II. ELECTRON OPTICS

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A. HIGH-RESOLUTION HIGH-CONTRAST ELECTRON MICROSCOPY

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Joint Services Electronics Program (Contract DAAB07-71-C-0300)

John G. King, John W. Coleman

1. RESEARCH SUMMARY

The purpose of our work is to develop a new type of lens that will increase resolving power, image contrast, or both, for all kinds of electron optical scientific instruments. We shall also provide support to the Molecule Microscope project by helping to solve various problems in electron and ion optics.

Auger Emission Microscope (AEM)

We are now testing AEM-1, the first of three planned prototypes of the Auger microscope; this represents the first step in the development of an electron microscope capable of resolving both positions and types of individual atoms in complex molecules or on surfaces, without the use of heavy metal stains. Our ultimate goal is the direct demonstration of low-Z atoms such as nitrogen, oxygen, and carbon in biological specimens.

Our results with AEM-1 indicate that the scaled-up mirror lens works qualitatively as anticipated from the results of our original computer studies, but that refinements are needed in alignment capability, optical spacing, tilt control, and voltage ratios before the AEM-1 goal of 1000 Å resolution can be achieved (see Sec. II-A. 2). We expect to have enough data from AEM-1 by October 1974 to proceed with the design and construction of AEM-2.

Spherical Aberration Corrector Module (SACM) and Multioptical Bench

During this period, the development of SACM has continued principally in vacuum interfacing between the module and the elements of the multioptical bench. In particular, problems of traversing the several elements have required special attention, in

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order not to disturb the vacuum differential between the two systems.

We are now ready to begin quantitative testing on this foil-type lens for correcting spherical aberration. We expect that the new lens will improve the resolution of existing microscopes from 8 Å to 4-5 Å and for probe-type instruments will allow twofold or threefold more current into a given focused spot.

2. FIRST RESULTS WITH THE AUGER ELECTRON MICROSCOPE (AEM-1)

John W. Coleman, Steven R. Jost

Introduction

The AEM-1 is the first prototype of an Auger electron microscope, an emission-type instrument capable of identifying the species and resolving the positions of individual atoms in complex molecules and on surfaces. Because Auger electrons have energies dependent only upon the structure of the atoms from which they are ejected, they act as atom signatures if their energies are measured. If they can be collected by high-quality imaging optics, the sites of the emitting atoms within the specimen can also be established. With such an energy-analyzing optical-imaging system, there is no need for heavy metal staining or isomorphic replacement for low-Z atoms, and thus our ultimate goal with AEM is the direct observation of atomic carbon, oxygen, and nitrogen in biological specimens. The use of AEM is not fundamentally limited, however, to any particular kind of specimen. When fully developed the instrument will have wide application, especially in materials science.

Program Organization

The AEM development program as proposed, in 1967, by E. H. Jacobsen to J. G. King was concerned at first with theoretical research in several pertinent areas and computer studies of wide-angle achromatic electron lenses. This research continued until 1972 when a formally planned program was initiated with emphasis on developing a prototype which was based initially upon the preceding theoretical studies. The program was organized to be carried out in three phases: Phase 1 (1972-1974), design, construction, and testing of AEM-1 and design of AEM-2; Phase 2 (1975), construction and testing of AEM-2 and design of AEM-3; Phase 3 (1976), construction and testing of AEM-3 and completion of the program.

The specific purpose of constructing AEM-1 was to enable study of the computer-designed electron optics of the imaging system, in order to exclude constraints that would be placed on the electron optics by the subsequent optics of the energy-analyzing system. In particular, we are using a simulated Auger electron source, injected into optics scaled

