CHARACTERIZATION OF A SUPERCONDUCTING Pb PHOTOCATHODE IN A SRF GUN CAVITY

R. Barday*, T. Kamps, O. Kugeler, A. Neumann, M. Schmeißer, J. Völker,
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Germany
J. Sekutowicz, DESY, Hamburg, Germany
R. Nietubyc, NCBJ, Centre Swierk/Otwock, Poland
J. Smedley, BNL, Upton, NY, USA
P. Kneisel, JLab, Newport News, VA, USA

Abstract

Photocathodes are a limiting factor for the next generation of ultra-high brightness photoinjector driven accelerators. We studied the behavior of a superconducting Pb cathode in the cryogenic environment of a superconducting RF gun cavity related to the quantum efficiency (QE), its spatial distribution and the work function. The cathode surface contaminations can modify the performance of the photocathode as well as the gun cavity. We discuss the possibilities to remove these contaminants.

INTRODUCTION

Superconducting gun cavities are well-suited for the production of a high brightness electron beam with long cathode lifetime. An implementation of a suitable cathode with high QE and low contribution to the dark current into the cavity is one of the main challenges of the development of the SRF guns. The simplest way to integrate a photocathode into the SRF gun is to use a superconducting cathode. The back wall of the Nb cavity can be used as a photoemitter [1]. The major advantage of this solution is a possibility to avoid contaminations of the cavity and to preserve an excellent cathode surface typical for the superconducting cavities. The main disadvantage of the Nb cathode is its low QE$\sim 10^{-5}$ at 248 nm and high work function $\sim$4 eV. Alternatively, Nb can be coated with another superconductor with higher QE. For example, lead is a superconductor with a quantum efficiency of a factor of 30 higher than the one of Nb at the same wavelength [2]. With the present state-of-the-art laser technology the average beam current is limited to a maximum of few hundred μA, restricting the use of the Pb for high average current applications, but making it suitable for the FEL applications.

GUN 0.1

In the first version of the 1.3 GHz SRF gun [3] a Pb cathode with a thickness of about 200 nm and 8 mm diameter was deposited directly on the back wall of the gun cavity at the Soltan Institute by means of arc discharge at base pressure of 10^{-8} mbar. During the cathode deposition the gun cavity can be contaminated, so that the cavity must be cleaned after the cathode deposition. After the film was deposited the gun cavity was sent to JLab for buffered chemical polishing (BCP), high pressure water rinsing and RF tests. At JLab the Pb spot was covered with a Teflon ring for BCP [4] to reduce the size of the Pb cathode and to protect the Pb spot from all other treatment steps. The final BCP was performed with a weak solution for 1 minute without any protection of the Pb film.

In-situ Laser Cleaning

The cathode can be contaminated during the cavity treatment or after the cavity is cooled down by a reaction with residual gases causing an increase of the work function and, hence, decrease of the emission current. Therefore a final in-situ cathode cleaning is required after the gun cavity is cooled down. A laser cleaning of the emission surface was performed to remove the cathode contaminations in the gun 0.1. The major advantage of this method is an ability to localize the "heat" source into desired area, so that the gun cavity remains unaffected by this procedure. The laser pulse should provide a high temperature rise to remove the contaminations effectively. The laser used for cleaning has a thermal diffusion length $l = 2\sqrt{D \cdot \tau_{\mathrm{laser}}}$ that is much larger than the photon absorption length $\lambda_{\mathrm{opt}} \sim 7\,\mathrm{nm}$, where D is the thermal diffusivity and τ_{laser} is the laser pulse duration. So that for the Gaussian ns laser pulses the maximum temperature rise of a laser heated surface can be estimated as

$$\Delta T \sim 2\frac{F_0\,(1-R)}{k}\sqrt{\frac{D}{\pi\tau_{\mathrm{laser}}}}, \qquad (1)$$

where F_0 is the incident energy density, R is the reflectivity and k is the thermal conductivity. As seen from Eq. 1 for a constant energy density temperature rise increases when the pulse duration decreases as $1/\sqrt{\tau_{\mathrm{laser}}}$. During the laser cleaning the energy density F_0 should be high enough to remove the contaminations from the cathode surface. On the other hand, it should be below the damage threshold [2] and not modify the surface morphology, which can enhance the field emission and worsen the beam emittance. For the laser cleaning a KrF excimer laser (Xantos XS) at 248 nm ($h\nu$=5 eV) with a FWHM pulse duration of 5 ns and a repetition rate of 500 Hz was used. The surface was irradiated for 10 minutes (corresponds to 300.000 shots) at nearly normal incident angle to the cathode surface. We performed laser cleaning with the laser energy density F_0, increased

