Chapter Four

The Electron Beam and Electron Optics

4. Introduction

In this chapter we will begin a detailed discussion of electron-beam instruments. More specifically, we'll study the electron gun, electromagnetic lens optics and how the electron beam is modified from its point of origin to just before final interaction within the target. The scanning electron microscope (SEM) and the electron probe microanalyzer (EPMA or microprobe) are very similar in basic design of the electron column, and indeed many facilities have an SEM with most of the analytical capabilities of a microprobe. Electron microprobes are designed to specifically maximize the stability, resolution and sensitivity of x-ray detection for quantitative analysis, but many are also able to image secondary and backscattered electrons as well as most SEMs. Conversely, the SEM is specifically designed to optimize SE and BSE imaging, but many are also equipped with an x-ray spectrometer. The electron gun and electron optics are common to both, and aside from minor design considerations of the basic instrument, the difference in operation between the two is simply knowing how to best configure the instrument for the desired task with adjustable parameters that are available on all electron beam instruments. This chapter is designed to provide the basis for understanding these types of instrumental parameters.

Earlier, the term *spot size* was introduced with regard to the electron beam and its relationship with specimen interaction. It will be the primary subject of this chapter, and we also hope to provide you with a good understanding of the source for electrons (the electron gun) and the electron column. Ultimately, we want you to understand the resultant interaction volume or spot size on the specimen, so you will be able to modify its character to suit your needs, be they imaging or x-ray analysis.

4.1 The components.

A brief discussion of the instrument's fundamental components will allow you to understand how they all work together. Each component will be discussed in more detail later in the chapter. Before we begin, however, let's briefly discuss the optical microscope and the role it plays in research with either the SEM or the microprobe.

It should be realized that the optical microscope and the electron microscope are often inseparable in both formulating and conducting research projects. Whether the subject is a thin section or multi-scale material, the capabilities of an optical (or confocal) microscope can be utilized before relying upon the electron microscope. Not only are optical microscopes used to formulate the questions we wish to answer with electron microscopy, optical microscopy often provides a better context for generalizing research problems and justifying microanalysis, or it may simply may provide the microanalyst with "road maps" of what to analyze.

As synergistic as the two microscopes are, it is a bit unfortunate that many components of the electron microscope can be confused with similarly named components of its optical counterpart; for example, the condenser lens or the objective lens, or the electron gun might even be confused with the 15 Watt lamp used to illuminate specimens in an optical microscope. There are as many analogies as there are applications for both types of microscopes, and you should try to keep them separate, because although an analogy can be useful it must be kept in proper perspective.
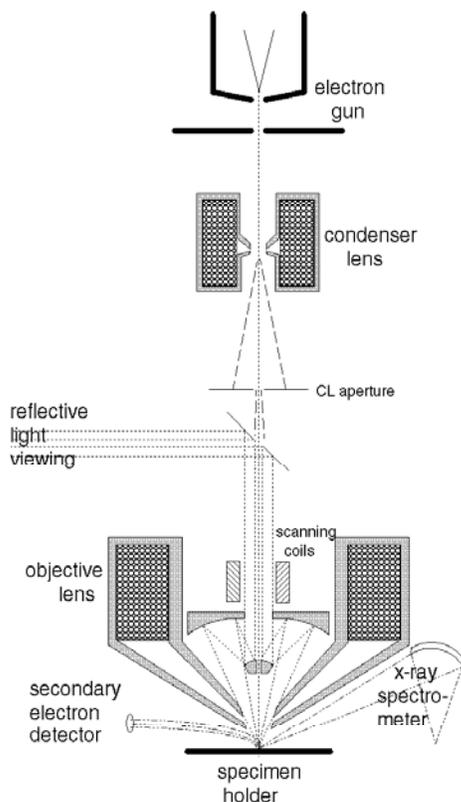
Figure 4-1 shows the general configuration of an electron microprobe (a basic scanning electron microscope would not include the viewing optics or the x-ray spectrometers). As we explain the components, from electron source to target, we will concentrate on the resultant 'spot' of electrons with its probe diameter, d_p.

The **electron column** and all of its components listed below are under vacuum. The vacuum system for any electron beam instrument is an integral part of the instrument; a high vacuum is necessary to prevent electrons within the beam from interacting (scattering) with anything other than the specimen. Without a vacuum, it is conceivable that 90% of the electron beam would still reach the specimen, but half of the electrons would retain only a fraction of their

Figure 4-1 Cross-section schematic of an electron probe microanalyzer.

initial energy after Coulombically interacting with gaseous molecules.[1]

The *electron gun* provides the source for the electrons. It is primarily responsible for the electron beam's energy, and the first focal point that is termed the *initial crossover*, d_0 (diameter ≈100μm). The three primary components of the gun are the electron emitter (filament or cathode), the biasing cylinder (Wehnelt or grid cap) and the anode (see Figures 4-1 & 4-2).

The *condenser lens* is the first electromagnetic lens below the gun and is generally a combination of two separate lenses. Its function is two-fold: (1) it is the primary de-magnifier for the electron gun's crossover (approximately 1/10,000X), and (2) adjustment of its focal point relative to the *CL aperture* by which the user varies the amount of the electron beam (i.e., the *beam current*) which will ultimately reach the specimen or target. Below the condenser lens, the intermediate spot's diameter, d', might be de-magnified to 50-200 nanometers.

The *objective lens* has only one primary purpose -- to focus (or defocus) the primary electron probe on the target. Depending on the instrument, it can de-magnify the intermediate spot, d', after the condenser lens on the order of 10 to 100 times, ultimately reducing the final probe diameter, d_p, to approximately 5nm. The objective lens also has an aperture associated with it that is not shown in Figure 4-1. The final aperture is important because the aperture's diameter is an adjustable parameter of the electron column, and is often used to coarsely modify the character of the instrument; for example, from high resolution imaging to quantitative x-ray analysis. This aperture can also be considered analogous to a camera's aperture … that is, not only controlling illumination but also offering control of *depth of focus*.

The *specimen holder*, although not part of the electron column, plays an important role in the interaction of the beam and sample. Its primary purposes are to orient the specimen in x-y-z space relative to the beam, move the specimen in the x-y plane and provide rotation and tilt if desired. In terms of the relationship between the specimen and the focusing of the electron beam, the most important function of the sample stage is in controlling the working distance from the final lens, or *pole piece*, to the specimen. This distance, known as the *working distance*, is sometimes continuously adjustable and is a consideration along with the size of the objective lens aperture for optimizing such imaging parameters as the *depth of focus*, and ultimate spot size.

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[1] A relatively new instrument on the market is the *environmental SEM*, which allows specimens to be examined under relatively high vacuum pressures (e.g., 100torr). These instruments allow for "wet" specimens and can, for example, include morphological study of crystallization from aqueous solutions. Only the specimen chamber is exposed to these pressures however, with the electron column relatively isolated by being differetially pumped. Nevertheless, the "spot" size of an environmental or variable pressure instrument can be severely affected by the gas molecules in the beam path from the objective pole face to the specimen. This usually manifests itself as a wide low intensity "skirt" of scattered primary electrons around a higher intensity central spot of unscattered electrons. The intensity of the "skirt" is proportional to the gas pressure.

The *scanning coils* provide the means by which the electron beam is scanned or rastered over an area on the target, much the same way an electron beam in your television or computer screen is rastered across the face of the picture tube. The scanning coils and display CRT are synchronized with the *scan generator,* which can also provide other scan related features such as image shift, scan rotation, selected area scans, picture within a picture, etc.

The *secondary electron detector* is one of several detectors, many of which are located in close proximity of the electron beam's interaction with the specimen. All detectors send a signal to the *viewing* and *photo* CRTs via amplification and synchronization with the scanning coils. Some of these detectors are necessarily configured for *line-of-sight detection,* which include all x-ray spectrometers, cathodo-luminescence and backscattered electron detectors.

Components we might make special note of with regard to the basic design of EPMA versus SEM instruments are the *specimen stage,**reflected light viewing* and the *objective lens*. The specimen stage in an EPMA generally does not include capability for variable working distance and tilt because such variability would alter the *take-off angle* to the x-ray spectrometer(s). Even the capability to rotate the specimen within a microprobe is found only in a very few instruments.

Reflected light viewing is generally more convenient for finding your way around on a large flat specimen, and so it is generally considered a requirement for EPMA. *Cassegrainian* mirrors (Figure 4-1) that allow a pathway for electrons along the optical axis are generally preferred over oblique optical viewing. Commonly found in geological laboratories is the transmitted light option available on most microprobes, sometime including an option for cross polarized (darkfield) light.

The objective lens on a microprobe is designed specifically for line-of-sight detection toward the x-ray spectrometer(s). Notice in Figure 4-1 (and 4-6) how the final lens accommodates the *take-off angle* to the x-ray spectrometer.

4.2 The electron gun

The *electron gun* is shown schematically in Figure 4-2. The most common configuration uses electrons that are thermally emitted from the tip of a tight bend in a tungsten wire — the cathode or *filament*.

When an electric current is passed through the wire it heats up to the point at which thermally excited electrons escape from the surface. In the absence of an external electrical field these electrons will simply recombine with the filament, as in the case of a common light bulb. However, if the electrons are exposed to an attractive high positive voltage potential they are accelerated toward that potential. The acceleration they are given is their energy, E_0, and the voltage across the cathode and anode components of the gun is called the *acceleration voltage*. The dimensional unit describing the potential is that of energy, and includes the mass of the electron — the *electron Volt*, eV. Commonly used voltages for imaging are 10 —

40keV, although some instruments are capable, and some applications may require acceleration voltage as low as 100 volts. For EPMA, voltages between 10 and 25keV are common, and for mineralogical specimens, most geologists have standardized with 15 keV for silicates and 20 keV for sulfides (Sweatman and Long, 1969).

