No. 46 EXPERIMENTAL INVESTIGATIONS ON ELECTROSTATIC FILTER LENSES WITH WIDE IMAGE ANGLES

by ALVAR P. WILSKA AND J. A. DEN BOER

June 9, 1964

ABSTRACT

More than 900 combinations of electrodes of various shapes were built and evaluated for their efficiency as projector filter lenses in a low-voltage electron microscope. Some of them are presented in detail. Filter lenses having either 2 or 3 crossovers and possessing a wide image angle and low distortion can be built.

1. *Introduction*

As is well known, a considerable proportion of the electrons passing through a specimen examined in an electron microscope are scattered inelastically. Since the mean scattering angle is small, a large number of these electrons pass through the objective aperture. Inelastic scattering effects are deleterious to the image quality because the reduction in energy of the scattered electrons produces focusing properties different from those of the unscattered and of the elastically scattered components of the beam. An improvement in image quality can be expected if the inelastically scattered electrons are prevented from reaching the image. This removal can be accomplished by an electron energy filter, as first proposed by Boersch (1947).

Previous workers have investigated several types of energy filters. Boersch (1953, 1959), Beaufils (1959) and Catalina (1959) formed an intermediate image on a grid electrode, which had a potential low enough to reflect the inelastically scattered electrons. Möllenstedt and Rang (1951), Boersch (1953), Schiekel (1952), Lippert (1955), Hahn (1959, 1961), Bykhofskaya and Der-Shvarts (1959), and Der-Shvarts and Belen'kiy (1962) also worked on filter lenses. These lenses have been unipotential with a central electrode at a sufficiently low potential to trap all, or almost all, inelastically scattered, and therefore slower, electrons. Möllenstedt (1947), Castaing and Henry (1962), as well as Watanabe and Uyeda (1962), have used spectrometers operated in such a way that only electrons with the desired energy can pass through the exit of the spectrometer and form an image.

Due to its simplicity, the filter lens has received more attention than other types of electron filters. The main disadvantage of the filter lens has been the smallness of the image angle. One of the objects of the present study was to find a filter lens possessing an angular field wide enough for the lens to be used as a projector. As will be seen, such lenses differ considerably from the conventional unipotential lenses. The components, although sometimes strangely shaped, are always axially symmetric.

2. *Experimental Procedures*

A low-voltage microscope column, details of which have been published previously (Wilska, 1964), was modified for the experiments, most of which were carried out at a beam potential of 6.5

kV. The use of low-beam voltage made it possible to build a versatile and easily operable device in which the number and the shape of the electrodes could be changed almost at will with little fear of discharge or breakdown of insulation. Figure 1 shows the large number of components used in this investigation. A plexiglass cylinder, 140 mm long and of an inner diameter of 46 mm, could be filled with metal electrodes and plexiglass spacers in any desired sequence. Through 95 holes in the cylinder, each electrode could be connected with any of the 9 channels of an auxiliary voltage source by using specially made small plugs which were held in contact with the electrodes by means of rubber bands. Figure 2 shows the parts needed for the assembly of one of the combinations; this is shown in detail later (Fig. 9). Figure 3 shows the same combination fully packed, and in Figure 4, the assemblage has been inserted into the upper part of the microscope column.

Fig. 1. Components used for the experimental filter lenses.

As in conventional unipotential lenses, the outer electrodes of our filter lenses were held at the potential of the anode which is the same as that of the main column. The potentials of the inner electrodes use the cathode potential as a reference, but can be individually and continuously varied within the range of ± 500 volts. It was very important to use the potential at the middle point of the filament as

