GENERAL PHYSICS

I. MOLECULAR BEAMS[*]

Academic and Research Staff

Prof. J. R. Zacharias	Dr. T. R. Brown	Dr. M. G. R. Thomson
Prof. J. G. King	Dr. E. H. Jacobsen	Dr. J. C. Weaver
Prof. J. R. Clow		F. J. O'Brien

Graduate Students

S. A. Cohen	H. F. Dylla	D. G. Payan
W. B. Davis	G. A. Herzlinger	D. M. Payne

A. ACHROMATIC CORRECTED ELECTRON FOIL LENSES

We have previously discussed problems and advantages involved in the use of axially symmetric foil electron lenses (characterized by the placing of one or more thin metal foils across the electron beam axis).[1] In this report we give examples of lenses corrected to be free from third-order spherical aberration (henceforth referred to as "spherical aberration"), and we also discuss an achromatic lens.

The use of two foils with an electric potential distribution between them offers great flexibility so far as electron-optical properties are concerned. Such a lens can be either converging or diverging, with the coefficient of spherical aberration either positive or negative. This enables us to design a converging lens that is free from spherical aberration. Similar results can often be obtained by using a single foil, but the required potential distributions become more complicated, and involve electrodes which are much closer together and are difficult to machine. For this reason we are dealing only with two-foil lenses, at present.

To obtain a converging lens, we require a net positive curvature of the axial potential (V). To be more specific, the focal length F is approximately given by

$$\frac{1}{F} = \int_{\text{Object}}^{\text{Image}} (V''/4V)\, dZ.$$

A zero coefficient of spherical aberration requires a net positive V^{iv} such that

$$\frac{1}{\sqrt{V_o}} \int_{\text{Object}}^{\text{Image}} \left(V^{iv}/\sqrt{V} - V''^2/V^{3/2}\right) dZ$$

must be approximately zero. On the basis of these equations we investigated a lens with an axial potential of the form

---

[*]This work was supported by the Joint Services Electronics Programs (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB07-71-C-0300.

$$V = V_o\left\{1 + v\left[\frac{1}{1+a}\cos\frac{\pi Z}{2\ell} + \frac{a}{1+a}\cos\frac{3\pi z}{2\ell}\right]\right\}$$

with foils situated at $Z = \pm\ell$. In this usage v must be negative, and a must lie in the range $1/27 \leq a \leq 1/3$. We set it equal to 0.1.

Accurate integration of the nonrelativistic formulas given by Hawkes[2,3] established that a lens with $a = 0.1$ and $v = -0.3$ has a focal length F approximately equal to 6ℓ, and is free of spherical aberration (see Fig. I-1). We applied Laplace's equation, and found the off-axis potential in the form of an infinite but rapidly convergent power series. Numerical summation and inverse interpolation yielded sets of equipotential surfaces of revolution, and two of these are also shown in Fig. I-1. We can thus construct this lens by placing charged conducting electrodes on these surfaces.

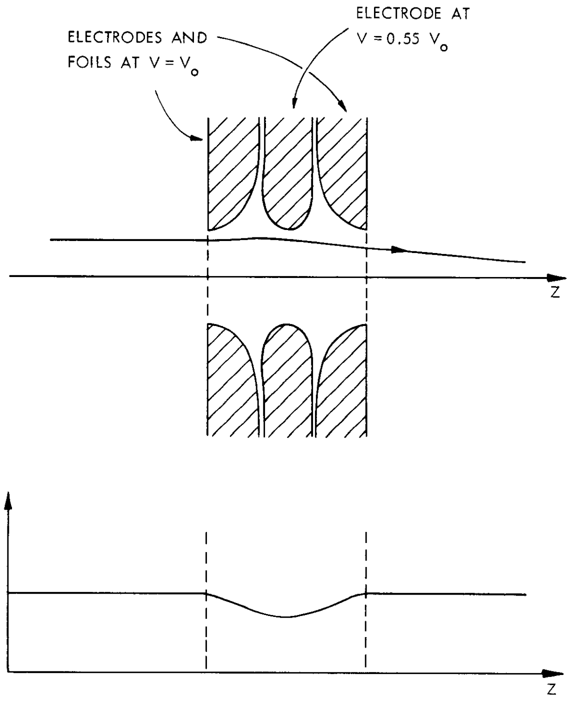

Fig. I-1. Converging two-foil electrostatic lens of focal length F with a zero coefficient of third-order spherical aberration.