The details of the electron gun[2] are illustrated in Figure 4-2. The acceleration voltage is actually applied as a negative voltage to the Wehnelt, or what might be functionally called the *biasing cylinder*. Between the filament and Wehnelt is the *bias resistor,* which is an adjustable electron gun parameter. The *anode*, which is connected to ground potential (zero volts), is the high positive potential the electrons actually "see". All three of these components and the filament make up the *self-biasing electron gun.*

Self-biasing refers to this gun's ability to stabilize or regulate itself. Examination of the specimen current graph in Figure 4-2, shows that at 'D' or 'E', the beam current levels off as a function of increased heating of the filament. This "shoulder" is referred to as *saturation*, and is generally the desired operating point for the gun with respect to the voltage applied to the filament for heating (V_F)[3]. **Any voltage for heating applied higher than the *saturation* point yields little or no additional electron flux and instead shortens the life of the filament.**

Self-regulation works as follows. Referring to Figure 4-2, with the filament voltage at 'A', the filament is hot but not enough to emit electrons. With additional filament voltage (i.e., filament heating) electrons are emitted, and current flows through R_B. This voltage across R_B creates a voltage difference and an electrostatic field between the filament and Wehnelt. (the zero volt contour is drawn in Figure 4-2, above which electrons return to the filament, and below which they accelerate towards the anode.) As emission increases with increasing V_F, more voltage is dropped across R_B, and less of the filament is exposed to the positive potential. At saturation, only the tip of the filament actually sees positive potential and is emitting electrons, and any increased emission due to increasing V_F is counteracted by increased bias and fewer electrons seeing the anode's potential. In other words, increased emission due to filament heating results in reduced emission because of increased bias.

The graphs in Figure 4-2 depict a low bias setting, 'D', and a high bias setting, 'E', which correspond to two different settings for the bias resistor, R_B. High bias is desirable because the initial *cross-over* is so much better defined, i.e., **the *cross-over*, d_0, is as small as possible**. It can be said that for higher bias, the electrostatic "lens" due to biasing is stronger, and so the

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[2]   The following pages address the tungsten gun specifically as it is the most common; however, the lanthanum hexaboride (LaB6, pronounced "lab six") is also a thermal emitter type gun, and so the following will be conceptually relevant, if not in actual use. We will also speak of the filament and cathode interchangeably, however it is common to refer to the tungsten gun's cathode as the filament, while it is more appropriate to refer to a LaB6 as cathode.

[3]   You may be confused with the filament having two voltages applied, V_F and E_0. *Cathode heat*, V_F, may be only 3 to 6 volts, but is applied such that 2 to 5 amps flow through the cathode. *Acceleration voltage*, E_0, is a potential between the cathode and anode, and any current which may be the result of this applied potential will be the *emission current* (typically 60 to 100μA), that is, electrons actually leaving the cathode.

resulting focused image of the beam should be smaller. However, if the bias is set too high the filament will be too positive and no part of it will be able to see the anode's potential, and there will be no emission. Generally speaking, the higher the emission the higher the cross-over point and better the resolution. However, the filament life will be significantly shortened at high emission currents. Therefore, most instruments, are run at the lowest emission that yields the required resolution. Note that, because the x-ray emission volume is usually significantly larger than the secondary electron production volume, resolution is of less concern for electron microprobe instruments and for SEM instruments. This is the first of many compromises that the user must be aware of in adjusting the instrument.
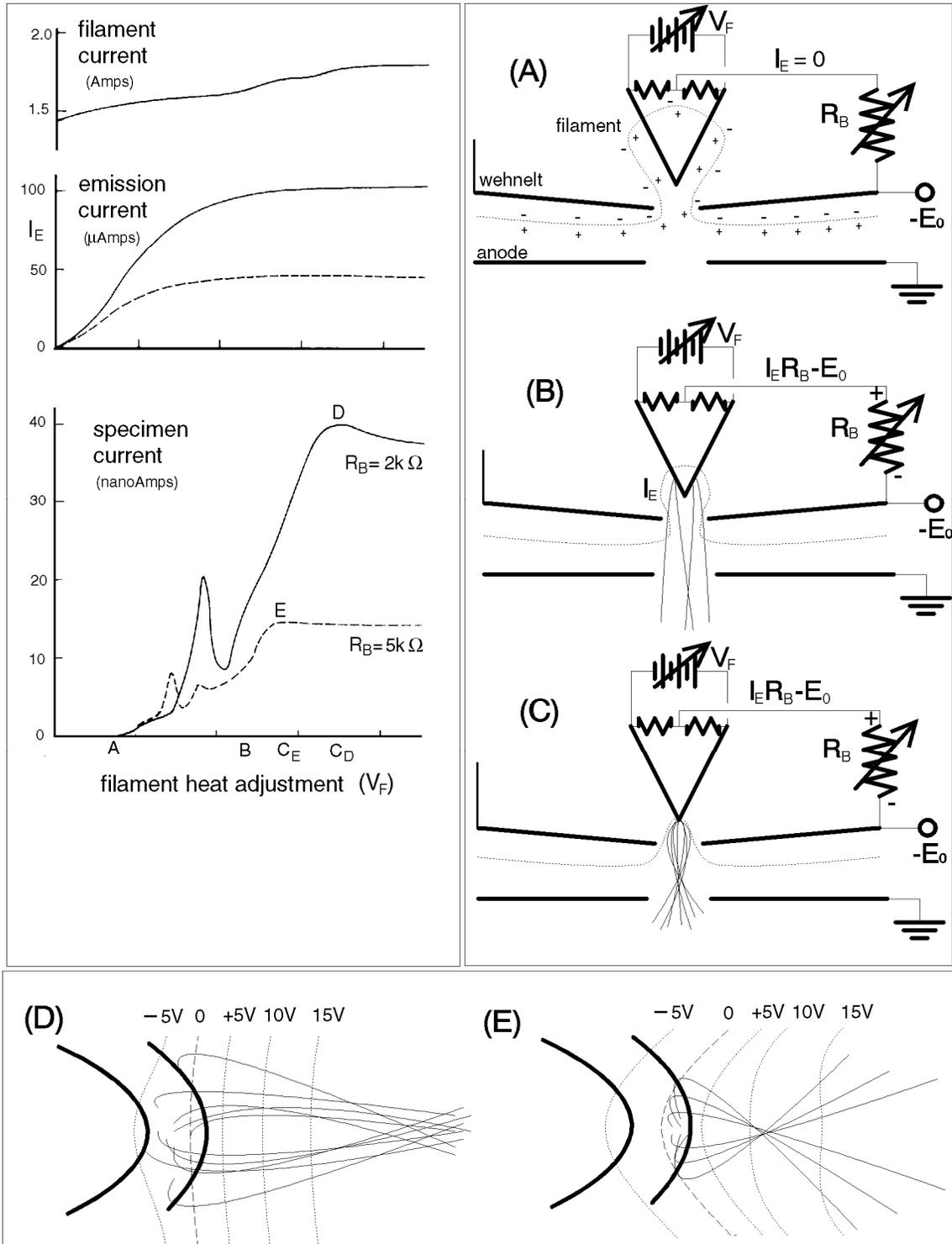
Figure 4-2 **Left**: emission and specimen current as a function of filament heating (A-B-C). **Right**: the *zero volts* electrostatic contour (dashed) relative to the filament saturation process (A-B-C). **Bottom**: the effect on cathode emission for the two bias settings (D & E). Note the result of the bias on the filament saturation.

Another bias adjustment that should be mentioned is the physical distance between the filament tip and Wehnelt. In most SEM and EPMA instrument manufacturers' handbooks any distance other than what is "optimum" is discouraged, however, an operator with good familiarity with the instrument may modify this distance when trying to optimize the gun for low-acceleration-voltage applications (e.g., less than 5keV).

Notice that the graphs in Figure 4-2 also imply that for different values of R_B, the filament will saturate at different filament heating (V_F). This implies that <u>every time the operator adjusts the acceleration voltage</u> (which, on some SEMs, requires a different bias setting) <u>the operator should also readjust for proper saturation</u>. Filaments are expendable items and not terribly expensive (~$20 - $40 each) but the replacement procedure can take several hours (vent, replace, adjust, pump down and longer to "break-in"), so their life should be conserved as much as is practical. It is therefore important to avoid "oversaturation" of the filament.

Also of interest, Figure 4-2 depicts a peak in beam current not associated with saturation. Its exact character can vary from instrument to instrument, even from one filament to another, and the resultant probe current for this ***false peak*** can sometimes even be greater than what is achieved at saturation. It's cause can remain unexplained because it is of little practical use, but it's presence could be the result of gun geometries during filament heating and the electro-static creation of the gun's cross-over. It is worth mentioning that adjusting a filament to the false peak saturation point will generally result in extremely long filament life, but the beam current stability is usually very poor. This can be avoided by noting at what voltage full saturation typically occurs.

Coaxial alignment of the filament, Wehnelt and anode is critical. For all types of electron beam instruments, the instrument operator will be responsible for physical alignment of the filament within the Wehnelt, but for most instruments the alignment of the Wehnelt and anode will be fixed. In older instruments however, the operator might also be given x and y translation for the anode.

When installing a replacement filament, there is generally provision for physical alignment with the eye (or hand lens) of the cathode within the Wehnelt. This is generally not good enough, and when the new filament assembly is in the instrument, there are other provisions for fine-tuning the alignment under operating conditions. In older instruments this fine alignment was mechanical; that is, physical x and y translation of the filament within the Wehnelt while monitoring and trying to maximize the specimen current. In modern instruments, this fine alignment is accomplished electro-magnetically; that is, electronically shifting the beam in x and y space (see lenses and scanning coils, below).

The gun's alignment relative to the rest of the column below is achieved by "tilting" the gun. In older instruments, this is accomplished by manipulating the gun's position in a "dished" seat. In newer instruments, this is again done electro-magnetically with a second set of coils below the gun shift x-y alignment coils.

How often these alignments are made is determined by the mechanical stability of the filament, which is likely to vary from one filament to another, and especially from one filament manufacturer to another. All of these alignments will of course be necessary for a new filament. "Shift" alignment for the beam within the gun is generally done on a daily basis, but the "tilt" might only be required when the filament is new.

Exactly where the filament saturates with respect its temperature and bias setting will remain the same for a given acceleration voltage and bias. However, as the filament thins with age, the voltage needed to achieve this temperature will decrease. Referring again the graphs in Figure 4-2, this means that the saturation curves will shift to the left as the filament ages. A filament that was correctly saturated one day will be over-saturated a week later. The normal lifetime of a tungsten filament is on the order of 100 to 1000 hours depending on the emission current, saturation and vacuum quality. It can be shortened considerably with improper saturation, and can be lengthened considerably if it is saturated with care often. Beam current stability is further enhanced on newer instruments with ***beam regulation***, rather any reliance on the stable portion of the filament-heating curve. Beam current regulation relies on feedback from beam current readings, which are monitored by a *beam current controller* to compensate for changing conditions. This allows a small amount of under-saturation of the filament to be tolerated that would prolong filament life, or to ensure it will not expire prematurely. A slight amount of gun instability due to under-saturation will generally cause few problems. Either the gun will be stable enough over the relatively short period for a image to be acquired, or in the case of modern microprobes, long term probe current regulation is taken care of by other means. However, as you will see below, the gun will be slightly brighter if over-saturated, in which case for high resolution applications, a slight amount of increased heat (and shorter filament life) can be tolerated.

