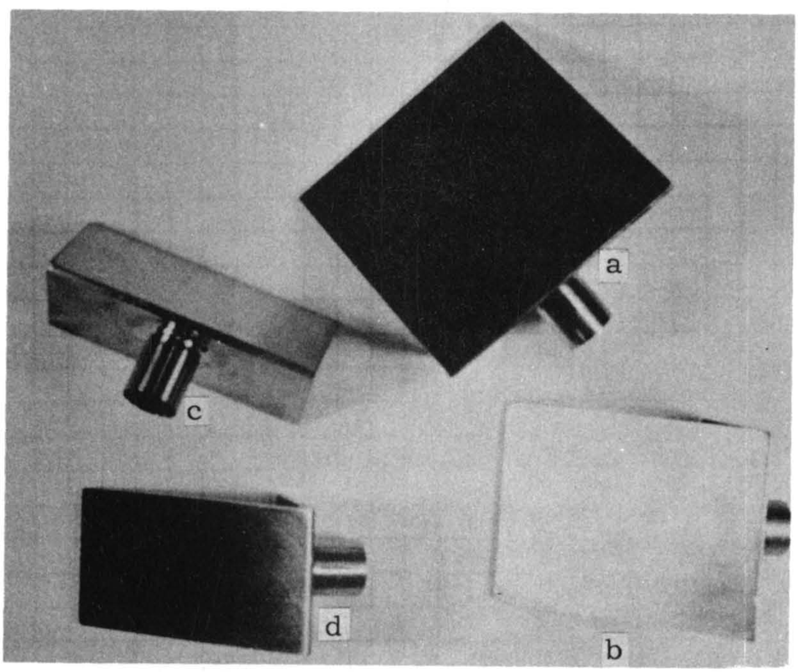


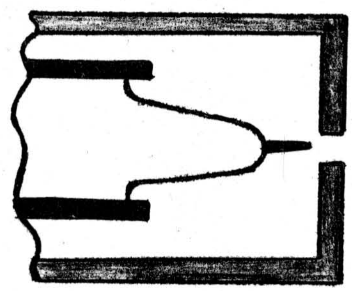
Fig. 16. Deflection performance through mirror.

Fig. 17. TV picture on mirror.



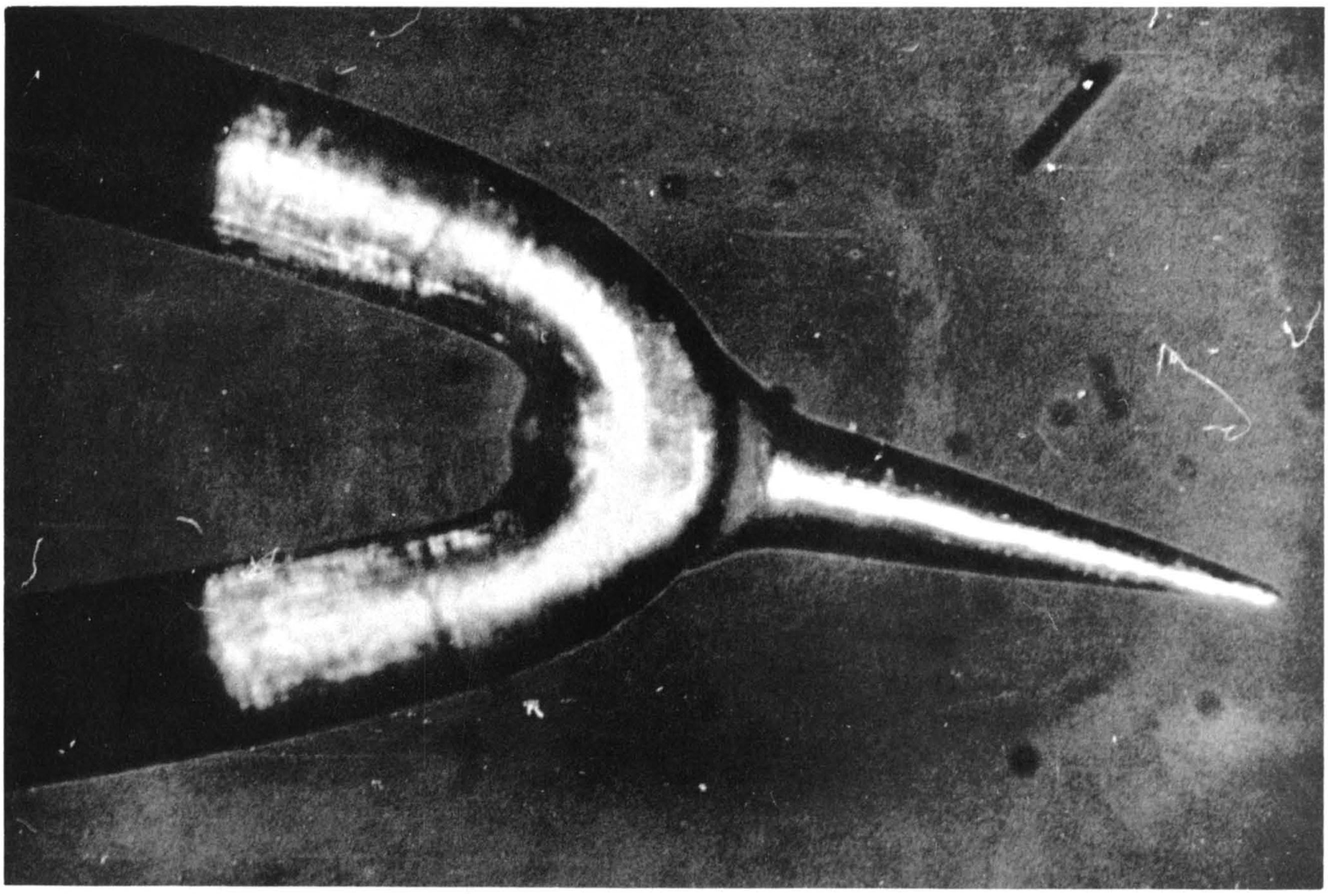
(a) 2" by 2" square
(b) Square as seen by beam
(c) Tall slender mirror
(d) Broad short mirror

Fig. 18. Set of test mirrors.



