# PHOTOEMISSION STUDIES OF NIOBIUM AND LEAD PHOTOCATHODES USING PICOSECOND UV LASER*

R. Xiang [#], A. Arnold, P. Lu, P. Murcek, J. Teichert, H. Vennekate, HZDR, Dresden, Germany
R. Barday, HZB, Berlin, Germany

*Abstract*

We present the results of our investigations on superconducting photocathodes for supercondcuting rf injectors. Bulk niobium and lead film on niobium have been considered as the best candidates. The quantum efficiency (QE) at room temperature has been measured with 258 nm UV laser pulses of 14 ps duration. A QE of $10^{-4}$ has been obtained for the lead film. In order to improve the photoemission yield of niobium, new treatment methods, like Cs-activation and implantation with alkali metals, have been applied and the results are reported.

## INTRODUCTION

In the past two decades, superconducting RF photoinjectors (SRF gun) have drawn a lot of attention because of their continuous-wave (CW), low emittance and high bunch charge operation. Different research projects have been launched at a growing number of accelerator laboratories [1-3]. A lot of efforts have been spent on solving the conflict between the normal conducting photocathodes and the superconducting cavity. The most direct and easiest way is to use superconducting materials as photocathodes. Previous experimental results showed that lead and niobium are the most promising candidates [4,5].

At HZDR, $Cs_2Te$ is the standard photocathode material, and the drive laser has the wavelength of 258 nm in CW mode with adjustable repetition rate 100-500 kHz, and the pulse length is 14 ps FWHM. In this work, we used the present drive laser to investigate the photoemission properties of lead layer and bulk niobium, and tried to find a new recipe to improve the QE for niobium photocathode.

## THIN LEAD LAYER

Lead is an attractive option for a low to moderate average current source. Arc deposition technique has been proved to be the best choice for coating [5]. QE investigation was done with the SRF gun drive laser for the lead layer produced at National Centre for Nuclear Research (NCBJ) of Poland [6].

### *Experimental Setup*

The vacuum chamber used to measure the QE of cathodes is shown in Fig. 1. It consists of an anode ring and a cathode in a parallel geometry with a spacing of 10 mm. The anode ring can be biased up to 400 V. The cathode is connected to a picoammeter Keithley6485 for the photocurrent measurement. The laser used for photoemission was focused on the cathode surface with a diameter of 1 mm, illuminating at normal incidence through the anode ring. A turbo-pump was used to keep the vacuum inside the chamber at a level of $10^{-7}$ mbar.

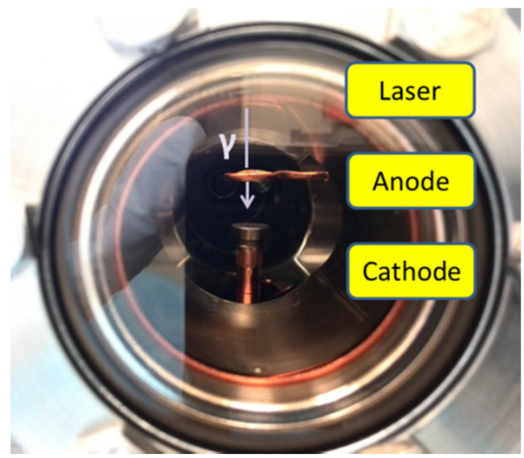


Figure 1: The experimental setup for QE measurement.

### *Preparation Progress*

The 2 µm thick lead layer was coated on polycrystal niobium plugs. The mirror-like Ø 10 mm Nb plugs were mechanically polished with diamond suspension, resulting in a mean roughness of 25 nm.

The lead layer deposition was done at NCBJ (Swierk) using an UHV arc device equipped with a 30° bent plasma duct for droplets filtering at a deposition rate of 200 nm/min. Sample #C2 was additionally treated with three Ar plasma pulses in the IBIS rod plasma injector at NCBJ. Energy-dispersive X-ray spectroscopy (EDX) measurement showed 86 – 93 % lead in the 2 µm layer [6].

For all samples, the lead layers were briefly exposed to air between deposition, post-processing, SEM studies and QE measurement.

### *QE Measurement and Laser Cleaning*

The QE of the layer was determined by measuring the laser power on the cathode and the current leaving the cathode. The bias on anode was adjustable from 30 V to 400 V.

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#r.xiang@hzdr.de

For the sample #C1 the initial QE before laser cleaning was measured as $2\times10^{-5}$ at 258nm (4.8 eV). Then a serious laser cleaning was performed with various laser power for different positions on the surface (Fig. 2). The maximum QE reached $1\times10^{-4}$ after laser cleaning with laser intensity up to 1.2 μJ/mm$^2$. This is lower than the QE for the arc deposited Pb in the former work [5], where the authors obtained about $7\times10^{-4}$ for 4.8 eV photons after cleaning with 248nm excimer laser up to 200μJ/mm$^2$. The reason can be the lower laser density and shorter laser pulse duration in our experiment. The action time between the ps laser pulse and the metal surface may be too short for the cleaning task.

