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## Abstract

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# Initial Test of an RF Gun with a GaAs Cathode Installed

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ABSTRACT

The operation of an rf gun with a GaAs crystal installed as the cathode has been tested in anticipation of eventually producing a polarized electron beam for a future $e^+/e^-$ collider using an rf photoinjector.

An rf gun is today a strong candidate as the electron source for a future $e^+/e^-$ collider if the electrons can be polarized. DC photoinjectors employing III-V semiconductor photocathodes such as GaAs have been used to produce polarized electrons for accelerators since 1978.[1] When the development of rf photocathode guns began in 1985[2], GaAs was not seriously considered as a possible cathode material primarily because the quantum yield following activation was known to deteriorate rapidly in a poor vacuum environment.

In late 1995, we conducted a test to determine the effects of the presence of a GaAs crystal on the operating properties of an rf gun cavity. For this test, the crystal was not activated. Consequently, although Cs was applied to the surface, the electron affinity was definitely positive.

At SLAC, two bulk-grown GaAs crystals, p-doped to $\sim 5 \times 10^{18} cm^{-3}$, were cut roughly into a circle of diameter 12 mm from a 356-$\mu$m thick wafer. At CERN, two of the standard Cu plugs on which $Cs_2Te$ cathodes are normally grown for the CLIC Test Facility (CTF) gun were modified to have a detachable Mo nose. The 2 noses were shipped to SLAC where a step was machined into the end of each nose to match the volume of a crystal. The exposed Mo was then cleaned, diamond-paste polished to a 1-$\mu$m finish, chemically cleaned one final time, and then fired. The crystal was next placed in the Mo step with a small amount of In inbetween. The assembly was then heated in vacuum until the In melted, "gluing" the crystal to the nose and filling in the crack around the edges of the crystal. See Fig. 1.

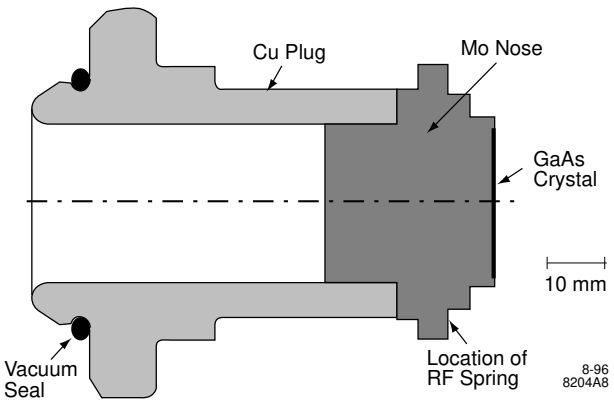


Figure 1: Cross section of cathode plug assembly.

The Mo noses were then returned to CERN where they were cleaned in ethanol and ultrasonically rinsed, then installed in the CTF cathode transport apparatus.

The cathode transport apparatus is used to prepare cathodes and transport them under vacuum between a dc-biased testing gun and the CTF rf gun. The transporter with plug was baked at 120°C for 48 hours. The initial outgassing was quite bad, but the final pressure, $2 \times 10^{-10}$ Torr, was only slightly higher than normal. A plug was then installed in the rf gun for low-power rf testing. A cross section of the S-band rf gun used in this test is shown in Fig. 2.

The Slater perturbation theorem can be used to show that the frequency shift for a material change in a small volume of a cavity wall should be

$$\delta = \frac{\omega - \omega_o}{\omega_o} = \epsilon_o \left(1 - \frac{1}{\epsilon_{r1}}\right) \frac{E_o^2 \pi r^2 h}{4U}$$

where $\epsilon_{r1}$ is the relative dielectric constant of the perturbing volume of radius $r$ and height $h$. The unperturbed field and resonant frequency are $E_o$ and $\omega_o$ respectively. The time-averaged rf energy stored in the total volume of the 1.5 cell gun is $U = \omega_o Q W$. For power loss $W = 7$ MW and quality factor $Q = 11000$, $U_{max} = 4.0$ J. It can be shown that $\epsilon_{r1}$ for GaAs/$p = 5 \times 10^{18} cm^{-3}$ should be about -800 at 3 GHz, and that the skin depth should be about $\delta_s = 50$ $\mu$m. Consequently this crystal is very metal-like.

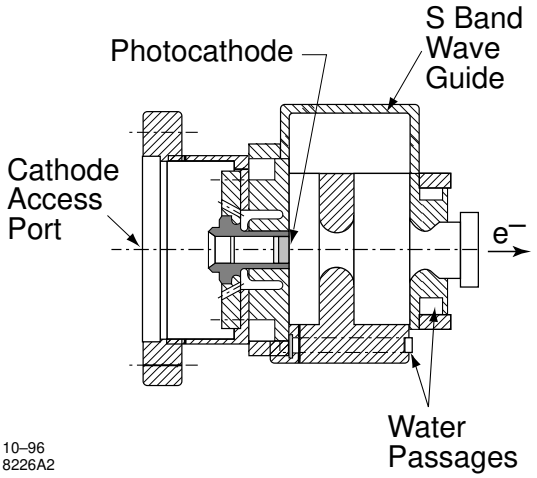

Figure 2: Cross section of rf gun.

