Emission Myths

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Most electron microscopists appreciate that proper operation of the source is vital to the operation of the entire instrument. But because the gun involves a complex interplay of phenomena, few of which can be directly observed, some common misconceptions have gained currency. Typically these myths contain a kernel of truth, but they can also mislead when accepted uncritically. In this series of articles, we explore three areas of common misunderstanding relative to operation of the thermionic (tungsten filament or LaB_6) gun. Field emitters are subject to very different considerations.

Myth # I -- The Saturation Myth

The essence of this myth is the notion that "saturating the gun" involves creating such a high density of electron emission that further emission cannot occur -- in other words, that physical space available to the beam is saturated with electrons and emission is thus maximized at some sort of physical limit. In a variant of this myth, some have thought that the filament itself has somehow become electronically "filled up". Indeed, something along these lines is precisely what our use of the word "saturation" seems intended to convey. Moreover, the idea of reaching a physical limit seems like a plausible explanation for an effect that every microscopist is familiar with -- the way that the emission of the gun stops increasing as the temperature is increased past a certain point (Figure 1). This knee in the emission curve is generally identified as the onset of saturation.

The kernel of truth in this perception is that such a physical saturation does limit emission in high perveance electron guns, as used in microwave tubes and the like. "Perveance" is a term used to quantify space charge -- the electrostatic interaction of electrons in the beam. In a high perveance gun, the field created by the high density of (negatively charged) electrons effectively screens the cathode from the accelerating field of the (positively charged) anode; once a limiting density is reached, no further electrons can be added to the beam. In such a gun, increasing the filament temperature above a limiting value does not increase the emission since the electron beam is indeed saturated.

Fortunately for electron microscopists, the high perveance condition described above is not the regime in which electron microscopes operate by design. A microscope designer works to stay away from this condition because the screening action defocuses the beam and increases the energy spread (the Boersch effect) long before it appreciably limits the emission current. This effect becomes more important at low accelerating voltages since the electrons are being accelerated more slowly and can hang around in front of the filament tip longer. This is the reason for reducing the cathode-to-anode spacing at low beam voltage -- to increase the accelerating field and get those electrons out of there as rapidly as possible. So it is in fact possible to operate an electron microscope gun under conditions where there is a true space-charge saturation effect (*i.e.,* low beam voltage with a large anode spacing), but this degrades the imaging and, given any choice in the matter, it is best to avoid this situation.

In the early days of electron microscopy. it was commonly assumed that the knee in the saturation curve (Figure 1) was a result of such space-charge saturation. Haine disproved this in a 1952 paper (Haine & Einstein, Characteristics of the Hot Cathode Electron Microscope Gun (British Journal of Applied Physics, Volume 3, p40, 1952). He instead demonstrated that the saturation knee shown in Figure 1 can be attributed to the action of the self biasing (or "auto biasing") circuit employed in most electron microscopes. Unfortunately, the power of the word 'saturation" is such that the false notion of a fundamental physical effect continues to hang around.

In a self-biased gun (Figure 2a), the negative high voltage is connected directly to the Wehnelt (grid) and hence to the filament (cathode) via the bias resistor. All current flowing from the filament must pass through the bias resistor (R), resulting in a voltage drop (V= R*Ie) which makes the cathode more positive than the Wehnelt -- the bias voltage. As seen by electrons leaving the cath-

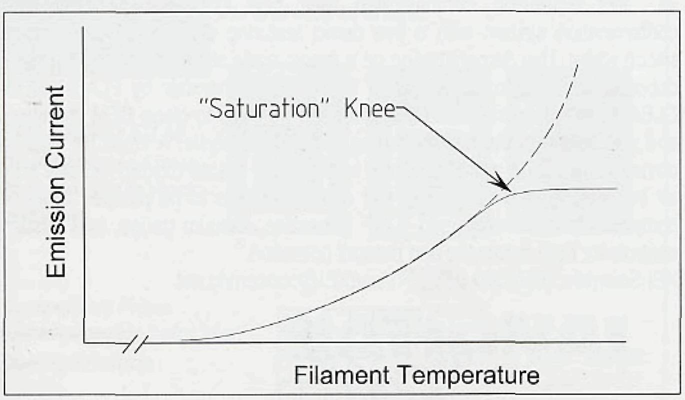

Figure 1: Plot of emission current versus filament temperature. The solid line is the curve obtained with a self-biased configuration and displays the characteristic "saturation" knee. The dashed curve illustrates the behavior of an independent-bias configuration

