RECENT PHOTOCATHODE R&D FOR THE LCLS INJECTOR*

F. Zhou, J. C. Sheppard, T. Vecchione, E. Jongewaard, A. Brachmann,
J. Corbett, M. Ferreira, S. Gilevich, J. Lewandowski, S. Vetter, S. Weathersby,
SLAC, Menlo Park, CA 94025, USA

Abstract

The Linac Coherent Light Source (LCLS) has used three copper photocathodes since its commissioning in 2007. Two of three copper cathodes had low initial quantum efficiency (QE) ($<1\times10^{-5}$) in the LCLS radio frequency (RF) gun. The two cathodes were exposed to the plasma cleaning in the cathode test chamber before installation in the RF gun. Recent studies at the SLAC RF gun test bed at the Accelerator Structure Test Area (ASTA) reveals that the pre-cleaning in the test chamber followed by cathode exposure to air for installation in the gun is the major factor leading to the low initial QE. All four cathodes, without the plasma pre-cleaning prior to the installation in the gun, have demonstrated initial QE$>4\times10^{-5}$ at the ASTA. Systematic studies also demonstrate that high-power RF gun operation provides an initial QE boost. In-situ laser cleaning for three new cathodes in the RF gun is extensively investigated, and a robust laser cleaning procedure is established at the ASTA with improvements of previous cleaning recipe for the LCLS cathode. The QE was shown to reproducibly evolved to $>1\times10^{-4}$ from about 4×10^{-5} immediately following the laser cleaning over ~3 weeks, a time much shorter than a few months for the previous laser cleaning for the present LCLS cathode. The intrinsic emittance of copper cathodes is recovered to the normal value within 1-2 days following the laser cleaning, much shorter than 3 weeks for previous laser cleaning for the present LCLS cathode. The experimental results at the ASTA, including comparison with the previous cleaning for the present LCLS cathode, are presented in the paper. Physics of the laser cleaning process and the evolution of the QE is discussed.

INITIAL QE WITHOUT IN-SITU CLEANING IN THE RF GUN

An RF gun test bed located at the SLAC's Accelerator Structure Test Area (ASTA) has been constructed [1] to study photocathodes for the Linac Coherent Light Source (LCLS) injector cathode operations. The beamline of the ASTA gun test bed duplicates the existing LCLS injector gun system [2], consisting of a chirp-pulse-amplifier laser tripled to 253 nm wavelength, LCLS-type RF gun, a solenoid for emittance compensation, one pair of magnet correctors, a Faraday cup to measure the bunch charge, and a YAG screen to measure beam size and intrinsic emittance. Similar to the LCLS injector, the drive laser is configured for normal incident injection to the photo-cathode surface using a 45° in-vacuum mirror. The final electron beam energy from the RF gun is about 5.5 MeV.

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The Cause for Low Initial QE in the RF Gun

The LCLS located at the SLAC National Accelerator Laboratory has been successfully operated for users for about 5 years. Its copper-based photo-injector has produced an ultra-low emitance and ultra-fast electron beam for the x-ray free electron laser (XFEL). Since its commissioning in 2007, three identical copper cathodes have been used for the LCLS injector operations with different initial quantum efficiency (QE) values. As illustrated in Fig.1, the first and third (present) LCLS cathodes had unexpectedly very low initial QE [3], about 5×10^{-6}, while the second one had 6.5×10^{-5} of initial QE as expected. Lately, it is realized that both the first and third LCLS cathodes were exposed to the plasma cleaning in the test chamber before cathode exposure to air for installation in the RF gun, while the second one did not have this cleaning process. Very low QE measured in the test chamber drives to proceed to plasma cleaning for the cathode prior to the installation in the gun. During the cathode installation in the LCLS RF gun, the cathodes have to be exposed to air for about 3 minutes for the cathode change due to the lack of loadlock system. The recent observations at the ASTA RF gun reveal that the laser-cleaned areas are much more susceptible to the air exposure than the non-cleaned areas do. The ASTA RF gun is vented to nitrogen and then exposed to air for about 3 minutes to mimic the LCLS cathode change before its vacuum starts to be pumped down. Figure 2 (left) and (right) shows the QE maps before and after the RF gun vacuum venting to air, respectively. Before the RF gun vacuum venting, areas A, B, C, D, E, F, G and H on the cathode have been cleaned by the intensive laser, while the circled center area is not exposed to any laser cleaning. In Fig. 2 (left), bunch charge from areas A, B and C have been evolved to about 7500 units for a given laser energy, equivalent to 1×10^{-4} of QE, while the cathode center area has about 3500 units of the bunch charge for the same laser energy, equivalent to about 4×10^{-5} of QE. After gun vacuum venting, bunch charge productions from the previously cleaned areas A, B, C, D, E, F, G, and H were dropped to 1500-2000 units shown in Fig. 2 (right), equivalent to about $1\text{-}2\times10^{-5}$ of QE, but the QE of the cathode center area still remains unchanged, at 4×10^{-5}. The observations indicate that the cleaned or activated surface is susceptible to the air-exposure, revealing the pre-cleaning is the cause for low initial QE measured in the RF gun.