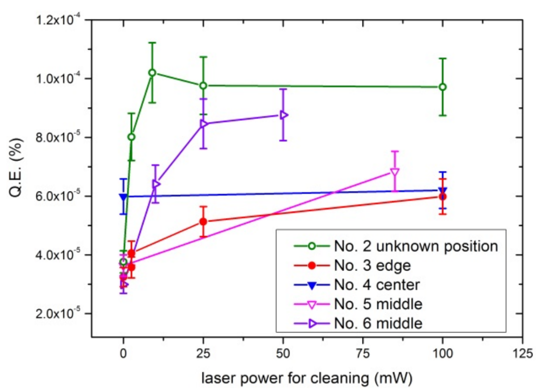


Figure 2: The laser cleaning for the Pb layer on #C1.

For the sample #C2, the original QE before laser cleaning was slightly more than that of #C1, $2.7\times10^{-5}$, and after cleaning with laser intensity up to 3.2 μJ/mm$^2$, the QE was limited to $6\times10^{-5}$ @ 258nm (4.8 eV), lower than in case of #C1. Figure 3 shows the cleaning procedure vs. laser power. The photocurrent was measured with a weak laser of 0.6 mW for diagnostics. The higher power does not lead to much efficiency as expected.

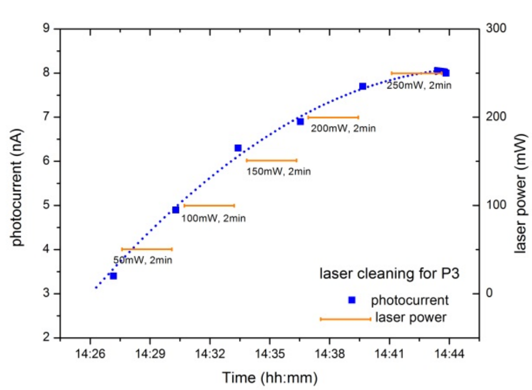


Figure 3: Laser cleaning progress for sample #C2. Photocurrent was measured by a weak laser with power of 0.6 mW. The anode was biased up to 200 V.

*Test in SRF Gun*

One Pb-coated Nb plug has been tested in the ELBE SRF gun. In this experiment, the cathode bias was -5kV, and the accelerating rf field of 5.2 MV/m was launched. A 4 nA beam current was achieved with 200 mW drive laser in repetition rate of 125 kHz. No obvious dark current was detected from the Pb layer.

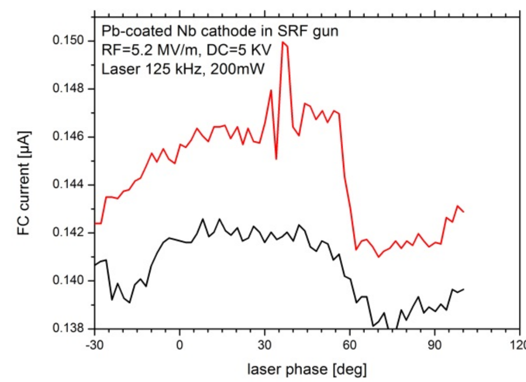


Figure 4: Phase scan during the beam test with Pb layer on Nb plug in ELBE SRF gun. The two curves were measured with the drive laser spot on different cathode positions.

## BULK NIOBIUM CATHODE

Previous studies of photoemission in niobium have shown a small initial QE in level of $10^{-6}$ at 248 nm [7] and an exciting value of $10^{-4}$ for 248 nm though the high energy laser cleaning up to 0.84 mJ/mm$^2$ [4]. Here in our study, effort is made to look for a recipe to improve the QE for this wavelength range by reducing the work function of the bulk surface.

Niobium samples are 0.5mm thick bulk material of 99.9% purity, with a size 4.5 mm × 4.5 mm, mechanical polished to roughness of 10 nm, washed in solvents, ultrasonically cleaned and stored in dry air.

*QE Measurement*

The QE of virgin Nb after polishing and solvent cleaning was measured as $5.72\times10^{-6}$ at 258 nm. This result is similar to the reported results [7]. In our measurement, the anode was set up to 5 kV (the electric field on cathode surface was 500 kV/m ), lower than that in Smedley's experiments [4]. A range of bias values was used for QE measurement to establish the dependence of the QE on the electric field (Fig. 5). After one hour illumination, the QE increased slightly and the dependence changed also. The improvement may be caused by the laser cleaning effect.

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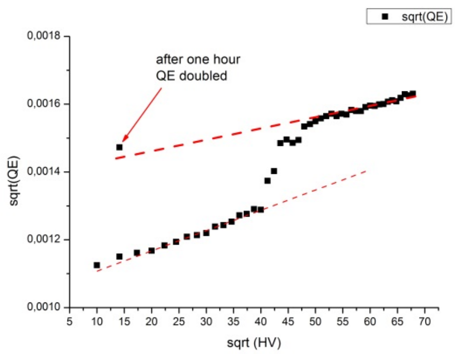


Figure 5: $(QE)^{1/2}$ vs $(bias)^{1/2}$ for mechanically polished Nb. The red lines are only used to guide viewer's eyes.