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* roman.barday@helmholtz-berlin.de

stepwise from $0.045\,\mathrm{mJ/mm^2}$ to $0.23\,\mathrm{mJ/mm^2}$, to minimize the risk of surface damage. During the laser cleaning treatment the gun cavity was cooled down to 2 K, but no RF power was applied to the gun cavity.

QE Map after Laser Cleaning

The photocathode was illuminated by a UV drive laser operating at 258 nm with a pulse length of 2-3 ps delivered at 8 kHz. Prior to the laser cleaning the maximum QE of $3.6 \cdot 10^{-5}$ was registered in the center of the photocathode (Fig. 1). For the first laser treatment the cleaning laser was focused on the cathode with transverse FWHM size of 3.9x4.7 mm^2, so that the laser cleaning was performed without scanning the cathode surface. After the first laser cleaning with an energy density of $0.045\,\mathrm{mJ/mm^2}$ the maximum QE changed by approximately 30 % to $4.8 \cdot 10^{-5}$. At the same time an "island" with the same QE as in the center of the cathode occurs near the boundary between the Pb cathode and Nb substrate. Here an improvement of QE by a factor of 2.5 was observed. Laser cleaning with double laser energy of $0.087\,\mathrm{mJ/mm^2}$ (performed 80 minutes after the first one) changed neither the maximum of QE nor the QE distribution. The third laser cleaning was performed with the same energy density of $0.09\,\mathrm{mJ/mm^2}$, to investigate, whether the longer treatment influences the cathode quantum efficiency.

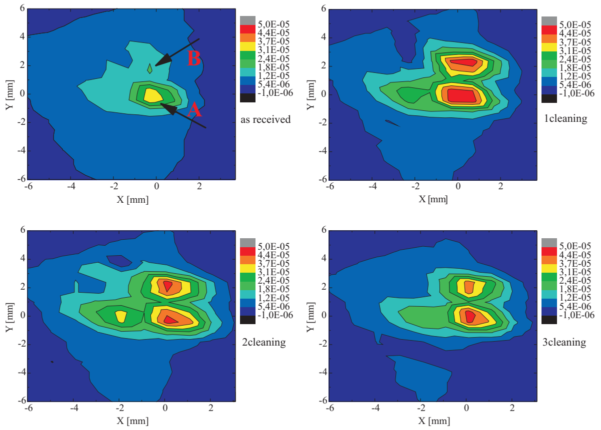

Figure 1: QE map before laser cleaning (a), and after laser irradiation with an energy density of $0.045\,\mathrm{mJ/mm^2}$ (b), $0.087\,\mathrm{mJ/mm^2}$ (c) and $0.09\,\mathrm{mJ/mm^2}$ (d).

Vacuum measured by residual gas analyser, which is located about 1.5 m away from the cathode was dominated by hydrogen and water. During the laser cleaning we observed a pressure rise of few 10^{-8} mbar. After the third run vacuum rise was 30 % smaller than after the second one, indicating contaminant removal during the laser cleaning.