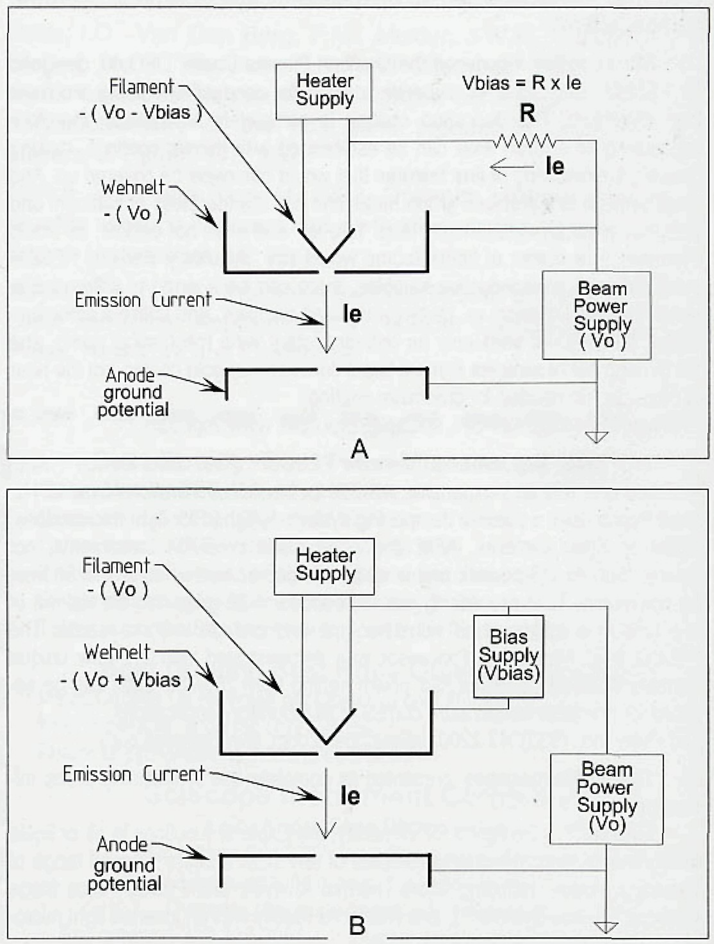

Figure 2: configurations of the thermionic gun. (A) the "self-biased" gun employing a bias resistor [R]; and (B) the "independent bias" configuration employing a separate bias supply [Vbias].

ode, the negative bias potential on the Wehnelt opposes the attractive field of the anode and thus restricts emission. This arrangement creates a self regulating situation: any *increase* in emission current drives the Wehnelt more negative relative to the cathode and chokes off emission, and conversely, a *decrease* in emission causes the bias to decrease, thus enabling greater emission. The end effect is that a constant emission current is maintained, despite minor variations in filament temperature, cathode-tip geometry, and the like. So the knee in the emission vs. temperature curve shown in Figure 1, which microscopists are used to calling "saturation" is nothing more than reaching the operating point in the emission current stabilization circuit established by the bias resistor -- there is no profound electron optical effect involved.

But, if this is the only reason for the knee in the saturation curve, why is this the best point to operate the gun? The most basic answer is "because the microscope designer is not stupid". Assuming a designer knows the best conditions for imaging, why stabilize the emission current anywhere else? However, should one wish, it is a simple matter on most electron microscopes to adjust the bias resistor such that the knee occurs at a point where the actual emission pattern of the gun is distinctly sub-optimal (and this is why most users don't mess with the bias resistor).

