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On the use of CsK_2Sb photocathodes in RF linacs

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Abstract

The use of CsK_2Sb photocathodes in an RF linear accelerator is investigated. Several fabrication techniques for this type of cathodes are reviewed. Measurements are performed on the drop in quantum efficiency due to the use of the cathode in the linac at several wavelengths in the visible. A better lifetime has been found for shorter wavelengths. Finally, the effect of high energy laser pulses on the quantum efficiency in the green is demonstrated.

1. Introduction

Recently, alkali-antimonide photocathodes have been used as electron emitters in RF linear accelerators [1]. The advantages of photocathodes as an electron source compared with a thermionic emitter are the expected better beam quality and higher peak current. Although alkali antimonide photocathodes have been intensively studied since their discovery in the early sixties [2–4], little is known about their properties under actual operating conditions in an RF linac. The use of an alkali-antimonide photocathode in an electron gun is completely different from the use in a closed and clean system. For one thing, the peak current drawn from such a cathode is much higher (350 A) than in any other application. Second, in a large system such as a linear accelerator usually more impurities will be produced than in a small glass envelope, and consequently the cathode lifetime is much shorter. Third, since the system is open (vacuum pumps are constantly removing vapours from the linac) any materials that evaporate from the cathode will be removed from the system.

In the present paper, several fabrication techniques for CsK_2Sb photocathode are reviewed. Also, the drop of the quantum efficiency at several wavelengths in the visible, caused by the use of the cathode in the accelerator, is investigated. Finally, the effect of irradiating the cathode with high energy laser pulses on the quantum efficiency (QE) is discussed.

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2. Fabrication of CsK_2Sb cathodes

In Fig. 1, a sketch of the photocathode preparation chamber is given. The cathode itself is placed on an actuator, which is used to move the cathode into the first cell of the linac. The containers with the evaporation materials are mounted on another actuator, perpendicular to the first one. Thus when we wish to evaporate a certain material on the cathode, we move the respective container in front of the cathode. During fabrication, the cathode is kept at a potential of roughly 100 V, so that a green 1.5 mW HeNe laser can be used to illuminate the cathode and monitor the photocurrent with a picoampere meter. The quantum efficiency of the cathode, defined as the number of emitted electrons per incident photon, is given by:

$$\mathrm{QE} = \frac{h\nu}{e}\frac{I_{\mathrm{cat}}}{P_{\mathrm{las}}}, \tag{1}$$

where I_{cat} and P_{las} are the cathode current and laser power, respectively. The cathode can also be illuminated with a white halogen source enabling us, by the use of band filters, to measure its spectral sensitivity.

An alkali-antimonide photocathode is prepared by letting a gaseous alkali-metal A react with a pre-deposited layer of antimony [5,6]:

$$\mathrm{Sb_{(s)}} + 3\mathrm{A_{(g)}} \leftrightarrow \mathrm{A_3Sb_{(s)}}. \tag{2}$$

This is an equation of thermodynamical equilibrium, i.e. the process is reversible. The reaction is exothermic, so it is possible to prepare a mono-alkali-antimonide photocathode at room temperature [7]. We have indeed succeeded in preparing cold, single layer Cs_3Sb cathodes with quantum efficiencies comparable to those of heated cathodes.

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Usually, however, the substrate temperature is kept at 120°C. The main advantage of evaporation on a heated substrate is that it is possible to add multiple layers of alkali-metal and antimony. This is necessary when producing photocathodes that are used in transmission: The efficiency then has an optimum as a function of the thickness of the cathode, so it is necessary to carefully add subsequent layers of Sb and A. On a cold cathode, the second Sb layer does not mix very well with the first A_3Sb layer, so it remains present as a film on top of the cathode. This causes the QE to drop dramatically, and another layer of alkali-metal is then needed to re-activate the cathode.

When producing CsK_2Sb cathodes, it is essential to use a high substrate temperature. A CsK_2Sb cathode is fabricated from a K_3Sb cathode by the following substitution reaction:

$$K_3Sb_{(s)} + Cs_{(g)} \rightarrow CsK_2Sb_{(s)} + K_{(g)}\uparrow \quad (3)$$

Of course this substitution first occurs near the surface; the Cs atoms next diffuse to the bulk material, trading places with the K atoms that have not yet been substituted. Now suppose that the arrival rate of the Cs atoms is much larger than their diffusion rate into the bulk material. Then we will find multiple substitutions of K atoms near the surface:

$$CsK_2Sb_{(s)} + Cs \rightarrow Cs_2KSb_{(s)} + K_{(g)}\uparrow, \quad (4a)$$

$$Cs_2KSb_{(s)} + Cs \rightarrow Cs_3Sb_{(s)} + K_{(g)}\uparrow. \quad (4b)$$

Since there now is a stoichiometric excess of Cs near the surface, the QE will drop. This is a signal to the operator to stop the evaporation of the cesium, but there is no way he can be sure that there really is a stoichiometric amount of cesium present in the cathode. Given time, the excess Cs will slowly diffuse into the bulk material.