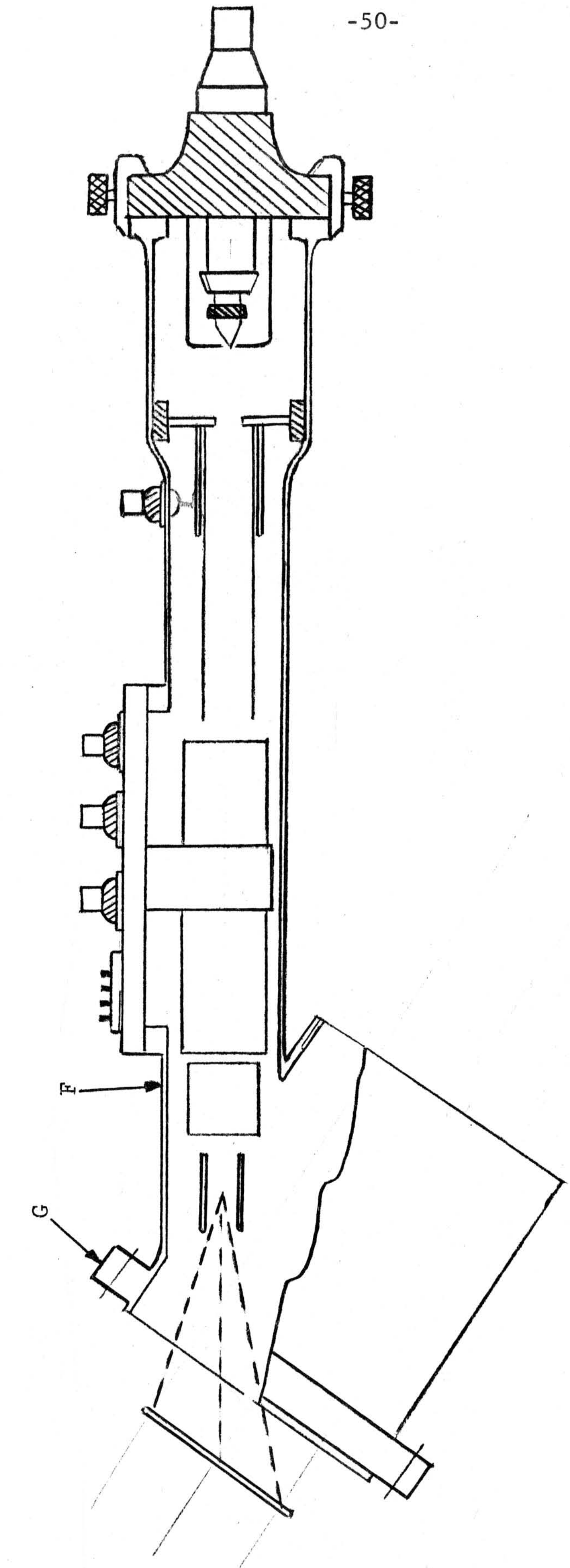
HIBI POINTED CATHODE

Figure 19



Scale: 100 microns

Fig. 20. Typical pointed cathode produced at GEL.
Note: Weld is uniform but tip is too long and too large. This point was not used because it was not alinged with the filament.



BASIC GEOMETRY OF MARK III GUN

Figure 21

LIST OF REFERENCES

Ref. #

1 Fernandez-Moran, H., J. A. Phys. 31, p. 1840, 1960.

2 Maloff, I.G. and Epstein, W.D., "Electron Optics in Television", Wiley, N.Y., 1938.

3 Jernakoff, G. and Newberry, S.P., TIS #61GL39.

4 Scherzer, O., J. A. Phys. 20, p. 20, 1949.

5 Klemperer, O., "Electron Optics", 2nd Ed., Camb. U. Press, 1953.

6 Aiken, Wm. R. (to Kaiser Ind.), U.S. Patent #2,945,974, July 19, 1960.

7 Weinmer, P.K. and Ryan, N., RCA Rev. 12, p. 503, 1951.

8 Hibi, T., J. El. Mic. Soc. Japan 3, p. 15, 1955.

9 Maruse, S. and Sakaki, Y., Optik 8, p. 485, 1958.

TABLE OF CONTENTS FOR APPENDIXES

Appendix I

Letter, Newberry to Schilling, Instructions for Mark III Gun

The two Mark III electron guns were picked up this morning by Frank Romano along with the deflection circuit which you loaned us and a portable TV set which we purchased to give a signal for modulation tests of the guns.

To help you operate the gun prior to receiving the full report of the gun program, the following operating notes are offered:

The filament as it is now set in the cap at 5 mils below the surface should be run at 1.8 amperes as you receive the guns. New 4 mil filaments as purchased from X-ray (Cat. #421D100 G-1) can start at 1.9 amperes.

To operate the gun the voltages must be set up according to the accompanying sketch by an electrostatic voltmeter and, if the voltage dividers are not stiff enough, the voltages may need to be readjusted to value with full beam current. This is especially true of the anode voltage since up to 300 microamps flows to it. Once a spot is obtained, it should be reduced to small dimension by a combined use of the grid bias and the grid lens focus A_2. If the spot becomes a line instead of a small spot, one will observe that the line changes over to a line at right angles to its original direction as it goes through focus. To correct this condition, set A_2 to the midpoint between a good line and the change-over point, then move the control which makes the line shorter in this direction. The lenses C_1 and C_3 work in the same direction, C_2 works at right angles to them. When the line focus elements, (C_1, C_2&C_3) are properly adjusted, passing through focus with A_2 will not depart from a circle.

This mode of operation is good for beam currents from 1/2 microampere to 6 microamperes or more (we have had 12 microamperes output on the electron optical bench mockup). At a given beam current level the filament should of course be operated just hot enough to make the spot focus well. If three lines appear instead of a spot, this is due to the source producing a spot within a circle of electrons. This condition can be caused either by too low filament heater current or by setting the filament too high in the grid.

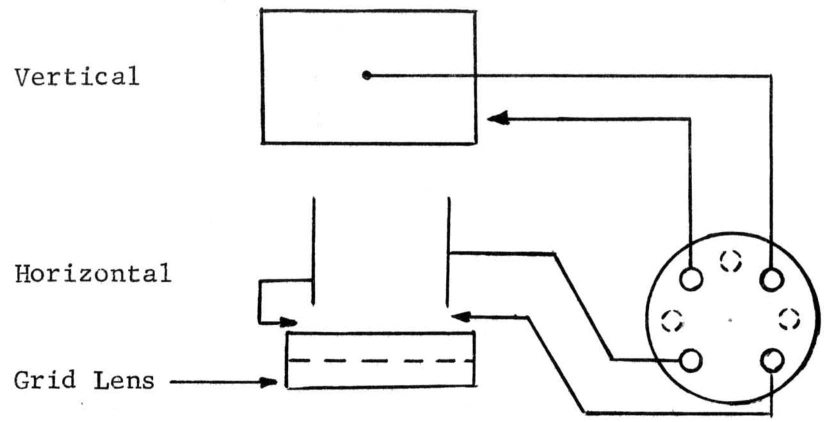
The above mode of operation should cover the range of currents required in Talaria with a spot diameter to the 50% point of less than a mil. The gun can be operated at other voltage settings which give a smaller spot at considerable sacrifice in beam current. It can also be operated with the anode at true ground providing you have positive voltage below ground available from the same supply. One must not mix voltages from two different supplies unless they are very closely regulated. These other modes of operation will be covered in the report.

I believe the status of the gun development to be as follows. Apparently the specific configuration in the Mark III guns using the combination of grid lens and line focus elements in a relay lens setup has reached a plateau and may be at the actual limit of its performance capabilities. To the best we are able to determine, without having had a chance to produce a color raster, the gun does not meet the specification of 1 x .6 mils. We judge the intense part of the beam to be less than 1 mil because in all cases of fluorescent screen damage the damaged area was less than 1 mil in diameter. The total stationary spot glow was greater than two mils yet the rasters were well resolved so we are somewhat uncertain what is the right value to assign for the spot size.

The spot formed by the demagnification lens is less than 1/2 mil by 1/4 mil. If we could relay this at 2:1 magnification, then the spot would be as desired. It is possible that a different type of relay lens should be employed for higher resolution or that we are somehow misusing the grid lens, perhaps by failing to make the grid coincide with an equipotential surface. It may even be that Klemperer is wrong about the location of the principle planes of the grid lenses. We simply did not have time or justification for testing those possibilities.

