Abstract

For photocathode rf guns with electric fields of more than 40 MV/m at the photocathode and with an rf pulse length of 100 µs or more, the amount of dark current might be comparable with the photoelectron beam. At the photoinjector test facility at DESY Zeuthen (PITZ) the dark current was measured with a Faraday cup for various settings of the solenoid fields at the rf gun. We discuss the dark current behavior for different photocathodes. Experimental results are compared with simulations.

INTRODUCTION

The photoinjector test facility at DESY Zeuthen (PITZ) has been developed with the aim to achieve high quality electron beams and study their characteristics for future applications at free electron lasers and linear colliders. At PITZ, the photocathode rf gun is operated with a rf frequency of 1.3 GHz, a maximum electric field of 41 MV/m at the photocathode, a maximum rf pulse length of 900 µs, and a maximum repetition rate of 10 Hz.

Due to the high electric field and the long field emission time, the amount of dark current might be comparable to the photoelectron beam. Such a strong dark current degrades the electron beam quality and impairs emittance and energy spread measurements. More seriously, a large dark current is a severe hazard for a superconducting linac as it may produce X-rays, cryogenic losses, and radioactive activation. In the following paper, the generation of dark current and its properties are studied with measurements and simulation.

FIELD EMISSION AT THE RF GUN

The field emission of electrons is the main source of dark current. The field emission current at the rf gun can be parameterized in terms of the modified Fowler-Nordheim equation [1]

\[
I_F = \frac{1.54 \times 10^{-6} \times 10^{4.52φ - 0.5} A_e(βE)^2}{φ} \times \exp\left(-\frac{6.53 \times 10^9 φ^{1.5}}{βE}\right),
\]    

Figure 1: Intensity distribution of the field emission and the strength of the rf electric field for an rf cycle. The field emission curve was computed from the modified Fowler-Nordheim equation (Eq. 1) with a sinusoidal rf field and the typical β and φ values of 200 and 4.5 eV, respectively.

The average field emission current during one rf cycle is described as [1]

\[
\bar{I}_F(φ) = \frac{5.7 \times 10^{-12} \times 10^{4.52φ - 0.5} A_e(βE_0)^2}{φ^{1.75}} \times \exp\left(-\frac{6.53 \times 10^9 φ^{1.5}}{βE_0}\right),
\]    

where \(E_0\) is the amplitude of the sinusoidal macroscopic surface field in V/m.

MEASUREMENTS

The experimental setup is shown in Fig. 2. A molybdenum (Mo) cathode is a circle with a radius of 8 mm and a cesium telluride (Cs₂Te) cathode is a circle with a radius of 4 mm on a Mo substrate which has the same geometry as the Mo cathode except for the Cs₂Te coating. The
Mo cathode is used for conditioning of the rf gun and the 
Cs$_2$Te cathode is used to produce the photoelectron beam 
in normal operation. A main solenoid is located at 28 cm 
downstream of the cathode. The rf frequency is 1.3 GHz 
and the rf power is transferred into the gun cavity through 
a coaxial coupler. A laser with a wavelength of 262 nm pro-
duces the electron beam with a pulse length of 8 ps. The 
bunch repetition rate of the laser pulse train is 1 MHz.

Figure 2: Schematic view of the gun and diagnostic sec-
tions.

Dark current signals were obtained with a removable 
Faraday cup which is located about 76 cm downstream of 
the cathode. The average dark current during an rf cycle 
was measured at the end of the rf pulse. Using the spec-
trometer dipole it was determined that the dark current has 
early the same momentum as the electron beam, which 
means the major part of the dark current is generated near 
the photocathode.

The dark current is higher for the Cs$_2$Te cathode than for 
the Mo cathode (Fig. 3) and the magnetic field dependen-
cies are different for the Cs$_2$Te and Mo cathodes (Fig. 4, 5).

The amount of dark current reaching the Faraday cup 
depends on the strength of the magnetic field of the main 
solenoid. This is related to the current by $B_0$ [mT] = 0.6
$\times 10^{-7}$, [A]. The iris in the gun, the beam tube, the 
entrance to the coupler, and the mirror reflecting the laser 
beam onto the photocathode play a role as apertures for 
the dark current beam. A guiding force provided by the 
main solenoid field and the rf field guides the dark current 
through these apertures. The focusing behavior (see Fig. 4 
and 5) of the dark current shows that the dark current has 
an energy comparable to the electron beam and starts near the 
cathode because the best focusing condition on the Faraday 
cup of the electron beam with low charge is about 250 A at 
40 MV/m accelerating electric field.