4.2.1 Gun brightness

A fundamental property of the emission from any type of electron gun is its area normalized ***current density, j_0*** (Amp/cm^2), or its angular normalized ***brightness, b*** (Amp/cm^{2}steradian). We want to take a good look at brightness because it can be shown that it remains constant from the first cross-over to the ultimate spot on the sample. Brightness is a function of the inherent properties of the electron source, as is the current density, j_0, generally expressed as

$$ j_0 = A_0 T^2 e^{\left(\frac{E_w}{kT}\right)} $$

<div align="right">eq. 4-1</div>

where A_0 is a constant, and E_w is the thermal energy needed for electron escape, both of which are constants for a given cathode material. Note the familiar work barrier expression involving k, Boltzmann's constant and temperature, T. If E_w is given in eV, T is given in Kelvins, and k is 8.61733´10^{-5} eV/K. From this equation, we can see that likely materials for electron sources would have large values for A_0, and low values for E_w. These values for tungsten are

$60A/cm^2K^2$ and 4.5eV, and for LaB_6 are $40A/cm^2K^2$ and 2.0eV. At their respective operating temperatures of 2700 and 2000K, they achieve current densities of 1.75 and 100 Amps/cm^2. Notice that the two orders of magnitude improvement, is attributable to half the energy required for electrons escaping LaB_6.[4]

Brightness is the term we ultimately want to deal with if we want to understand the properties of the electron gun, and how it pertains to the properties of the final spot on the target. For any system of lenses, brightness will remain a constant. To use a practical example, if we want to photograph a street lamp, for proper exposure we would need to realize that its absolute brightness doesn't change as we move away from it (this fact allows astronomers to determine the distance of distant supernoves). An experienced photographer would therefore use the same exposure regardless of the distance. What does change, of course, is the amount of light that falls on objects at various distances away. That is, change your camera exposure as a function of distance for objects lit by the same lamp, but not for the lamp itself. The term brightness, for which the dimensional units are intensity per area per solid angle, can be used to describe any image's intensity anywhere in a multi-lens system because it is normalized to the solid angle from focusing and takes into account any magnification or demagnification. The brightness of the electron probe on the target is a function of the gun's brightness. That is, a brighter probe as a result of a brighter gun means more intense electron interaction for a constant probe diameter and yields more specimen information with better spatial resolution.

Gun brightness at the cross-over can be expressed in terms of the gun's *current density* via an equation credited to Langmuir.

$$b = \frac{E_o J_o}{\pi k T}$$

eq. 4-2

This equation implies two parameters are available to the operator for increasing the gun's brightness. Because the current density is proportional to the square of the temperature (eq. 4-1), the gun's brightness is proportional to temperature. However, the proper adjustment for cathode heating properly saturates the gun and optimizes the filament's lifetime. Increasing the acceleration voltage is another possibility, but other considerations might dictate the value for that parameter. A third option might be understood regarding the electrostatic field contours due to the gun bias, that is, adjustment of R_B. Increasing the bias has a stronger effect on focusing the electrons for the initial cross-over. This affects the brightness but not in a systematic or predictable way. As a rule, the bias resistor and filament to Wehnelt distance are generally optimized once and left alone. Therefore, practically speaking, E_0 is the only adjustable parameter, and the cathode material is the only means for significantly changing how bright we can make a spot on the target.

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[4]   A point we can make here regarding the LaB_6 gun, besides its 2 orders of magnitude in brightness over tungsten, is that even at its operating temperature, it can last ten times longer. At 1500 K it can virtually last forever (replacement once a year or longer) and still be brighter than tungsten.

4.2.2 The LaB$_6$ electron gun

Lanthanum hexaboride has been shown to be an excellent material as a source for electron emission because of the low work barrier for electron escape. Only recently, however, has the manufacture of single crystals become economical so as to be a practical option for a multi-user facility. This type of gun has generally not an option for x-ray analysis (EPMA) until recently because it exhibits relatively unstable emission, both because of material characteristics and ease of contamination. New advances in beam current regulation electronics now make its stability sufficient for quantitative microanalysis in the latest generation of microprobe instruments. It is of course perfect for SEM imaging that typically occurs over a much shorter time period (e.g., an 80 second image capture), but less desirable for quantitative analysis over periods of up to several hours if not appropriately regulated. As high-vacuum guns become more common, LaB$_6$ sources are becoming more stable. Because many probes today rely on other types of beam stabilization (rather than the "self-biasing" or saturation mentioned above for the tungsten gun) the LaB$_6$ gun will continue to be seen in increasing numbers, even on microprobes.

This type of gun is only slightly different from a tungsten gun; conceptually it is the same because it has a heated source, a Wehnelt and an anode. The source is not heated the same way, however; the LaB$_6$ material is heated indirectly with a heater coil of resistive carbon. The major requirement for a LaB$_6$ gun is a very good vacuum, because LaB$_6$ crystals can be contaminated by almost anything. The source actually is a single crystal with a very sharp point from which electrons are emitted as its holder applies heat. The *saturation* curve described above does not apply to this gun, because the sharp emission tip and a requirement for higher bias voltages creates a very strong electrostatic field. The emission versus heating curve is generally monotonic without any definable operating point, so care needs to be taken so as not to overheat. As stated earlier, this material can however, be operated at below optimum temperatures if high brightness is not of demanding concern. Typical lifetimes for this type of source may approach 1000 - 2000 hours, compared to 100 - 1000 hours for tungsten. Although LaB$_6$ is more expensive, given their long expected life, they are cost-effective if used with proper care.

4.2.3 Field emission guns

This type of gun (FE for Field Emission) takes advantage of the lowering of the barrier for electron escape if the tip of the cathode is very small and influenced by a very high electrostatic field (bias). The source material is generally crystalline tungsten with a very sharp tip-diameter of approximately 100 nanometers. In close proximity to a highly positive anode, electrons are said to "tunnel" through their barrier without any thermal requirement. This type of gun is commonly referred to as *cold cathode* emission. With the work barrier reduced to nil, these guns can produce emission current densities on the order of 1000 Amps/cm^2. Like the

LaB_6, they are extremely susceptible to contamination, because a single atom on the surface of the emitter can increase the work barrier, thereby reducing emission and stability.

The latter two types of guns, can increase the ultimate resolution for imaging on the order of 5 to 10 times. For an application like EPMA, this is of little interest because of the inherent size of the interaction volume. Even for acceleration voltages of 30 to 40keV, SEM manufacturers claim only a 2-fold improvement in resolution over tungsten. However, what is apparent from secondary electron images taken with a LaB_6 or FE SEM, is the reduced noise in the photographs. Greater improvements in resolution, on the order of 10-fold, are achieved for applications which require low acceleration voltages, e.g., 100 to 10000 Volts.

An even newer modification of the field emission gun is the thermal field emission gun. This electron source (sometimes called a Schotsky emitter) has similar resolution to the cold cathode emission source, but can produce much higher and more stable beam currents making it very attractive for electron beam lithography, which requires carefully controlled electron dosages to the PMMA specimen.

4.3 Electron optics

We use the terms *electron optics* and electro-magnetic *lenses* only because they exhibit analogous behavior to optical lenses with which we are more familiar. For electron optics there are even analogs for index of refraction, and the common aberrations, spherical, chromatic, diffraction and astigmatism. However, in electromagnetic lenses we are not dealing with radiation, but are dealing with bending the paths of charged particles. Furthermore, we are not concerned with magnification of a image of interest, but are concerned with de-magnifying the image of the electron beam's source, i.e., the electron gun's cross-over. In spite of what are major differences between optical and electron lens systems, we can still understand them in terms of concepts that have been around for hundreds of years. Although there is no real need to go into great detail, some understanding of electron optics is necessary for intelligent operation of either the SEM or the microprobe.

A magnetic lens consists of a conductive wire winding which is symmetrical about the column axis. A magnetizable material, such as iron, encases the lens except for a gap adjacent to the beam, as shown in Figure 4-3. When a current is passed through the wire winding, the lens creates a magnetic field (with a north and south pole) that emanates from the gap. It is this magnetic field that acts to focus the electrons passing through the lens.

The force on an electron passing through the lens is given by a vector cross product

$$\vec{F} \ = \ e(\vec{v} \ x \ \vec{H})$$

<div align="right">eq. 4-3</div>

where e is the charge on the electron and v is its velocity vector. The H vector is the strength of the lens, and is parallel to the magnetic field (perpendicular to the lines of constant field strength shown in Figure 4-3). The electron's velocity is directly related to its energy, E_0, but to be rigorous should be relativistically corrected as its velocity approaches the speed of light.

$$v \ = \ E_o(1 \ + \ .000001E_o)$$

<div align="right">eq. 4-4</div>

The net result of the interaction between the electrons and the magnetic field is shown schematically in Figure 4-3 by means of electron paths from a source object, d_0 (which might be either the first cross-over for the condenser lens, or the intermediate image formed by the condenser lens for the objective lens), to the demagnified image, d_i. The electron paths do converge as depicted analogous to optical lenses, even though the electrons travel in a helical
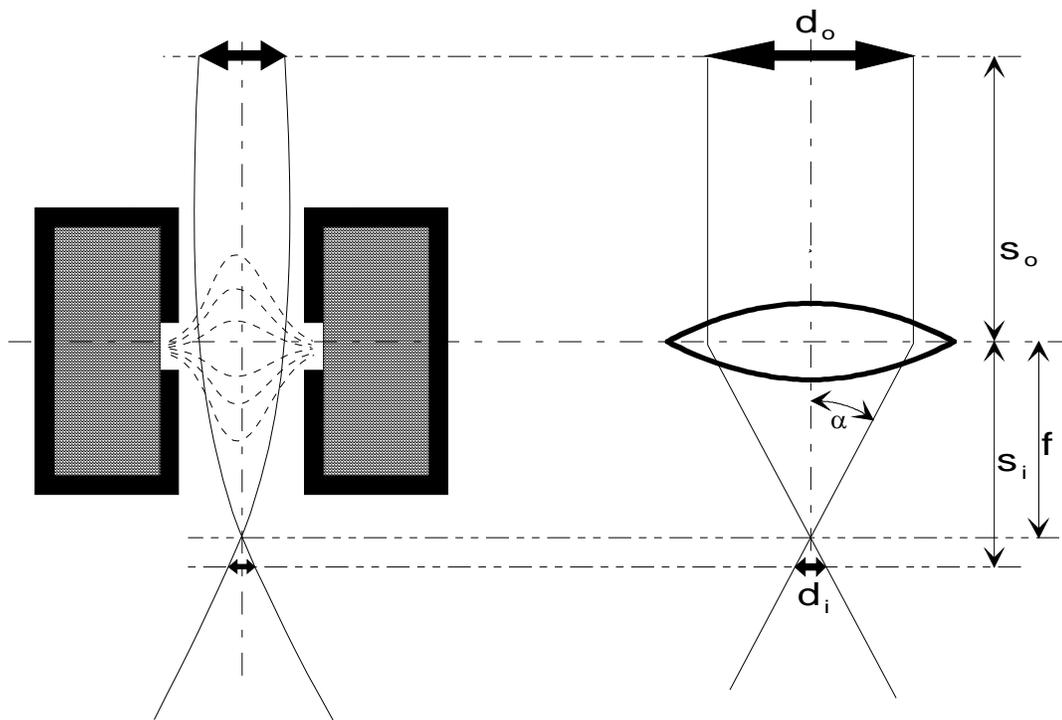

Figure 4-3   The electro-magnetic lens and its thin-lens counterpart.

path as they are focused.