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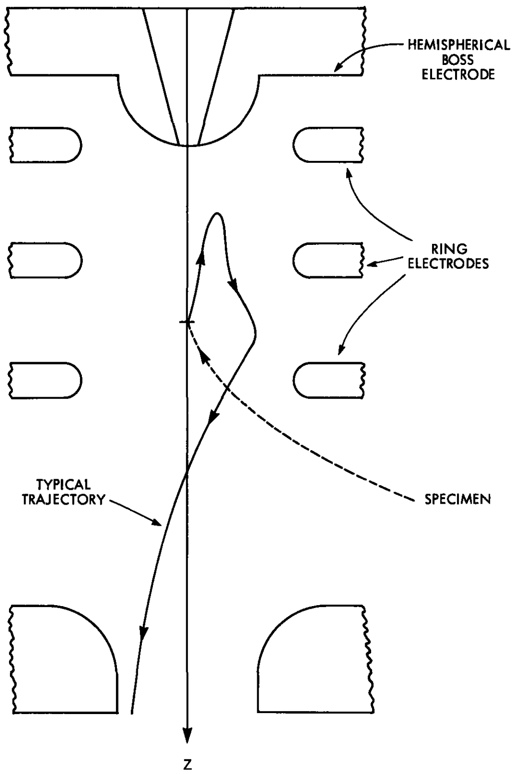

Fig. II-1.
"Most promising" geometry.

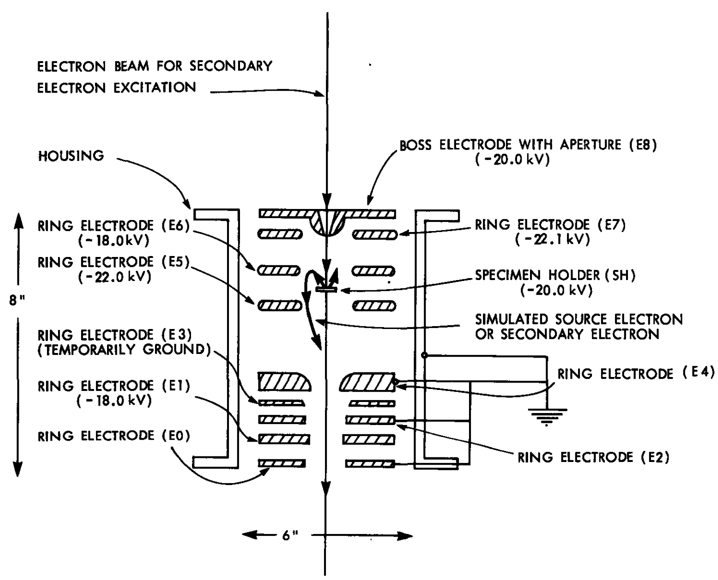

Fig. II-2. Mirror accelerator objective system. Voltages are for 300 eV electrons from the simulated source situated in the specimen holder (SH).

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JS up to facilitate study of geometric tolerances and alignment. Energy analysis in AEM-1 is limited to that which is chromatically inherent in the imaging optics as a function of input electron energy and lens voltages.

Construction of AEM-1

With the exclusion of the vacuum and electrical systems, the construction of AEM-1 has been implemented with the following design.

a. Mirror Accelerator Objective System

The geometry of this system is based upon the computer studies of Jacobsen and Ofsevit[1] and of Thomson[2] which are related to the design of achromatic lenses with extremely wide acceptance angles by the standards of conventional electron optics. These lenses are wide cones of the order of 10° that have been seen heretofore only in visible optics. The cylindrically symmetric geometry was selected as "most promising" for the starting point, and the dimensions that we used (see Figs. II-1 and II-2) furnish improvement by a factor of 4 over the dimensions given by computer. Because of the scale factor and uncompensated spherical aberration, we expect resolution of only ~1000 Å with AEM-1. This is not important in this phase of the program.

b. Simulated Source of Auger Electrons

The simulated source (Fig. II-3) is a coil-form thermionic emitter used in a

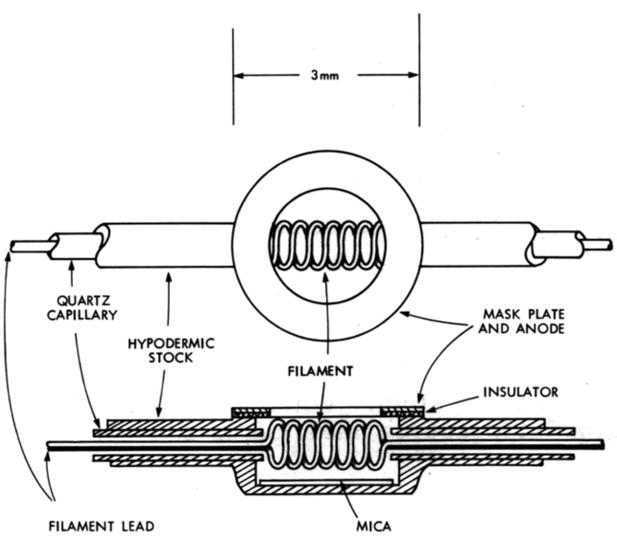

Fig. II-3.
Simulated source (325 eV max) of Auger electrons.