It is probably not possible to make 2ℓ much less than 1 cm (assuming $V_o \sim 20$ kV), so we can obtain a focal length of 3 cm at best. By optimizing the parameter "a" we could undoubtedly reduce this to some extent.

Since existing conventional symmetric magnetic electron lenses have been brought to a high degree of perfection, to correct the aberration of a good magnetic lens is a more promising approach than to design a corrected foil lens (which can be thought of as the correction of an electrostatic lens). The electrostatic foil corrector can be placed within the pole pieces of the magnetic lens, or, if there is insufficient space, as close as possible to them. It simply requires a sufficiently strong aberration coefficient of suitable sign to exactly balance out that of the magnetic lens. Preferably the first-order focusing properties should be weak. The most convenient lens with these properties is simply one with an axial potential of the form

$$V = V_o v \cos \frac{\pi Z}{2\ell},$$

where v will be positive. Such a lens, which will be diverging, is shown in Fig. I-2. With $2\ell = 1$ cm and $v = 0.1$ we can correct a magnetic lens of 1 cm focal length. We have represented the magnetic lens by a thin-lens theory which assumes that the deflection of a ray passing through the lens at a distance r from the axis is given by

$$\theta = \frac{r}{F} + Cs \frac{r^3}{F^3},$$

where F is the focal length, and Cs the coefficient of spherical aberration. We calculate the chromatic aberration coefficient by assuming

$$\frac{\delta F}{F} = \frac{\delta V}{V}.$$

The ill effects of chromatic aberration increase with increasing focal length, and a 1-cm focal length lens would not be suitable for high-resolution work. Even using 100-kV electrons a maximum of only 2 mm is permissible if we demand a 1 Å resolution distance. To use this form of corrected lens, we must thus correct the first-order chromatic aberration too.

The basic method of correcting chromatic aberration is to combine a converging lens of low dispersion with a weaker diverging lens of high dispersion. In light optics we simply use two different types of glass; in electron optics we must somehow find two different types of lenses with different dispersions.

We can construct a diverging electrostatic foil lens as described above, but unfortunately it will have the same dispersion as a conventional magnetic lens, and less than that of a conventional electrostatic lens. Somehow we must decrease the dispersion of the converging lens. The electron-optical refractive index is proportional to $\sqrt{V}$, and the dispersion thus to $1/\sqrt{V}$. If an accelerating region is placed between the lenses so that the mean electron energy differs by a ratio of 10, for example, the dispersions will differ by a factor of $\sqrt{10}$. Consequently we can obtain first-order chromatic correction with the focal length of the electrostatic lens three times

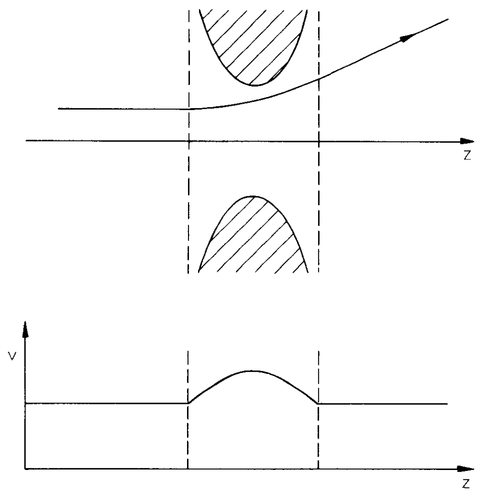

Fig. I-2. Diverging two-foil electrostatic lens that may be used to correct the third-order spherical aberration of a converging axially symmetric magnetic lens.

