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THE OPTIMAL ARRANGEMENT OF THE ENERGY SELECTING ELECTRON MICROSCOPE WITH THE DOUBLE MAGNETIC PRISM

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Résumé. — Après une étude théorique et expérimentale des propriétés du filtre, on définit le mode de fonctionnement optimal d'un microscope électronique à sélection d'énergie composé d'un double prisme magnétique et d'un miroir électrostatique.

Abstract. — On the basis of a theoretical and experimental study of the properties of a filter, the optimal arrangement of an energy selecting electron microscope with a double magnetic prism-electrostatic mirror filtering system is designed.

1. Introduction. — The Castaing-Henry microscope with the double magnetic prism [1-6] is one of the best known devices for the energy selecting electron microscopy, i. e. the spectroscopy of the electron beam forming the image or the imaging by electrons from a certain narrow energy interval.

The most used arrangement of the Castaing-Henry microscope is shown in figure 1. The electrons of a certain energy are selected with the help of the filter consisting of the double magnetic prism (i. e. the homogeneous transverse magnetic field between the pole pieces of triangular shape) and the electrostatic mirror. In this device good-quality images have been obtained with an energy resolution of about 1.5 eV. Nevertheless, it was found that the image of the back focal plane of the objective formed by the filter was considerably deformed, namely elongated in the prism field direction. Hence, the first of the two auxiliary lenses between the objective and the filter demagnifies the cross-over to improve the energy resolution and the second one is then necessary in the case of energy filtration of the diffraction pattern for changing the order of the focal and the image planes and for demagnification of the image. In addition, the projection system operates with a fixed, distant intermediate image. This fact makes the attainment of higher magnifications difficult. Finally, we have found in our experiments that the field of view is considerably restricted in the arrangement of figure 1 and the alignment of the microscope is relatively difficult.

This paper deals with possible arrangements of the Castaing-Henry microscope. The aim is to design an arrangement suitable for routine use, i. e. an arrangement of easy alignment and control, providing a large field of view and a wide range of magnifications.

2. Imaging properties of the filter. — 2.1 THE BASIC ARRANGEMENT. — As the magnetic prism is not an axially symmetrical element, the axial astigmatism is the main problem. The focusing effects of the homogeneous field in the prism and the fringing field near the pole-piece edges combine in such a way that only one real and one virtual object plane can stigmatically be transferred through the prism. Let the stigmatic image planes arising from the first passage through the isosceles prism (see Fig. 1) be the self-conjugate planes of the mirror. Then the whole ray diagram is symmetric and the resulting image is stigmatic. We will denote this operating mode of the filter usually used (see [1-6]) as the basic one.

Let us define the coordinate system according to figure 2. The radius of the circular electron path in the homogeneous field of the prism will be the unit of length. The paraxial image equations [2] for the isosceles prism can be written in the form

$$\begin{aligned} y(A') &= [x(A) - 1]^{-1} + \operatorname{tg} \varepsilon + 1, \\ y(B') &= [x(B) - 1]^{-1} + \operatorname{tg} \varepsilon + 1, \\ y(A'') &= [x(A) - 1] \{ [x(A) - 1] \operatorname{tg} \varepsilon - 1 \}^{-1} - \frac{\pi}{2} + 1, \end{aligned} \quad (1)$$

$$y(B'') = [x(B) - 1] \{ [x(B) - 1] \operatorname{tg} \varepsilon - 1 \}^{-1} - \frac{\pi}{2} + 1$$

$$\begin{aligned} [y(V) - y(A')]^{-1} + [y(V) - y(B')]^{-1} &= \\ &= 2[y(V) - y(S)]^{-1}, \end{aligned}$$

$$\begin{aligned} [y(V) - y(A'')]^{-1} + [y(V) - y(B'')]^{-1} &= \\ &= 2[y(V) - y(S)]^{-1}. \end{aligned}$$

FIG. 1. — The scheme of the Castaing-Henry microscope in the basic arrangement (1 : specimen, 2 : objective, 3 : back focal plane and 4 : image plane of the objective, 5 : auxiliary lenses, 6 : magnetic prism, 7 : mirror, 8 : energy selecting aperture, 9 : projection system, 10 : screen).