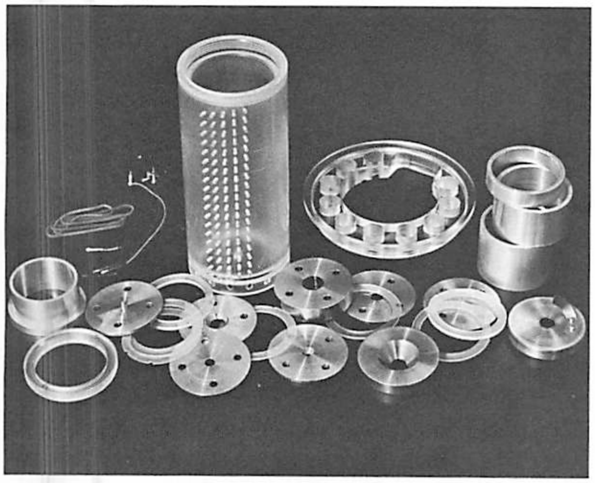

Fig. 2. Filter lens components (see Fig. 9).

a reference and not that at the Wehnelt cylinder, with its automatic and thus varying bias. The filter lens projected the image on the fluorescent screen, located about 100 mm from the exit electrode. The distance between the objective and the filter lens was approximately 190 mm.

In order to obtain better information on magnification, distortion, and image sharpness of the filter lens, a 100-mesh grid was placed in front of the

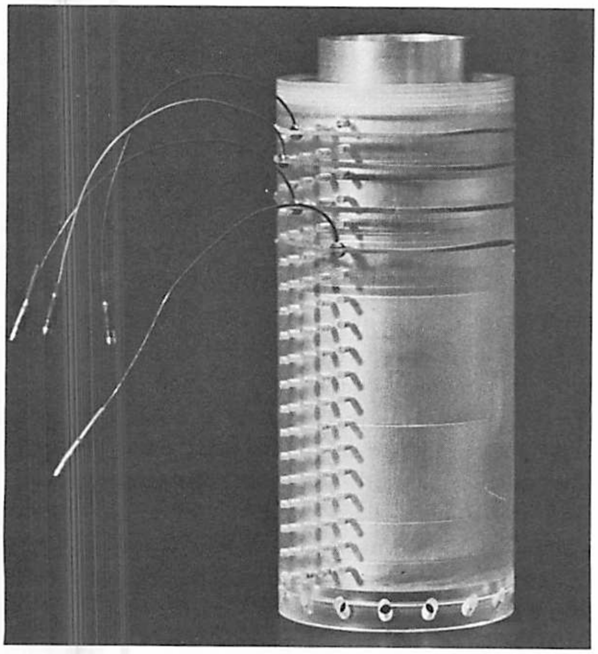

Fig. 3. The previous filter lens combination, fully packed.

entrance electrode. The image of the test object superposed by the grid image was viewed with the naked eye, with a magnifier, and also magnified up to 50x with an optical microscope.

If the potentials of all the inner electrodes were above the cathode potential, there was always some sort of image visible on the screen. However, the passage of the beam could be stopped completely by lowering the potential of one of the electrodes enough to bring the saddle point down to the potential of the cathode. In the case of multi-electrode combinations, the field of each electrode is considerably influenced by the fields of neighboring electrodes. If the lowest saddle point of the whole system is only a few volts above the cathode potential, a filter effect is obtained.

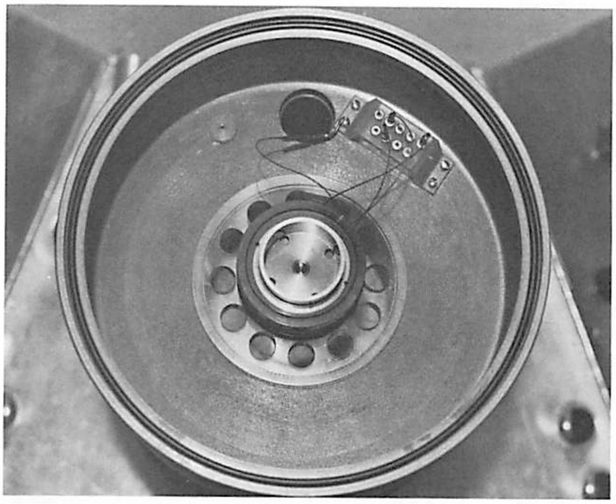

Fig. 4. The same filter lens, inserted into the microscope column.