Between September 1993 and March 1994, photocathodes were daily produced to be used in the RF linac. We have measured the QEs of these photocathodes before they were inserted into the accelerator: The results are shown in Fig. 2. As can be seen, the efficiency of the different K_3Sb cathodes is relatively constant at about 0.3%, while the QE of the different CsK_2Sb cathodes varies widely, with an average value of 1.2%. In our experience, there appears to be little correlation between the QE of a K_3Sb cathode and

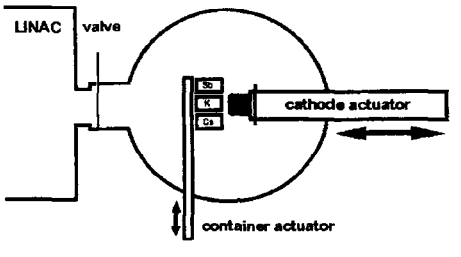

Fig. 1. A sketch of the photocathode preparation chamber.

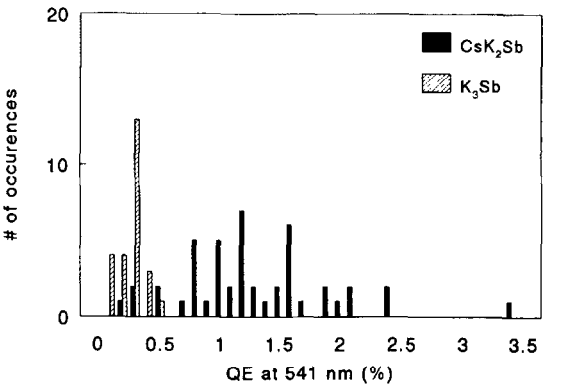

Fig. 2. Statistics of the K_3Sb and CsK_2Sb photocathodes that were produced, between September 1993 and March 1994.

that of the corresponding CsK_2Sb cathode. These facts indicate that most contaminations and crystal defects in the cathode are introduced during the substitution of K by Cs. In contrast, we find that after a recent opening of the vacuum (thus, when many contaminants are present) it is very difficult to produce a K_3Sb cathode with a QE over 0.1%, but that it is very easy to produce high QE (3–4%) CsK_2Sb cathodes. Apparently the contaminations in CsK_2Sb cause an energy band shift which have a beneficial influence, whereas in K_3Sb such a band shift has a harmful effect on the quantum efficiency.

3. Spectral sensitivity

In Fig. 3, the dependence of the spectral sensitivity on the fabrication process is shown. Here, we have first produced two K_3Sb cathodes: one on a substrate at 120°C, and one on a substrate of 180°C. At these temperatures, we expect to produce a cubic and a hexagonal K_3Sb photocathode, respectively. Clearly, the cubic K_3Sb has a much

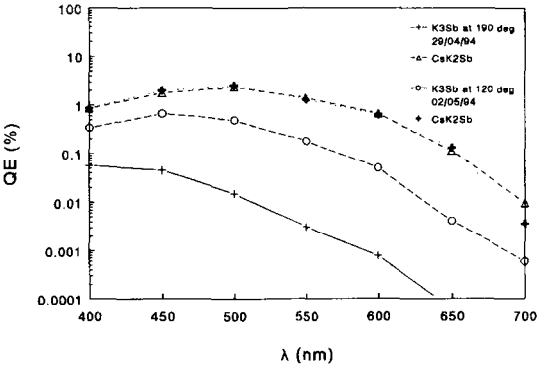

Fig. 3. Spectral sensitivity of a cubic and a hexagonal K_3Sb cathode, and of the CsK_2Sb cathodes that were grown on them.

larger quantum yield in the green and red portions of the spectrum than the hexagonal type, as has previously been reported. After completion, a layer of Cs is added to these cathodes. The cesium atoms substitute part of the K atoms in the cathode, thus transforming it into a CsK_2Sb cathode. We found that the spectral sensitivity of the resulting cathode did not depend on the sensitivity of the initial K_3Sb cathode: this can clearly be seen in the figure.