I did make some interesting qualitative tests last Saturday. It turns out, as I have previously suggested, that one can place the deflection plates before the grid lens. This might be used in later versions to reduce the final magnification or might be used for an entirely new approach.

If the pointed cathode or other small source could be developed, then one could make a very simple system using the lens shown on the second attached page. I made a mockup of this lens and found that it gives a deflection defocus of about 2:1 at $\pm$ .875" and that its deflection sensitivity when operated as an einzel lens is roughly the same as with no lens at all. I did not get to try it as an accelerating lens. If these ideas could be made to work out, they could be adapted directly to the present housings since the electron optics package is on a removable platform.



When target voltage at ground
and source at -10.00 kv
then:

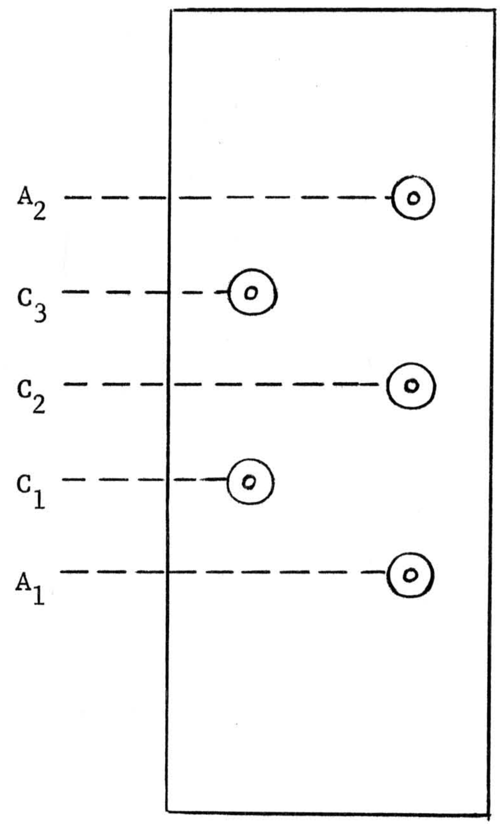
A_2 = 2.45 kv = Grid Lens

C_3 = 5.40 kv = 2nd Strong Element

C_2 = 6.15 kv = 1st Strong Element

C_1 = 6.50 kv = Corrector Element

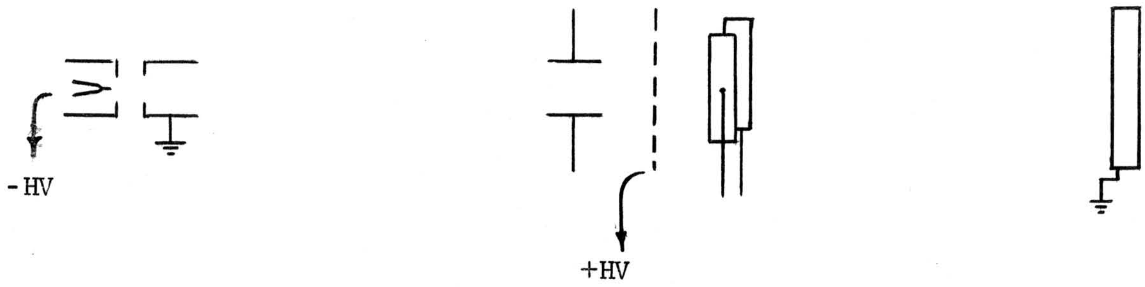
A_1 = 5.00 kv = Anode



Pin Connections

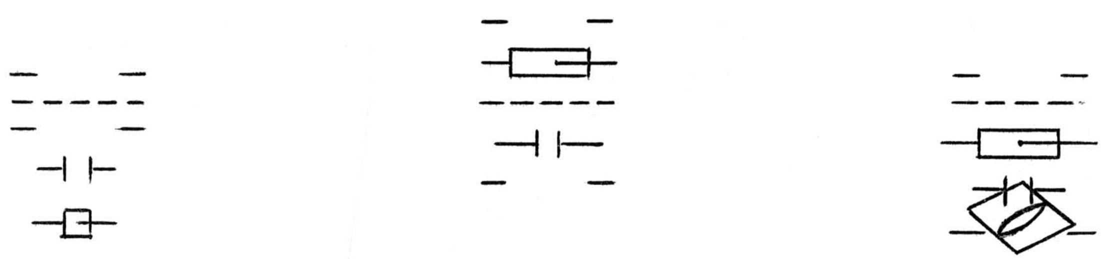
RECOMMENDED VOLTAGES TO APPROACH FOCUS
AND CORRESPONDING PIN CONNECTIONS
FOR MARK III GUN

Figure A-1



Source | Deflection and Lens | Screen

I. Test Setup Used for Combined Deflection and Grid Lens Unit



a) Preceding But Independent of Lens

b) Plates on Either Side of Grid

c) Both Plates Preceding Grid with Astigmatism Corrector

II. Possible Alternate Arrangements of Basic Principle

DEFLECTION THROUGH A GRID LENS
TEST SETUP AND POSSIBLE ALTERNATE ARRANGEMENT

Figure A-2

Appendix II

Chronological Summary of Laboratory Findings, 1960

Page	Test # or Date	Finding
		On December 24, 1959, set the parameters for the MSVD electron gun, based on a new form of einzel lens employing two line focus elements.
-	1-18-60	High current density proved possible with line focus elements.
-	4-21-60	Defocus modulation proves attractive.
-	4-22-60	Preliminary test of Demag./Mag. System - Can't relay spot from ordinary einzel lens but can relay spot from line focus einzel.
5	4-26-60-2	Relay lens must have low spherical aberration butterfly pattern shows effect of beam too divergent for the relay lens.
9	7-21-60	Talaria work started problem areas spelled out.
11	7-21-60	Calculation of magnetic prism for Talaria.
14	8-22-60	Test fixtures for Talaria designed and placed in shop.
20	8-22-60	Test fixtures available - work started.
-	8-22-60	Pinwheel effect encountered.
23	8-22-60-3	Obtained 1 mil spot with Demag./Mag. system, decided to place major emphasis on this approach.
25	8-24-60-1	Source to strong lens distance of 6" established, with 4 mil aperture 12 micron wide line obtained without halo.
27	8-25-60	Ultrasonic cleaning of molly apertures found to be effective.

Page	Test # or Date	Finding
28	8-25-60-2	Eight micron wide line obtained at 143 mils working distance for direction of least demagnification; two micron wide line obtained in most favorable direction. Demonstrated to Williams, Lemmond, et al.
30	9-1-60	Pointed filament given strong endorsement by Frandez-Moran of Boston Hospital.
31	9-1-60-1	Relay system gives 10 micron by 10 micron spot with 15 inch gun length (7, 4, & 3-1/2 in.).
32 34	9-1-60-2 9-2-60-2	Beam striking lens, apparently making much wider excursions within the lens than expected.
35	9-2-60-3	Photograph taken of relayed spot, focus voltages measured, complete line focus system.
36	9-6-60-1	Star pattern returns with more critical viewing conditions.
37	9-6-60-2	Rotation of relay lens with respect to strong lens does not affect star pattern. Rotation test device described. Forty-five degree rotation does not help either.
39	9-7-60	Decision to increase aperture of relay lens. Preliminary measurements of beam divergence. Useful beam current must be increased.
42 49	9-8-60-2 9-9-60-2	Maximum beam divergence accepted by relay lens measured. One quarter inch aperture accepts 160 mil beam.
44	9-8-60	Phototape, preliminary tests of.
50	9-12-60	Large aperture relay lens - first tests inconclusive.
52	9-12-60-3	Relay lens close to strong lens, accept magnification troubles in exchange for smaller beam entering relay lens. See also pg. 117.
54	9-19-60	Beam divergence discussion of problem status.