In addition, in the basic arrangement the intermediate images inside the filter are required to be stigmatic, i. e.

$$y(A') = y(A''), \quad y(B') = y(B''). \quad (2)$$

From eq. (1) and (2) we obtain for $x(A)$ and $x(B)$ two identical quadratic equations with the solution

$$\begin{aligned} x(A_{1,2}) = x(B_{1,2}) = 1 + \\ + \left(\frac{\pi}{2} \pm \sqrt{\frac{\pi^2}{4} + 4 \operatorname{tg}^2 \varepsilon + 2 \pi \operatorname{tg} \varepsilon - 4} \right) \\ \times (2 \operatorname{tg}^2 \varepsilon + \pi \operatorname{tg} \varepsilon - 2)^{-1}. \end{aligned} \quad (3)$$

FIG. 2. — The definition of the parameters of the filter arrangement.

The parameter ε determining the prism shape remains free. Castaing and Henry [2, 3] chose $\varepsilon = 40.1^\circ$ so that $x(A_1) = x(B_1) = 3.000$, $x(A_2) = x(B_2) = 0.517$. The calculation of the image aberrations showed that for a slightly different choice $\varepsilon = 41.0^\circ$ the axial astigmatism in the real image plane was zero even for electrons with a small energy difference from the basic level. Then

$$x(A_1) = x(B_1) = 2.881, \quad x(A_2) = x(B_2) = 0.524.$$

The corresponding positions of the points

$$A' \equiv A'' \equiv B' \equiv B''$$

are determined by the coordinates $y = 2.400$ and $y = -0.234$. Into these intermediate image planes the self-conjugate points of the mirror (i. e. the vertex and the curvature centroid) must be placed. They can be placed in an arbitrary order because the interchange of these two points does not affect the image position in the case of a spherical mirror.

2.2 THE GENERAL ARRANGEMENT. — In the basic arrangement, the mirror is used only for changing direction of the optical axis and its imaging properties are not used. In figure 3 the functioning of the immersion objective as an electron mirror is explained. Evidently, the convex mirror corresponds to the objective forming the real image of the cathode surface and the concave mirror corresponds to the

FIG. 3. — The immersion electrostatic objective as a convex (a) and a concave (b) mirror (1 : object plane, 2 : back focal plane and 3 : image plane of the immersion objective, 4 : curvature centroid plane and 5 : vertex plane of the mirror, C : cathode, W : Wehnelt grid, A : anode of the immersion objective).

objective in the virtual image mode. It follows from the study of the immersion objective properties (e. g. [7]) that a wide range of mirror parameters can be realized and even considerably changed by changing the Wehnelt grid potential.

The possibility of using the imaging properties of the mirror and of extending substantially the number of filter operating modes can be obtained when omitting the requirement for the stigmatic intermediate images between the prism and the mirror. Only the resulting image remains stigmatic.

The conditions (2) can now be omitted from the image equations. Then in the solution of eq. (1) (for a certain value of ε) two parameters remain free, for example $y(V)$ and $y(S)$. For certain values of these parameters we obtain (if the solution of eq. (1) is real) a couple of object planes. The conjugate couple of image planes lies symmetrically with respect to the y -axis. The image plane nearer to the prism center is conjugate with the more distant object plane and vice versa. As can be seen from figure 4, by a proper choice of the mirror mode an arbitrary object plane can be stigmatically transferred.

In the set of possible filter arrangements the basic arrangement is the singular case of intersection of

FIG. 4. — The positions of the object and image planes of the filter (—, --- are two solutions of the image equations) in the dependence on the mirror parameters for $\varepsilon = 41^\circ$. Individual curves are labelled by values of $y(V)$.

two branches of the stigmatic-plane-positions versus mirror-mode dependence. In addition, the couples of planes degenerate into single planes in this point.

