

SUPERCONDUCTING PHOTOCATHODES*

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We present the results of our investigation of lead and niobium as suitable photocathode materials for superconducting RF injectors. Quantum efficiencies (QE) have been measured for a range of incident photon energies and a variety of cathode preparation methods, including various lead plating techniques on a niobium substrate. The effects of operating at ambient and cryogenic temperatures and different vacuum levels on the cathode QE have also been studied.

1. Introduction

Several projects now being considered require injectors capable of delivering significant average current (>1 mA) with CW operation [1-4]. Some of these applications also require significant peak current, and would benefit from high (20 MV/m+) accelerating gradients. For these applications, a photoinjector based on superconducting technology is a leading contender.

Designing a superconducting photoinjector entails many challenges. As with any photoinjector, the choice of cathode material is of critical importance. The cryogenic environment of the superconducting cavity places additional considerations on the cathode choice compared to room-temperature copper cavities. Any cathode that is not itself a superconductor must be thermally isolated from the cavity, and must be mounted in such a way as to minimize RF loss in the cavity. A solution to these isolation problems has been proposed and investigated by D. Jensen at Rossendorf [5], using an RF choke-joint on the back wall of the cavity. This is an attractive solution, as it potentially enables the use

of nearly the entire range of cathodes developed for room temperature cavities. Chemical contamination of the superconducting cavity may also be a problem for some cathode materials. To address this concern, a group at Brookhaven National Laboratory [6] is investigating the use of a diamond capsule to enclose the cathode, with the diamond acting both as an electron multiplier (via secondary emission) and as a barrier to prevent contamination of the cavity by the cathode and contamination of the cathode by the cavity.

Another option is to use a superconductor as the cathode. This eliminates the need for isolation and simplifies the overall design. These cathodes can be expected to exhibit the benefits and drawbacks of traditional metal cathodes – low quantum efficiency ($<10^{-3}$) and nearly unlimited operating life. The niobium that comprises the cavity walls is the obvious first choice, and a cavity utilizing a niobium cathode has been built and tested at BNL [7]. The quantum efficiency (QE) of niobium was found to be poor ($<10^{-5}$), even for a metal [8]. For this reason, this paper investigates the photoemission properties of lead. Lead is a type I superconductor commonly used in cavities for ion accelerators, with a critical temperature of 7.9 K and a critical magnetic field of 54mT [9]. This low critical field would limit the accelerating gradient achievable in a cavity constructed entirely of lead. For this reason, we focus primarily on coating a niobium substrate with lead - we hope to coat only the cathode region of a niobium cavity with lead. As the magnetic field on the beam axis is typically small, we were not expecting the maximum electric field in the cavity to be impacted by the lead coating. This has been verified in recent tests at Jefferson Laboratory [10].

The primary focus of this paper is the experimental measurement of the quantum efficiency of various lead coatings, both at room and cryogenic temperatures. A theoretical investigation of the QE of lead using Spicer's three-step model of photoemission [11] has been performed, and will be reported in the companion paper to this article [12]. Portions of the experimental section were previously reported [13,14], and are included here for completeness.

2. Preparation of Cathodes

Five distinct types of lead cathodes were investigated in this work - four methods of plating lead along with a solid, polished lead sample. In all cases the cathodes/substrates are 9 mm in diameter and 8 mm thick.

Electroplated samples were prepared at Stony Brook University, on both copper and niobium substrates. The polished cathodes were electroplated with lead by a procedure developed for use on superconducting cavities for heavy ion

accelerators [15]. The plating solutions are based on methane-sulfonic acid chemistry and are created from commercially available products [16]. Each copper cathode was immersed in plating solution and flashed four times for several seconds with 10 mA/cm^2 plating current to prepare the surface. The current was then lowered to 2 mA/cm^2 , corresponding to a plating rate of $10 \text{ }\mu\text{m/hour}$, and a plating thickness of $8 \text{ }\mu\text{m}$ of lead. The cathodes are then rinsed with de-ionized water and dried with a stream of nitrogen gas. The procedure for plating niobium is identical to that for copper, except that the coating thickness is $2 \text{ }\mu\text{m}$.

The bulk lead cathode was prepared from cylindrical stock obtained from Goodfellow (99.95% purity). The surface was mechanically polished with Beuhler diamond polishing compounds. Nine, six and one micron polishing compounds were used, resulting in a finish with scratches on the order of one micron wide. Scanning electron microscope (SEM) images taken after the photoemission measurements revealed diamond inclusions covering roughly 5% of the cathode surface, likely imbedded during polishing (see fig. 2).