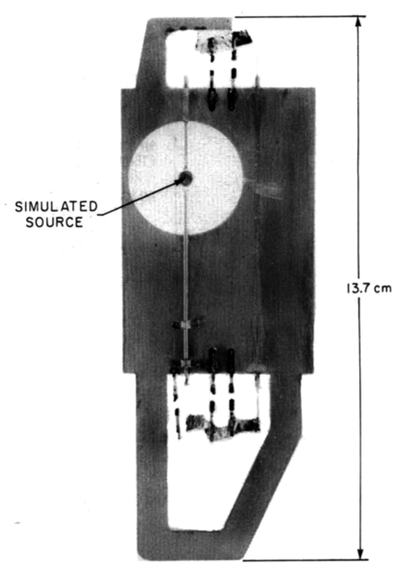

Fig. II-4.
Specimen holder.

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miniature triode gun to send a spray of electrons of controllable energy into the mirror accelerator objective system. The source rests in the specimen holder (SH) (Figs. II-2 and II-4). JS

c. Projection Recording System

The projection recording system (Fig. II-5) has two sets of magnetic deflectors and two magnetic lenses, with a final throw of 15 cm. This system, with a pick-up object plane 6 cm in front of the gap of the first lens, allows variable magnification from approximately 40-1970 X; further magnification ranges are possible if the position of the pick-up plane is other than at 6 cm. The deflectors are for alignment, and the final image is caught on a fluorescent screen on a glass prism. Photographs of the image are made with an MP-4 Polaroid camera exterior to the vacuum.

d. Secondary Electron Excitation System

The secondary electron excitation system in AEM-1 (Fig. II-6) is the forerunner of the Auger electron excitation system that will be used in AEM-2 and AEM-3. In AEM-1 the whole system is electrostatic. It is built from a Braucks-type electron gun, an Einzel (unipotential) lens, and two sets of electrostatic deflectors. The excitation beam enters the mirror accelerator objective system (see Fig. II-2) by means of an aperture (E8) and is stopped by the specimen holder (SH). In this way, secondaries with a wide range of energy may be sent through the mirror system, in contrast to electrons of a much narrower range of energy which may be sent through with the simulated source.

The overall assembly is shown schematically in Fig. II-7, and a view of the instrument is seen in Fig. II-8.

Data Collection

We are now taking three kinds of data with AEM-1.

i. Focused and/or shadow images of grids (100-1500 mesh/inch) at selected sites within the mirror accelerator objective system.

ii. Azimuthal intensity patterns (field energy profiles) measured from the fields photographed from the fluorescent screen.

iii. Specular reflection patterns recorded by photographs of the fluorescent screen.

All photographs are tabulated on worksheets (Fig. II-9) and filed. In this way we are acquiring the hundreds of images that are necessary to gain statistically definitive knowledge of the effects in the crucial areas of beam energy, electrode voltage, and system alignment, including the effects of electrode machining tolerances, tilts, and JS

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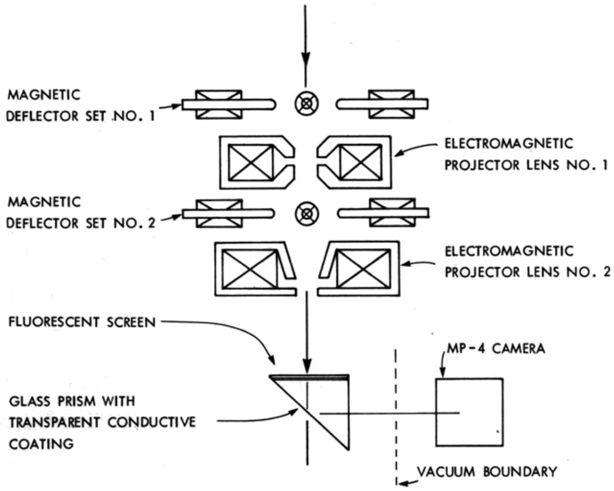

Fig. II-5.
Projection and recording system.