The spectral sensitivity of a typical CsK_2Sb photocathode is shown in Fig. 4. It was measured four times: On completion of the cathode, after a 60 h rest period in the preparation chamber, after a 2 h use in the linac, and after enhancement of the cathode by adding some extra Cs. Note the (with respect to the values given by Sommer [2]) decreased sensitivity in the UV. This is caused by the fact that we did not correct for absorption losses in the preparation chamber window, which we know to be present at wavelengths below 500 nm. We have not yet found a satisfactory explanation for the increased photoyield in the near infrared. As can also be seen, the decrease in quantum yield due to the use of the cathode in the linac is most dramatic in the red part of the spectrum. This suggests the use of shorter wavelength radiation to illuminate the cathode.

4. Effect of laser pulses

To learn more about the decay of the photocathodes while using them in the accelerator, we illuminated CsK_2Sb cathodes with frequency-doubled trains of pulses from a Nd:YLF laser system [8]. The pulse trains, having a length of 15 μs, consisted of 1200 pulses with a 20 ps duration, and an energy contents of 3.5 μJ per pulse. These parameters are comparable to those under actual operating conditions of the electron gun. In Fig. 5, the quantum efficiency in the green is plotted versus the number of pulse trains fired on the cathode. The laser pulses initially cause the

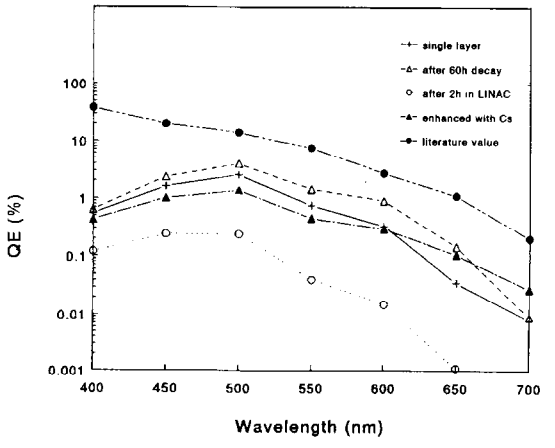

Fig. 4. Spectral sensitivity of a CsK_2Sb cathode, at several moments in its existence.

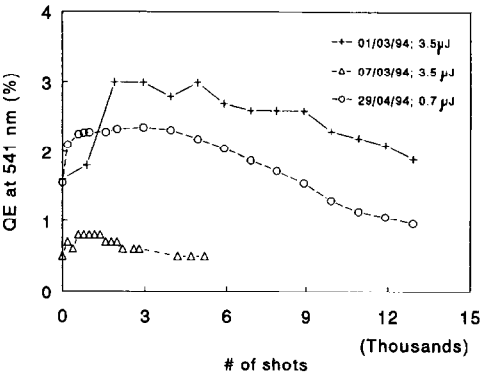

Fig. 5. The effect of high-energy laser pulses on the quantum efficiency of a CsK_2Sb cathode in the green.

QE to increase, until after about 1000 shots (at the repetition rate of 5 Hz, this takes 3 min and 20 s) a maximum is reached. This maximum is roughly twice as high as the initial value. Then, the efficiency starts to decrease. This behaviour is also observed when photocathodes are kept inside the preparation chamber (the maximum QE then typically occurs after one day). A possible explanation of this effect is as follows. Initially the surface material of our cathodes does not correspond to the ideal stoichiometric ratio: there is an excess amount of cesium. Gradually this diffuses into the bulk material, causing the increase of the efficiency of the cathode. This process can be stimulated by irradiating the cathode material with high-energy laser pulses. The fact that the final efficiency is below the peak sensitivity indicates that there is a cesium-deficiency in the cathode as a whole. The material can be described by the stoichiometric formula $Cs_{1-x}K_{2+x}Sb$.

5. Conclusions

In our experience, the quantum efficiency of a CsK_2Sb cathode does not depend strongly on the evaporation procedure. That is to say, the variation in QE of several photocathodes that were produced using the same recipe, is larger than the variation between cathodes grown according to different recipes.

Fig. 4 clearly shows that the decay of a multi-alkali photocathode is the most dramatic for wavelengths in the red part of the spectrum. Thus, it will be advantageous to use a shorter wavelength laser for the cathode illumination. Although it is possible to enhance a used cathode (by adding extra Cs) to about half its initial QE in the green, cathode lifetime remains a problem.

When irradiating the cathode with high energy laser pulses, the quantum efficiency initially increases. During operation of a photocathode linac, one can expect that, in the beginning of the experiment, the total beam current increases due to the increase in quantum efficiency. A possible explanation for this increase is the stimulated

diffusion of Cs atoms to the bulk material of the photocathode.

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