Page	Test # or Date	Finding
58	9-20-60-2	Sixty mil aperture too large for strong lens, 30 mil aperture ok.
60	9-22-60	Phototape test resumed.
63	9-27-60	Fifty mil aperture too large for strong lens. Scherzer's correction demonstrated with multiple element lenses.
67	10-60	Test of grid in lens aperture. See also pg. 112. Result discouraging.
72	10-18-60-1	Rotation of image due to misalignment.
80	10-20-60-5	Rotation of image due to misalignment corrected.
82	10-21-60-1	Operating voltage for 1/2" WD.
82	10-21-60-2	Depth of focus measurements (movable screen).
85	10-24-60	Depth of focus measurements - cont'd.
89	10-25-60	Simple lens long object distance not promising.
95	10-27-60	Eyepiece calibration for 50X.
97	10-27-60-3	Photo which demonstrates that aperture removes halo without reducing spot intensity. Also, simple lens long object distance test cont'd.
98	10-27-60-6	Current attainable at long distance from source.
102	10-28-60-2	Misalignment due to geometrical errors, not to dirt or other fortuitous causes.
110	10-30-60	Comparison single lens and two-lens system.
111	10-30-60-3	Comparison with Siemens' illumination system.
112	10-30-60-4	Rotation between lens sets not critical or useful.
112	10-30-60-5	Concluding tests which prove that grid no good in entrance or exit apertures of lens. Some halo reduction but prismatic action very bad.

Page	Test # or Date	Finding
113	10-30-60-5	Possibility of transparent membrane.
117	10-30-60-14	Moving relay lens closer gives better results, loss due to increased mag. made up by smaller beam cross section. See also pg. 52.
118	10-30-60-15	Combined strong and relay lenses in same package. Image rotation less important, indication of mutual correction but too much interaction of focus when focus both directions at same time. Not recommended at this time for Talaria development.
120	10-30-60-17	Grid in center element - result very encouraging.
127	10-31-60-1	Strong lens astigmatism magnified by relay lens.
128	10-31-60-3	Third element beneficial, obtained independence of focus.
137	11-3-60-2	Successful relay of line foci by grid lens.
138	11-3-60-3	Three to five micron spot with 1" WD gun.
139	11-3-60-4	1.8 x .9 mils obtained by grid lens alone with 1" WD.
144	11-4-60-1	Current intercepted by grid is small. Also from Klemperer learn that principle plane is on image side giving gain in working distance for given lens strength.
144	11-7-60-1	Coarse grid shows strong prismatic action, and thereby increases 2 mil spot to 20 mils. Smaller grid does not collect more current.
148	11-7-60-2	Limiting aperture should not be in lens field.
149	11-7-60-4	Optimum ground element to grid spacing approx. 3/8".
153	11-9-60-4	Current through grid lens is very small unless lens is accelerating.*
155	11-9-60-8	Grid lens does not make good strong lens.

*Later found to be in error, see Test 2-16-61-1 (pg. A-14).

Page	Test # or Date	Finding
157	11-10-60-1	Grid lens best strong lens performance at 200 mil WD is 2 to 3 mil spot of unsharp edges.
158	11-10-60-2	Prove feasibility of using negative voltage on correcting element. Also, produce intermediate image of 10 x 2 microns.
159	11-10-60-3	Attempt to use four elements shows promise but can only get small spot in one direction because cannot stack in less than 2" space with present equipment.
165	11-11-60-6	Mark III system mockup with grid relay lens gives good performance.
167	11-14-60-1 thru 3	Must guard against tendency to make strong lens a weak correcting element for relay lens. This is what happens if one tries to focus by trial and error - must set voltages very close to right values before attempting to focus visually.
173	11-16-60-2	Inversion of focusing voltage due to interaction of two directions, good example of.
175	11-17-60-1 & -2	3/4" radius element gives almost independent focus in the two orthogonal directions, need different radius for the two directions.
195	12-5-60-2	Electron mirror composed of conducting plane looks very attractive.
197	12-7-60-8	Photographs of mirror performance, grid of spots.
200	12-12-60-2	Deflection through lens shown to be reasonably linear in test of MSVD gun.
202	12-12-60	Optical alignment of line focus, method employed.
211	12-13-60	Preliminary test of pointed filaments looks encouraging.
219	12-14-60	Continued tests of pointed filaments, need smaller and shorter points.

Page	Test # or Date	Finding
228	12-16-60-2	Exact replica of Mark III strong lens proves: 1. Design is sound. Electrode radii approx. right. 2. Correcting element works. 3. When lens mechanically aligned, then it is also electrically aligned.
234	12-20-60	Electron mirror - photographs of TV images with both hairpin and pointed cathode - point apparently too large.
237	12-20-60	Initial tests of Mark III gun produce TV picture - look encouraging.
	1961	
6	2-7-61	Make exact demountable mockup of Mark III gun and find performance considerably better than Mark III (cannot resolve spot at 10X mag. which is 1 mil resolution or better) so decide Mark III must have some basic difficulty other than its design.
7	2-7-61	Test effect of insulators close to lens, find no difficulties.
9	2-8-61	Arcing over difficulty cured by sealing crack between two adjacent insulators.
9	2-8-61	Found lens spacer incorrect causing poor contact. Corrected by metallic shims.
9	2-8-61-1	Find some barrel distortion in strong lens of Mark III mockup. Strongest element of strong lens over-compensated.
12	2-8-61-3	Change of grid lens spacing from 300 to 375 mils gives improvement. Spot 1.2 mils wide (total spot; not 50% point).
12	2-8-61-4	Substitution of 5/8" radius for 1/2" radius causes more distortion.
14	2-9-61-1	Substitution of 5/8" radius for 1/2" radius with photographs.

Page	Test # or Date	Finding
15 16	2-9-61-3&4	Try to test magnification of grid lens - learn that beam current drops drastically when cross over of strong lens made small and that relayed image can be made to follow size of strong focus image.
17	2-9-61-5	Try 125 mil aperture in front of relay lens instead of 80 mils. Obtained line foci of 1.2 mils x 0.6 mils but had terrific halo around them in butterfly pattern showing spherical aberration limit or distortion.
19	2-10-61-1	Substituted 3/4" radius instead of 5/8". Halo slightly worse.
19	2-10-61-2	Went back to 3/8" radius as in Mark III obtained better spot; halo reduced. Image again a small square. Note effects of dirt on the grid causing much of the general halo.
20	2-10-61-3	Tried extreme condition of 1/8" round hole for the last element of the strong lens. Obtained more halo than in test 2. Can operate as an axially symmetrical lens with line focus corrections but axially symmetrical element should come first.
21	2-10-61-4	Replace grid relay lens by line focus relay lens. Could get spot less than 0.6 mil x 1 mil but current only 1/10 microampere. When increased, beam current spot grew rapidly to 3 or 4 mils.
22	2-10-61-5	Examined fluorescent screen to see if spot might be enlarged due to large areas being destroyed. Found only two burn marks larger than one mil. Very many burn marks less than 1 mil diameter. This and the above test make one suspect that the fluorescent screen will spread high current, stationary spots. Therefore, don't know whether line focus relay system has failed at high current or not. So tried shadow image of 250 mesh grid with one mil wide grid bars and obtained good image strongly indicating that complete line focus system gives less than 1 mil spot.