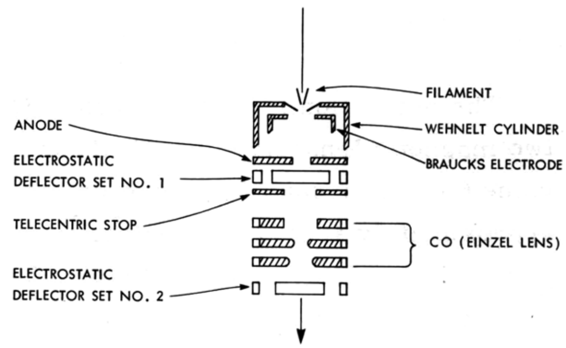

Fig. II-6.
Secondary electron excitation system.

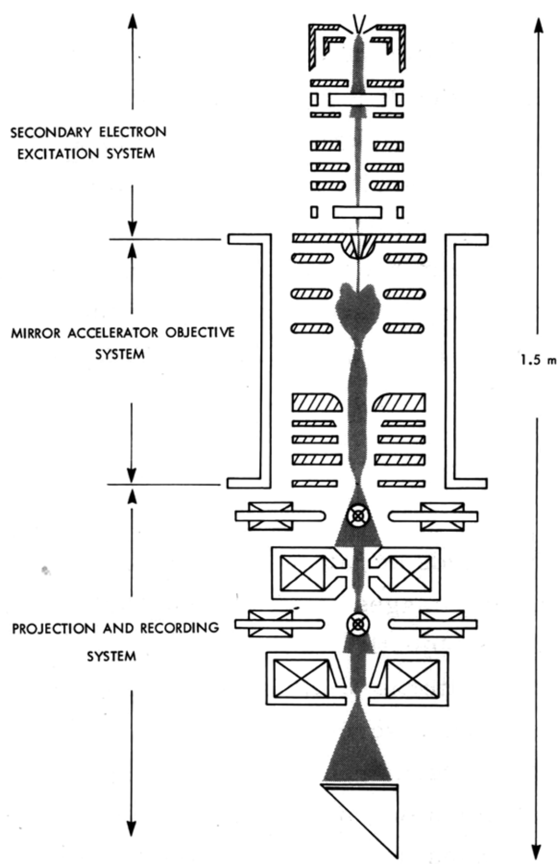

Fig. II-7.
AEM-1 overall assembly.