### *Activation with Cesium*

In order to improve the QE, we tried to use low work function coating to reduce the surface barrier of the metal, therefore to assure more photo-excited electrons passing through the surface barrier. Cesium was our primary choice. In Fig. 6, the QE rose from $5\times10^{-6}$ to $3\times10^{-5}$, which was achieved without any further treatment methods and the vacuum conditions were rather poor. With a better vacuum environment, the QE could be possibly even more. However, cesium coating is not the best approach to lower the surface barrier: (1) It has the potential pollution risk in case of practical SRF gun tests, because it is actually difficult to obtain properly clean surface; (2) The low laser damage threshold of the alkali layer on surface will impede its application.

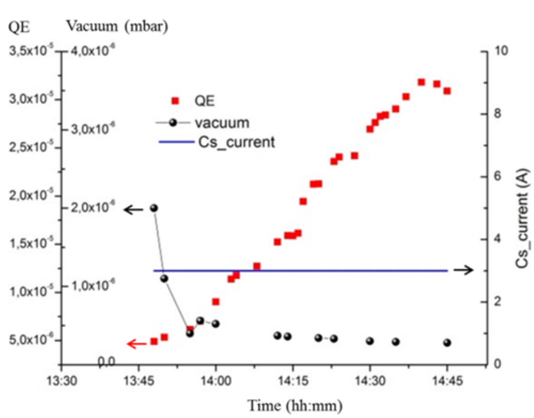


Figure 6: QE improvement, the vacuum condition, and the cesium dispenser current during the cesium activation of niobium.

### *Implantation with Alkali Metals*

Another technique used for reducing the work function of metal cathodes is ion implantation with lower work function alkali metals or alkaline-earth metals. This technique is known to enhance the photoelectric emission of tungsten up to a factor of 50 [8] and to improve the QE of magnesium cathode up to 10 times [9].

Simulation was done with the code SRIM [10] to search for proper implantation energy, angle, density, and then perform the implantation at ion beam centre (IBC), HZDR. The first test was done with 10 samples. Among them, five pieces were implanted with $133Cs^{+}$ to a theoretical depth of 24 nm – 59 nm and cesium atom content of about 1%; other five samples were implanted with $39K^{+}$ to the same depth and density. No post-annealing was performed after the implantation.

The samples were exposed to air after the implantation and stored in dry air till QE measurement was performed. The QEs of the samples were measured with 258 nm, 14 ps, 3 mW laser in vacuum, and the attracting electric field on surface was 40 kV/m. However, the results did not show improvement to the virgin niobium. The reason for that could be (1) the long waiting period in air, and (2) the weak electric field on the surface and the strong laser in picosecond pulse duration.

## SUMMARY

In conclusion, the quantum efficiency of superconducting photocathodes, thin lead layer and bulk niobium, was investigated under DC field and RF field by using the picosecond UV drive laser of the ELBE SRF gun at HZDR. Lead layer on Nb plug has been applied in ELBE SRF gun for one beam test, 2 nA beam has been detected with the Faraday cup.

In order to search a recipe to improve the QE of niobium, cesium coating and alkali ion implantation have been performed on the mechanical polished niobium samples. The study of the effect of implantation on the photoemission of niobium will be continued.

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## REFERENCES


[1] A. Arnold, and J. Teichert, Phys. Rev. ST Accel. Beams 14, 024801 (2011).

[2] J. Teichert, et al., "Free-electron laser operation with a superconducting radio-frequency photoinjector at ELBE", Nucl. Instr. and Meth. A. 743 (2014) pp. 114–120.

[3] A. Neumann, et al., "SRF photoinjector test at HOBICAT", Proc. of SRF2011, July 2011, pp. 962-968; http://www.JACoW.org

[4] J. Smedley, T. Rao, Q. Zhao, "Photoemission studies on niobium for superconducting photoinjectors", J. Appl. Phys. 98, 043111 (2005) .

[5] J. Smedley, T. Rao, J. Sekutowicz, "Lead photocathodes", Phys. Rev. ST Aceel. Beams 11, 013502 (2008)

[6] J. Lorkiewicz, et al., "Deposition and optimization of thin lead layers for superconducting accelerator photocathodes.", Phys. Scr. T161 (2014) 014071.

[7] L.N. Hand, U. Happek, "Photoelectric quantum efficiency of niobium for λ = 193 nm and λ = 248 nm", Nucl. Instr. and Meth. A 372 (1996) pp.335-338.




ISBN 978-3-95450-133-5

[8] J.P. Girardeau-Montaut, et al., "Enhancement of photoelectric emission sensitivity of tungsten by potassium ion implantation", Appl. Phys. Lett. ett., Vol. 66, No. 15, 1995, pp 1886-1888.

[9] K. Zhao, et al. "Researches on new photocathode for RF electron gun." Nucl. Instr. and Meth. A. 445.1 (2000), pp. 394-398.

[10] J.F. Ziegler, J.P. Biersack, & M.D. Ziegler, “SRIM, the stopping and range of ions in matter”, Lulu. com, 2008.



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