Emission Myths #2

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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 LaB6) gun. (Field emitters are subject to very different considerations.)

Myth #2 -- The "more is better" myth

The essence of this myth is the belief that "optimizing the gun" means maximizing the emission. Like any good myth, there is a kernel of truth being expressed here. Certainly, it is hard to argue with the general observation that, if an instrument is operating properly and all other things being equal, a decrease in emission is going to be accompanied by a decrease in performance. However, it doesn't necessarily work the other way around, and in any case, "all things" are seldom equal when one starts tinkering with gun parameters. Thus, though there is a real connection between emission quantity and beam quality, it does not necessarily follow that maximizing the former will also optimize the latter.

How can this be? If I produce more electrons in the gun, isn't it automatic that more of them will find their way to the sample? Not necessarily. I'll attempt to demonstrate this important point with an intuitive example: suppose I enlist two people for a contest and offer a prize to the individual who can use a water hose to spray the maximum amount of water through a knothole 20 feet away. I then tell each contestant that they have a choice of two hoses, one with a discharge rate of 10 gallons per minute and the other with a discharge rate of 1 gallon per minute. One contestant immediately opts for the higher flow rate, and quickly realizes his error when I then hand him a hose whose nozzle produces a fan-shaped stream -- although the total flow is large, it is distributed over a wide angle and only a small fraction of it can be directed through the knothole. The more thoughtful contestant first asks to see the shapes of the streams produced by the two hoses and then chooses the lower-flow hose which also happens to have a narrowly collimated stream -- and wins the contest. Clearly, the **quality** of the stream (as characterized by its directional distribution) is more important than the **quantity** of the stream, as measured by its flow rate.

The situation for an electron gun is analogous: the electrons which will ultimately be projected onto the specimen must pass through a very tiny "virtual knothole" (entrance pupil) defined by the beam-limiting aperture and the excitation of the condenser lens(es) -- the rest of the emission represents excess "spray". Thus, the **shape** of the emission distribution is of paramount importance. The distribution shape can be directly imaged with a TEM, and some SEM guns are also equipped with scanning coils, which allow a similar distribution to be viewed. Figures 1-4 were taken with a Personal SEM™ operating in "source imaging" mode and progress from "undersaturated" through "saturated". (As readers of the previous installment will recall, I don't much like the word "saturation", however, this is the term we all use.) These

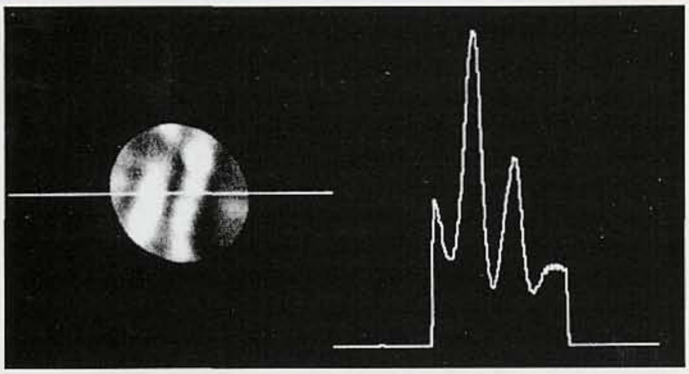

Figure 1: A severely "undersaturated" source image (drive = 4.7, 30 microamps emission).

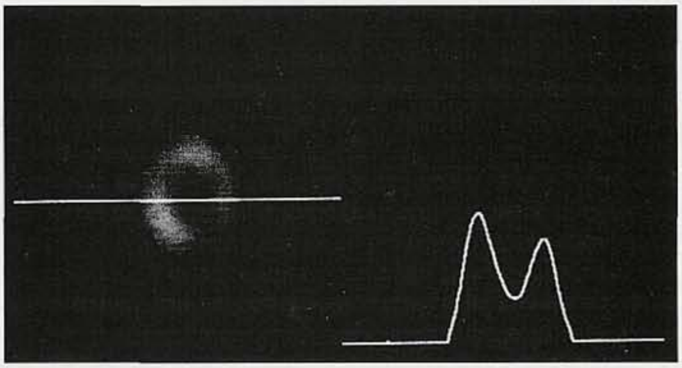

Figure 2: The characteristic "smoke ring" distribution of a moderately undersaturated filament (drive=5.9, 52 microamps emission).

figures were produced by a tungsten "hairpin" type of filament whose tip is a 'V' shaped piece of amorphous tungsten wire. For a LaB_6 emitter or any other oriented crystalline type, there will be preferred directions of emission which will be manifested as bright "lobes" in the emission pattern. However, allowing for these discrete emission lobes, the overall envelope of the emission distribution will still be similar to that depicted here.

