DARK CURRENT MEASUREMENTS AT THE ROSSENDORF SRF GUN*

R. Xiang [#], A. Arnold, P. Murcek, J. Teichert, HZDR, Dresden, Germany
V. Volkov, BINP, Novosibirsk, Russia
P. Lu, H. Vennekate, HZDR & Technische Universität Dresden, Germany
R. Barday, T. Kamps, HZB, Berlin, Germany

Abstract

The injector plays a significant role in accelerator facilities for FEL sources, electron colliders and Thomson backscattering sources [1-3]. During the operation of an electron gun, the dark current creates significant background to the accelerator users. In this work, we used the existing beam line to study the dark current from the SRF gun at HZDR. The dark current emitted from the niobium cavity and the Cs_2Te photocathode was separately measured. A multi-peaked energy spectrum for the dark current has been observed.

INTRODUCTION

Recently, superconducting RF photoinjectors (SRF gun) draw a lot of attention because of its continuous-wave (CW) operation, low emittance and potential application for polarized beam generation [4]. The ELBE SRF gun under the cooperation of HZDR, BESSY, DESY and MBI has been successfully commissioned [5] and firstly operated for the ELBE IR-FEL [6]. It is operated with the gradient up to 6 MV/m at CW mode or with 8 MV/m at macro pulse mode. With a Cs_2Te photocathode driven by the 13 MHz UV laser the ELBE SRF gun has produced the photocurrent beam up to 0.5 mA.

During the operation of the gun, the dark current can induce beam loss, increase the risk of damages to accelerator components, and raise additional background for users [7]. Especially for SRF guns and superconducting accelerators, the dark current increases the rf power consuming and the heat load for the liquid helium system.

EXPERIMENTAL SETUP

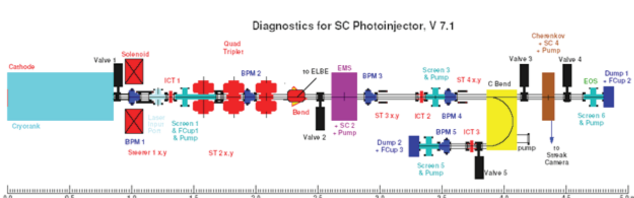

Figure 1: The diagnostic beam line for SRF gun. [8]

The diagnostic beam line was designed and built in 2007 by HZB [8], schematically shown in figure 1. Behind the exit of the gun a solenoid locates, followed by the laser input port and a Faraday cup. A group of quadrupole triplet is used to optimize the beam before the dipole to ELBE dogleg beamline. Several beam position monitors (BPM) and steerers (ST) are used to guide the beam, and six screen stations to view the beam spot. The 180^o dipole (C-bend) is installed for energy and energy spread measurement.

FIELD EMISSION IN THE CAVITY

The field emission from the inner wall of the niobium cavity and from the photocathode builds up the dark current. For the ELBE SRF gun it is possible to detect separately the field emission from the niobium cavity and that from photocathode.

Field Distribution in the Cavity

In Figure 2, the cavity shape of ELBE SRF gun is shown on top. The distribution of the surface electric field on the cavity wall and the field on the axis are presented along the cavity axis z at the bottom. The solid red line is the surface electric field of the cavity with cathode, the blue dashed line presents the surface field for the same cavity without cathode, and the black dots show the acceleration field E_z along the axis z.

Obviously the existing of a cathode does not change the field distribution in the TESLA cells or the maximum field in the half cell. It is worthy to note that the peak field in the half-cell located at the edge of the cathode hole, where the peak field reaches 20 MV/m, i.e. about 123 % of the peak field on axis E_{max} 16.2 MV/m.

From the surface field distribution, possible emission sources can be found at the rim of cathode hole, the cavity iris and the half-cell back wall. If one compares the surface field and axis acceleration field distribution, logically the field emission around the cathode hole is the main part of the dark current, where the field emitted electrons can be accelerated forward together with the photo electrons by the electric field. The other field emitted electrons are not synchronized well to the rf field. However, these electrons can hit the cavity wall leading to more helium consummation, or bombard the cathode layer degrading the photocathode quality.

