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Abstract

A directly heated lanthanum hexaboride tapered filament has been tested in a plasma generator. A uniform temperature distribution at 1820 K has been achieved. The heating and cooling power calculated from measured quantities are balanced. A maximum arc current of 80 A was obtained, limited only by the power supply and plasma generator. The corresponding hydrogen ion current density was 0.6 A/cm² when the arc voltage was 80 V and the filament heater current was about 5 A. The filament was capable of emitting 100 A of current at an operating temperature of 1900 K. The estimated lifetime for this filament is 900 hours.
I. Introduction

Previous testing of lanthanum hexaboride (LaB$_6$) filaments$^{(1)}$ has demonstrated their capability of operation as cathode in high density plasma generators. In particular, these filaments were directly heated by an electric current. Many applications in modern technology require the cathodes to emit relatively high electron current densities. Since this means higher operating temperatures, filament lifetime becomes a factor because of evaporation. In addition, some applications require continuous operation and frequent filament replacement is undesirable. From the data presented in Ref$^{(1)}$ it is clear that LaB$_6$ filaments provide a significant improvement in lifetime over tungsten or tantalum filaments.

In a high density plasma discharge where the filaments emit a significant electron current density, the temperature distribution along the filament is non-uniform. Thus only a part of the filament provides the bulk of the electron emission current and hence the lifetime is not as long as desired. As previously mentioned$^{(1)}$ the electron emission can be made uniform over the full filament length by constructing it with a variable cross-section. Such a design has been followed$^{(2)}$ for the use of tungsten filaments. In this paper, results of measurements made using a tapered LaB$_6$ filament in a plasma source are presented.

II. Filament Design

A rectangular LaB$_6$ filament having uniform thickness $t$ and variable width $w$ was chosen as the most useful shape. The correct width variation for constant electron emission was obtained by assuming a third order polynominal dependance of the width on the length beginning from the negative leg.

$$w(x) = w_0 + ax + bx^2 + cx^3$$  \hfill (1)
The coefficients $w_0$, $a$, $b$, and $c$ can be evaluated by considering the power balance at each point along the filament length. If the heat conduction to the filament chuck is neglected, then the power balance between heating by ohmic dissipation and plasma ion bombardment and cooling by radiation and electron emission can be written as

$$
e \left\{ I - j_e \int_0^x 2[w(x) + t]dx \right\}^2 + 2Vj_1[w(x) + t] = 2c\sigma T^4 [w(x) + t] + 2Vw j_e [w(x) + t]$$

where $V_w$ is the work function, $j_1$ is the local plasma ion density, $I$ is the discharge plus heater current, $\rho$ is the electrical resistivity, $c$ is the emissivity, $T$ is the temperature and $j_e$ is the emitted electron current density. The ion bombardment energy delivered to the surface $V = (V_a + V_i + V_p - V_w)$, where $V_a$ is the discharge voltage, $V_i$ is the ionization potential and $V_p$ is the plasma potential. Both the filament heater discharge current are assumed to flow into the negative leg and $w$ is a parameter which depends on the total emission plus heater current. If the discharge is space charge limited, then the emission current is plasma density dependent instead of being temperature dependent, as it is for emission limited operation. In writing down the above relationship, the emission current density $j_e$ is a chosen parameter. The filament length is also a free parameter to be chosen for structural strength and for total emission current requirements. Once the plasma parameters are chosen and the filament length and thickness are decided, there is only one taper geometry which will provide a uniform temperature over the entire filament.
Operation at other source plasma conditions will result in a non-uniform temperature distribution.

A parameter which may affect the emission of electrons from the filament$^{(3)}$ is the self magnetic field of the current. This is not included in Eq.(2) and its influence on the emission can only be inferred experimentally.