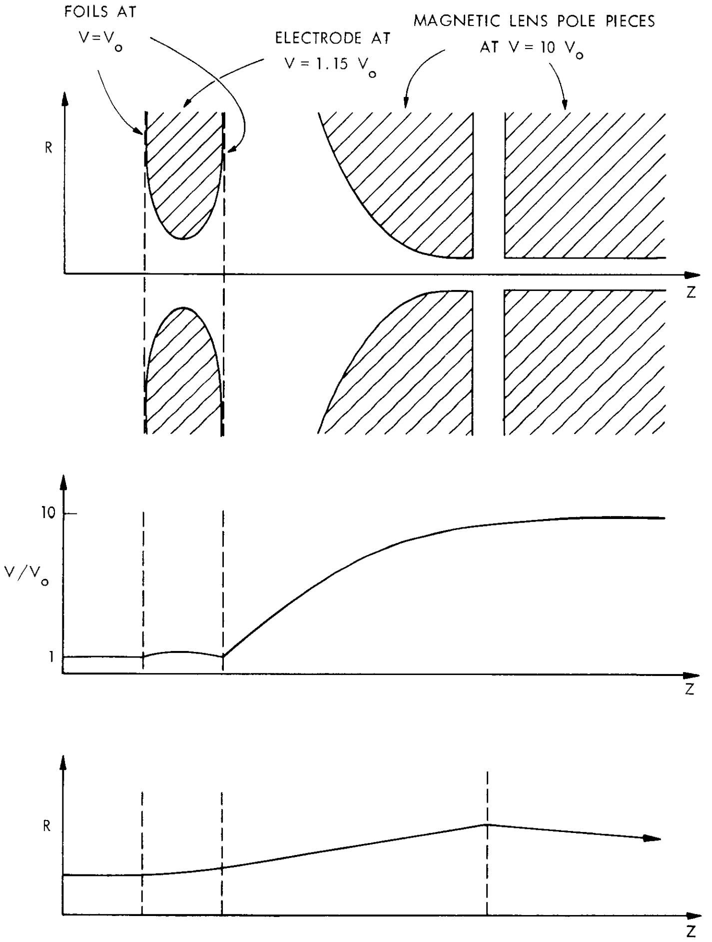

Fig. I-3. Combination lens that is free from both first-order chromatic and third-order spherical aberrations. The foil lens is the same as that shown in Fig. I-2. The magnetic lens and accelerator electrodes have not been accurately represented. The variation of the axial potential and the behavior of a paraxial electron trajectory through the lens are shown.

that of the magnetic lens (if the accelerating region is negligibly short).

The situation is complicated by the need to preserve the spherical-aberration correction, and further by the fact that the accelerating region must separate the two lenses by a distance comparable to their focal lengths. The ratio of the focal lengths is restricted, and in our best example thus far, illustrated in Fig. I-3, we have used a foil separation of 0.5 cm, v = 0.1, and a lens center-to-center separation of 2.0 cm. The focal point is 6 cm beyond the magnetic lens.

The accelerating region is not critical; we have used an axial potential distribution of the form

$$V = V_o + (V_1 - V_o) \tanh \frac{Z - Z_o}{h},$$

where V_o is the foil potential, V_1 is the potential within the magnetic lens, and h, the characteristic distance, is 1 cm. Because of the inelastic scattering from any of the foils now under consideration, it is most unlikely that V_o can be allowed to be less than 10 kV, and consequently V_1 will not be less than 100 kV.

This long-working-distance lens is of little use in a high-resolution microscope where we might demand 1 Å resolution. It is, however, of great potential in the field of scanning electron microscopy which often requires that detectors, ionizer, and spectrometers be placed between the final lens and the specimen, and which can tolerate a resolution distance of approximately 100 Å.

It is not possible to use this lens for high resolution because the construction and alignment tolerances will be impossibly severe, and the effects of fifth- and higher order aberrations will not be negligible. These aberrations can be corrected by further shaping of the fields or the foils, but the tolerance problem can only be removed by reducing the overall focal length. This can most obviously be achieved by increasing the ratio of V_1 to V_o beyond 10 (already a large value). Alternative investigations are proceeding.

M. G. R. Thomson

References

1. M. G. R. Thomson, Quarterly Progress Report No. 102, Research Laboratory of Electronics, M.I.T., July 15, 1971, pp. 6-11.

2. P. W. Hawkes, "Quadrupole Optics," Springer Tracts in Modern Physics, Vol. 42 (Springer-Verlag, Berlin, 1966), pp. 19-34.

3. P. W. Hawkes, Optik 22, 543 (1965).