The vacuum-deposited (evaporated) sample was prepared at SBU in a vacuum evaporator, with a background pressure of $5 \text{ }\mu\text{Torr}$ and a deposition time of 9 minutes. The coating thickness is $6 \text{ }\mu\text{m}$. A polished copper cathode was used as a substrate. Subsequent evaporations have been prepared on niobium substrates, but have not yet been measured.

A sample was covered by means of the magnetron sputtering technique at the Soltan Institute. Deposition of lead was performed using a cylindrical cathode, in the presence of argon under 3 mtorr of pressure. The Nb substrate was placed at a distance of 3 cm from the sputtered cathode. The current discharge was set at a value of 100 mA. Such conditions ensure stable discharge without any surface melting of the cathode. The obtained film was smooth and macrodroplet-free. Total deposition time was 60 minutes and the estimated thickness of the layer was $4 \text{ }\mu\text{m}$.

The arc-deposited sample was prepared at the Soltan Institute by means of arc discharge with a planar cathode in UHV conditions. This process is characterized by a high ionization ratio of metallic plasma, higher energy of ions in comparison with the magnetron sputtering technique and also a higher purity of the deposition process due to the absence of a working gas. A discharge current of 25 A allowed stable arc operation (typical value for niobium is 100 A). The deposition process was performed with an Aksenov-type magnetic filter connected to the plasma source in order to eliminate macrodroplets. The coating thickness is $1 \text{ }\mu\text{m}$ on a niobium substrate.

3. Laser Cleaning

Laser cleaning with 248 nm light was used to improve the QE of all of the samples measured. The 248 nm light was provided by a KrF excimer (GAM Laser EX5), with a pulse duration of 10 ns and a repetition rate of 20 Hz, with the exception of the initial test, for which a Lambda-Physik LPX105 was used, with a 20ns pulse duration and a repetition rate of 10Hz. The change in surface morphology induced by various energy densities of 248 nm light was determined using an electroplated lead sample (shown in fig. 1). After irradiation, the cathode was removed from the vacuum and observed with an optical microscope and a SEM. The SEM was used to perform an analysis of the surface composition via X-ray fluorescence, as well as the surface structure. The first observable change in the surface morphology (fig. 1c) occurred at an energy density of 0.26 mJ/mm^2 . An energy density of 1.8 mJ/mm^2 was found to locally melt the coating and expose the substrate – the dark areas in fig. 1f correspond to the copper substrate. Based on these results, an energy density of 0.2 mJ/mm^2 was chosen as the starting point for the cleaning.

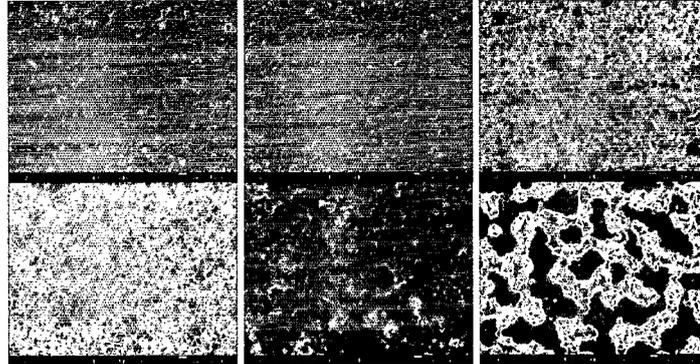


Figure 1. Surface structure of a lead coated cathode after 248 nm laser irradiation: (a) no laser (b) 0.11 (c) 0.26 (d) 0.52 (e) 1.1 (f) 1.8 mJ/mm^2 . Scale: – is $10 \mu\text{m}$.

The surfaces were each irradiated for ~ 10 minutes, with the laser operating at 20 Hz. To avoid alignment difficulties, the region of the cathode exposed to the cleaning beam was significantly larger than the measurement area. For the solid lead, evaporated and electroplated samples, the cathode was cleaned a second time at an energy density of 0.4 mJ/mm^2 . In both cases, little improvement was observed in the QE due to this increase. The samples were analyzed with an SEM after removal from the measurement system. Figure 2 shows the surface structure for four of the cathodes before cleaning. Figure 3 shows the surface structure after cleaning. In all four cases, the X-ray

fluorescence spectrum in the SEM showed only lead, indicating that the coating was intact.