Let us mention finally that although the described modes are stigmatic, the image can be deformed due to the different spherical aberrations in planes parallel and perpendicular to the pole pieces. The deformation depends on the mirror mode and on the shape of the beam entering the filter.

2.3 THE SELF-CONJUGATE IMAGING. — The cases of self-conjugate imaging, when the object and the image planes are identical, are of great practical interest. In these cases the main optical axis of the microscope can be aligned by leaving the filter off. In aligning the filter, the alignment of the remaining microscope elements need not be changed. In distinction to the basic arrangement higher magnifications can easily be obtained if the self-conjugate plane below the filter and near the first projection lens is used. Also the angular aperture of the beam (and therefore the spherical aberration) is relatively small in this case.

To eq. (1) the condition

$$x(A) = -x(B) \quad (4)$$

must now be added. The system has then only one free parameter, e. g. the self-conjugate plane position $x(B)$. Eq. (1) and (4) are solved by the coordinates y_1 and y_2 of two points on the horizontal optical axis (see Fig. 5) into which the vertex and the curvature centroid of the mirror have to be placed (in arbitrary order). Of course, two planes lying symmetrically with respect to the prism centre become self-conjugate simultaneously.

An interesting arrangement is defined by relations

$$y_1 = 1 + \operatorname{tg} \varepsilon, \quad y_2 = 1 + \operatorname{cotg} \varepsilon - \frac{\pi}{2}. \quad (5)$$

In the neighbourhood of these values $x(B)$ rapidly diverges so that by a slight change of the mirror mode

FIG. 5. — The coordinates y_1 (—) and y_2 (---) of the curvature centroid and the vertex of the mirror (or vice versa) in the self-conjugate imaging mode in the dependence on the distance of the self-conjugate plane from the filter centre.

the self-conjugate plane position can be shifted over a wide range. In a proper arrangement this shift may allow great changes in the magnification of the projection system and therefore of the resulting image.

2. THE ENERGY DISPERSION. — The energy dispersion is usually defined by the relation

$$D = E \left| \frac{dy}{dE} \right| \quad (6)$$

i.e. it is proportional to the image shift from the optical axis due to a certain change of electron energy. (The quantity D/E in $\mu\text{m}/\text{V}$ units is also often used.) The calculation of the dispersion according to eq. (6) is a matter of calculation of the intersections of the circles and straight-lines. The result is following :

$$D = \rho \left| y(V) \frac{x(B)[y(S)-1-\text{tg } \varepsilon] + \text{tg } \varepsilon - y(S)}{y(V) - y(S)} \right|. \quad (7)$$

In the basic arrangement ($\varepsilon = 41^\circ$) we obtain for the concave mirror $D = 4.51 \rho$ in the real image plane and $D = 0$ in the virtual one ; then for the convex mirror $D = 0$ and $D = 0.11 \rho$, respectively. Using the convex mirror it is reasonable to make the energy selection in the intermediate image between the prism and the mirror as, indeed, stated in [4]. In this plane the dispersion $D = y(A')/2$.

By properly choosing the mirror mode, in the general arrangement, a wide range of dispersion values can be attained in any image plane.

The dispersion in the self-conjugate images is plotted in figure 6 against the position of the self-conjugate plane. At the singular points $y(V) = y(S)$ the dispersion D diverges, as is evident from eq. (7). In the arrangement according to eq. (5), i. e. in the mode of the *distant* self-conjugate planes, the concave mirror gives a considerable dispersion in the resulting

FIG. 6. — The dependence of the dispersion on the self-conjugate plane position for the concave mirror (—) and the convex one (---).

FIG. 7. — The axial ray path in imaging the distant self-conjugate plane by electrons of different energies for the concave mirror (—) and the convex one (---).

image, being of linear dependence on the image-to-filter distance (thus, possibly, also on the image magnification). On the other hand, the convex mirror gives a very low dispersion practically independent of the image position so that the image can be assumed to be achromatic (see Fig. 7).