The coefficients a, b, and c in Eq. (1) determine the filament taper. In a typical multicusp ion source, the ion flux density in the region of the filaments is 0.4 A/cm$^2$,$^{(4)}$ if the extractible current density is 0.2 A/cm$^2$. A filament length of 10 cm was arbitrarily chosen and a total emission current of the same magnitude as the discharge current was considered desirable. A filament thickness of 0.2 cm was chosen to fit the already existing molybdenum chucks in the plasma generator. With an ion flux density of 0.4 A/cm$^2$ the electron emission current could be as high as 19 A/cm$^2$ based on the emission limit. For a long filament lifetime operation the electron emission level was chosen to be 10 A/cm$^2$ which is equivalent to a temperature of 1910 K. The emissivity of LaB$_6$ has been reported$^{(5)}$ as 0.7 and the electrical resistivity at the above temperature is 140 $\mu$ohm-cm. Using these parameters the coefficients for the filament taper were found to be: $w_0 = 0.45$ cm; $a = -3.5 \times 10^{-2}$; $b = 1.0 \times 10^{-3}$; $c = 1.9 \times 10^{-5}$. For the 10 cm long filament the final width was calculated to be 0.20 cm; and the heater current was 90 A. The emission area of the filament was 10 cm$^2$.

III. Filament Fabrication

The filament was cut from an available sheet of LaB$_6$ material into the shape shown in Fig. 1. The third order term of the taper equation was small
and was neglected. The fabrication of the filament permits only straight cuts to be made, so that the dimensions matching the polynomial were those at the ends of the straight sections. A few mm of length were added to each end to ensure that the thermal gradient to the supporting chuck does not occur on the tapered part. A 0.5 mm thick piece of rhenium foil was sandwiched between the chuck and the filament to prevent the boron from attacking the base material of molybdenum.

IV. Filament Operation

The filament was mounted in a closed multicusp plasma source with an arc power supply capable of only 80 A discharge current. The first tests showed that the multipole fields attenuated the plasma density in the region of the filament. Longer supporting chucks were installed to ensure that the filament was located completely in the field-free plasma region. The chuck surface area collects plasma ion current in addition to that collected by the filament. Thus the true electron current emitted from the filament is less than the arc current by the amount of plasma ion current collected by the chucks and the filament.

A heater current of 90 A was applied until the filament reached steady state temperatures. Figure 2 shows that the filament was hot (1900 K) only at the positive (narrow) end. The negative (wide) end had a temperature of 1380 K which is a little lower than the calculated value of 1420 K. An arc voltage of 80 to 100 V was needed to initiate the discharge. The discharge current increased slowly (10 to 20 sec), building up the plasma density which in turn would increase the heating and emitting area until the maximum operating current of 80 A was attained. The arc voltage was set at 80 V as
was assumed for the design. The filament was also operated at 20, 40, and 60 A of arc current.

Measurements were made of the arc and filament power supply heating current. The ion saturation current at a few centimeters from the filament was recorded. The temperature of the filament surface at the center of each straight portion of the filament was measured with an optical pyrometer. A local power balance can be obtained from the measured and known parameters. An estimate of the electron emission current density was based on the arc current and the ion flux density. This estimate is compared (Table I) to one based on the measured temperature. In the power balance the plasma potential was assumed to be 3 volts, as has previously been measured in such sources (4).

The first set of measurements shown in Table I had an ion current density higher than the design value (as high as 0.6 A/cm²). For a given input discharge power the ion current density depends on the plasma production efficiency. Since the plasma generator was a closed bucket, the arc efficiency was high. As the discharge current was increased, the required filament heater current was reduced. The amount of the reduction depends on the ion bombardment power deposited on the filament compared to the power losses. When the ion current density reached 0.6 A/cm² with 80 A of arc current, the measured filament current in the positive leg was small (less than 5 A). The temperature of the four legs was fairly uniform (see Fig. 3): 1820 ± 20 K (Table I, Case 1). The total emission current is obtained by subtracting the ion current flux (j₁) collected by the chucks and the filament from the total arc current of 80 A. The net electron current is 65 A which, for a 10 cm² of emission area, gives an average emission current density of 6.5 A/cm². Then the current density
on any of the four legs is divided according to the electron emission current density \(j_{e1}\) based on the filament temperature. The emission current dependance on temperature is a very sensitive function and the emission area may be underestimated by 10 percent so that the difference between \(j_{e1}\) and \(j_{e2}\) is within the experimental error. The largest heating term (52 W/cm\(^2\)) is due to ion bombardment. The cooling terms are the 42 W/cm\(^2\) of radiation and 19 W/cm\(^2\) of electron emission. This leaves a net 8 W/cm\(^2\) of cooling. The calculated ohmic heating term at the negative (wide) leg is 7 W/cm\(^2\), or a net imbalance of 4 W/cm\(^2\) of heating.

