Some Things You Might Like To Know About Electron Lenses

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The performance of an electron lens depends solely on the size of the space between the pole pieces. This may be a simplification, but not much of one.

In this article, I will describe the operation of electron lenses in general but with specific reference to how they relate to working with SEM long working distances. The theme is related to EBSD performance when long working distances are needed with steeply tilted samples, and where large beam currents are needed to reduce noise in the EBSD pattern.

The lenses in electron microscopes are made of magnetic fields. The field bends the path of the electrons as they travel through it and so focuses them. The magnetic fields are themselves produced by an electric current flowing through a coil of wire. As the current is increased, the field gets stronger and so the lens focuses more strongly – up to a point.

The current-carrying coil is surrounded, except for a small gap, by magnetic material. This magnetic material, or rather the gap in it, shapes the field that the electrons see and, thus, determines the properties of the lens.

The parts of the magnetic material adjacent to the gap are the pole pieces. There are generally two pole pieces and their shape is described (for our present purposes) by the separation between them and the bore of each. There are thus three parameters which fix how the lens operates. We shall simplify still further and use only one number to describe the physical configuration of the lens. This length, which we will call 2L, is the diagonal distance from one pole piece to the other – see figure 1.

If you know the "L" of your lens you know all you need to know for nearly everything you do. It may come as a surprise that a single length tells us everything. After all, the manufacturers of microscopes work long and hard to design lenses. And they fight, in their advertising, to say that they are better than their rivals. But they are fighting over trifling differences and we are concerned with general principles. By changing the material of the pole pieces and changing the details of their shapes, the manufacturers can improve the performance of a lens by perhaps 20% but this translates to an improvement of microscope resolution of only 5%.

The strength of a lens is measured by its focal length. That you knew, but you may not have realized that electron lenses

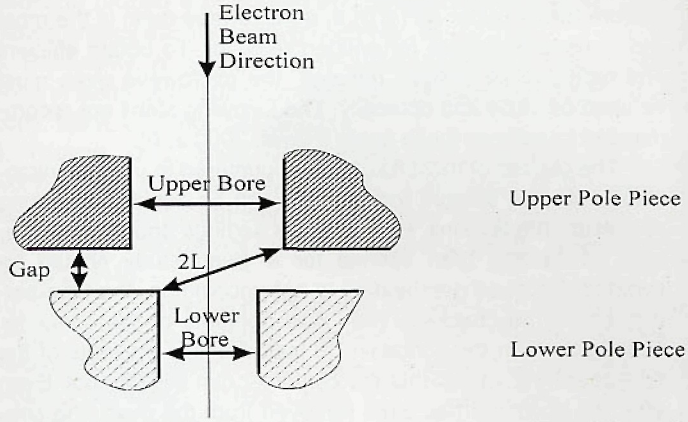

Figure 1: Schematic diagram of the important dimensions of the pole pieces of a magnetic lens. The dimension L determines lens properties.

have two focal lengths. The *projector focal length* is the focal length that applies when we do not care what happens inside the lens. It is the focal length for the lens as it operates to magnify an image or to demagnify an illuminating probe. It is the focal length that applies to the use of condenser lenses (in both SEM and TEM) and the use of intermediate and projector lenses (in the TEM). The *objective focal length*, by contrast, is the focal length of the lens as it operates when we are most concerned with what happens inside the lens. It is the focal length which determines how the lens will focus the beam to make a probe on the sample (when it operates as an objective in the SEM or STEM) or to form an image of a specimen (as it does when it is the objective of a TEM).

As the current in the lens coil is increased, the focal length gets shorter. However, the projector focal length reaches a minimum value $f_m \sim L$ (for a lens current we can call I_O) and then starts to increase with a further increase of lens current. See figure 2. When the lens is very weak, the objective focal length is the same as the projector focal length - since the lens is too weak to form an

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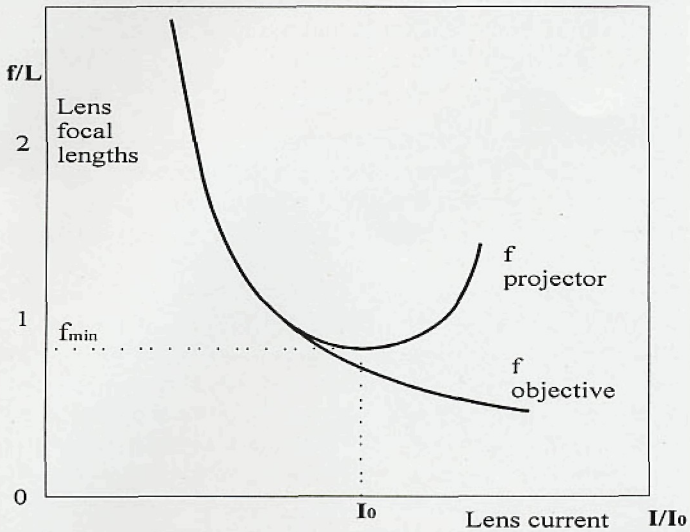

Figure 2: Graph showing how the focal length of a magnetic lens changes as a function of the current through the lens coil. This is a universal curve. To a good approximation it applies to all lenses.