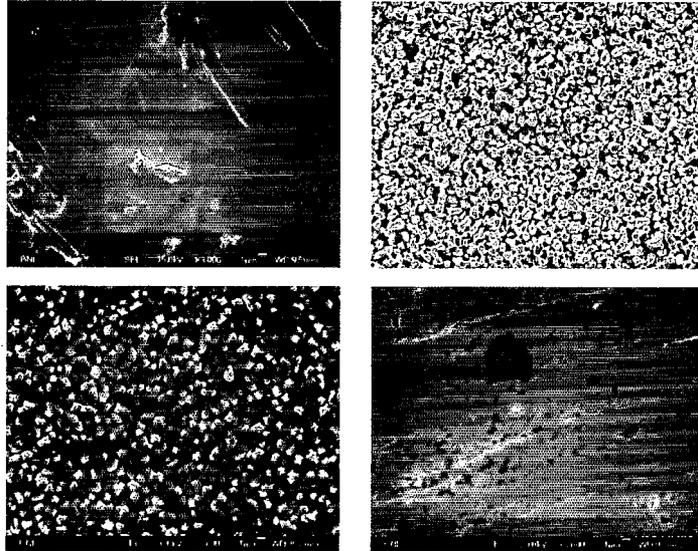


Figure 2. Lead cathode surface morphology prior to laser cleaning. (a) Arc-Deposited (b) Sputtered (c) Evaporated (d) Polished Solid Lead. Scale: $- 1\mu\text{m}$.

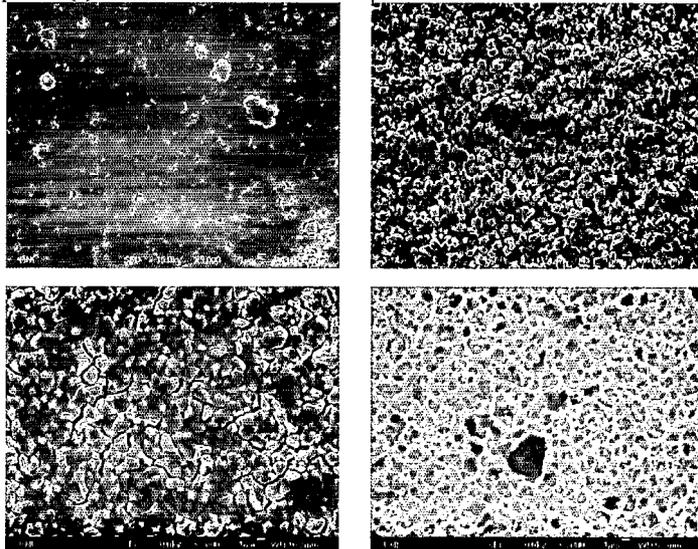


Figure 3. Lead cathode surface morphology after irradiation with 0.2 mJ/mm^2 . (a) Arc-Deposited (b) Sputtered (c) Evaporated (d) Polished Solid Lead. Scale: $- 1\mu\text{m}$.

4. Photoemission measurement

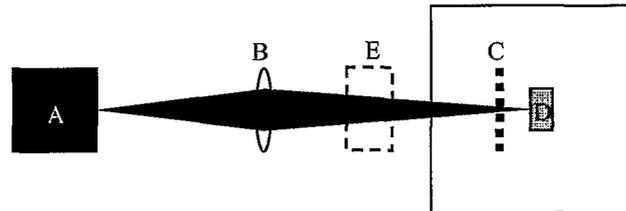


Figure 4. Schematic of experimental arrangement, showing: (A) Monochromator, (B) Lens, (C) Anode Grid, (D) Cathode and (E) Location of Power Meter.

A schematic of the photoemission measurement system is shown in fig. 4. A deuterium light source (Ocean Optics DH-2000-S-DUV) is fiber-coupled to a monochromator with a 300 micron exit slit. The desired wavelength λ is selected by the dial on the monochromator (Edmund DCM1-01). The output bandwidth is 2 nm, measured with an Ocean Optics HR2000 spectrometer. A fused silica lens is used to focus the light on the cathode through a vacuum window and the anode mesh. The output of the monochromator is measured for each wavelength before and after each QE measurement, at a point after the lens but prior to the vacuum window, using a power meter (Newport 918-UV). For the QE measurement, the anode is held at a positive voltage, and the current is measured leaving the cathode by a picoammeter (Keithley 487). The optical transmission of the vacuum window and the mesh are calibrated separately for each wavelength. Typical values for optical power P (in a 2 nm band) are 10-100 nW, and typical values for current I are 0.1 to 10 pA. For each wavelength, QE is calculated using the formula $QE = I (hc) / (P \lambda)$.