Page	Test # or Date	Finding
23	2-10-61	Discussion of validity of shadow test method. Conclusion: very reliable for high angle short working distance setup - can be misleading at long working distance.
25	2-13-61	Returning to grid relay lens with adjustable slit aperture (3" distance required between lenses) obtain 4μ amps with approx. 1 mil dia. to 50% point - definitely Gaussian distribution.
26	2-13-61-1	Substitution of 10 mil aperture for 80 mil and returning to standard 2" between lenses do not find the image behaving as if sensitive to either strong lens demagnification or to spherical aberration of grid lens. However, get invariant beam size at focus regardless of beam current. Perhaps screen is imposing a fundamental limit.
27	2-13-61-2	Substitute 40 mil aperture - no change of spot size - final spot size is independent of relay lens aperture and demagnification of strong lens.
28	2-13-61-3	Series of qualitative tests show that only way to change spot characteristics is to change ratio of anode voltage to screen voltage. At high negative anode voltage very small spot low current while anode close to ground small spot but high halo and current not high. Relay lens alone gives three images (source found later to be emitting from three spots) about 3 mils dia.
31	2-15-61	Status note and review - postulate that 2" separation limits the operational modes in which focus is possible. When focus is possible, may have relay lens magnification as high as 5:1 giving 1-1/2 to 2 mil spot. Raise possibility of a telefocus combination between strong and relay lens since grid lens makes possible a purely diverging electron lens. Conclude that we now have a gun with Mark II performance in a smaller package. Explanation for square spot proposed.

Page	Test # or Date	Finding
37	2-15-61-2&3	Find circuit discrepancy which has kept the anode from being stiff enough partially explaining some previous anomalies of very strong dependence of focus on gun bias setting and why current was sometimes limited.
39	2-15-61-4	With anode potential tightly pegged and system aligned from bottom up could obtain 10μ amps in finished relayed spot about 2 mils outside diameter without halo on one axis. Find grid lens would have to go positive below ground to focus when anode at 1/2 voltage. Suggest improvements to move strong lens focus further from grid lens or smaller diameter tube for grid lens.
41	2-15-61-5	Separate lens 1/2" more (2-1/2" - center to center). Can now focus but can't increase demagnification of strong lens without sharply decreasing current. However, spot size is not function of current for given focus condition.
42	2-15-61-6	Qualitative test of grid einzel lens rather than grid tube lens is encouraging. Is expected to shift principle plane toward final screen and thus have same beneficial effect as separating lenses physically.
43	2-16-61-1	Obtained three microamperes operating as grid einzel lens and for the first time on the Mark III mockup find the relayed image has all the focus properties of the strong image - however, now bothered by halo in one direction indicating lens error or distortion.
45	2-16-61	Discussion - grid einzel lens properties.
47	2-17-61-1	Substitute 1/4" tube for 1/4" aperture in grid lens and operate as a tube grid lens. Again find strong interaction between gun bias and focus. Halo in one direction. Grid einzel appears to be better mode of operation.
48	2-17-61-2	Put 15 mil aperture in front of grid einzel lens can get large spot at 5μ amps but can't get greater overall demagnification. Can't trade beam current for spot size. Indication again of screen blooming.

Page	Test # or Date	Finding
50	2-17-61-5	With normal Mark III geometry and correcting element C_3 at higher voltage obtained good image at 3μ amps but still one to two mils outside diameter.
51	2-18-61-1	Test of balanced line focus system, i.e., strong line focus elements sandwiched between two weaker ones so demagnification will be the same in both directions. Results inconclusive because line focus elements not flat.
53	2-18-61-2	Same but successful - 4μ amps obtained.
54	2-18-61-3&4	Check demagnified image, find 0.2 x 0.4 mil.
54	2-18-61-4	With grid lens in place, find it relays a spot which looks like a magnified image of strong lens focus but is magnified too much.
56	2-18-61-6	Rechecked single lens operation with grid relay lens alone - not quite as good as demagnification system. Suggest trying deflection through a grid lens.
57	2-18-61-7&8	Find can deflect through grid einzel lens if open up entrance and exit apertures. Deflection of 0.4 - 35" with 280 volts spot size increases with beam current. This is another drawback of single lens operation.
59	2-18-61-9	Combined deflection plates with lens entrance aperture - results encouraging but gives line focus.
59	2-18-61-10	Horizontal plates below vertical plates above grid and no other grounded elements. Get symmetrical focus - deflection sensitivity vertical 0.8 - 35" for 280 volts and .520" with 125 volts horizontal. Combining deflection with grid lens looks very good.
61	2-20-61-1	Checked deflection without grid lens action at same distance, find 280 volts gives .890".
61	2-20-61-2	Return to exact replica of Mark III gun with new piece of 750 mesh grid except left 80 mil aperture out altogether but could replace it as desired without altering rest of setup. New grid abolished multiple images and much of halo. Established good operating voltages.

Page	Test # or Date	Finding
64	2-21-61-1&2	Comparison of 750 mesh grid and 250 mesh grid shows slightly larger spot with 250 mesh grid (perhaps 50% increase). Guns wrapped up and delivered.

Appendix III

Comparison with the Results of Others

It is interesting to compare our result with the theoretical maximum current density given by Klemperer[5]:

$$i_{max} = i_{cathode} \left(V' \frac{e}{kT} + 1\right) \sin^2 \theta'$$

where $i_{cathode}$ = cathode current density

V' = terminal voltage

θ' = semi-angle converging to spot

If we take the maximum excursion of the electrons to be 50 mils from the axis, then $\theta' = 50/5000 = 1 \times 10^{-2}$ radians. Substituting this and other values for the Mark III gun we obtain:

$$i_{max} = 10 \left(10^4 \frac{11600}{3000} + 1\right) \quad 10^{-4}$$

$$= 1.56 \text{ amps/cm}^2$$

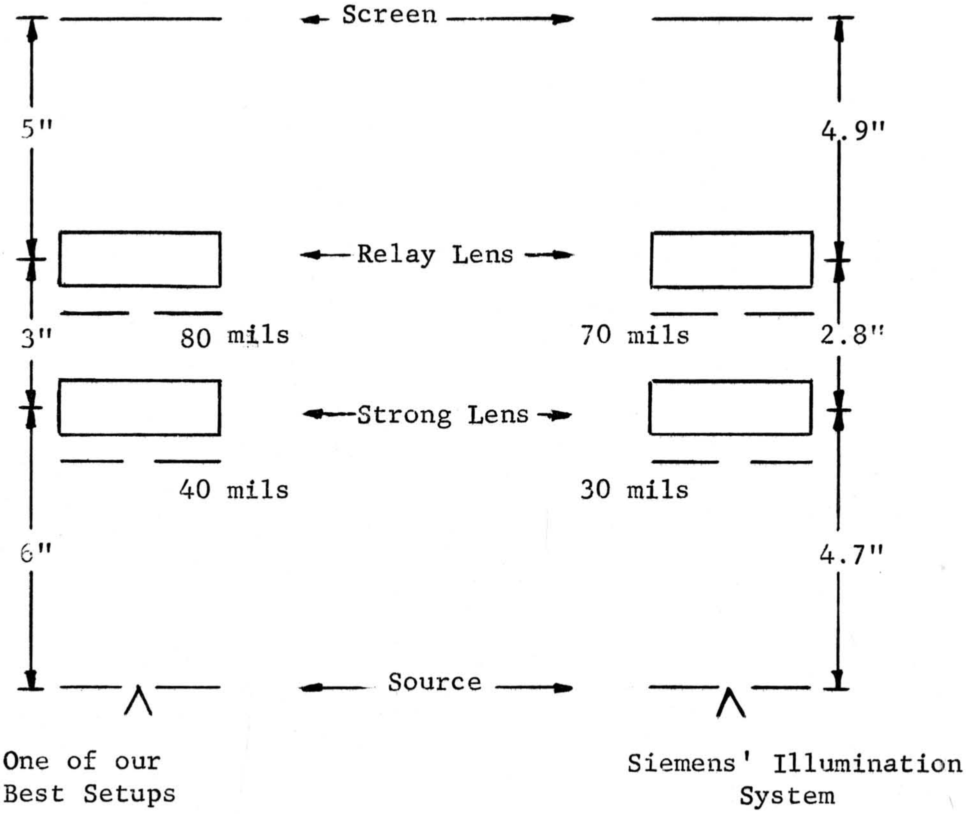
Our result of 10μ amps in a 25 micron circle gives

$$\frac{10^{-5} \text{ amps}}{625 \times 10^{-8} \text{ cm.}} = 1.6 \text{ amps/cm}^2$$

Recent tests of Schlesinger's FRM gun give 1.4μ amps in 10μ spot or 1.4 amps/cm^2.

The demagnified spot of our strong lens has 10 microamperes in 5 x 10 microns or 20 amps/cm^2. If we could relay this spot at 2:1 magnification without loss of current, then we would expect the current density to decrease by 4:1 or 5 amps/cm^2. Our best electron optical bench tests indicated the relay lens could transmit at least half of the current.

It is also interesting to compare the geometry used on the electron optical bench at one stage of development with the geometry found in the illumination system of the Siemens' electron microscope. This system operates at 100 kv with magnetic lens and obtains one microampere in a two micron diameter beam or 25 amperes/cm^2. The comparison is shown in Figure A-3 on the next page.



COMPARISON OF ONE OF THE BEST
RELAY-LENS SYSTEMS FOUND WITH ILLUMINATION
SYSTEM OF SIEMENS' ELECTRON MICROSCOPE

Figure A-3

Appendix IV

Memo, H. Poritsky, Calculation of Field Distribution in Three Dimensions

If V is symmetric about the plane $\theta = 0$, it admits the Fourier series expansion in θ

$$V = \sum_{n=0,1....} V_n(r,z) \cos n\theta \quad . \tag{1}$$

If V is symmetric about both $\theta = 0$ and $\theta = \pi/2$, then only even multiples of n occur in the Fourier expansion:

$$V = \sum_{n=0,2....} V_n(r,z) \cos n\theta \quad . \tag{2}$$

Expanding V_o in powers of r and substituting in Laplace's equation, one obtains

$$V_o(r,z) = \phi_o(z) - \frac{r^2}{2^2}\phi_o''(z) + \frac{r^4}{2^2.4^2}\phi_o^{(4)}(z) + \ldots \quad . \tag{3}$$

where ϕ_o is an arbitrary (analytic) function of z. This can be written symbolically as

$$V_o = J_o\left(r\frac{\delta}{\delta z}\right) \cdot \phi_o(z) \quad . \tag{4}$$

where $J_o(r\frac{\delta}{\delta z})$ is the Bessel function of order zero, provided J_o is expanded as a power series, each term is multiplied by ϕ_o, and interpreted as follows:

$$\left(r\frac{\delta}{\delta z}\right)^k \phi_o = r^k \frac{\delta^k \phi_o(z)}{\delta z^k} \quad . \tag{5}$$

Similarly, one proves that for any integer n

$$V_n(r,z) = J_n\left(r\frac{\delta}{\delta z}\right) \phi_n(z) \quad . \tag{6}$$

where ϕ_n is an arbitrary function of z. Thus

$$V_2(r,z) = J_2\left(r \frac{\delta}{\delta z}\right) \phi_2(z) = \frac{(r)^2}{2^2\ 0!\ 2!} \frac{\delta^2 \phi_2}{\delta z^2} - \frac{r^4}{2^3\ 1!\ 3!} + \ldots \tag{7}$$

By renaming the coefficient of r^2 as ϕ_2, this may also be put in the form

$$V_2(r,z) = r^2\phi_2 - \frac{r^4\phi_2^4}{4^2-2^2} + \frac{r^6\phi_2^{(4)}}{(4^2-2^2)(6^2-2^2)} \quad \ldots \tag{8}$$

More generally, one may replace (6) by

$$V_n(r,z) = r^n\phi_n(z) - \frac{r^{n+2}\ \phi_n''(z)}{\left[(n+2)^2 - n^2\right]} + \frac{r^{n+4}\ \phi_n^{(4)}(z)}{\left[(n+4)^2 - n^2\right]\left[(n+2)^2 - n^2\right]} + \ldots \tag{9}$$

Neglecting powers of r beyond r^4, eq. (2) becomes

$$\begin{aligned} V(r,z) &= \phi_o(z) - \frac{r^2}{2^2}\phi_o'' + \frac{r^4}{2^2.4^2}\phi_o^{(4)}z \\ &+ \cos 2\theta \left[r^2\phi_2(z) - \frac{r^4\phi_2''}{4^2 - 2^2}\right] + \cos 4\theta \left[r^4\phi_4(z) + \ldots\right] \\ &= \phi_o(z) - \frac{r^2}{4}\phi_o''(z) + \frac{r^4}{64}\phi_o^4(z) \\ &+ (x^2-y^2)\left[\phi_2(z) - \frac{r^2}{12}\phi_2''(z)\right] + (x^4 - 6x^2y^2 + y^4)\left[\phi_4\right] . \end{aligned} \tag{10}$$

The quadratic terms are

$$x^2\left(\phi_2 - \frac{\phi_o''}{4}\right) - y^2\left(\phi_2 + \frac{\phi_o^4}{4}\right) \quad . \tag{11}$$

They (along with ϕ_o) give rise to linear or Gaussian optics and to astigmatism (unless ϕ_2=0). The fourth order terms are

$$r^4 \left[\frac{\phi_o^{4}(z)}{64} - \cos 2\theta\, \phi_2^{''}(z) + \cos 4\theta\, \phi_4(z)\right]$$

$$= \frac{r^4}{64}\phi_o^{(4)} - \frac{x^4-y^4}{12}\phi_2^{''} + (r^4-4x^2y^2)\,\phi_4 \quad . \tag{12}$$

They give rise to aberrations.