A final laser treatment with an energy density of $0.23\,\mathrm{mJ/mm^2}$ did not significantly change the QE distribution but enhanced the QE in the center of the cathode to $9.2 \cdot 10^{-5}$. This value is still a factor of five lower than QE achieved at BNL for Pb witness samples cleaned at room temperature, but a factor of five higher than the QE for laser cleaned Nb. Additionally there are two areas above and under the center with $\mathrm{QE} = 8.1 \cdot 10^{-5}$ and $\mathrm{QE} = 5.5 \cdot 10^{-5}$, respectively. After the final laser cleaning the gun cavity was warmed up and exposed to dry nitrogen by accident. After this the cavity was cooled down and the QE map was measured once again. QE in the center of the Pb spot was still $6 \cdot 10^{-5}$, so that the maximum quantum efficiency was affected by dry nitrogen very slightly. Figure 2 presents the history of the quantum efficiency in the center of the cathode "A" and near cathode boundary "B" (see Fig. 1).

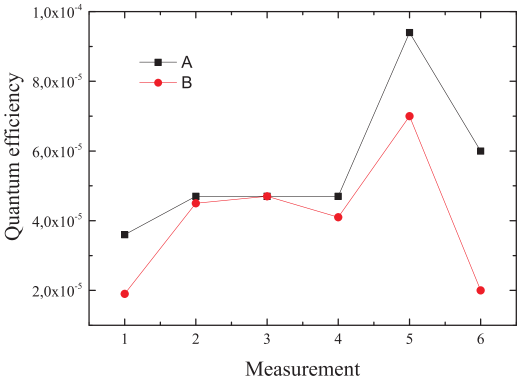

Figure 2: History of QE: (1) prior to the laser cleaning, (2) after the first laser cleaning with $0.045\,\mathrm{mJ/mm^2}$, (3) after the second laser cleaning with $0.087\,\mathrm{mJ/mm^2}$, (4) after the third laser cleaning with $0.09\,\mathrm{mJ/mm^2}$, (5) after the fourth laser cleaning with $0.23\,\mathrm{mJ/mm^2}$, (6) after the cavity was vented and warmed up.

GUN 0.2

In the second version of the gun a Pb cathode with a diameter of 3.5 mm and a thickness of about 500 nm was deposited on a Nb plug with a diameter of 5 mm, which can be inserted into the backplane of the cavity. For this purpose 5 mm hole was drilled in the back wall of the cavity and the plug was vacuum sealed with an indium wire on the outside of the gun cavity. The advantage of this design is a possibility to change the photocathodes, test different deposition methods and to make some optical measurements of the coating ex-situ after beam production. The gun cavity with the coated plug was tested at HZB up to a peak field on the cathode of 28 MV/m with $Q_0 = 2 \cdot 10^9$ [5].

Cathode Work Function

Quantum efficiency of the metal cathodes near the photoemission threshold can be roughly estimated as [6]

$$QE \sim \frac{1 - R}{1 + \frac{\lambda_{\mathrm{opt}}}{\lambda_{\mathrm{ee}}}} \frac{E_{\mathrm{F}} + \hbar\omega}{2\hbar\omega} \left[1 - \sqrt{\frac{E_{\mathrm{F}} + \phi_{\mathrm{eff}}}{E_{\mathrm{F}} + \hbar\omega}} \right]^2 , \quad (2)$$

where R is the cathode reflectivity, λ_{opt} is the photon absorption depth, λ_{ee} is the electron-electron scattering length, E_{F} is the Fermi energy and $\phi_{\mathrm{eff}} = \phi_0 - \phi_{\mathrm{Schottky}}$ is the cathode effective work function including work function lowered by the local electric field. The Schottky work function is given by $\phi_{\rm Schottky} = e\sqrt{\beta_{\rm ph}\frac{eE}{4\pi\varepsilon_0}}$, where $\beta_{\rm ph}$ is the field enhancement factor for photoemission. For the peak gradient on the cathode surface of 10 MV/m the emitted dark current was below the sensitivity of the Faraday cup, so that the value of $\beta_{\rm ph}$ was assumed to be close to 1. We measured the QE dependence on the cathode field (Fig. 3), fit the data with Eq. 2 and extracted the reflectivity R and the cathode work function ϕ_0. For $\lambda_{\rm opt} = 7.3\,{\rm nm}$, $\lambda_{\rm ee} = 17\,{\rm nm}$, $E_{\rm F} = 9.4\,{\rm eV}$ we get $R = 0.9$ and the cathode work function $\phi_0 = 4.45\,{\rm eV}$.