Figure 3 illustrates the way the Wehnelt does its job of restricting cathode emission. The only reason that electrons can get past the negatively biased Wehnelt at all is because the orifice in the Wehnelt allows some of the anode's positive field to penetrate to the tip of the filament. When properly adjusted, there is a small circular region on the tip (inside the "zero equipotential"[1]) where electrons can escape to the anode -- everywhere else, the low energy electrons which are boiled off the filament are repelled back into it. If the retarding bias of the Wehnelt is increased, the anode field doesn't penetrate as far, the size of the emitting region on the filament tip shrinks, and fewer electrons can escape. Conversely, when the bias is decreased, the anode's field penetrates farther and the size of the emitting region increases, resulting in more emission[2].

The relationship between bias and emission can be easily observed in a microscope equipped with the kind of independent bias supply illustrated in Figure 2b. With this arrangement, the bias can be set (and thus the emitting region selected) without changing the temperature of the filament. By applying a sufficiently high bias, it can become energetically impossible for any part of the filament to emit (cutoff condition), or a very high emission can be created (up to the current limit of the supply) by setting the bias at a very low value such that almost all of the filament is emitting. In this kind of "independent bias" configuration, changing the filament temperature has no effect on the bias, and thus no effect on the position of the emitting region. However, increasing the filament temperature increases the emission density (electrons per unit area) and thus for any bias setting below cutoff, emission increases continuously with temperature as illustrated in the dotted line of Figure 1[3]. In his 1952 paper, Haine cited this absence of a knee in an independently-biased gun to disprove the idea of a physical saturation effect.

But most microscopes use the self-biasing circuit of Figure 2a. it is simple, reliable, effective, and tends to be operationally forgiving (*e.g.,* cutoff isn't possible). However, an obvious downside to the auto-bias circuit for anyone trying to understand the performance of an electron gun in detail is that the emission stabilization effect of the bias resistor confuses the physical relationships between temperature, bias, and emission. Thus, above the knee in Figure 1, a change in emission density (such as results from a change in filament temperature) is immediately compensated by a change in the *size of the emitting region* so as to maintain a constant emission current. This interplay of effects is often difficult to sort out and undoubtedly accounts for some of the confusion surrounding the topic of filament saturation. However, the fact remains that a particular bias voltage value is still established via this circuit, and for equal bias and equal temperature, either the self-biased or independent-biased configuration will produce identical emission.

Before leaving the topic of saturation, it is appropriate to note that the process of adjusting the bias of the gun for the best emission conditions is far from arbitrary. In fact, when the biasing of the gun is correctly adjusted, the emitted electron trajectories create a bright source which represents the most favorable imaging condition. This emission pattern can be readily observed in a TEM, and some SEMs are also equipped with scanning coils in the gun which permit a very similar visualization of the emission pattern. We provide this kind of "source imaging" feature on our Personal SEM™ and it is my preferred way to optimize the gun. Calling this kind of optimization "saturation" is a reasonably apt way to describe how the emission pattern seems to collapse into a dense spot. You can also accomplish a rather equivalent kind of optimization on a SEM which does not have this source imaging feature by maximizing the beam current under high magnification conditions (typically done by observing the waveform signal). So ideally when microscopists are talking about saturation, they are visualizing this kind of optimization procedure. We will look harder at the implications of this kind of adjustment in the next installment.

In summary, there are at least *three different concepts* which electron microscopists have sometimes associated with the term "saturation":

1) The erroneous notion that space charge or some other physical mechanism inhibits the gun's emission. Space charge effects are present in all electron guns, but this is not typically the dominant factor limiting emission in an electron microscope gun.

2) The phenomenon observed in electron microscopes equipped with a self-biasing circuit (essentially any scope which is not a field emitter) whereby the emission current reaches a maximum value as the filament temperature is increased and then increases no further. This effect is due solely to the operation of the self-biasing circuit and has no intrinsic optical meaning.