Figures 1-4 were accomplished by increasing the filament temperature while the bias resistor is maintained at a fixed value (the role of the bias resistor in regulating the emission of a self-biased gun was treated in the first installment of this article). Note that the total emission current remains essentially constant for the last three figures. Thus, "saturating the filament" by changing the filament temperature has scarcely effected an increase in emission at all, but thanks to the increased bias voltage, the emission has been restricted to the tip of the filament and focused so as to achieve a well-formed distribution. And finally, to drive home the point that large emission doesn't necessarily mean good imaging, I have deliberately misadjusted the bias resistor in Figure 5 to produce high emission, but a lousy distribution.

In Figure 1, the bias is small and the electrons are only weakly deflected as they emanate from the cathode. Consequently, this emission pattern is essentially a projection of the filament tip (the striations in the figure are due to the topography of the drawn filament wire). As the bias is increased, the off-axis electrons are ever more strongly focused until we arrive at the "crossover" image of Figure 4. The crossover is not a physical object but an optical abstraction: the locus from which the beam appears to originate when viewed from downstream. In Figure 6, the crossover is indicated as the "waist" where the electron trajectories are most tightly bundled. It is this luminous "object" which the subsequent lenses image and whose dimension represents the "source diameter" which appears in equations which express the focused beam diameter.

However, it is not just the size of the crossover which matters, but also the angular distribution of electrons which are leaving it. The ideal beam would originate from a very small source diameter and diverge very little. We call this desirable quality "brightness" and define it as the combined spatial and angular density of the beam. Brightness is the important quality which we should worry about (rather than emission current) because it dictates the size and intensity of the image spot which we can form on the sample. At considerable risk of over-simplification, I will nonetheless make a couple of general observations to summarize this part of the discussion: (1) the objective of optimizing the gun is to optimize the "brightness" of the source; and (2) the desired condition is approached when the "source image" indicates an intense, compact beam distribution.

So if brightness is such an important quality, why isn't it a big competitive issue when you shop for a microscope? One reason is that it is sensible to compare brightness values only if the temperature of the filament is known, and accurately measuring this temperature is a challenge in itself. But the most relevant reason is that the maximum attainable brightness of a particular kind of emitter is constrained by physical laws which don't offer much latitude for innovation. Now it is true that there are big differences when you compare different **kinds** of emitters. Compared to a tungsten "hairpin" source, for example, a LaB_6 source can achieve a factor of ten greater brightness, whereas a field emission source is up to a thousand times brighter -- it is this huge difference in brightness which makes microscopists shell out the big bucks for field emitter units. But when comparing a tungsten gun to another tungsten gun, for example -- assuming that both are operating at their optimal settings -- they should both be operating

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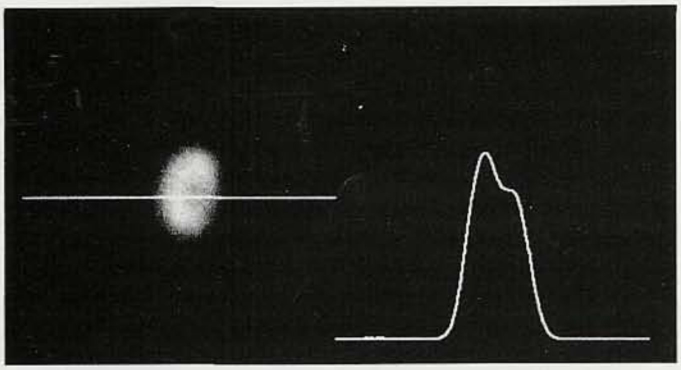

Figure 3: Approaching saturation. There is still an indication of an open center (drive=6.2, emission=54 microamps).

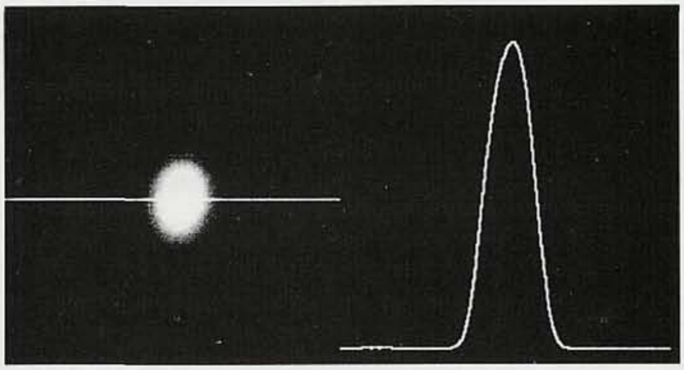

Figure 4: "Saturated". The distribution is compact and intense (drive = 7.0, emission=56 microamps).

