Kimball Physics, Inc.
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# KIMBALL PHYSICS ES-423E $LaB_6$ CATHODE
## STYLE 60-06 (60° Included Cone Angle, 6μm Diameter Flat)

## Introduction

The ES-423E, Style 60-06 Cathode has the tip of an ES-423E $LaB_6$ single crystal ground with a 60° cone terminated with a polished truncation of 6 μm diameter. This profile is similar to that of the cathode studied by Gesley and Hohn[1] where a Schottky barrier height reduction of 0.2 eV was measured in the field of a typical electron microscope gun. Hence for the <100> surface at the tip of Style 60-06 cathodes, the effective work function is close to 2.5 eV, rather than 2.69 eV generally quoted as the zero field work function for the <100> surface. The implication of this is that at a specific temperature, this type of cathode can provide a higher brightness than cathodes with larger truncations, such as the regular Style 90-15 cathode (a 15 μm diameter truncation on a 90° total included cone angle).

It is desirable that the reader be familiar with the information in Kimball Physics Technical Bulletin #$LaB_6$-01, "General Guidelines for Operating ES-423E $LaB_6$ Cathodes," in order to better understand the material presented here.

## Application

The main application of the Style 60-06 cathode is in high resolution TEM work where the total beam current is frequently restricted to minimize electron energy spread due to the Boersch effect. With the 60-06 cathode, adequate axial brightness is attainable at very low emission currents (1 to 2 μA).

This gain in brightness is achieved with the Style 60-06 cathode because of the Schottky effect at the tip. This is illustrated in Tables 1 and 2. Here the emission current at saturation is assumed to come almost exclusively from the truncation, since the zero equipotential of the gun intercepts the cathode at the junction of the conical surface and the truncation. Emission from the tip is calculated to a first approximation, assuming uniform emission over the surface of the tip and no space charge limitation.

Table 1 shows the anticipated electron emission as a function of temperature for a Style 90-15 cathode (90° cone with a 15 μm diameter flat), assuming a work function of 2.69 eV. Table 2 gives similar information for a

TABLE 1

ES-423E $LaB_6$ Cathode, Style 90-15
Emission from a 15 μm diameter truncation.
Based on work function of 2.69 eV for <100> surface.
Assumes uniform emission over truncation.

| Temperature [K] | Current Density [$A/cm^2$] | Emission [μA] |
|---|---|---|
| 1600 | 1.1 | 1.9 |
| 1650 | 2.0 | 3.6 |
| 1700 | 3.7 | 6.6 |
| 1750 | 6.7 | 11.8 |
| 1800 | 11.6 | 20.5 |
| 1850 | 19.6 | 34.7 |

TABLE 2

ES-423E $LaB_6$ Cathode, Style 60-06
Emission from a 6 μm diameter truncation.
Based on work function of 2.5 eV for <100>.
Assumes uniform emission over truncation.

| Temperature [K] | Current Density [$A/cm^2$] | Emission [μA] |
|---|---|---|
| 1600 | 4.2 | 1.2 |
| 1650 | 7.7 | 2.1 |
| 1700 | 13.7 | 3.8 |
| 1750 | 23.6 | 6.6 |
| 1800 | 39.5 | 11.1 |
| 1850 | 64.5 | 18.2 |
| 1900 | 102.8 | 29.0 |

[1]M. Gesley and F. Hohn, "Emission Distribution, Brightness, and Mechanical Stability of the $LaB_6$ Triode Electron Gun", J. Appl. Phys. 64, (1989), pp 3380 - 3392.

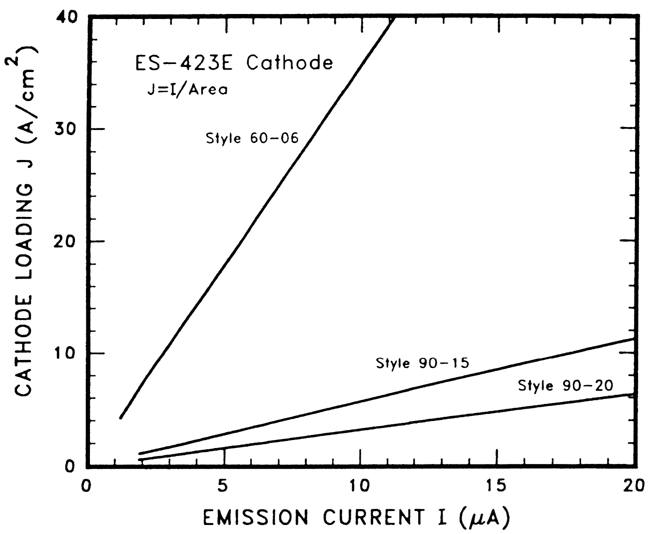


*Figure 1. Cathode loading J in $A/cm^2$ versus emission current I at saturation of the <100> truncation for Styles 60-06, 90-15, and 90-20, of the ES-423E Cathode. Since the axial brightness is directly proportional to the cathode loading, this plot shows the higher cathode loading (higher brightness) achieved with the Style 60-06 at any given total emission.*