Since $| \epsilon_{r1} | >> 1$,

$$\delta = -\epsilon_o \frac{E_o^2 \pi r^2 h}{4U}.$$

If we let $h = \delta_s$, then we can expect the maximum frequency shift to be:

$$\Delta f_{max} = \delta_{max} \frac{\omega_o}{2\pi} \simeq 100 kHz$$

Table 1: Low-power frequency measurements (in order).

| Cathode | Meas. freq. | Comments |
|---|---|---|
| $Cs_2Te$ | 2.99851 GHz | Original Cu plug |
| GaAs-1 | 2.99845 | First Mo plug |
| GaAs-2 | 2.99862 | Second Mo plug |
| $Cs_2Te$ | 2.99859 | Original plug reinstalled |

at 3 GHz if $E_o = 100$ MV/m. Using a network analyzer, the resonant frequency of the cavity was measured for a sequence of 4 cathode plug insertions. The results are summarized in Table 1. The measured frequency shift ranges from 30 to 110 kHz. The frequency shift associated with removing and reinserting the same plug was 80 kHz. These results are consistent with an upper limit of 80 kHz for the frequency shift due to inserting a 12-mm GaAs crystal.

The cathode assemblies were next tested in the dc gun. A Faraday cup equipped with a picoammeter was located ~1-m downstream of the gun. The maximum field at the cathode was ~10 MV/m (1-cm gap, 100 kV bias).

The dc gun was cleaned and baked before the test. Each of the two plugs with GaAs was installed in succession. At the maximum field, no dark current could be

observed. Then a layer of Cs ∼1-nm thick (measured with a quartz-crystal thickness monitor and assuming a sticking coefficient of 1) was applied to the 2nd plug; again no dark current was observed at the highest field. Finally, a factor of 10 more Cs was applied. Under these conditions dark current of ∼10 nA at 9 MV/m (after conditioning) was observed, which is an order of magnitude higher than typical for a poorly prepared $Cs_2Te$ cathode.

The crystals were then tested in the rf gun at high rf power. Using the GaAs sample without Cs, the rf gun was conditioned over a 12-h period to a maximum of 87 MV/m at the cathode surface. Further conditioning was precluded due to frequent rf breakdown. The pressure during breakdown would temporarily rise from a base of $1 \times 10^{-10}$ to $\sim 1 \times 10^{-8}$ Torr.

At the highest rf field, no dark current was detected at the intensity monitor located about 1-m downstream of the gun. However, visible light was observed from a spectrometer screen about 2-m downstream. The upper limit of the dark current estimated from this light was 60 pC/($\mu$s of rf), which is 30 times less than an earlier measurement using an L-band rf gun with 26 MV/m at the cathode.[3] Upon removal, the cathode plug was seen to have been damaged by arcing, especially near the rf spring.

A $Cs_2Te$ cathode was then briefly installed and the field rapidly raised to the nominal operating value of 110 MV/m with no unusual behavior observed.

The GaAs crystal with the 10-nm Cs layer was then installed. Over a 6-h period the gun was rf conditioned to 60 MV/m with only minor rf breakdown activity. The pressure was mostly kept $< 10^{-9}$ Torr. The conditioning was then stopped in order to preserve the cathode for future testing.

Post-measurement analysis indicated some damage to the surface of the first crystal. In addition, traces of In estimated to be $\leq$0.1-nm thick were found on the crystal surface. There was no sign of any damage to the second crystal nor to the cathode plug.

In conclusion, the rf frequency of the gun cavity was not affected by the presence of a GaAs crystal. Also, the rf cavity operated at high fields was not contaminated by the presence of a GaAs crystal, by the thick Cs coating on the surface, nor by the In used to "glue" the crystal to the cathode plug. Finally it was found that the dark current associated with an unactivated GaAs crystal with a thin Cs coating (as would be used during activation of a clean crystal) operated with high electric fields was extremely low.

[1] J.E. Clendenin, Proc. 1995 Part. Acc. Conf., Dallas, TX, p. 877.

[2] J.E. Clendenin, "RF Photoinjectors," SLAC-PUB-96-7253 (1996), to be published in proceedings of the 1996 Linear Accelerator Conference, August 26-30, 1996 Geneva.

[3] A.H. Lumpkin, Proc. 1991 IEEE Part. Acc. Conf., San Francisco, CA, p. 1967.