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[#] r.xiang@hzdr.de

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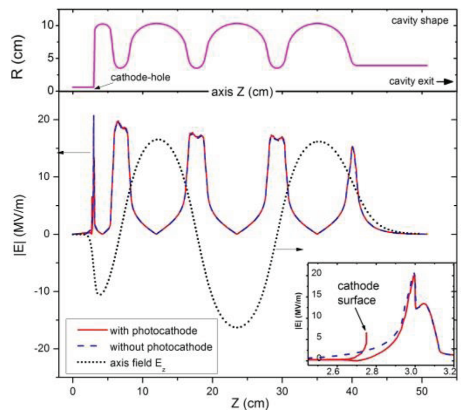

Figure 2: (Top) The cavity shape of ELBE SRF gun. (Down) The distribution of the electric surface field and the axis field, simulated using Superfish with E_{acc} = 6 MV/m. (Inset) The distribution of the electric surface field in the zone closed to the cathode.

Dark Current From Cavity and Cathode

The dark current was measured by using the Faraday cup which is located 1.4 m away from the cathode (Fig. 1). For the pulsed mode, the current in the pulse was measured by a 10 kΩ resistor and an oscilloscope.

We compare the dark current data of the gun with different photocathodes and of the empty cavity (see figure 3). One can see that most of the dark current comes from the cavity itself. The cavity without cathode plug and with metal cathodes exhibits the same character. But the plugs deposited with Cs_2Te layer contribute additionally 30 % of the total dark current.

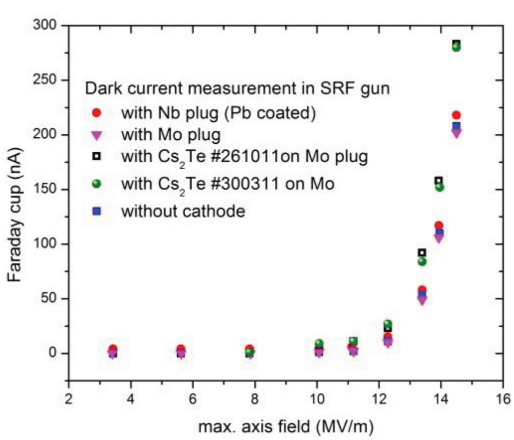

Figure 3: The dark current from the SRF gun.

Field Enhancement Factors

J. W. Wang and G. A. Loew have analyzed the field emission current at the rf field based on the Fowler-Nordheim equation [9]

$$I(E) = \frac{5.7\times10^{-12}\times10^{4.52\phi^{-0.5}} A(\beta E_0)^{2.5}}{\phi^{1.75}} \exp\left(-\frac{6.53\times10^9\times\phi^{1.5}}{\beta E_0}\right) \quad (1)$$

where I is the time-averaging current (in A), Φ is the work function of the emitting material (in eV), E is the instantaneous electric surface field (in V/m), A is the emitter size (in m^2), and β is the field enhancement factor.

From this equation the following lineal relation can be deduced:

$$\frac{d\left(\frac{\log_{10} I}{E^{2.5}}\right)}{d\left(1/E\right)} = -\frac{2.84\times10^9 \phi^{1.5}}{\beta} \quad (2)$$

The F-N plot is shown in figure 4. The slope of the linear fitting is used to calculate the field enhancement factor β. The work function Φ of pure niobium is 4.3 eV [10], so the field enhancement factor can be calculated as β = 307. Here we use the work function of cesium 2.14 eV in the calculation for photocathode, and the field enhancement factor for photocathode is 456.

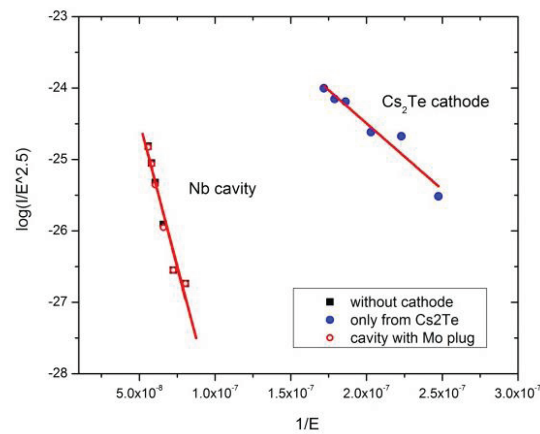

Figure 4: The graphical presentation of the measurement data in the way of Fowler-Nordheim plot.

DARK CURRENT MEASUREMENT

Dark Current Energy

The energy of the dark current was measured with the dipole magnet and the screens downstream. Figure 5 shows the energy spectra with normalized intensity relative to the total dark current measured with the Faraday cup.