The focal point for an electro-magnetic lens is defined the same as for optical lenses, i.e., the position of the cross-over point below the lens for parallel paths above the lens. The relationships between object size, d_o, image size, d_i, object-to-lens distance, s_o, image-to-lens distance, s_i, and focal length, f, for an electro-magnetic lens are analogous to those for a thin refracting lens system.

Likewise, the relationship between f, s_o and s_i is given by the thin lens equation:

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$$

eq. 4-5

the de-magnification, M (magnification being the reciprocal), given by

$$M = \frac{d_o}{d_i} = \frac{s_o}{s_i}$$

eq. 4-6

For an electro-magnetic lens, adjustment of the focal length for the lens is related to the current through the windings with the proportionality

$$f \propto \frac{E_0}{I^2}$$

eq. 4-7

where E_0 approximates the relativistic velocity of the electron.

Figure 4-4   Definitions of electron column parameters for the first and final lens systems.

All SEMs and microprobes will use a magnetic lens system similar to as shown in Figure 4-4, although modern instruments will utilize two condenser lenses in tandem. If the gun cross-over diameter, d_0, and its distance to the condenser lens, s_0, are instrumental constants, and if f_1 is decreased, then s_1 will also decrease, resulting in greater de-magnification of the beam's intermediate
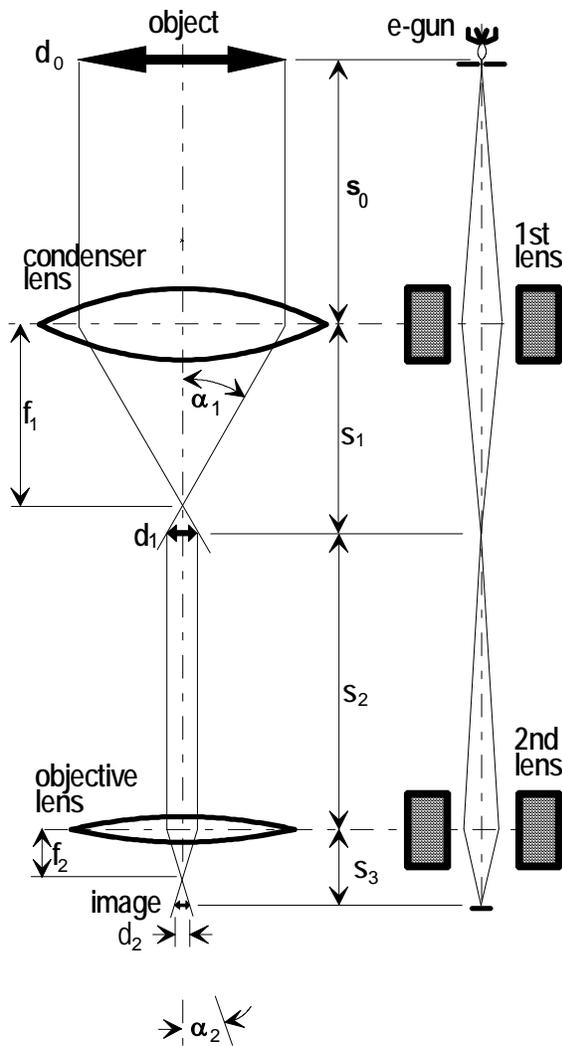
diameter. The condenser lens is the primary de-magnifying lens and is used for controlling the size of the probe's spot. However, the ultimate spot is as much a result of beam current as de-magnification by the lens systems. This fact does not diminish any of the responsibility for this lens in producing the smallest possible spot possible for the final lens. Let's examine the above parameters for the entire electron column. If

$$\frac{d_1}{d_0} = \frac{s_1}{s_0} \quad and \quad \frac{d_2}{d_1} = \frac{s_3}{s_2}$$

eq. 4-8

the de-magnification is given by

$$\frac{d_0}{d_2} = \frac{s_0 \, s_2}{s_1 \, s_3}$$

eq. 4-9

The parameter s_2 is very much larger than s_1, and can be considered to be an instrumental constant. The same is true for s_3 because **working distances** remain fairly constant for a given application. We can reduce the above equation relative to instrumental constants, and the focal lengths over which we have direct control.

$$\frac{d_0}{d_2} = \frac{s_0 \, s_2}{f_1 f_2} \frac{s_2 \, s_0}{f_2 f_1} + 1$$

eq. 4-10

While we might also want to consider f_2 an instrumental constant as well (the working distance generally defines it — especially for microprobes), typical operating value parameters for a microprobe might be: s_0=20cm, s_2=30cm, f_1=2cm and f_2=2cm. This implies de-magnification of the initial cross-over by 126 times, i.e., 100 microns to less than a micron. This case is for early microprobes, which forsake quite a bit of lens design and de-magnification while accommodating high beam currents, and other options, (e.g., cassegrainian optics). Double condenser lens systems have improved this example by several orders of magnitude, and have allowed modern microprobes to image as well as scanning electron microscopes, if so optimized.

4.3.1 The first lens

The **condenser** or *first* lens can be relatively simple in design, for example, as shown in Figure 4-3. As already mentioned, this lens in modern electron microscopes will probably be a

increased lens current
increased focussing power
decreased beam current
decreased spot size
better spacial resolution

decreased lens current
decreased focussing power
increased beam current
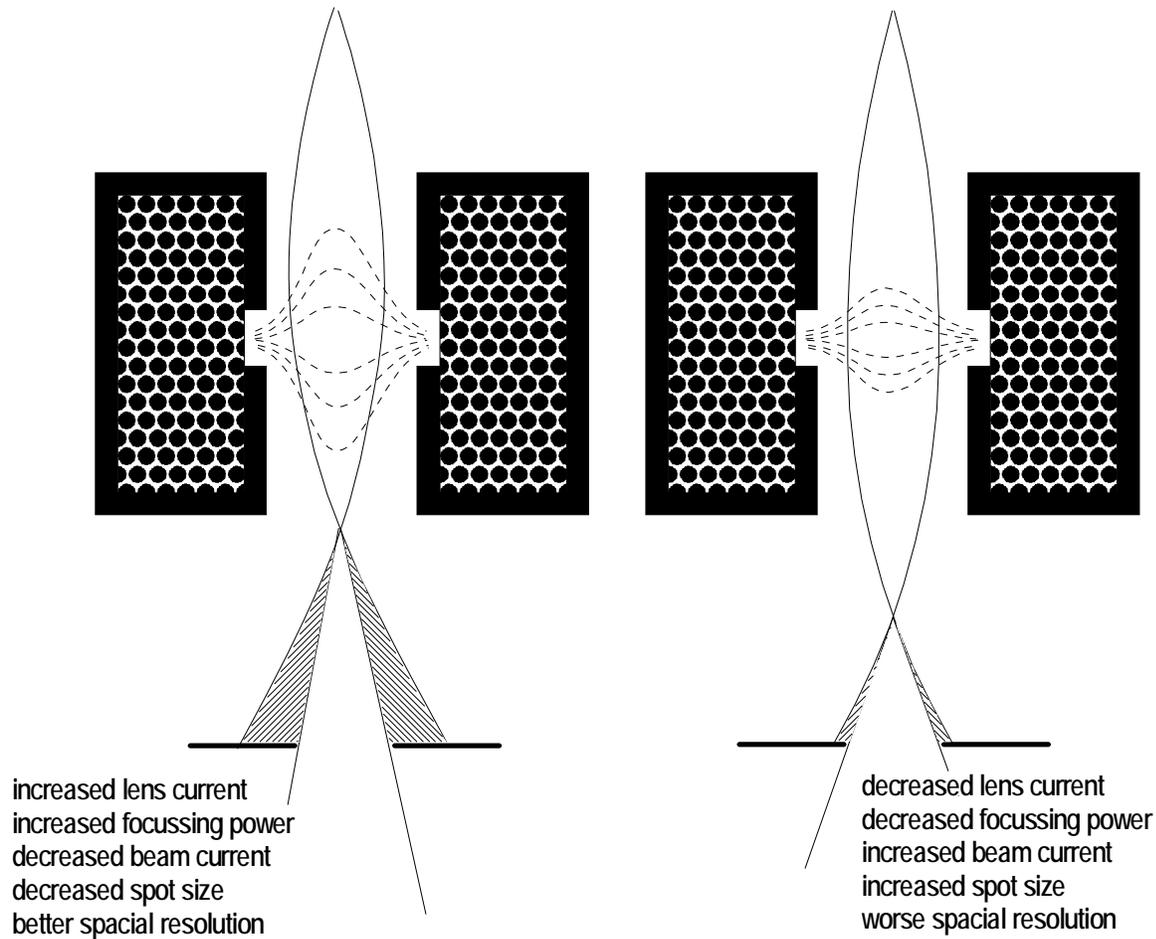increased spot size
worse spacial resolution

Figure 4-5 The condenser lenses' role for adjustment of the beam current. As lens current is increased, the beam current which passes the CL aperture is decreased.

two-lens design, that is, two physical lenses functioning as a single unit. Also, as mentioned previously, the condenser lens is the primary de-magnifying lens; that is, it is likely to de-magnify the 100μm first cross-over 1000 times and provide an image for the *last* lens.

The SEM operator has control over this lens with ability to adjust the current to its windings, thus controlling its focal length and de-magnification. Some instruments actually label the condenser lens adjustment knob "*spot size*" in recognition that it is this lens that is going to determine just how small the spot on your specimen can become. However, this label oversimplifies how the lens works, and obscures its primary function.