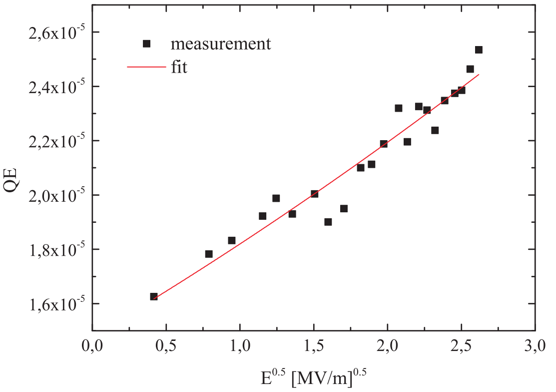

Figure 3: QE dependence on the square root of the field gradient on the cathode surface and a fit.

QE Map

Figure 4 shows the QE map of the cathode of the gun 0.2 with no laser cleaning. The maximum QE of $2 \cdot 10^{-5}$ (measured ∼1 mm away from the geometrical center of the coated area) is comparable to the QE of the uncleaned cathode in gun 0.1. While scanning of the back wall of the cavity with the drive laser some emission was registered with the CCD-camera in the visible range of the light spectrum, as shown in Fig. 4. No RF power was applied during this measurement. The emitted light probably cannot be referred to the pure reflection of the drive laser, because the camera is not sensitive to UV light ($\lambda < 400\,{\rm nm}$). Probably the emitted light is associated with fluorescence of impurities on the cathode surface. Furthermore, it seems that quantum efficiency correlates with the emitted light: areas with higher QE have lower “fluorescence” intensity, and “fluorescence” map provides precise information about cathode impurities/contaminations.

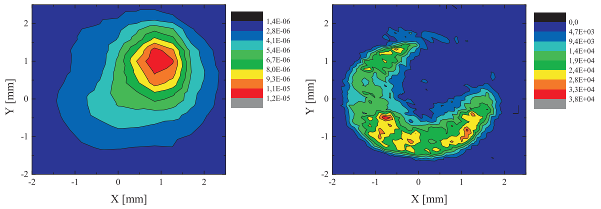

Figure 4: QE and “fluorescence” map.

QE Stability

Electrons emitted in the RF gun in a ”wrong” phase can reverse its direction before they exit the gun cavity. Some of these electrons can hit the cathode surface, causing heating, production of secondary electrons and changes to the cathode quantum efficiency. To study the influence of the electron back-bombardment on the cathode QE the RF phase was scanned to produce back streaming electrons. We measured the influence of the electron back-bombardment on the cathode quantum efficiency at 82 deg for 30 minutes and at 117 deg, the phases at which electrons should reverse its direction, for 45 minutes at a peak gradient on the cathode surface of 9.7 MV/m. For the total emitted charge of $\sim 3\,\mu$C no change of QE was observed. It was shown that the cathode QE can be improved by the cathode illumination with high energy density. The drive laser is too weak for this purpose, but the energy of the drive laser photons (4.76 eV) exceeds the binding energy of the Pb-O oxides (3.9 eV at room temperature). To measure the influence of this low energy density laser on QE, the photocathode was illuminated with the drive laser for 12 hours with an average laser power of $\sim$ 1 mW. No pressure rise was observed during the cathode illumination and no change in QE was observed.

CONCLUSIONS

Superconducting Pb cathodes have the potential to satisfy the requirements of FEL’s and deliver an electron beam with high peak and medium average current. The key challenge is to remove the cathode contaminations after the cavity treatment and to get a homogeneous QE distribution over the entire cathode surface without changing the cavity performance. For a SRF gun with Pb cathode it is absolutely necessary to implement some appropriate cathode cleaning techniques. The maximum QE value of $9 \cdot 10^{-5}$ at 258 nm was achieved in gun 0.1 after the laser cleaning with energy density of $0.23\,{\rm mJ/mm^2}$. To get a more homogeneous distribution of QE more attention should be paid to the cavity treatment and laser cleaning with smaller spot scanning across the cathode.

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