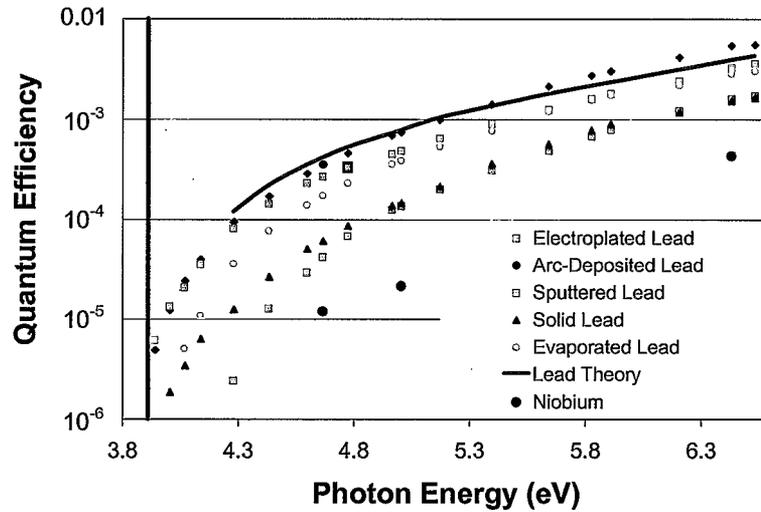


Figure 5. QE of various laser cleaned lead cathodes for photon energies between 3.9 and 6.5 eV. The vertical line represents the expected work function accounting for the Schottky effect (3.91 eV).

The quantum efficiency of the five lead cathodes is shown in fig. 5 as a function of incident photon energy. The theory line in the plot comes from the three-step model of photoemission [11,12]. The electron density of states was obtained from the NRL structures database [17]. The optical constants for lead and the “theoretical” work function were obtained from the literature [18,19]. The niobium data is included for reference [8].

Figure 6 shows the data for sputtered lead plotted as $(QE)^{1/2}$ vs. photon energy. This plot should be approximately a straight line, with a horizontal-intercept equal to the material work function. Data for both an electrode bias of 1 MV/m (1 kV across 1 mm) and 5 MV/m are shown. The Schottky effect (the reduction of the material work function due to the applied field) is evidenced by the lower work function for the 5 MV/m data. The work functions have been calculated using the method of Fowler [20,21]. No attempt was made to account for the 2 nm bandwidth of the lamp light. This introduces an uncertainty of ± 0.04 eV on the values for the work function. Table 1 shows the best fit work function for each cathode, cleaning energy and bias field, along with the QE at 213 nm and 193 nm. For some cathodes, the QE prior to cleaning was too low to be reliably measured; in these cases, only the QE after cleaning is shown.

Table 1. Work function (Φ) and QE of cathodes, including Cleaning Energy Density (C.E.D.) of 248 nm light used, and bias field applied between the cathode and anode. A C.E.D. of 0 represents the value prior to laser cleaning.

Cathode	C. E. D. mJ/mm ²	Field MV/m	Φ (eV)	QE ($\times 10^{-4}$)	
				213 nm	193 nm
Solid	0	1	4.52	0.49	2.6
	0.18	1	4.19	5.5	13.1
	0.4	1	3.93	7.8	15.3
	0.86	1	4.02	5.6	12.8
Evaporated	0	1	4.22	0.65	2.9
	0	5	4.17	0.70	3.1
	0.21	1	3.97	15.6	28.4
	0.21	5	3.84	14.2	27.9
	0.37	1	3.92	13.3	25.4
	0.37	5	3.86	15.3	30.4
Arc	0.21	1	3.88	27.2	54.1
Sputtered	0	1	4.21	0.10	0.22
	0.23	1	3.83	16.0	32.6
	0.23	5	3.71	17.9	36.4
Electroplated	0.22	1	4.20	6.8	16.0
	0.37	1	4.11	7.1	16.3

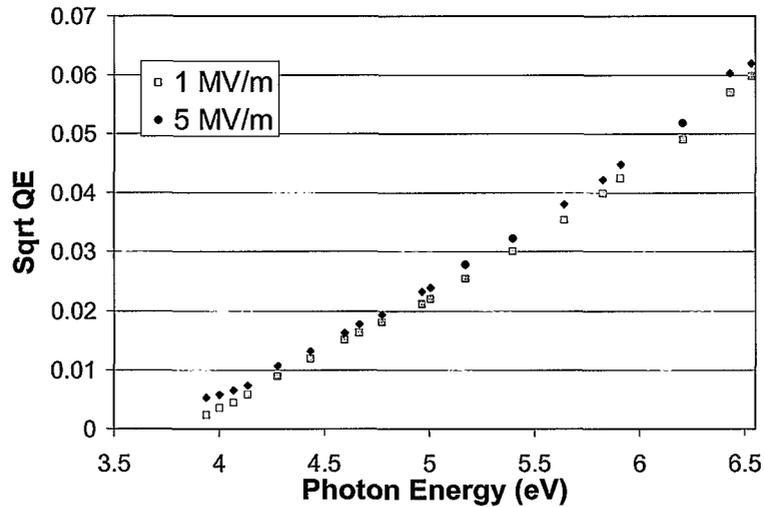


Figure 6. $(QE)^{1/2}$ vs. photon energy for sputtered lead.