The primary function of the condenser lens is more fundamental than de-magnification. Its primary role is to control how many electrons interact with the target, that is, control of the **beam current**. As we will see later when we discuss optimization of the electron probe's spot size on the surface of the target, its diameter will ultimately be a result of inherent aberrations in the column and of the gun's brightness, and will be a function of beam current.

Figure 4-5 shows how the condenser lens works with the ***condenser lens aperture*** to control the beam current. As current to the lens increases, the focal point decreases and the optical angle, α, increases. As the optical angle increases, the fixed aperture below the lens passes less of the beam that has entered the lens, and that which is not passed on to the last lens and target is captured by the grounded lens' ***liner tube***. It is also noteworthy to realize that decreased beam current works in tandem with increased de-magnification.

The beam current is a very important instrumental parameter. You might ask: "*Why not optimize the condenser lens for minimum current, if it means the smallest spot and best resolution*?" The answer needs to take into account the specific application. For example, do you need the best resolution? If so, then you should optimize the first lens for the smallest spot. However, what if you are imaging at relatively low magnification which doesn't demand the smallest spot, and your images lack contrast or are very "noisy". In this case you need a stronger signal from your target, and this can be achieved by increasing the beam current. The requirement for higher beam currents has application for both backscatter imaging and x-ray analysis as well, because these production cross sections are smaller than for secondary electron production. So when the electron beam instrument is optimally configured for high magnification imaging, the primary beam intensity will generally be too low for efficient backscatter imaging and x-ray analysis (see the explanation of the brightness equation to understand this).

The knowledgeable operator realizes how to play one parameter against another for the sake of specific applications. The x-ray analysis application is a very good example, because the interaction volume is very much larger than the optimum spot size anyway; that is, the subsequent trade-off might be with respect to imaging secondary electrons, but not with respect to the generation of x-rays.

Adjustment of the condenser lens is one of the means by which the operator changes the instrument's mode of application.[5] For example, it is either optimized for quantitative x-ray analysis or high magnification imaging, and there is lots of gray between; for example, qualitative analysis with EDX while imaging backscattered electrons. All modes play the probe's diameter and spatial resolution against the strength of the information gained.

4.3.2 The final lens

Whereas the first lens can be designed entirely for the purpose of de-magnification without other considerations, the ***objective*** or ***final lens*** generally needs to accommodate the specimen's freedom of movement (e.g., tilt), all detectors, and provide a magnetism-free environment for the information emitted from the target.

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[5]   Regarding the mode of the instrument, the condenser lens should be used secondarily to the final aperture (see below). That is, make coarse changes with the final aperture (e.g., imaging to x-ray analysis) and fine tune the condenser lens to optimize x-ray count rates or for removing noise from the image.

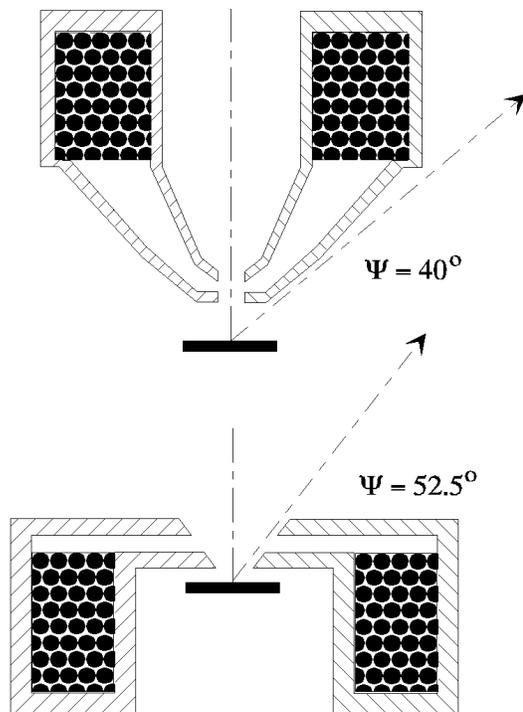$\Psi = 40^\circ$

$\Psi = 52.5^\circ$

Figure 4-6 The objective lens design for the Cameca (top) and ARL (bottom) EPMA instruments. Notice the design considerations for x-ray line-of-sight to the spectrometers.

Figure 4-6 shows two examples for two very different objective lenses for electron microprobes. The Cameca design is the more traditional, maintaining good characteristics for imaging, but still accommodating optical mirrors for light viewing of the target, as well as the x-ray take-off angle to the spectrometers (see Figure 4-1). The ARL lens on the other hand, was designed entirely for their x-ray spectrometer and its extremely high take-off angle. It also allows for Cassegrainian optics above, but is not a very good lens for de-magnification, and the ARL probe was not known for its high resolution capabilities. As an x-ray microanalyzer, however, it was considered one of the best for many years.

Modern SEMs utilize a "***minilens***" design, that makes the objective lens as small as possible and eliminates many of the design requirements needed by microprobes. Mini-lenses need to be manufactured with a much higher degree of precision, and they can not accommodate Cassegrainian mirrors, so optical viewing of the specimen is not possible unless the viewing is from an oblique angle.

The primary purpose of the final lens is to focus the electron beam on the target, whether it be a spot as small as it can be (focused) or larger (de-focused). The ***working distance*** needs to be a consideration as well*,* since it determines whether the focal point will be long or short, and to what degree the final lens is used to de-magnify the spot, d_i. If the working distance is short, the final lens' focal length will be short, and it will de-magnify to a greater degree than if the focal length is long and focused at a longer working distance. *So why use a longer working distance*? Longer working distances are intended to accommodate physical dimensions of specimens, as well as providing the capability to tilt the specimen. An x-ray spectrometer or EDS detector might also be *aimed at* a longer working distance.

Also associated with the final lens is the ***final aperture*** that is shown schematically in Figure 4-7 (we say "schematically" because the actual location of the aperture may be considerably higher in the column relative to the pole piece). The final aperture should be considered as an important adjustable parameter for changing the instrument's configuration to fit the application. Like the condenser lens, the beam current which reaches the target can be controlled by selecting an appropriate final aperture size. Quite simply, the larger it is, the more electrons get through. As shown in Figure 4-7, changing the size of the final aperture or the

working distance has a significant effect on the final optical angle, α. No electron microscope offers a continuously variable aperture size, but most provide a means for selecting one of several apertures of fixed diameter. Which aperture is chosen varies with the application (see, for example, Fig. 4.12). Generally, for x-ray analysis, choose the largest aperture, and for highest resolution choose a small aperture and a short working distance.

Figure 4-7 also defines ***depth of focus*** or ***depth of field***, (see discussion in Chapter 2). Depth of focus is highly dependent on the optical angle. If the optical angle is high, as it is for high-magnification light microscopy, then the depth of focus will be very shallow; that is, only the plane of sharp focus will "appear" to be in focus. If, however, the optical angle is small, as it is for electron microscopes, then there will be considerable depth above and below sharp focus, for which any object will be in "acceptable" focus. While the SEM is known for its

$$\alpha \cong \tan \alpha = \frac{d_F}{D_F} = \frac{D_A}{2D_W}$$
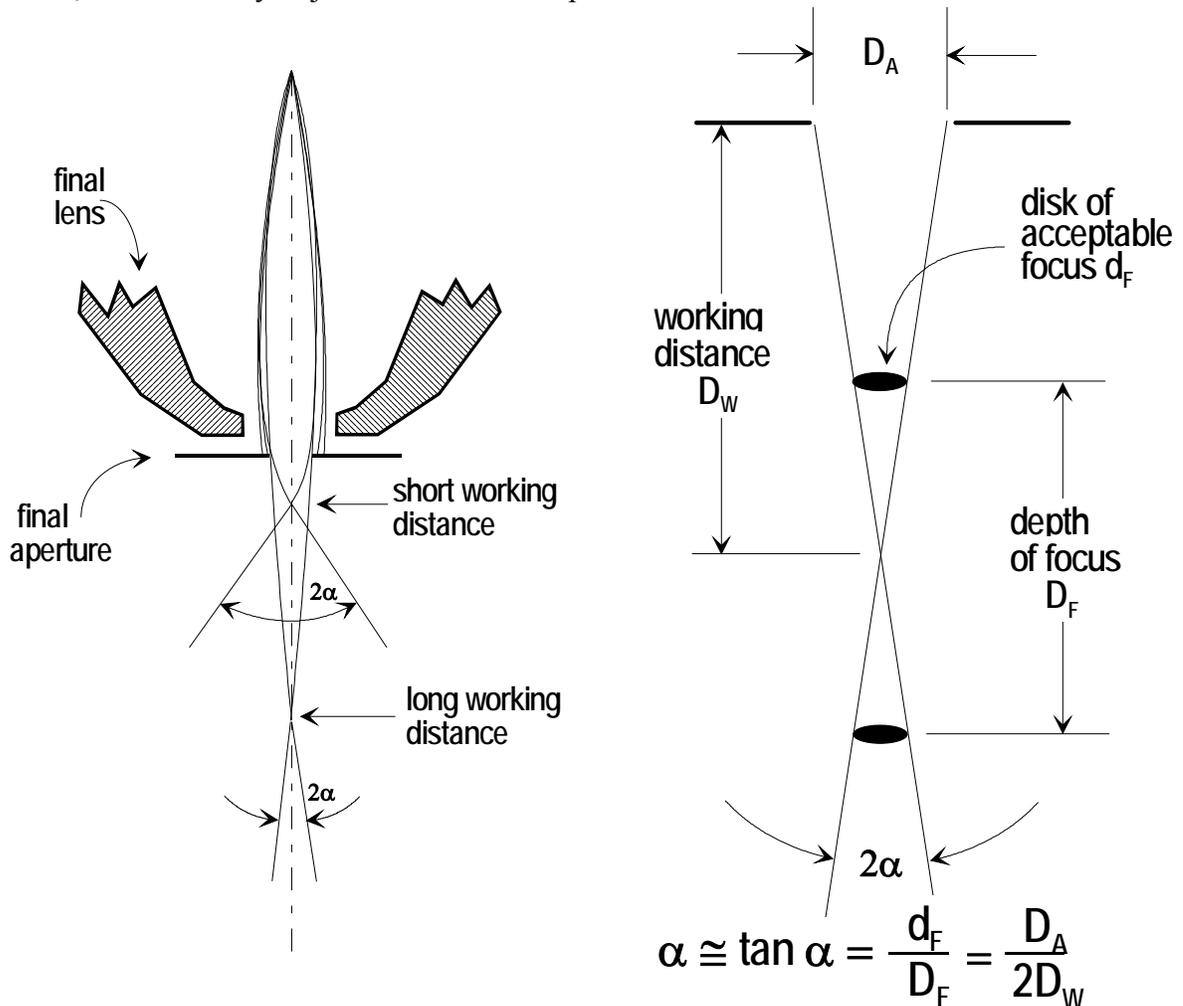
Figure 4-7 The final lens and its final aperture, and their relationship with working distance and "depth of focus".

depth of focus, the demanding operator will constantly try to maximize it. Generally, to maximize the depth of focus use a long working distance and a small final aperture.