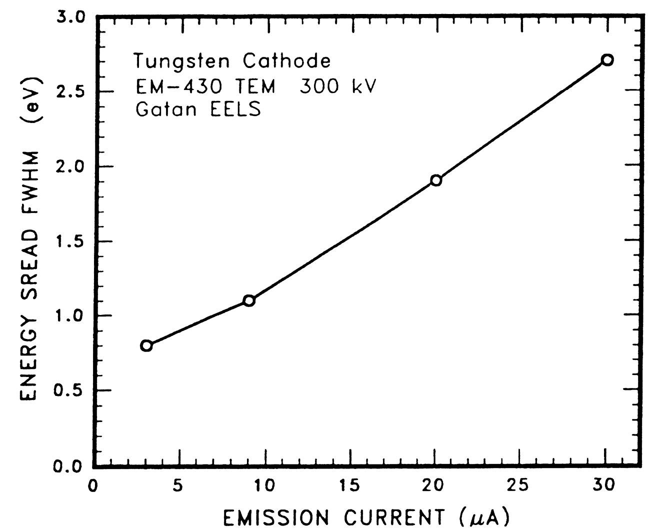


*Figure 2. Typical result for increase in energy spread as a function of total electron emission for a slightly under-saturated tungsten cathode in the Philips EM-430 TEM. Results recorded at 300 kV on the zero loss beam with Gatan Serial EELS. Similar results obtained from Style 90-15 ES-423E $LaB_6$ Cathode.*

Style 60-06 cathode assuming a work function of 2.5 eV. It is seen that for the Style 90-15 cathode for a total emission of 2 μA, a cathode temperature of 1610 K is required with a cathode loading of 1.2 $A/cm^2$. However, with the Style 60-06 cathode, a temperature of 1650 K is required to achieve a total emission of 2 μA. At this temperature, the cathode loading is 7.7 $A/cm^2$. Since the axial brightness is proportional to the cathode loading (in the absence of space charge), the gain in brightness for the same emission current is 7.1 over 1.2 or, about 6 times.

This relationship is illustrated in Figure 1 where the cathode loading (directly related to relative brightness), is plotted against the total emission current, assuming no space charge limitation in the gun.

As the total emission current is increased, the energy spread in the beam increases as shown in Figure 2. Thus, high total emission currents, which imply high brightness as in Figure 1, also result in high energy spread as in Figure 2. Therefore, the operator must make a decision on operating conditions to maximize the cathode performance for the application at hand.

For the ES-423E Cathode, Style 60-06, an energy spread (FWHM) of 0.7 eV has been measured for a total electron emission of 3 μA at 200 kV in an Akashi 002B instrument fitted with a Gatan parallel EELS facility. While similar low energy spread is observed from tungsten cathodes at low, unsaturated emission, it is estimated that the Style 60-06 cathode provides at least 20 times the brightness of tungsten at the same beam current.

## Cathode Lifetime

The time required for truncations to disappear by congruent evaporation has been measured and calculated by Davis et. al.[2] Their results include the behavior of $LaB_6$ in oxygen at various pressures, where the tip loss is accelerated by the presence of oxygen. Similar accelerated oxidation losses will occur in the water vapor background of the gun of an electron microscope.

A simplified analysis of the tip loss is given in Figure 3, where the loss of the microflat truncation (of original diameter d, and cone half angle $\alpha$) assumes that the evaporation loss $r_s$ of the wall of the cone is the same as that for the surface of the truncation. The Davis formulation allows for differences in these rates, but his formulation is the same as that derived here when the evaporation or oxidation loss is uniform.

It is seen in Figure 3, that the radial loss of the truncation is given by the relationship:

$$\Delta r_t = \Delta r_s \, (1/\cos\alpha - \tan\alpha).$$

For a total included angle of 60° (30° = $\alpha$), this becomes:

$$\Delta r_t = 0.577 \times \Delta r_s.$$

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[2]P. R. Davis, G. A. Schwind and L. W. Swanson, "The Effect of Oxygen Pressure on Volatility and Morphology of $LaB_6$ Single Crystal Cathodes," J. Vac. Sci. Technol. B4 (1), (1986), pp 112 - 116.