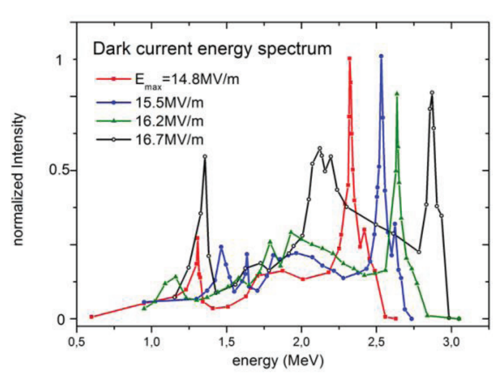

Figure 5: Energy spectra of the dark current of the SRF gun with a Mo photocathode.

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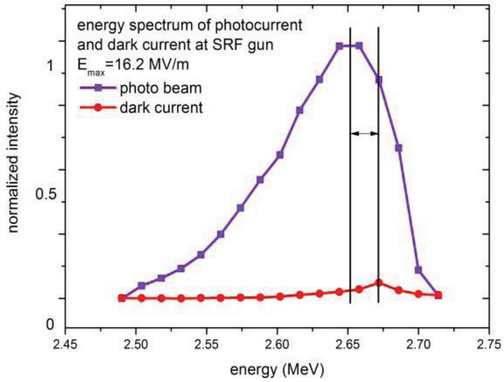

Figure 6: The energy comparison of the photoelectron beam and the dark current beam.

The energy spectrum presents a multi-peaks structure. The reason for the energy split could be the variable RF phase when the field emission happens. The electrons emitted near the cathode in the accelerating phase are able to catch enough energy to fly to the next cell for continuing acceleration and gain the maximum energy, similar to the tracking of the photocurrent beam at the proper RF phase. However, some electrons emitted in the "wrong" rf phase and trapped in the cell can still be accelerated during the next rf cycles, thus they built the other peaks with lower energy.

In figure 6 the energy of the highest peak is very close to that of photoelectron beam, only about 20 keV different. Thus it is difficult to distinguish the two beams with an energy filter.

Dark Current Phase Space

With the slit mask and YAG screens in the beam line, we did phase space measurement for the dark current in order to see more details of the field emission. The measurement result for the cavity with Cs_2Te photocathode #170412 shows that there are two emission sources (figure 7).

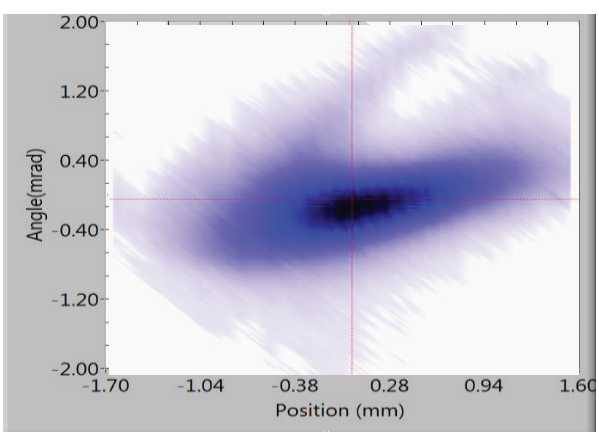

Figure 7: The phase space of the dark current.

SUMMARY

The experimental investigation and analysis of the dark current at the ELBE SRF gun has been performed. Field emission is the main source of dark current, which rises exponentially with increasing gradient, following the Fowler-Nordheim equation. The photocathode material contributes very little to the total dark current in the case with the low gun gradient. Due to the multi cell structure of the gun cavity, the dark current is found to have multi-peaked energy spectrum. The highest energy of the dark current is comparable to that of the photocurrent. We can find two emission sources through the phase space measurement.

In the cooperation with JLab we are fabricating two new 3+1/2 cell cavities with the same geometric structure but an improved quality. The field distribution in the new cavities is similar to the present cavity, but the field amplitude ratio of the half-cell to the full TESLA cells is changed to 80% instead of 60% of the present one. With a peak field of E_{max} = 43 MV/m or acceleration field E_{acc} =16 MV/m, the new gun is believed to improve the beam quality. On the other hand, one has to pay attention to the possible dark current from the new gun [11]. Of course, the proper cavity processing will lead to a lower field enhancement factor for the niobium cavity. However, the photocathode itself will contribute significant high dark current. If rest cesium is still the dominant emission source and the data from the F-N plot in figure 4 is used, the dark current from the Cs_2Te photocathode could be up to hundred μA. In order to reduce the dark current, a smooth photocathode surface without free cesium is required.

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