A radiolarian skeleton provides an excellent example for an exercise in choosing parameters for optimizing for depth of focus. Let us say, for example, we want to image this specimen with the SEM. The fossil is spherical with a diameter of 250 microns[6]. If we want to print a 10cm wide picture with its image, then the magnification needs to be 400X (i.e., 100,000μm per photo/250μm per critter). We can calculate the ***disk of acceptable focus*** by the method described in Chapter 2. However, in this case, let us just say we want to publish this photo in a scientific journal that prints its photomicrographs at 5 lines per mm. For this photomicrograph, the resolution we require (i.e., the "acceptable" spot size) will be 0.5μ (i.e., 250μ per image/5 lines per mm/100mm per image). According to Figure 4-7, if our disk of acceptable focus (d_f) is 0.5μ, and the working distance (D_W) is 39mm, and if we want our depth of focus (D_F) to be 250μm, then our aperture (d_A) needs to be smaller than:

$$D_A \; = \; \left(\frac{d_F}{D_F}\right) 2 \, D_W \; = \; \frac{(0.50 x \, 10^{-6})}{(250 x \, 10^{-6})}(2(39 x \, 10^{-3})) \; = \; 156 x \, 10^{-6}$$

(a)

The selection of a 150μ aperture would be appropriate (if available), and since our disk of acceptable focus is quite a bit larger than what should be considered the ultimate resolution of any SEM, we should be able to use a relatively large beam current with this small aperture in order to insure that our image gray scales are smooth and not too noisy.

(b)

4.4 Probe diameter and its aberrations

The electron beam's spot on the target can be approximately described as an electron density distribution. Figure 4-8 shows how this intensity is distributed from edge to edge for two different values of gun brightness and two different condenser lens settings (i.e., two different guns (a & b) and two different beam currents). The figure is intended to show that for two different electron guns, (b) brighter than (a), and two identical beam current conditions (e.g., curve area for upper (a) equal to upper (b)), that the probe diameters (defined here as FWHM) are different. Pease and Nixon (1965) proposed that the probe diameter be defined at 20% peak intensity, which is to say if two diameters overlap at *I* equal 20% (i.e., no overlap for 80% of area under curve), the information gained from those two points can be
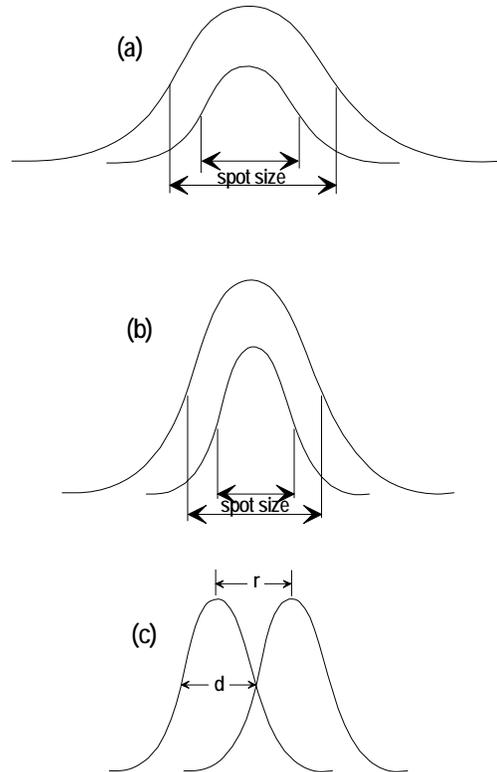
Figure 4-8 Intensity cross sections for the probe spot. (a) tungsten and (b) LaB6 cathodes. (c) definition for spot size, d, and resolution, r.

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[6] A radiolarian is a microscopic oceanic life form with a silica skeleton. The different species have a multitude of different shapes and geometries that are often strikingly beautiful under the SEM.

considered distinct or **resolvable**. The distance between these two points is defined as the **resolution** (see Figure 4-8c), which is generally equated with the **spot size**. For what follows, we will speak of spot size and resolution as if they are the same, and owing to the fact that such definitions are arbitrary, we will choose the **full width at half maximum** as shown in Figure 4-8 for the spot size. Our definition might seem extreme, but the difference between the areas under the curves is small, 80% vs. 70%, still enough to consider the information gained by separate spots distinct. Our definition will also allow us to examine these curves as if they were Gaussian, allowing us to consider aberrations as "error" distributions superimposed on the initial electron density distribution. Thus, we can add all intensity distributions (or so-called **disks of confusion**) for the gun (d_g), spherical aberration (d_S), chromatic aberration (d_C) and diffraction aberration (d_D) together in quadrature.

$$d_P = \sqrt{d_G^2 + d_S^2 + d_C^2 + d_D^2}$$

eq. 4-31

in order to understand how the column parameters can be optimized for the ultimate probe diameter, d_P.

If we use a generic definition for brightness, i.e., intensity per solid angle per area

$$b = \frac{i}{d^2 \alpha^2 (\pi/2)^2}$$

eq. 4-12

and combine this with the Langmuir's equation for the gun's cross-over (eq. 4-2), we get

$$d_G = \left(\frac{4i\, kT}{\pi E_0\ j_0} \right)^{\frac{1}{2}} \frac{1}{\alpha}$$

eq. 4-13

Eq. 4.13 implies if we want to increase the beam intensity for a constant probe diameter, we should make α larger, much the same way we open our camera's lens diaphragm in low light situations. However, because of several aberrations in our electron column (analogous with the camera's lens), it is best to keep α small. If we plot the probe diameter as a function of beam current without consideration of α we see a slope of 1/2 on a log-log plot. Figure 4-9 shows us this relationship for five different acceleration voltages. Notice that the curves become flat at small probe currents, which is due to column aberrations starting to limit any further decrease in the spot size.

4.4.1 Spherical aberration

Consider two electrons entering a magnetic lens, one along a path closer to the column's central axis than the other. As with two beams of light entering different parts of a glass lens (Figure 4-10), the electrons will tend to focus differently, with the outer region of the lens focusing more strongly. Intuitively, if we restrict the paths of the electrons entering the outer portions of the lens we can reduce the effects of this aberration, but this in effect either decreases the optical angle, α, or reduces the beam current, i. The equation for the diameter of this disk as a function of α is given as

$$d_S = \frac{1}{2}C_S\alpha^3$$

<div align="right">eq. 4-44</div>

where C_S is the spherical aberration constant for the lens, and is usually on the order of 2cm. As you can see, there is a high dependency for this error in the lens on high optical angles. This column aberration is the primary contribution to the increased probe diameter if we try to increase our probe current by opening apertures.

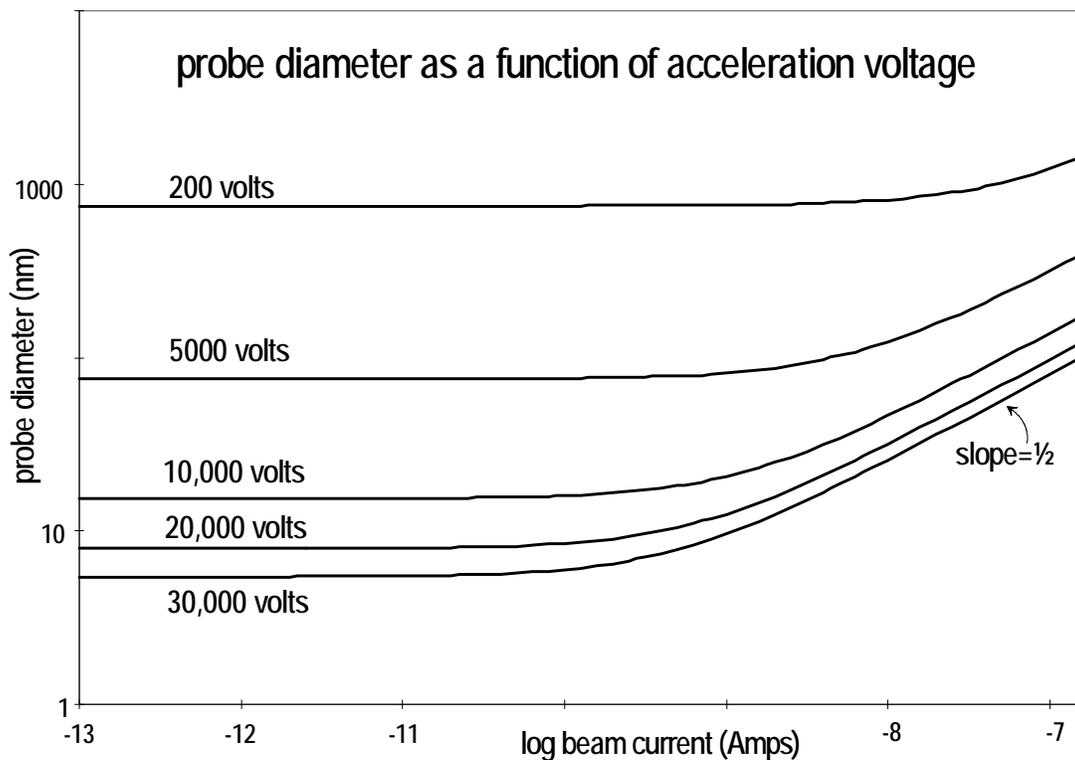Modern atomic resolution scanning tunneling electron microscopes (STEM) use specially

Figure 4-9 Probe diameter vs. probe current for five different acceleration voltages. Notice the influence of column aberrations at low beam currents.

designed C_S "correctors" to eliminate spherical abberations that are intrinsic to even the most carefully designed electron lens systems. With these devices, researchers are able to image single atoms in atomic lattices in real time.