The crucial parameters of operation are the ion flux density and the arc voltage. Compare case 1 and case 2 in Table 1 where an arc current of 80 A and voltage of 65 V resulted in a lower ion flux density of 0.56 A/cm\(^2\). To compensate for the reduced ion heating, the required heater current was 60 A instead of 2 A. The average filament temperature was lower by only 5 K compared to case 1 and the temperature was fairly uniform. Again the power balance was close. For case 3 where the arc current was only 20 A, the arc voltage was 90 V and the heater current was 85 A, the temperature was not as uniform (1690 K at the narrow end to 1645 K at the wide end). Note that the ion heating power is not the dominating factor and the temperature non-uniformity is related to the non-uniform ohmic heating along the filament. In this case the power balance is not so close.

In an attempt to match the design conditions the gas pressure was lowered and some permanent magnets were removed. The effect is to increase the anode area and thus decrease the plasma density. Upon matching the desired plasma density to 0.4 A/cm\(^2\), the filament current to 105 A, and the arc voltage to 85 V (case 4, Table I) the temperature was not uniform.
The arc current was only 40 A. Subtracting the ion flux density to the chucks and the filament, the average emission current is estimated to be 34 A. Each leg is assumed to emit \( j_e \) in proportion to the electron emission based on the temperature. Based strictly on the temperature measurements, an estimate of the total emission current is 55 A. The power estimated from the measured quantities leaves an imbalance of about 28 W/cm\(^2\) of heating. The same situation repeats for the operation at 50 A of arc current except that the overall temperatures were about 25 K higher (Case 5) and the imbalance is 35 W/cm\(^2\).

What effect causes the difference in the observed measurements? One option is that the self magnetic field of the current impedes the ability of the electrons to leave the filament region\(^3\). The field is large enough to trap the electron and they drift along the filament. With higher gas pressure the probability that ionizing collisions by the primary electrons as they drift along the filament becomes greater. Some of these electrons are dumped at the chucks and do not add to the emitted current. Thus the arc current will not reflect the true quantity of electrons emitted locally from the filament and the electron cooling power should be larger. The self magnetic field effect is reduced as the ion heating term becomes larger, and the filament heater current is reduced.

V. Summary

Tapering the filament has been demonstrated to compensate for the varying current through the filament caused by the emission of electrons. The heating and cooling power based on measurements is well balanced when the ion flux density is large. It appears that self magnetic fields play a
V. Summary (Continued)

significant role on the emission of electrons at lower operating pressures. Conceivably some filament configuration changes may allow the trapped electron to escape the filament region. These tests have demonstrated that a tapered LaB₆ filament can have a longer lifetime, which is particularly useful for cw plasma generators. Further tests are planned to test the use of a similar filament in a cw negative ion source.
VI. References


Table I.
Operating conditions and estimated power balance.

Figure Captions

Figure 1  Lanthanum hexaboride filament mounted in chucks.
Figure 2  Filament operating with 90A of heater current.
Figure 3  Filament operating with an arc current of 60A at 70V.
<table>
<thead>
<tr>
<th>Case</th>
<th>Operating Conditions</th>
<th>Leg</th>
<th>Temperature K</th>
<th>$j_{e2}$ A/cm²</th>
<th>$j_{e1}$ A/cm²</th>
<th>Ohmic W/cm²</th>
<th>Ion W/cm²</th>
<th>Radiation W/cm²</th>
<th>Electron W/cm²</th>
<th>Balance W/cm²</th>
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<td>3.9</td>
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</tr>
<tr>
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<td>12</td>
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**TABLE I.**
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