Figure 3: Maximum dark current measured as a function of 
the electric field at the cathode.

![Figure 3](image-url)

The dark current is higher for the Cs$_2$Te cathode than for the Mo cathode (Fig. 3) and the magnetic field dependencies are different for the Cs$_2$Te and Mo cathodes (Fig. 4, 5).

The amount of dark current reaching the Faraday cup depends on the strength of the magnetic field of the main solenoid. This is related to the current by $B_0$ [mT] = 0.6
$\times 10^{-7}$, [A]. The iris in the gun, the beam tube, the entrance to the coupler, and the mirror reflecting the laser beam onto the photocathode play a role as apertures for the dark current beam. A guiding force provided by the main solenoid field and the rf field guides the dark current through these apertures. The focusing behavior (see Fig. 4 and 5) of the dark current shows that the dark current has an energy comparable to the electron beam and starts near the cathode because the best focusing condition on the Faraday cup of the electron beam with low charge is about 250 A at 40 MV/m accelerating electric field.

With an rf electric field of 40.5 MV/m and a main solenoid current of 200 A, the dark current for a Cs$_2$Te cathode is about 180 $\mu$A. According to simulation results, about 50% of the field emitted electrons from a 4 mm rms area at the cathode reach the Faraday cup. This means the amount of dark current generated near the Cs$_2$Te cathode is comparable to the electron beam in normal operation.

The field enhancement factor $\beta$ was found from the Eq. 2 [1]

$$
\frac{d (\log_{10} I_F/E^{2.5})}{d(1/E)} = -\frac{2.84 \times 10^9 \phi^{1.5}}{\beta}.
$$

In this calculation, the work function $\phi$ was assumed to be 4.75 eV [2] for the Cs$_2$Te cathode and 4.2 eV for Mo cathode. The calculated field enhancement factors for the Cs$_2$Te and Mo cathodes are 220 and 164, respectively. The effective emitting areas were calculated to be 1.1 $\times 10^{-15}$ m$^2$ and 1.2 $\times 10^{-15}$ m$^2$ for the Cs$_2$Te and Mo cathodes, respectively.

In normal operation, the bucking solenoid is used to compensate the longitudinal magnetic field produced by
Figure 6: Fowler-Nordheim plots to find enhancement factors and effective field emission areas for each cathodes.

The main source of the dark current at the rf gun is found experimentally and in simulations to be the cathode and the surrounding area. The magnetic field dependence of the dark current is quite different for the Cs$_2$Te and Mo cathodes. The simulation using ASTRA without secondary electron emission is similar to the dark current behavior for the Mo cathode (see Fig. 8). The study on the dark current behavior for the Cs$_2$Te cathode is ongoing considering secondary electron emission.

**SUMMARY**

The main source of the dark current at the rf gun is found experimentally and in simulations to be the cathode and the surrounding area. The magnetic field dependence of the dark current is quite different for the Cs$_2$Te and Mo cathodes. The simulation using ASTRA without secondary electron emission is similar to the dark current behavior for the Mo cathode. The dark current behavior for the Cs$_2$Te cathode is possibly caused by secondary electron emissions, which will be studied in future.

**REFERENCES**


A particle tracking code (ASTRA) [3] was used to simulate the dark current. In this simulation, the dark current source was assumed to be the cathode itself and the surrounding area, a Gaussian distribution with $\sigma = 4$ mm was taken. The time structure of the field emission current has been derived from Fig. 1. A Gaussian distribution in the rf phase was assumed with a center value of 90° and a variance of 20°. The simulation result using ASTRA without secondary electron emission is similar to the dark current

Figure 7: Contour plot of the dark current at 40 MV/m for the Cs$_2$Te cathode with the combination of the main solenoid and the bucking solenoid currents.

Figure 8: Comparison of dark current measurements for the Cs$_2$Te and Mo cathodes with the ASTRA simulation. Measurements are normalized at the high magnetic field region.