4.4.2 Chromatic aberration

Chromatic aberrations occur in glass lenses because the index of refraction for the glass is different depending on the light's wavelength. We have already seen that the focusing power for a lens is dependent on the velocity of the charged particle, which we relativistically attribute to the acceleration voltage, E_0. The analogy for chromatic aberration is attributable to the electrons not being absolutely "monochromatic", … that is, there will be a small energy distribution about E_0. We cannot attribute this to the power supply because modern power supplies are generally stable to one part in a million. There will, however, be a natural skewness for a ΔE less than E_0 of approximately 3eV because of charged particle repulsion at the first cross-over (see Figure 4-11). The type of electron gun can also be factor because there is a natural distribution of energy as electrons leave the cathode, being on the order of 2eV for tungsten, 1eV for LaB_6 and 0.5eV for field emission. The chromatic aberration disk of confusion, d_C, is given by

$$d_C = \left(\frac{\Delta E}{E_0}\right) C_C \alpha$$

<div align="right">eq. 4-55</div>

where C_C is the chromatic aberration coefficient for the electron column, and is generally on the order of 1cm. Notice, that again, we have a dependency on the optical angle.

Again, modern STEM instruments utilize specially designed electron monochromators to ensure that all primary beam electrons are very similar in energy to enable imaging of single atoms.

4.4.3 Diffraction aberration

The most fundamental contribution to any final image is *diffraction aberration*, because of the inherent wave nature of both visible radiation and energetic electrons. Diffraction is the limiting factor for the ultimate resolution of light microscopes, and is why optical microscopists often rely on ultra-violet radiation for increased resolution. It is also the reason TEMs, which are able to image on the scale of crystal lattices or atomic dimensions, require acceleration voltages on the order of several hundred thousand or even millions of volts.

As radiation passes through an aperture the light scatters or is said to diffract, with longer wavelengths being the most affected. The disk of confusion for the diffraction
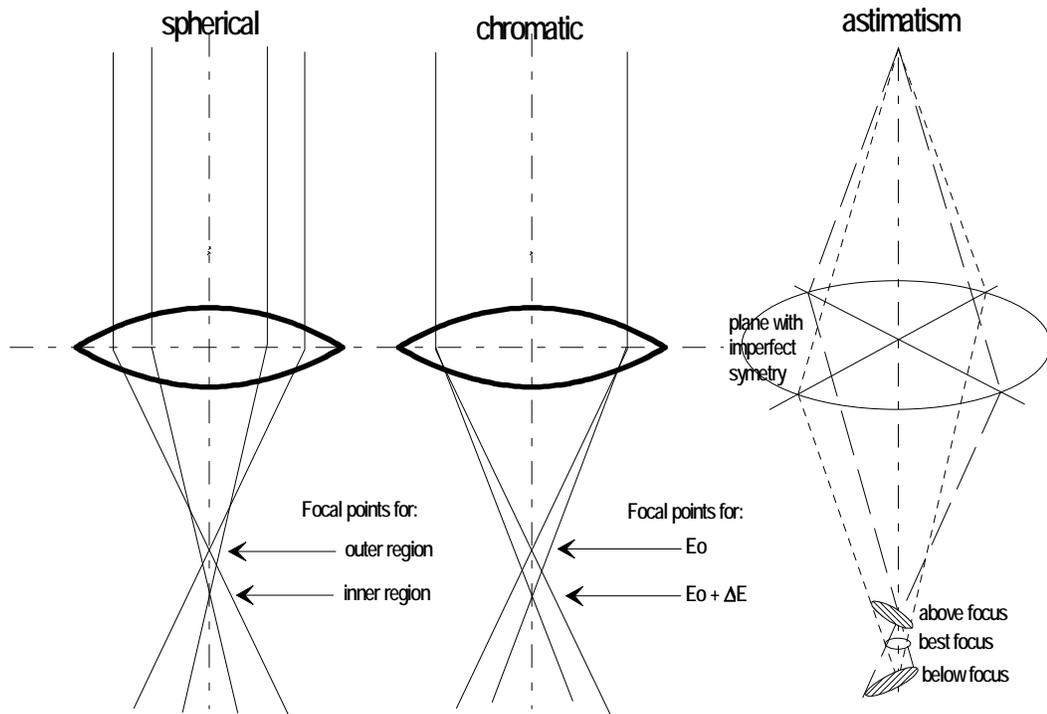
Figure 4-10 Aberrations for an electron probe. Spherical (left), chromatic and astigmatism (right).

aberration is given by the general equation for light

$$d_D = \frac{1.22\lambda}{n_i \sin\alpha}$$

<div align="right">eq. 4-66</div>

where n_i is the index of refraction for the lens. For electron microscopes the equivalent equation is

$$d_D = \frac{1.51}{\alpha\sqrt{E_0}}$$

<div align="right">eq. 4-17</div>

Notice that the root of E_0 substitutes for the index of refraction, and the substitution of α for $\sin\alpha$ when α is small. For a comparison between light microscopy and electron microscopy, the interested student might substitute into the above equations the values: $n\sin\alpha=1.4$ and 500nm (for blue light); $E_0=30,000$volts and $\alpha=0.005$ (for typical SEM); and $E_0=1,000,000$volts and $\alpha=0.01$ (for TEM).

4.4.4 Astigmatism

If, for any reason, the electron column's interaction with the electron beam is not perfectly radial, the beam will be *astigmatic*. For example, a minute quantity of dirt in an aperture will affect the electrons passing through it a non-symmetrical fashion (i.e., the aperture will be effectively "egg-shaped" rather than round). The result (see Figure 4-10) is that above and below sharp focus, the disk of confusion will be elliptical and mis-aligned by 90 degrees. At sharp focus, the spot will usually be round, however, the degree of confusion due to the aberration will still be a considerable contribution to its ultimate size.

There are no equations which can quantify this aberration because there can be so many contributing factors (e.g., dirty apertures or column-wall contamination). The ultimate contribution of astigmatism to the final spot size is usually ignored by assuming that the column is not astigmatic or that it has been corrected for. Small degrees of astigmatism can be removed with a *stigmator*, which can correct the probe with an elliptical influence equal in magnitude but opposite in orientation. The SEM will always have two controls for the stigmator, magnitude and orientation. Correction is achieved by best focusing with the objective lens, then best focusing with stigmator *orientation* and then best focusing with stigmator *magnitude*.[7] Although minor amounts of astigmatism can be corrected, it can never be removed, that is, without removing the column liner and apertures and either cleaning them or replacing them. Considering the fact stigmatism is an ellipsoidal correction while most contributions to astigmatism are egg-shaped, there is no substitute for a clean and contamination free electron column.

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[7] Magnitude and orientation is the best method to introduce students to corrective stigmatism, however many instruments manufactured today will label their astigmatism correction knobs as x and y, as if what was applied in "polar" space is now applied in x-y space. The operator will possibly find it easier to "focus" with a x-y stigmator.

If we consider all aberrations, Figure 4-11 shows the probe diameter vs. probe current relationship for the tungsten gun and a LaB_6 gun. The figure shows the combined effect of the above-mentioned aberrations. Two identical columns will have similar column aberrations in spite of the sources for the electrons being different electron guns. Both instruments, therefore, will have the same ultimate spot size at low probe currents, however the brighter gun allows smaller probe diameters at higher probe currents.

4.5 Minimizing the probe diameter and maximizing its current

For the best resolution, the *optimum* probe will have a minimum spot size and have a maximum current for the sake of strong or noise-free information. Combining equations 4-13, 4-14, 4-15 and 4-17, we arrive at:
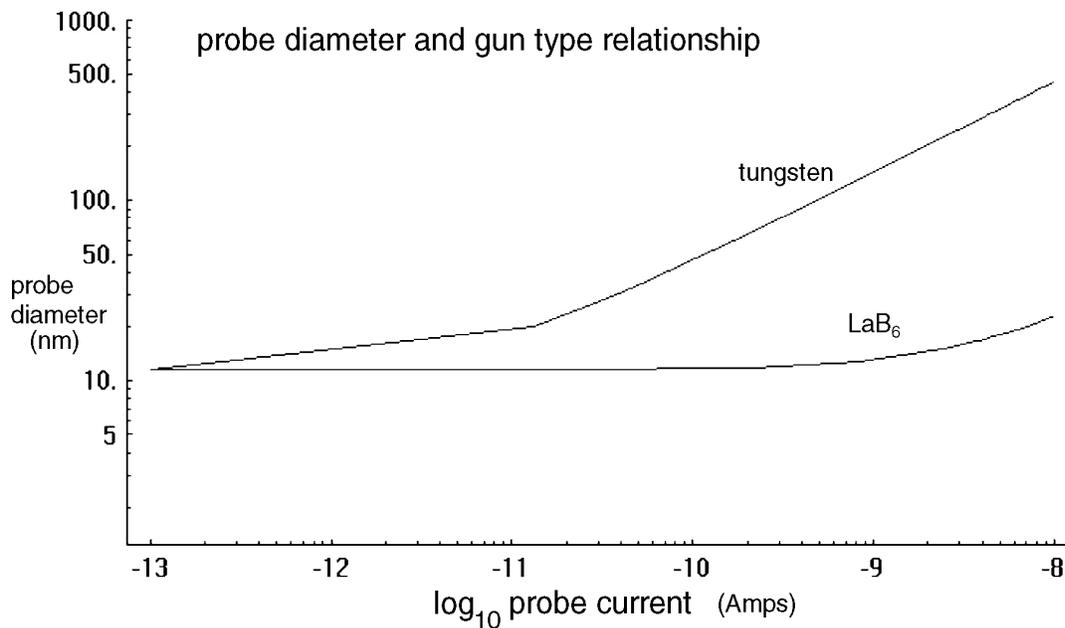

Figure 4-11 Probe diameter vs. beam current for two identical EM instruments for two different gun types; tungsten and lanthanum hexaboride. Note that both still have identical ultimate probe diameters at minimum beam currents.

$$d_p^{\,2} \;=\; \left[\frac{4i\,kT}{\pi\,E_0\,j_0} + \frac{2.28}{E_0} \right]\frac{1}{\alpha_2} \;+\; \left(\frac{1}{2}\right)^2 \alpha^6 \;+\; \left(\frac{\Delta E}{E}C_C\right)^2 \alpha^2$$

<div align="right">eq. 4-78</div>

Pease and Nixon (1965) obtained the theoretical limits to probe current and probe diameter by differentiating the first two terms (ignoring the chromatic aberration) in equation 4-18 with respect to aperture angle (α), so as to achieve the maximum current (i_{max}), and the minimum probe diameter (d_{min}), for the optimum optical angle (α_{opt}). The relations are

$$d_{min} \;=\; 1.52\,C_s^{\frac{1}{4}}\,E_0^{\frac{3}{8}}\left[7.92\left(\frac{iT}{J_c}\right)x\,10^9 \;+\; 1\right]^{\frac{3}{8}}$$

<div align="right">eq. 4-19</div>

$$i_{max} \;=\; 1.26\left(\frac{J_c}{T}\right)\left[\frac{0.33\,E_0\,d^{\frac{8}{3}}}{C_S^{\frac{2}{3}}}\;\;1\right]10^{10}$$