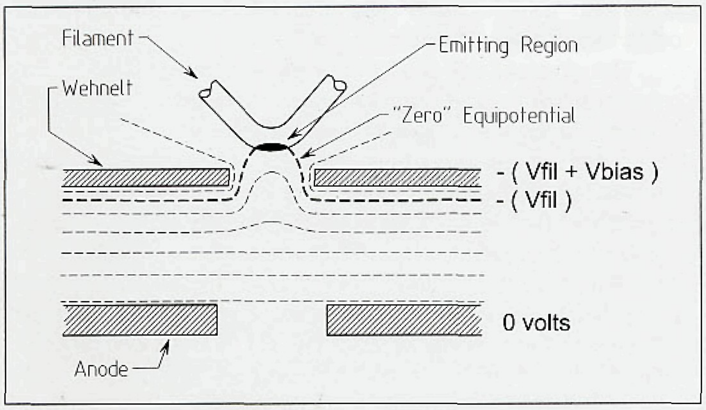

Figure 3: Sketch illustrating the manner in which the retarding bias on the wehnelt defines the emitting region of the filament's tip. Dashed lines illustrate contours of equal potential and become increasingly negative proceeding from anode to wehnelt. The "zero" equipotential (heavy dashed line) is the same voltage as the filament (Vfil) and encloses the region from which emission can occur.

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3) The process of optimizing the emission pattern of the gun so as to produce a compact source distribution.

Of these three uses, only the third constitutes a useful operational concept with respect to beam optimization -- but is it saturation? I personally think it's unfortunate that this term entered our vocabulary since it is more confusing than helpful. But "saturation" is probably a term we are stuck with (kind of like my other pet peeve: Energy "Dispersive" Spectroscopy). ■

1. The term "zero equipotential" describes the locus where the accelerating field is exactly zero. Outside of this boundary, electrons are repelled by a negative field, within it, they are accelerated by a positive field.
2. It will be apparent to the thoughtful reader that space-charge effects cannot be quite so blithely dismissed as my earlier comments might suggest. In the vicinity of the zero-equipotential boundary, the local accelerating field is weak, electron densities may be high, and space charge may indeed influence local emission. However, this effect, though indisputably present in some measure in any triode gun, is *not* the mechanism which produces the knee observed in the emission curve.
3. In those relatively rare commercial instruments where an independent bias supply is used, it is my observation that it is invariably implemented with a feedback mechanism so as to operate as a constant emission current source. The above observations would apply only if this feedback mechanism is disabled.

Avoiding Etching of Silver When Using Silver Staining With OsO4 Fixation

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Post-fixing with osmium tetroxide before silver-staining sections causes problems because the OsO_4 can etch the deposited silver. However, it is not a good idea to perform silver enhancement after osmium tetroxide treatment because the deposited osmium can also act as a nucleating site for silver deposition, and the osmicated regions of the sample will be silver enhanced. If gold-toning is used after OsO_4 post-fixation, the OsO_4 can also nucleate gold particles. OsO_4 should always come after silver enhancement.

The greatest risk of etching deposited silver is when both osmium tetroxide and uranyl acetate are used. In the absence of uranyl acetate, etching is often not a problem.

There are two ways to prevent the etching so that osmication can still be done after silver enhancement: use of a reduced concentration of osmium tetroxide and gold-toning.

Burry and co-workers have found that in situations where etching is a problem, etching may be greatly reduced by using 0.1 % OsO_4 instead of 1 %. This has also been found to give similar levels of staining[1]. Therefore, 0.1 % OsO_4 can be safely used after silver enhancement without gold toning. This is recommended in the absence of uranyl acetate.

Silver etching is only occasionally a problem in the absence of uranyl acetate, even at 1 % osmium, when it can reduce the size of the silver particles. However, if uranyl acetate staining is done with osmication, the etching of silver is often much worse, and the silver particles can be stripped away completely (as