5. Photoemission at Cryogenic Temperatures

A superconducting lead cathode will be used at cryogenic temperatures in a real injector. Tests with an all-niobium injector noted a QE at cryogenic temperatures that was inferior to the room-temperature QE [7]. For this reason, it was instructive to investigate the QE of lead cathodes at cryogenic temperatures. This was accomplished by mounting the cathode on a vacuum cold-finger attached to a LN₂ dewar. The cathode was electrically isolated from the thermal mass of the cold-finger by a ceramic standoff, but in adequate thermal contact. A thermocouple on the thermal mass was used monitor the cathode temperature. The cold-finger system has a 5 mm separation between the cathode and anode. A bias of 5 kV was used, yielding a field of 1 MV/m. The arrangement for the experiment was otherwise identical to that described above.

Table 2. QE and work function for arc-deposited sample at cryogenic temperature, for both good and poor vacuum conditions.

	Temp.		Vacuum	QE ($\times 10^{-4}$)		
	C			Φ (eV)	213 nm	193 nm
Initial	20		8	4.57	0.6	2.4
Cleaned						
0.23 mJ/mm ²	20		8	4.00	10.1	26.0
Cold	-169		6	4.01	9.6	23.2
Poor Vac	20		1300	4.04	8.6	23.5
Cold	-169		270	4.45	3.0	8.5
Cleaned						
0.22 mJ/mm ²	-169		270	4.06	10.0	24.4
2 hrs later	-169		270	4.26	4.6	11.1

Both electroplated and arc-deposited samples were studied in this apparatus. The QE of each cathode was determined at room temperature, in good vacuum (8 nTorr), before and after laser cleaning. The cathode was then cooled to -169C over the course of half an hour. Once the temperature stabilized, the cathode QE was measured again. The cathode was then laser cleaned, while still cold. The QE was measured immediately after cleaning, and every half-hour afterwards. For the case of the good vacuum, the cold QE did not vary much from the room-temperature value. However, when the above protocol was repeated for "poor" vacuum conditions (1.3 μ Torr), the QE was found to degrade significantly when the cathode was cooled. These vacuum conditions were achieved by backfilling the cavity with high-purity N₂, then pumping with only the turbo pump, leaving the ion pump valve closed. The room temperature QE could be restored by laser cleaning, but the QE would continue to degrade on the scale of hours after the

cleaning. Table 2 shows the vacuum level, QE and calculated work function for the arc-deposited cathode for each of the steps. In each case the QE was measured over a wide range of wavelengths, however only the QE @ 213 nm and 193 nm shown in the table. Note that, for the poor vacuum case, the act of cooling the cathode reduces the vacuum pressure in the cell considerably, suggesting that the cold finger is acting as a cryopump. This effect is likely the cause of the degradation of the QE in the cold, poor vacuum case – contaminants are being trapped onto the cathode. It should be noted that this is a second arc-deposited cathode, not the cathode described in section 4. This cathode has a slightly higher work function, and a slightly lower QE than the previous cathode. The results for the electroplated cathode cryogenic test were similar to those of the arc deposited, and are not shown.

6. Conclusion

Lead appears to be an attractive option for moderate average current sources. The best measured QE (arc-deposited) would require 2.1 W @ 213 nm to generate 1 mA. The optimal choice for lead coating method seems to be arc-deposition, as it provides a smooth surface (figs. 2a & 3a) and good QE. Electroplating is also an option, although the electroplated samples we tested seemed to have a work function significantly higher than the other lead samples, and correspondingly lower QE. The surface finishes of the evaporated and sputtered samples are likely too rough to use in an injector, at least at high field.

The three-step model of photoemission seems to well predict the QE of lead, especially given that no free parameters are used in the model. The work functions of the lead samples agree with the expected value, with the exception of the electroplated sample. Modest laser cleaning energy densities (~ 0.2 mJ/mm²) are sufficient to achieve the maximum QE without damage to the coating.

A niobium cavity has been constructed at DESY. This cavity has undergone cold tests, and is awaiting coating of the cathode region with lead via arc-deposition. This cavity will then undergo a second round of cold tests to confirm the RF performance, after which QE measurements will be performed.

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