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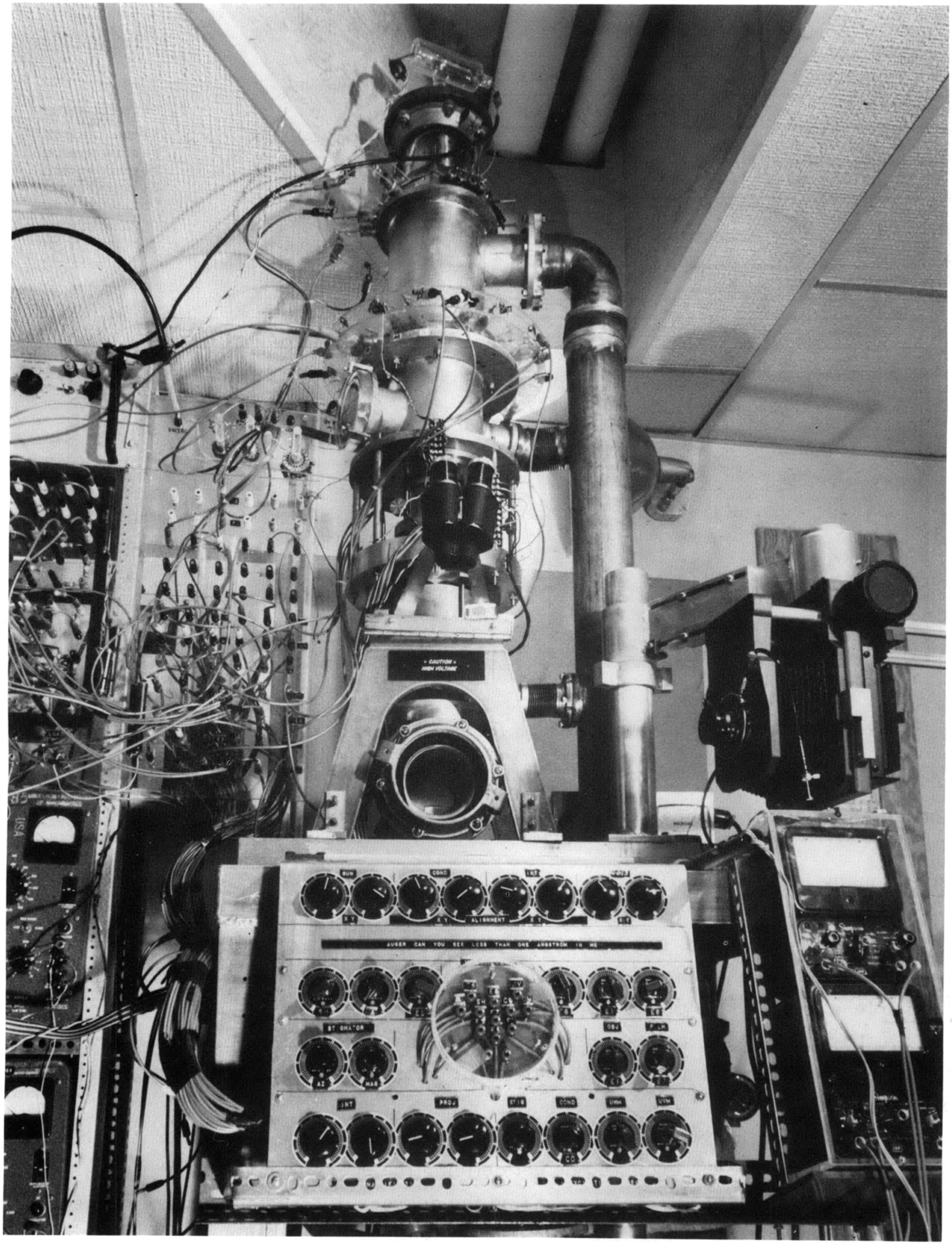

Fig. II-8. Photograph of AEM-1.

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INPUTS NUMBER 1				INPUTS NUMBER 2			
PD	-kV	PD	-kV	PD	-kV	PD	-kV
E7-⏚	12	E7-E1	1.25	E7-⏚	12.2	E7-E1	1.25
E7-E8	1.15	SH-E6	1.15	E7-E8	1.1	SH-E6	1.2
E7-SH	1.1	BS-E6	1.15	E7-SH	1.1	BS-E6	1.2
E7-E5	10V	BS-SH	0	E7-E5	20V	BS-SH	0
P1 (mA): 11		P2 (mA): 6		P1 (mA): 10		P2 (mA): 7.8	

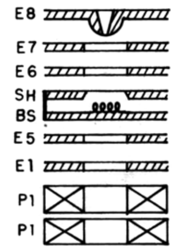
COMMENTS:

~12 kV ON GUN

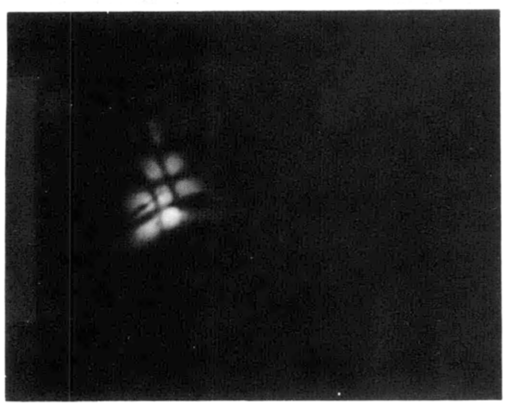
~1 min EXPOSURE

MESH ON E2

E7 SET TO GIVE
MAX BRIGHTNESS



RESULTS NUMBER 1



RESULTS NUMBER 2

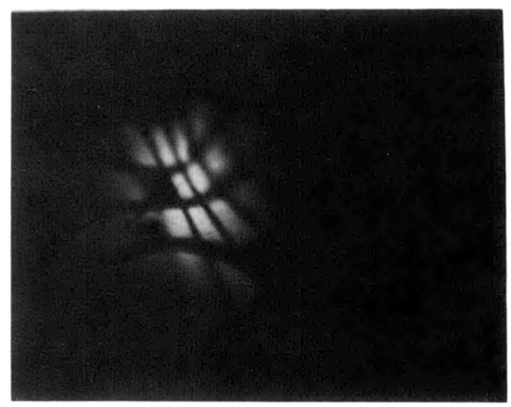


Fig. II-9. Sample AEM worksheet. (Series No. 1, May 14, 1974, S. R. Jost.)

concentricities with respect to each other.

<u>Preliminary Results</u>

We have used the data from AEM-1 to extract four kinds of information.

i. To study the use of the mirror accelerator objective system as a <u>compound projection</u> lens (before studying it as a <u>compound objective</u> lens).

ii. To find the kind and, as far as possible, the amount of geometric aberration in the system. (Spherical aberration, which will be treated independently at length, has been omitted.)

iii. To determine beam convergence and divergence in the preacceleration region (to determine the gross chromatic defect defining the energy window).

iv. To better align the system and find the degrees of freedom that are needed.

Although quantitative statements must await further statistics, our first results are qualitatively clear and reproducible. As shown in Fig. II-10, when the mirror accelerator objective is focused as a compound projection lens it delivers an image

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of less than unity magnification. Since the convergence/divergence characteristic of the preacceleration region is still not clear, we cannot separate the compound focal length into the contributing focal lengths, but we feel fairly certain that the JS

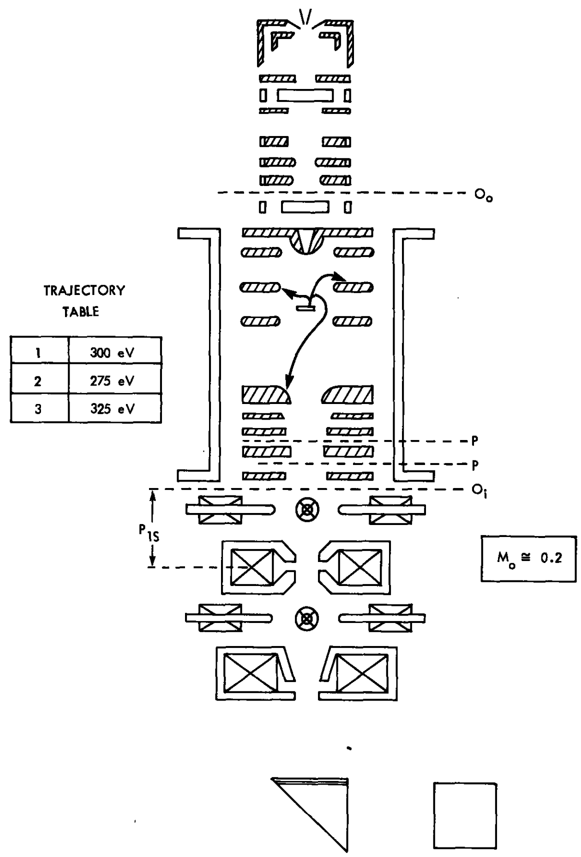

Fig. II-10. Mirror accelerator objective system focused as a compound projection lens.

postacceleration derived unipotential lens is limiting the overall magnification, and acts, at present, primarily as a transfer lens. Since we want magnification from the compound system of the order of 100 when it is used as an objective, and we estimate from the results when it is used as a projector that as an objective it can deliver maximum magnification of an order of magnitude less, we must eventually explore the possibility of changing the geometry and voltage ratio of the unipotential element.

Geometric aberration in the system is summarized in Table II-1. We feel that although there is still a great deal of aberration, we shall learn to remove it by alignment and compensate for it as our knowledge of the system grows. Spherical JS

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Table II-1. Mirror/Accelerator/Objective aberration.