However, in the majority of cases, multi-electrode combinations are unsuitable as filters for a number of reasons. Very often there is a bright spot in the center of the image which can be so intense, in the case of objects having very strong scattering, that it outshines the rest of the image. This spot is due to the inelastically scattered electrons for which the lens is telescopic. Sometimes a two-crossover peripheral image is combined with a three-crossover image in the center area. Bad distortion, strong curvature of the image, and overall haziness due to secondary electron multiplication in the system, are also common. In some cases, when the image is otherwise good, the overall field is too small, which makes the lens unsuitable as a projector. In the opinion of the authors, the proper way to use a filter lens is as a projector, because errors of filter lenses are necessarily larger than those of conventional lenses. For this reason, the filtered image does not tolerate a high aftermagnification, such as would be the case if the filter lens were used as an objective or as an intermediate lens. Furthermore, a small field with a small central spot becomes a large field with a large central spot.

The experimental series used in all a total of 990 different electrode combinations on a basis of trial and error. After the first 200 trials, which produced little reward, increasingly wider image angles were obtained. Figure 5 shows an example of the situation at about the 500th trial. The image angle of

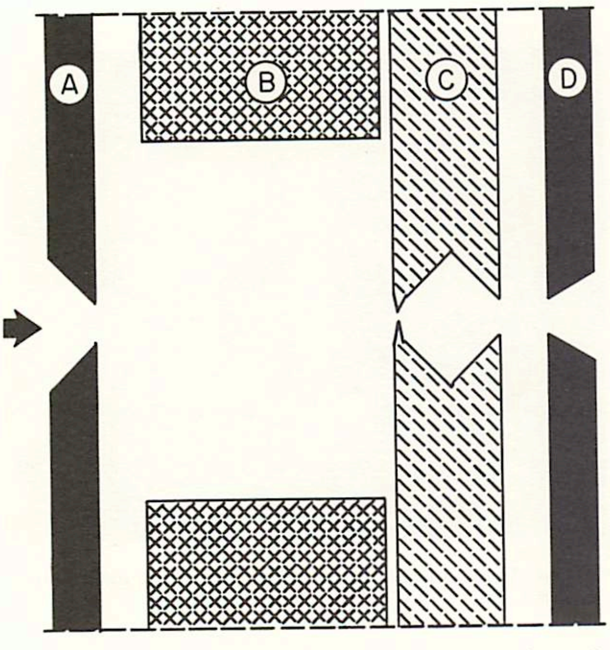

Fig. 5. Filter lens combination D 191 of the experimental series. $V_A = V_D = 6.5$ kV. $V_B = -500$ V. $V_C = -2$ V. Image angle = ~ 29°. Magnification = ~ 250x.

about 34° is reasonably good, but the magnification of the lens is about 350x, which is too high for ordinary use. With an objective lens magnification of 100x, the total magnification would have been 35,000x, which is impractically high for scanning, and often too high for photography also.

The lens shown in Figure 5 has two crossovers. A three-crossover combination is shown in Figure 6. At the voltage values considered here, the central spot is very small. In order to increase the image angle further, the exit electrode was given the shape of a sharp cone. This type of exit electrode is shown

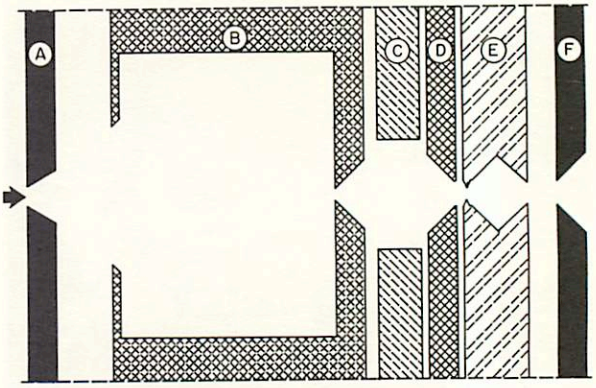

Fig. 6. Filter lens D 323. $V_A = V_F = 6.5$ kV. $V_B = +275$ V. $V_C = -320$ V. $V_D = +340$ V. $V_E = +8$ V. Image angle = ~ 32°. Magnification = ~ 104x.

in Figure 7; it was used unchanged in all subsequent lenses.