<div align="right">eq. 4-20</div>

$$\alpha_{opt} \;=\; \left(\frac{d}{C_S}\right)^{\frac{1}{3}}$$

<div align="right">eq. 4-21</div>

We are primarily concerned with equation 4-19, and we can see that we reduced the variation of the probe diameter with respect to the probe current to a power of $^3/_8$ by optimizing the optical angle. This is in contrast to equation 4.13, for which the dependency was a power of $\frac{1}{2}$. Although the $^3/_8$ power relationship should be understood and realized, in practice it is difficult to exploit because the SEM operator does not generally have a continuously variable optical angle available. Although it is possible to choose one of several final apertures and vary the working distance so as to achieve the optical angle of choice, it is still difficult and time consuming to calculate the optimum configuration. Figure 4-12 shows how the probe diameter varies with probe current for three optical angles, i.e., three different final apertures. If you draw tangents to the curves you can recognize the shallower $^3/_8$ power law. Because very little is gained by optimizing the optical angle ($^3/_8$ vs. $\frac{1}{2}$), the operator should realize the $^3/_8$ power law can be exploited if the application allows. Owing to the fact that working distance and final aperture most probably will be chosen with regard to other practical concerns (e.g., beam current or depth of field), the operator is left with the function, $d_p = f(i^{\frac{1}{2}})$, being the primary basis for understanding the probe diameter with respect to probe current.
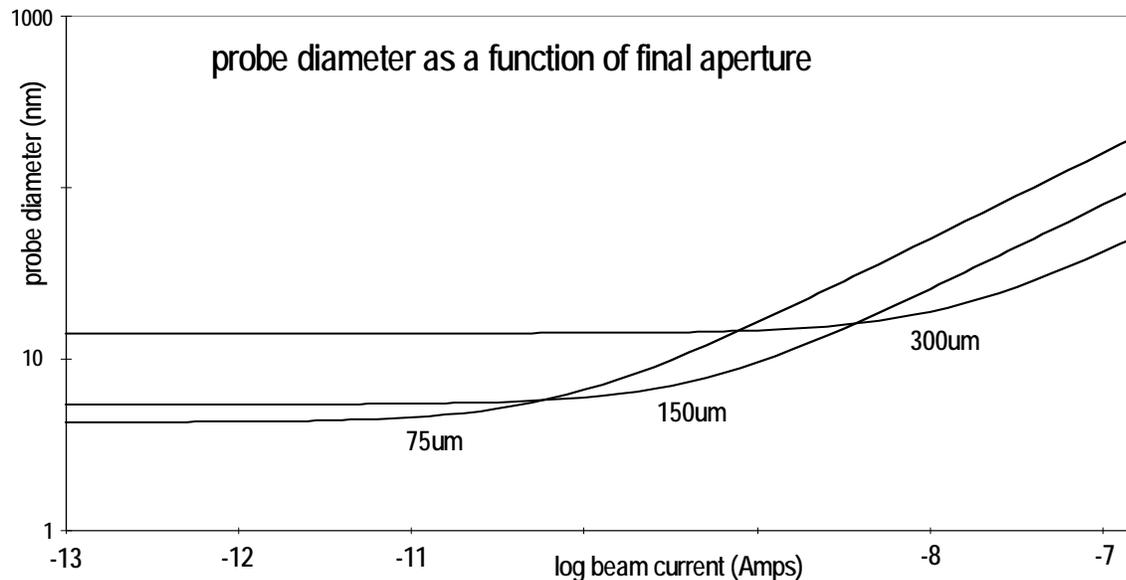
Figure 4-12 Probe diameter vs. beam current for three different final apertures. Notice that proper selection of the final aperture allows exploitation of the 3/8 power law.

The above equations do point out a couple of interesting concepts. Equation 4-19 can be used to calculate the theoretical minimum diameter for an instrument. For example, plugging the values of 40,000eV and 2cm into eq. 4-19 for E_0 and C_S yields a value of 2nm for the minimum probe diameter at i =zero. For a working distance of 1cm, the optimum optical angle implies that the final aperture should be 100μm. The last item to point out is the importance of the coefficient of spherical aberration in the calculation. Minimizing the constant by a factor of ten could increase the probe current by a factor of 5 or reduce the probe diameter by a factor of two. Such *mini-lenses,* have been developed recently and are capable of delivering these specifications.

4.6 Beam deflection and scanning

The primary function of the electron column is to produce a finely focused beam of electrons on the target. In electron microprobes, the location of the "spot" on the flat target is generally indicated by cross-hairs in the optical viewing system, and the alignment of the probe with crosshair can be confirmed by placing the beam on a cathodo-luminescing specimen. What should appear at the cross-hair is a circular spot of visible light. If the "spot" is not circular, and changes shape when the sample is raised and lowered from "focus", the beam is astigmatic. Optical viewing, usually at a magnification near 400x, generally suffices for microprobe analysis, but it is sometimes inconvenient because it is hard to know the probe's position relative to the cross-hair when a target location is very small (e.g., 10μm). It is more precise to know the probe's position relative to an image at 2000x, for example by viewing the target with a secondary electron or BSE image and using a beam deflection cursor to put the probe exactly where it is wanted.

Scanning *electron microscopy* refers to scanning or rastering the beam across the target, i.e., covering a certain amount of area over a period of time, and synchronously sending one of many detector signals to a display CRT. This is accomplished with two sets of *scanning coils* located between the first and second lenses and oriented at right angles. One set will position the beam in the x direction on the target, while the other positions the beam in the y direction. These scanning coils are not strictly part of the electron optical system, but they are physically part of the column. These coils when used together under the direction of a *scan generator*, can make the beam draw circles on the target simply by sending a sine wave to both coils. Modern *digital scan generators* are now used in the electronics industry and in materials science research to create micro-circuitry on silicon wafers by fine positioning of the electron beam with a computer (electron beam lithography). A computer can also generate a 3-dimensional virtual object by using the intensity of a line-of-sight signal (e.g., BSE or x-ray), generated from a small object as the computer systematically positions the probe on a rotating specimen (tomography).

These are all special applications, but indicate how the scanning coils work. Their primary function, of course, is to simply cover a rectangular area on the target, which proportionately, has the same aspect ratio as the display area or photo CRT. The scan generator usually sends a "sawtooth" voltage to both sets of scanning coils. Figure 4-13 shows how a horizontal 2 millisecond sawtooth combines with a vertical 2 second sawtooth for a *slow* 2 second display scan. The "ramp" part of the sawtooth pulls the beam across the target, the time taken to do so depends on the frequency of the sawtooth. The vertical part of the sawtooth instantly sends the beam back to the beginning. Typical scan rates, or rasters, are *TV rate* which is approximately analogous to your television's raster rate, or *slow rate*, for which the scan rate in the horizontal is fast, but the vertical scan rate is on the order of 2 to 20 seconds. The result of the latter is a horizontal line traveling from the top of the display to the bottom. While the electron beam is scanned in accordance with this rate, the electron beam inside the display CRT is scanned at the same rate across its face. The brightness of the image on the display CRT will be a function of the CRT's electron beam current, which is *modulated* by the secondary electron or BSE emission from the target.
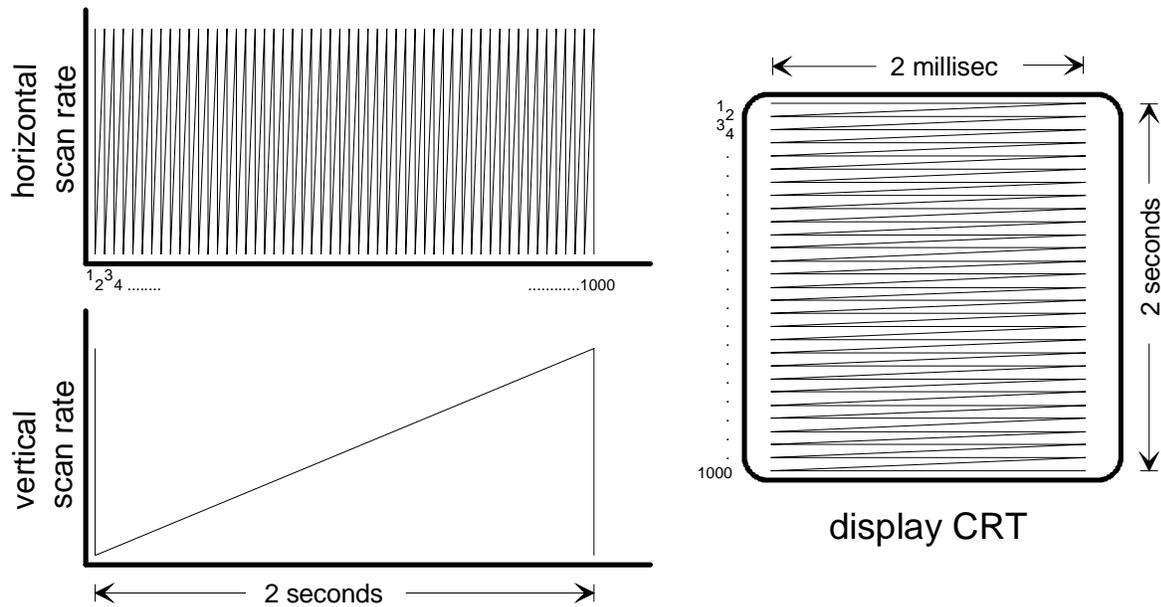
Figure 4-13 Scan generator "sawtooth" waveforms which are used synchronously by the scan coils for the electron beam within the column and by the display CRT. The resultant scan in this case would be a medium resolution 2 second "slow scan"

As we have discussed before, for some EPMA applications there will often be times when you will want to probe a larger area on your specimen because of the detrimental effects of a focused beam. Some operators have chosen to use a rectangular raster rather than defocusing the beam to a larger diameter. This can be advantageous because you can image while you analyze. However, you must be aware that the scan rate timing involves a "wait-to-start" synchronization, which means that for some instruments, the probe will be stationary (usually in the upper left corner) for a fraction of a second until it is given the signal to start the raster. An instrument manufacture might also choose to "blank" the beam while it waits, and/or during the horizontal "fly-back". In either case the time the beam spends on the target is not evenly distributed across the area you are trying to analyze, or count times will be subject to the time the beam is blanked. Your analysis, therefore, will be weighted to, or away from, the upper left corner of the area you thought you had analyzed homogeneously.

Therefore it is usually more advantageous to simply defocus the beam spot to analyze a larger region or to reduce damage to the specimen.