If the potential V is determined in an electrolytic trough for $\theta = 0$ and $\theta=\pi/2$, then

$$V\Big|_{\theta=0} = V_o + V_2 + V_4 \quad ,$$

$$V\Big|_{\theta=\pi/2} = V_o - V_2 + V_4 \quad . \tag{13}$$

Taking half the difference, yields

$$\frac{V\Big|_{\theta=0} - V\Big|_{\theta=\pi/2}}{2} = V_2 = r^2\,\phi_2(z) - \frac{r^4}{12}\phi_2^{''}(z) \quad . \tag{14}$$

Thus by plotting

$$\frac{V\Big|_{\theta=0} - V\Big|_{\theta=\pi/2}}{2r^2} = \phi_2(z) - \frac{r^2}{12}\phi_2^{''}(z) \tag{15}$$

vs. r^2, for various fixed values of z, one may obtain both ϕ_2 and $-\phi_2^{''}/12$, from the intercept along the axis and the slope. Since $\phi_2^{''}$ can be also obtained from ϕ_2 by graphical differentiation or by means of finite differences, this can serve as a further check on the accuracy of the trough measurements and for smoothing ϕ_2 further.

By taking half the sum of the potentials in (13), there results

$$\frac{V\Big|_{\theta=0} + V\Big|_{\theta=\pi/2}}{2} = V_o + V_4 = \phi_o - \frac{r^2}{4}\phi_o'' + r^4\left(\frac{\phi_o^{(4)}}{64} + \phi_4\right) \quad . \tag{16}$$

Subtracting ϕ_o and dividing by r^2, there results

$$\left[\frac{\frac{V\Big|_{\theta=0} + V\Big|_{\theta=\pi/2}}{2} - \phi_o}{r^2}\right] = -\frac{\phi_o''}{4} + r^2\left(\frac{\phi_o^{(4)}}{64} + \phi_4\right) \quad . \tag{17}$$

This is now plotted vs. r^2. Assuming that the intercept and slope may be obtained with sufficient accuracy, one may check ϕ_o'' from the ϕ_o curve, and, after determining $\phi_o^{(4)}$ from ϕ_o'', calculate ϕ_4 from the slope.

Thus the separation of ϕ_4 from (16) is more difficult to attain and involves fourth order differentiations of ϕ_o.

A smoothing operation consists in tabulating first order and second order differences of ϕ_o at equally spaced values of z, plotting $\Delta_2\phi_o$ and smoothing them by means of French curves, then reading off new $\Delta_2\phi_o$ from the plotted smoothed curves to one or two more significant figures. The values of $\Delta_1\phi_o$ are then recalculated, then the values of ϕ_o, and the two available additive constants adjusted to fit the behavior of ϕ_o at ∞.

The process might be repeated for $\Delta_4\phi_o$ to obtain even further significant figures.

If one could conveniently carry out measurements in the plane $\theta=\pi/4$, then the determination of ϕ_4 is more direct, since (2) now yields

$$V\Big|_{\theta=\pi/4} = V_o - V_4 \quad , \tag{18}$$

and this could be combined with (16) to yield V_4 directly.

Appendix V

Letter Report, Farr to Newberry, Accuracy Required for Calculation of Field Distribution in Three Dimensions

This is a progress report of the work done by the technician, R. Geguzys and myself on the phase of the Talaria project which deals with the calculation of the field potential for the line focus einzel lens.

The geometry of the problem is such that we must work with three variables. However, the problem does possess a certain symmetry which we can use to advantage. By a procedure outlined by Dr. Poritsky, we first expand the potential in a Fourier series and discard all terms higher than the fourth power of the distance from the lens axis. If we are given the potential data on two mutually perpendicular planes, whose intersection is the axis, we can make use of symmetry and determine (at least theoretically) all of the unknown parameters.

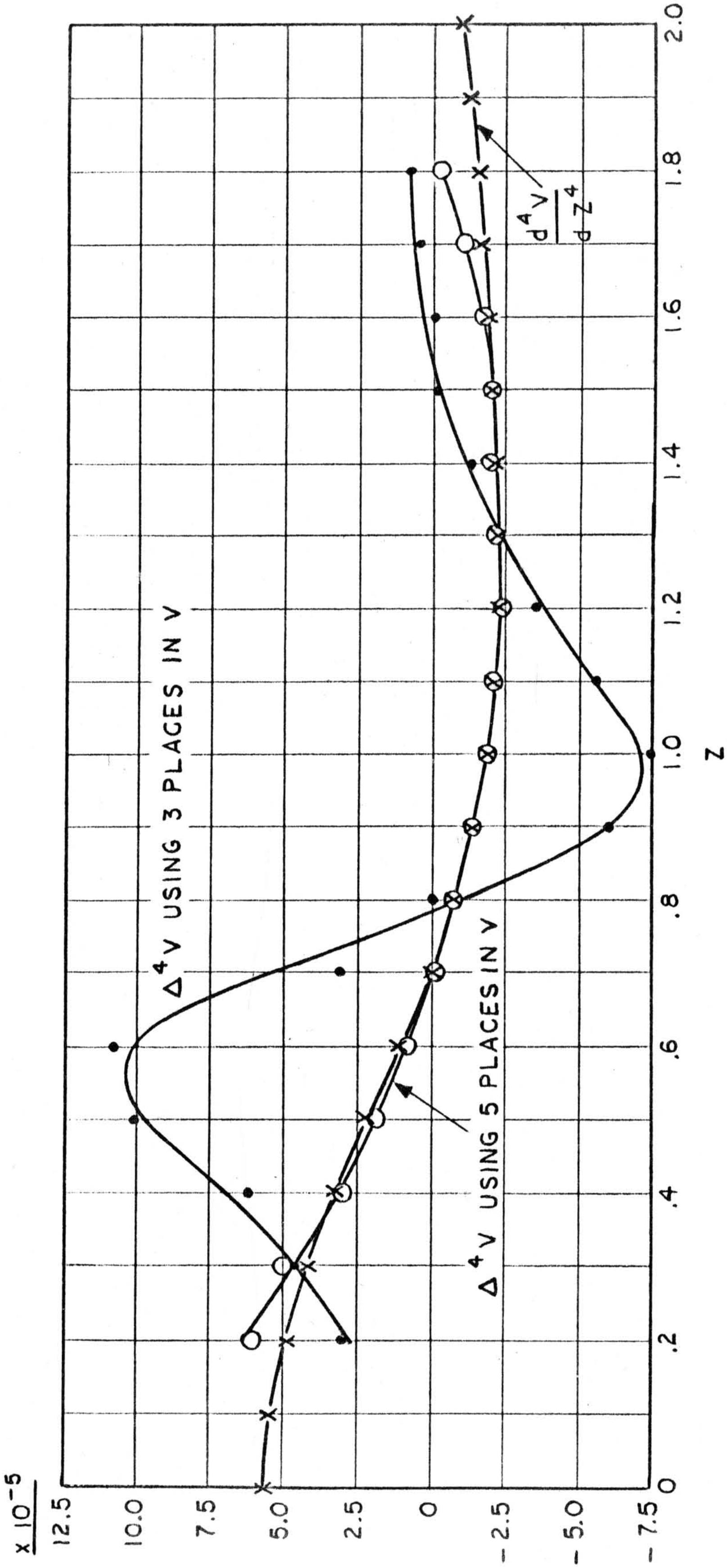
This method requires considerable numerical differentiation, smoothing, curve plotting, etc. In order to test out the method to determine its accuracy, we applied it to a hypothetical problem for which we know the answer. We place two point masses at coordinates (2,0,0) and (-2,0,0) in an X,Y,Z coordinate system. The potential V(X,Y,Z) is

$$V = \frac{1}{\sqrt{(X-2)^2 + Y^2 + Z^2}} + \frac{1}{\sqrt{(X+2)^2 + Y^2 + Z^2}}$$

The Z-axis represents the axis of the lens. Note that the equipotential surfaces are normal to the coordinate planes. We are required to determine the fourth derivative numerically along the axis so we evaluate this function from Z = 0 to Z = 2 in increments of 0.1. The results are shown in the attached graph where we give the exact fourth derivative, the best approximation we could get by numerical differencing using five significant figures in V, and the same using three significant figures in V. This clearly indicates that three significant figures in V are not enough whereas it suggests that five may be enough.