A combination consisting of a two-crossover system preceded by a one-crossover lens is shown in Figure 8. The first part of this three-crossover combination apparently has improved the image, mostly by making the central spot almost unnoticeable.

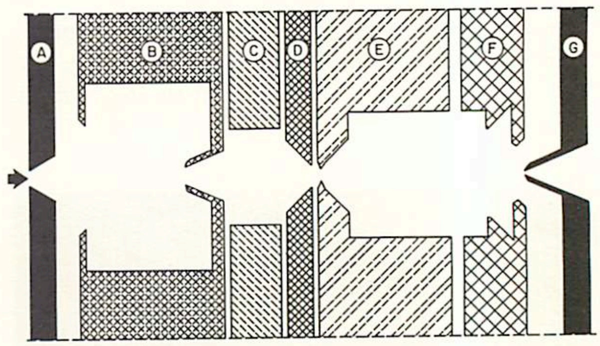

Fig. 7. Filter lens D 529. $V_A = V_G = 6.5$ kV. $V_B = +316$ V. $V_C = -110$ V; cutoff = −120 V. $V_D = +29$ V; cutoff = +19 V. $V_E = +360$ V. $V_F = -123$ V. Image angle = ~38°. Magnification = ~ 44x.

The three-crossover lenses appear to be superior to those with only two crossovers both in freedom from the central spot and in the image contrast. However, since they consist of a large number of parts, they are more difficult to make and to operate. They also take more space in the microscope column and require a complicated monitoring system, which has to be insulated for use at high voltage. In our final experiments, therefore, we went back to the two-crossover combinations.

The filter shown in Figure 9 was a very promising one. By making slight changes, this five-elec-

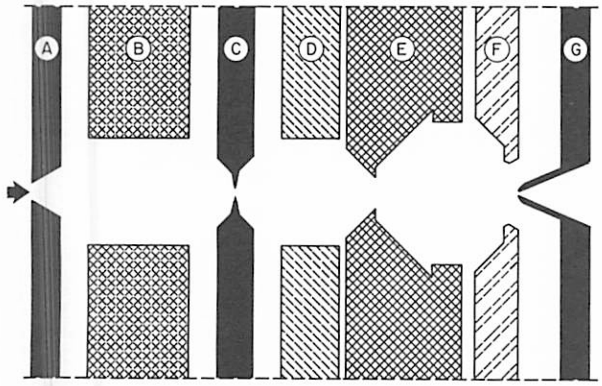

Fig. 8. Filter lens D 587. $V_A = V_C = V_G = 6.5$ kV. $V_B = +4$ V. $V_D = +366$ V. $V_E = +1$ V; cutoff $= -7$ V. $V_F = -80$ V. Image angle $= \sim 34°$. Magnification $= \sim 92$x.

trode lens was converted into a three-electrode one, as shown in Figure 10. It has now been duplicated in a compact form, and is serving as one projector in a projector-revolver consisting of three different lenses. Microphotographs made using this lens are to be published in a later paper.