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close to the maximum limit established by theory.

Langmuir's well-known equation establishes the maximum brightness value for a thermionic cathode*. The variables are the work function of the cathode material, the beam voltage, and the temperature of the filament. So how does one design a gun to achieve this maximum brightness? In the early days there appears to have been quite a lot of effort devoted towards innovating the "best" gun geometry. However, Haine demonstrated that details of the design didn't matter all that much. In particular, he showed that you can vary the size of the wehnelt opening and the spacing of the filament behind the wehnelt over wide ranges and still approach the Langmuir limit (so long as you adjust the biasing appropriately). What does change, however, is the "efficiency" of the gun, that is the ratio of brightness to total emission.

If the wehnelt opening is large and/or the filament set well back, then you will be able to achieve the Langmuir limit only by operating with a rather high emission current, most of which is well off-axis and thus of no value for image formation. Since there is really no advantage to having all of that wasted emission (and some practical disadvantages) it is generally preferable to design the gun for high efficiency. Modern SEMs are typically designed for more efficient cathode operation than was the case in the past. The highest efficiency is obtained by placing the filament tip close behind a small wehnelt aperture. But the closer the spacing, the higher the required bias and this can lead to unstable operation if pressed too far. Similarly,

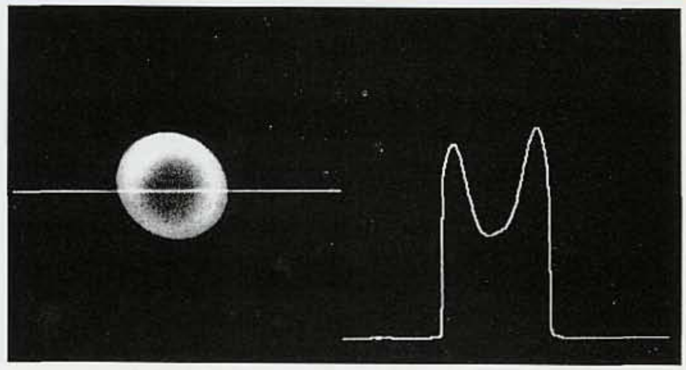

Figure 5: By misadjusting the bias resistor, one can obtain higher emission but still have a sub-optimal distribution (drive = 7.25, emission = 90 microamps).

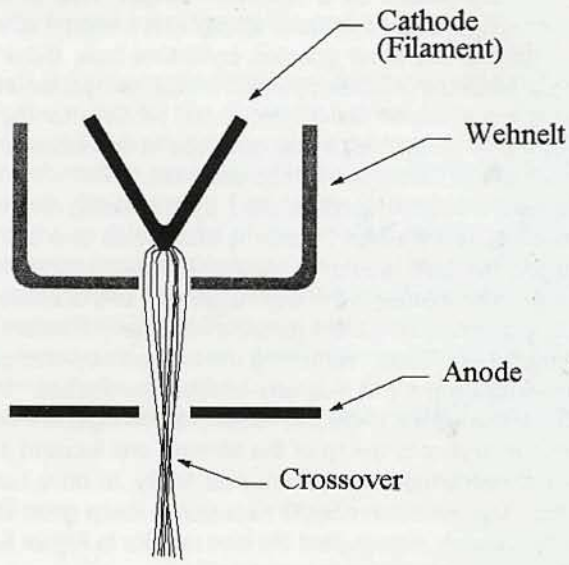

Figure 6: The formation of the gun's crossover

a very small aperture makes alignment of the gun particularly critical. Thus, there are practical tradeoffs which the microscope designer will weigh. The end user usually doesn't need to worry about these things, since if the setup is proper, any microscope gun should be capable of approximating the Langmuir brightness limit.

In summary, we can make the following observations: (1) it is **brightness**, not raw emission intensity which is the important quality of a gun; (2) for a given filament material operating at a particular beam voltage, the limiting brightness is determined by the operating temperature; (3) guns of varying geometries can all attain the limiting brightness, but with varying amounts of total emission; and (4) maximizing the emission **current** without consideration for the emission **distribution** is a misguided effort. ■

- The Langmuir equation is found in any standard reference on electron optics. When reduced to its basic dependencies, the equation has the following form:

$$\beta_{MAX}\, \alpha\, V\, T\, e^{(-Ew/kT)}$$

Where: V is the accelerating voltage
T is the filament temperature
Ew is the work function of the filament material
K is the Boltzmann's constant