Aberration	Present	Probable Cause
Pincushion Distortion	Yes	Lack of proper aperture and telecentric stop
Barrel Distortion	No	
Coma	Yes (tentative)	Unknown
Astigmatism	Yes	Concentricity tolerancing and misalignment
Spherical Aberration	Yes	Inherent in mirror system design (spherical aberration uncorrected)

aberration will be corrected in AEM-2 and AEM-3 by means of foil lenses, which are under development in another project in our laboratory. Astigmatism will be corrected eventually by conventional electron optical means.

The mirror accelerator objective geometry was computed from the postulate of achromatism, but this condition only applies for a given setting of electrode voltages and a corresponding input beam energy. If the beam energy is changed from that handled achromatically by the system, a new chromatic defect is introduced operationally. This results in an inherent "beam energy window" at any given setting of electrode voltages. We find that this window is no wider than ~50 eV at the voltage settings for 300 eV input, and it may be considerably narrower. This energy-selecting characteristic in no way obviates the need for additional means of energy selection in AEM-2 and AEM-3 because the Auger peaks must be isolated from the general secondary electron spectrum, and hence we need windows with widths two orders of magnitude smaller. The importance of finding this window in AEM-1 is great. Much earlier in the project than we had anticipated, we have the evidence that our computer-generated system is in the known class of electrostatic mirror lenses (for which such windows are hallmarks), and so the system can be scaled to use all results that are found in testing AEM-1 directly in the design of AEM-2.

We have found definitely that system alignment is critical. Prealignment with mandrels during assembly is insufficient; the system must be capable of adjustment in vacuo as the operator monitors the images. At present, we are beset with image sweep at each incremental voltage change on any electrode, and severe vignetting is evident in all cases. Figure II-11 gives a summary of the alignment facilities that we now have and those that we are going to need.

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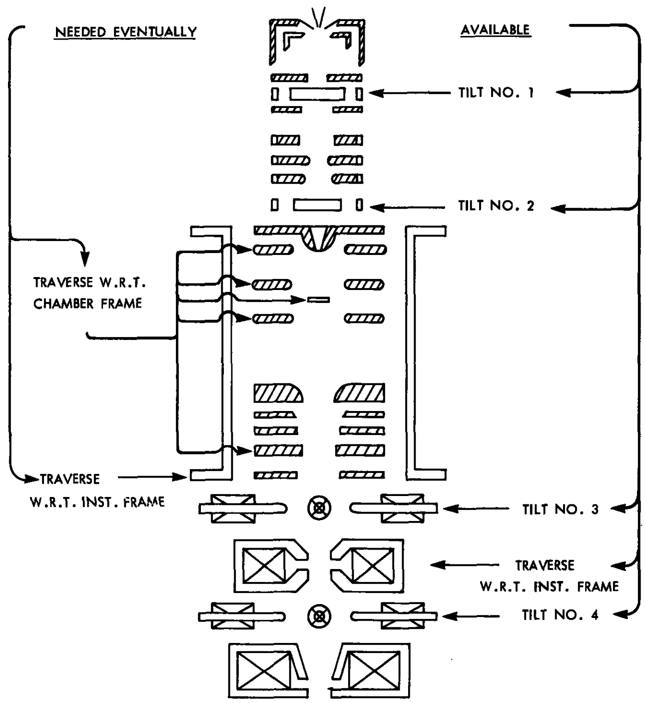

Fig. II-11. Available alignment facilities (right) and alignment facilities that are needed (left).

Conclusion

From our results with AEM-1 we draw the following conclusions.

i. Our mirror accelerator objective system is a practicable approach to developing wide-angle collection and optical processing of Auger electrons.

ii. Our data, although not yet definitive, have served to point up the severity of the problems that we must solve to achieve the goal of atomic identification coupled with resolution to the atomic dimensions. Nevertheless, we are encouraged to proceed because nothing has been found to indicate that we should not do so. At this point, we foresee only engineering problems that can be solved without recourse to further invention.

References

1. E. H. Jacobsen and D. S. Ofsevit, "Electron Microscopy," Quarterly Progress Report No. 99, Research Laboratory of Electronics, M. I. T., October 15, 1970, p. 2.
2. M. G. R. Thomson, "Design of an Achromatic Combined Electron Mirror and Accelerating Lens," Quarterly Progress Report No. 108, Research Laboratory of Electronics, M. I. T., January 15, 1973, p. 17.

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