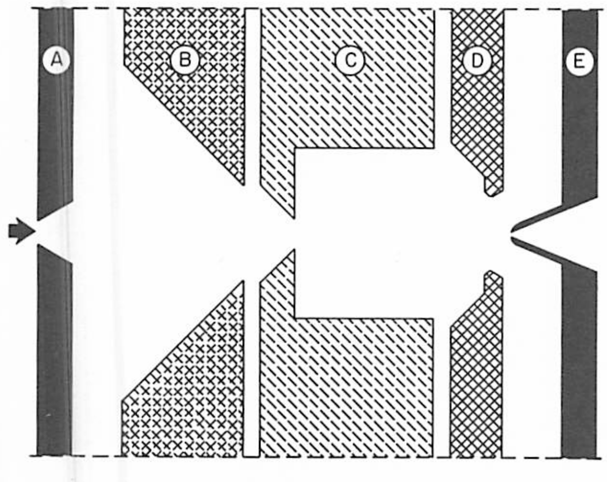

Fig. 9. Filter lens D 589. $V_A = V_E = 6.5$ kV. $V_B = +415$ V. $V_C = +5$ V; cutoff $= -5$ V. $V_D = +61$ V. Image angle $= \sim 38°$. Magnification $= \sim 48$x.

During the course of our experiments, it became evident that the cavity in front of the last crossover is largely responsible for the large image angles obtained. It was later confirmed by computations that the marginal rays make a deep bend inside the cavity. The results of these computations will also be published in a subsequent article.

Acknowledgments. The work reported here was supported by the National Aeronautics and Space Administration under Grant NsG-487.

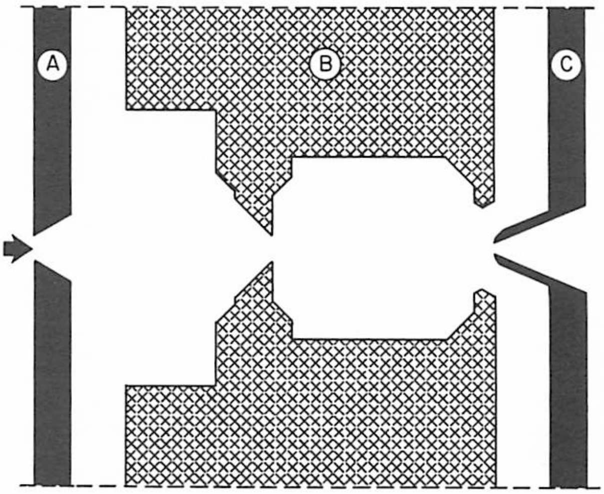

Fig. 10. Filter lens D 630. $V_A = V_C = +6.5$ kV. $V_B = +4$ V; cutoff $= -6$ V. Image angle $= \sim 38°$. Magnification $= \sim 53$x.

REFERENCES

Beaufils, R. 1959, *C. R. Acad. Sci., 248,* 3145–3147.
Boersch, H. 1947, *Z. Naturforsch., 2a,* 615–632.
———. 1953, *Z. Phys., 134,* 156–164.
———. 1959, *Optik, 7,* 436–450.
Bykhovskaya, L. N. and Der-Shvarts, G. V. 1959, *Radiotekhnika i elektronika, 4,* 1145–1152.
Castaing, R. and Henry, L. 1962, *C. R. Acad. Sci., 254,* 76–78.
Catalina, F. 1959, *An. Real. Soc. Esp. Fis. Quim. Madrid, 55a,* 15–22.
Der-Shvarts, G. V. and Belen'kiy, S.A. 1962, *Radio Eng. and Electr. Phys., 7,* 112–117.
Hahn, E. 1959, *Exper. Tech. Phys., 7,* 258.
———. 1961, *Jenaer Jahrbuch, II,* 326–398.
Lippert, W. 1955, *Optik, 12,* 173–180.
Möllenstedt, G. 1947, *Phys. Bl., 3,* 285.
Möllenstedt, G. and Rang, O. 1951, *Z. angew. Phys., 3,* 187–189.
Schiekel, M. 1952, *Optik, 9,* 145–153.
Watanabe, H. and Uyeda, R. 1962, *J. Phys. Soc. Japan, 17,* 569–570.
Wilska, A. P. 1964, *J. Roy. Opt. Soc., 83;* 207–209.