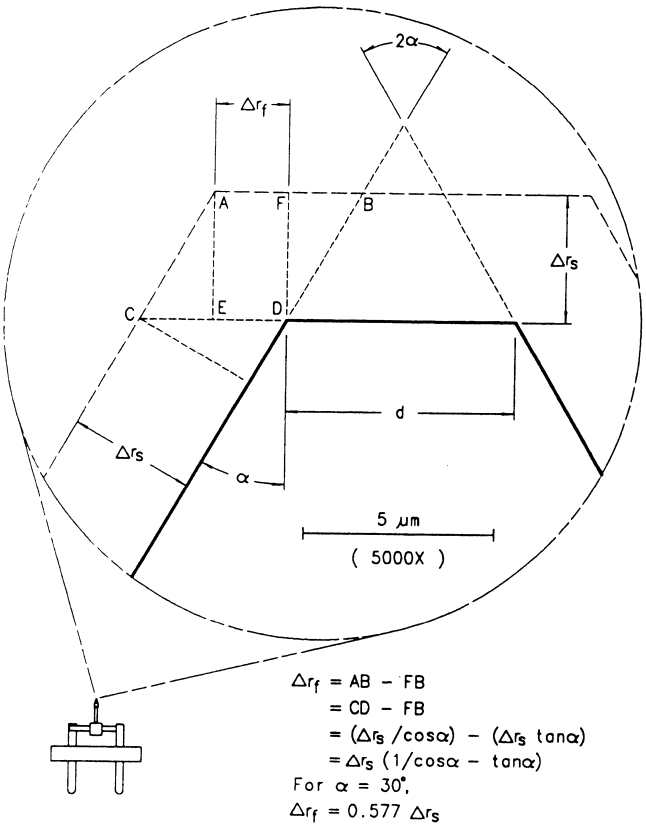


***Figure 3.*** *Evaporation model for corner of truncation of conical $LaB_6$ cathode of half-angle α. Model assumes equal evaporation rate from the cone wall and the truncation. (The number before the hyphen in the cathode Style Number is 2α (e.g. 60° = 2α for Style 60-06).)*

Since a 6 μm diameter truncation will disappear when the radial loss is 3 μm, then all evidence of the truncation disappears at a time:

$$T = 3/(0.577 \times \Delta r_S) \text{ hours.}$$

For an operating temperature of 1750 K (Table 3), this lifetime ranges from about 2070 hours in ultra-high vacuum to about 43 hours at $10^{-6}$ torr. Further estimates of life at various temperatures are given in Table 3. At lower cathode temperatures, the pressure effect dominates the cathode life.

Thus, the useful life of a Style 60-06 emitter can be limited by high temperature and high pressure and is much shorter than lifetimes found for Style 90-15 cathodes. By the same reasoning as above, the life of a 15 μm truncation is about 3000 hours in UHV and some 1000 hours at $10^{-7}$ torr. In practice, other factors such as back ion bombardment of the tip seem to prolong the life of the truncation of these cathodes to many thousands of hours before total loss of the profile of the truncation.

TABLE 3

Lifetimes (T) for Loss of Truncation on ES-423E $LaB_6$ Cathodes, Style 60-06.

| Pressure [torr] | 1800 K | | 1750 K | |
|---|---|---|---|---|
| | Loss [μm/hr] | Time [hours] | Loss [μm/hr] | Time [hours] |
| UHV | 0.006 | 866 | 0.0025 | 2070 |
| $10^{-7}$ | 0.018 | 288 | 0.015 | 345 |
| 5 x 10-7 | 0.05 | 104 | 0.05 | 104 |
| $10^{-6}$ | 0.12 | 43 | 0.12 | 43 |

Evaporation Loss Data from Reference 2.

## Operating Conditions

With Style 60-06 cathodes it is very important to ensure that the gun vacuum is in the low $10^{-7}$ torr region. Operation at pressures below $10^{-7}$ torr is desirable. As the tip sharpens, the electron optical performance of the cathode will change. From a sharp conical point, the dominant region of emission is a conical surface which complicates the structure of the cross over.[1] Higher temperatures will be required to maintain the same axial brightness as achieved from the original truncated cathode. This increased temperature further increases the evaporation of the cathode with a resulting change in the effective height within the Wehnelt, leading finally to further loss of brightness due to space charge limitation of the emission.

Users of Style 60-06 cathodes should be aware of these problems. The advantages of this cathode for high resolution imaging in TEM work are accompanied with shorter effective lifetimes than found in practice with Style 90-15 cathodes.

Additional details are available in the following Kimball Physics Technical Bulletins:

- $LaB_6$-01: General Guidelines for Operating ES-423E $LaB_6$ Cathodes
- $LaB_6$-02: The Relationship Between $LaB_6$ and Gun Vacuum
- $LaB_6$-03: Emission Drift - $LaB_6$ Gun Stability
- $LaB_6$-04: Oxygen Activation of $LaB_6$ Cathodes - The Double Saturation Effect
- $LaB_6$-06: Kimball Physics ES-423E $LaB_6$ Cathode Operating Instructions for Leica/Cambridge Stereoscan Series SEM's
- $LaB_6$-07: Recovery of Emission from ES-423E $LaB_6$ Cathodes Following a Vacuum Dump