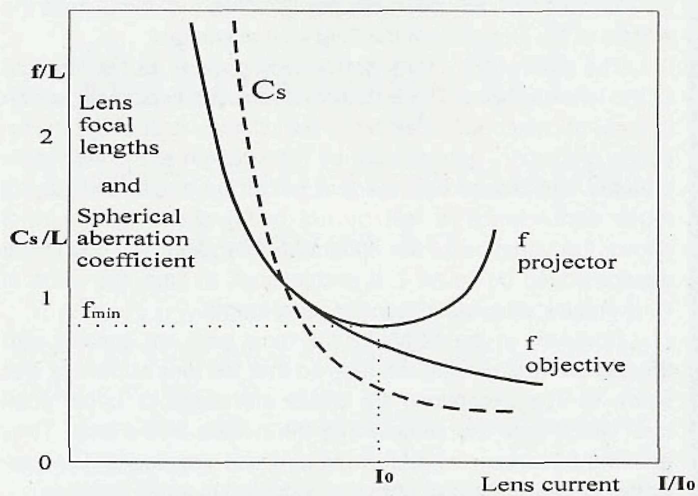

Figure 3: This graph repeats figure 2 except that, in addition to the focal lengths, the coefficient of spherical aberration is plotted. The spherical aberration becomes almost constant for high lens excitations but rises very rapidly as the lens excitation is reduced below I_0.

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image inside its own magnetic field. As the lens gets stronger the two focal lengths diverge and the objective focal length continues to get smaller - but much more slowly once the projector minimum is passed. One might suppose then that, for the objective lens, the lens current should be set well above I_O so to reduce the focal length. However, practical considerations make it very difficult to operate much above I_O. TEM objectives, for example, typically operate near I_O where the sample sits the middle of the lens, where the field is at maximum.

The aberrations of the lenses also change as the strength of the lens changes. The spherical aberration coefficient, which in most microscopes determines the ultimate limit of the microscope resolution, gets smaller as the strength of the lens is increased, but it becomes nearly constant beyond I_O and so not much performance is lost by not going above I_O. Figure 3 shows the variation of the spherical aberration, C_s, coefficient superimposed on figure 2. It is clear that, at best, the value of C_s is somewhat smaller than the focal length.

However, in the SEM, for the most part, we operate with the sample well outside the lens so that the lens current is well below I_O. The exceptions are SEMs with stage in "upper position" which puts the sample into the middle of the lens. They gain the advantage of performance which accrues to TEM objectives - but at the cost of being restricted to small samples.

When we operate the SEM in its normal mode of rather long working distances, the working distance and the focal length are nearly the same. As the lens current is weak, we are to the left of figure 3. As can be seen, for these lens currents the spherical aberration rises rapidly. In fact it goes roughly like the cube of the focal length (the cube of the working distance):

C_s » $f^3/2L^2$ » $w^3/2L^2$

where f is the focal length and w is the working distance.

In practice we do not want to think about the spherical aberration directly. We would rather know what it does to the operation of the microscope. Suppose we decide on the size, d, of the probe we require (the size of the electron beam hitting the sample) and then ask what is the beam current we can get. If the aperture size is set correctly, the answer is that the maximum current we can get in to a probe of size d is given by

$$i_{max} = A\, b\, d^{8/3}\, L^{4/3}\, w^{-2}$$

where A is a constant close to 3 and b is the brightness of the source. What this means is that we should do everything we can to use a short working distance since the current goes as the inverse square of the working distance. It also means that, if we must use a fixed working distance, a large lens (L large) is better than a lens with a small bore and gap. If we compare two, otherwise identical microscopes, one with a lens twice the size of the other, then the larger lens will give us about 2.5 times the current into the same probe. The problem with this, of course, is that on a different day we may wish to use the microscope at a much smaller working distance - and then the smaller lens is essential.

There is nothing new in these remarks, the ideas were established by the early 60's. All the information is in, for example: ■

Lentilles Electroniques Magnetiques Symetriques et Dyssymetriques J. Dugas, P. Duraneau and C. Fert Revue D'Optique 40 (1961) 277-305