3. **The experimental results.** — The filter (see Fig. 8) was inserted between the intermediate lens and the projection lens of the emission electron microscope [8]. The centre of the prism with an electron path radius of 27 mm was placed at a distance of

FIG. 8. — The drawing of the filter (1 : pole-pieces, 2 : magnetic circuit and 3 : excitation winding of the prism, C : cathode, W : Wehnelt grid and A : anode of the immersion objective).

370 mm from the back focal plane of the objective and 100 mm from the projector object plane. The test specimen prepared by vacuum evaporation of tungsten on the Nb-substrate through the grid of 40 μm period was imaged with the help of electron thermoemission. The aim of the experiments was

FIG. 9. — The image of the testing specimen : the filter in the described arrangement (a) and in the basic one (b) ; (c) the arrangement corresponding to (a), filter off.

to compare the main characteristics of the *distant self-conjugate plane* arrangement and of the basic one, especially the magnitudes of the geometrical image aberrations, i.e. the dimensions of the non-distorted field of view. In the first case (the objective image plane closely above the projector lens) the distortion is acceptable in the nearly elliptical field of view of the half-axes of 120 μm and 90 μm (see Fig. 9a). The magnification is available in the range 1 : 15 without changing the filter mode. If the intermediate lens transfers the objective image plane inside the prism and the back focal plane closely above the prism (an arrangement close to the basic one), a field of view as small as 20 ÷ 25 μm in diameter can be used (see Fig. 9b). The magnification is fixed in this case. The image of the objective cross-over is approximately circular in the first case even without the screening, while in the second case it is elongated approximately 1 : 50. Figure 9c shows the imaging in the same arrangement as figure 9a, only with the filter off. The pin-cushion distortion of the projector lens itself appears, which was compensated by the barrel distortion of the filter in figure 9a. The field of view dimensions are, however, limited by the anisotropic part of the filter distortion.

FIG. 10. — The ray diagram for the «distant self-conjugate plane» mode in the plane parallel (a) and perpendicular (b) to the prism field (1 : back focal plane and 2 : image plane of the objective, 3 : energy selecting aperture plane, 4 : intermediate image of the back focal plane and 5 : intermediate image of the image plane of the objective, 6 : lenses representing the focusing effect of the prism fringing field).

4. Conclusions. — From the calculations carried out the following arrangement seems to be the most advantageous: the filter is to be placed midway between the back focal plane and the image plane of the objective. These two planes are to be self-conjugately imaged. The distance between these planes should be as long as possible, compared with the prism dimensions. The convex mirror should be used and close to its curvature centroid (in the plane of the focal line A') the energy selecting slit should be placed perpendicularly to the plane of the pole-pieces. The dispersion in the aperture plane is $D = 0.934 \rho$ for $\varepsilon = 41^\circ$. Both the diffraction pattern and the image of the specimen are transferred stigmatically and achromatically by electrons from a certain narrow energy interval. In this arrangement for certain dimensions of the field of view the angular aperture of the beam entering the prism is the smallest attainable in the given device, providing the best possible energy resolution. Finally, as it follows from figure 10 both the diffraction pattern and the image of the specimen are reversed with respect to the axis parallel to the prism field and their dimensions are *mutually interchanged*. A certain anisotropic

distortion arises due to the different magnifications in directions parallel and perpendicular to the prism field.

The experiments showed that the advantages of the *distant self-conjugate planes* mode are conserved even in the rather non-symmetric arrangement with the diffraction pattern more distant from the filter than the image. In addition, the image is demagnified only slightly and the anisotropic distortion disappears if the filter is properly aligned. Lastly the objective image plane can be moved when changing the magnification within the whole magnification range.

The fact that the energy selecting aperture plane cannot be imaged onto the screen appears to be a certain disadvantage of the described arrangement.

The proposed arrangement does not restrict the imaging abilities of the basic microscope so that it allows one to combine the routine microscopy with the spectroscopy of the imaging electron beam.

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