Of course, the situation is even worse than this because we need the fifth derivative to solve the differential equations for the trajectories.

The plan was to determine from an electrolytic tank the data on the two perpendicular planes and from this calculate all the parameters that we need in the series. But it appears to be practically impossible to get even three-figure accuracy by the electrolytic tank and, hence, the procedure as outlined will not work. There is reason to believe that our potential along the axis for the actual problem will behave much like the potential from our test problem so there is little promise in hoping for a differently behaving potential that would yield greater accuracy in our numerical differentiating process.



TEST OF ACCURACY NEEDED TO FAITHFULLY REPRODUCE
THE 4TH DERIVATIVE BY NUMERICAL DIFFERENTIATION

Figure A-4

Appendix VI

Letter Report, Klotz to Newberry, Electrolytic Measurements

This is to summarize the results thus far obtained from the electrolytic tank studies made on the line-focus electron lens.

As you know, since the system does not possess axial symmetry, the electrostatic field can be plotted only in the two planes of symmetry. It is then necessary to calculate the entire three-dimensional field from the data obtained in the two planes using Dr. Poritsky's procedure as described by Dr. Farr in his letter of December 8, to you. Dr. Farr indicated in this letter that we must obtain data correct to five significant figures in order to make the method work.

Inasmuch as I had no idea of the degree of accuracy required at the outset of the experimental work, I took no particular pains to eliminate errors. That is, I used plain brass electrodes with tap water as an electrolyte, and I used the electrolytic tank setup in Building 5 "as is" without any attempt to improve its performance. Several of the drawbacks of the equipment are the following:

1. No provision for precise leveling of the tank so that plane of travel of probe is exactly horizontal thereby insuring constant probe penetration depth.
2. Rather flimsy probe holder - subject to accidental shifting of probe relative to holder.
3. Available probes made of heavy gage copper wire sharpened to rather blunt point. Several materials (such as platinum) are superior to copper. Blunt point aggravates variations in penetration depth since diameter varies rapidly with depth.
4. Plotting table not fixed in position relative to probe carriage. Much time is wasted checking to determine whether or not plotting table has been accidentally shifted.
5. Carriage drive motors subject to large overshoot when bringing probe to null position.

Several investigators have found tap water entirely satisfactory for use as the electrolyte. No data has been reported on the composition of the local tap water used, however, so I have no idea how Schenectady tap water compares with that found satisfactory. On the other hand, some investigators insist that if high accuracy is to be obtained, the electrolyte must be carefully prepared from distilled water, and that the concentration must be within definite limits. (This means preparing and carrying by hand some 60 gallons of electrolyte to the present setup.)

Also, with regard to the electrodes, Pierce[1] states that "any clean metal will do for rough work". Some of the investigators who have attained accuracies approaching 0.1% have worked with various platings on steel or brass electrodes in combination with specific electrolytes. P. A. Einstein[2] believes that Aquadag sprayed on and suitably baked is the best electrode coating material.

Aside from the use of a liquid capillary probe most investigators believe that a platinum wire of about 0.1 mm. diameter makes the best probe.

The theoretical considerations behind the above findings are covered in the following papers as well as those previously referenced:

D. McDonald, The Electrolytic Analog in the Design of H-V Power Transformers, Proc. IRE 100, p. 145, 1953.

K.F. Sander & J.G. Yates, The Accurate Mapping of Electric Fields in an Electrolytic Tank, Proc. IRE 100, p. 167, 1953.

K.F. Sander, J.G. Yates, & C.W. Oatley, Factors Affecting the Design of an Automatic Electron Trajectory Tracer, Proc. IRE 99, p. 169, 1952.

The results I actually obtained bear out very well the fact that none of the seemingly insignificant details mentioned by the investigators in the field can be overlooked if extreme accuracy is to be obtained. The field plots which I made could not be repeated consistently within better than 1% in regions of low field gradient, and in the strong field regions, errors are probably as much as 2% or 3%.

---

[1] J.R. Pierce, Theory & Design of Electron Beams, Van Nostrand, 1954.

[2] P.A. Einstein, Factors Limiting the Accuracy of the Electrolytic Plotting Tank, Brit. J. Appl. Phys., 2, p. 49, 1951.

Thorough research of the literature reveals that at best, even after careful attention to all probable sources of error, an accuracy of 0.1% (three significant figures) might be attained. In view of the fact that at least five significant figures would be required to calculate the three-dimensional field for the non-axially symmetric system being investigated, I would recommend that future work be confined to axially symmetric systems or "two dimensional" arrangements, and that the work on the line focus lenses be discontinued.

Fortunately, some of the electron mirror arrangements fall into the "two dimensional" category, and electrolytic tank studies (or perhaps even the Teledeltos Paper Analog) might prove very useful for investigating them.

Appendix VII

Magnetic Field Necessary to Bend 7 kv Beam on 2" Radius

The use of a magnetic prism to deflect the electron beam into the light optics axis looks encouraging. A simple calculation shows that only a modest field strength is required. The standard formula for the radius of curvature of an electron in a magnetic field is

$$R = \frac{3.3715\sqrt{V}}{B}$$

where R is in cm.

V in volts

B in gauss.

Substituting numerical values for 7 kv beam we find:

$$5 = \frac{3.3715\sqrt{7 \times 10^3}}{B}$$

or B = 57 gauss for a 5 cm. radius.

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TECHNICAL INFORMATION SERIES

AUTHOR	SUBJECT CLASSIFICATION	NO. / DATE
S.P. Newberry	Electron Optics Electron Guns	NO. 61GL98 DATE May, 1961

TITLE

ELECTRON OPTICS PROGRAM FOR TALARIA

ABSTRACT

This report covers work done during late 1960 and early 1961 on a writing gun for Project Talaria. Much of the work is applicable to the general problem of production of high resolution oscillograph-type electron guns. Work relating to the properties of grid lens and line focus lens will be published later in a Class II report.

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CONCLUSIONS

The electron gun problem is not yet solved. It is required that we do at least one of the following:

1. find a smaller, brighter electron source,
2. permit the electron gun to be larger,
3. improve the spherical aberration of the lenses,

or change to a system which is satisfied by presently available electron guns.

INFORMATION PREPARED FOR Cathode Ray Tube Department

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