Total four cathodes are characterized, which are not exposed to the pre-cleaning prior to the installation in the ASTA RF gun. All four ASTA cathodes have good initial QE in the RF gun ranging from 4×10^{-5} to 8×10^{-5}, as illustrated in Fig. 1. We conclude that the pre-cleaning

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process activates the cathode surface, extremely susceptible to the contaminations, such as air-exposure. Without plasma cleaning in the test chamber, high initial QE can be routinely achieved in the RF gun.

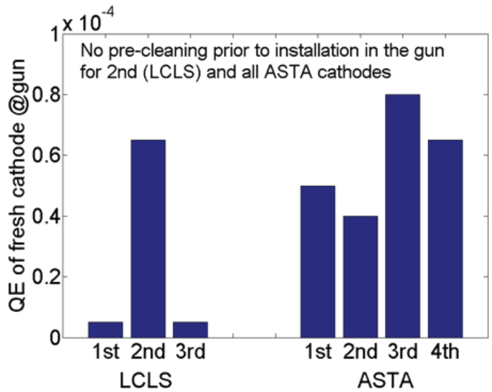

Figure 1: Original QE of cathodes in the LCLS and ASTA RF guns.

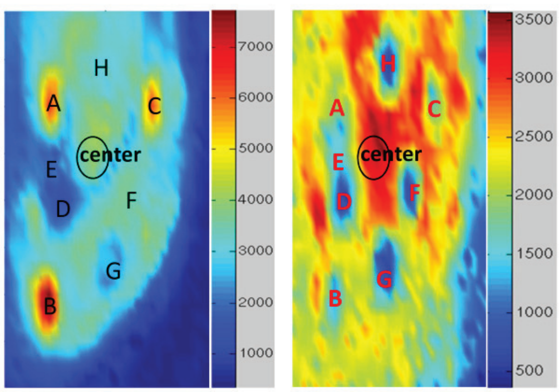

Figure 2: QE map before (left) and after (right) the gun vacuum venting. Before the gun venting, areas A to H are processed by laser cleaning while the center area is not cleaned by intensive laser.

QE Impact from the High-Power RF Processing

For LCLS operations all three photocathodes were characterized in a test chamber prior to the installation in the RF gun. The test chamber utilizes a broadband UV light source followed by a narrow-band monochromator to select the desired photon energy. The photoemission from the cathode under 2.6 kV/m of electric field is measured with nanometer. The QE measured in the test chamber is typically on the order of 1×10^{-7} at the desired photon energy of 4.91 eV (253 nm). The cathodes with the low QE observed in the test chamber are then directly installed in the ASTA RF gun. Surprisingly, following high-power RF processing all four cathodes in the gun have demonstrated an initial QE $>4\times10^{-5}$ under normal operation conditions, two orders of magnitude higher than in the test chamber. The Schottky effect enhances QE by less than an order of magnitude for a copper work function between 4.3-4.7 eV. The two orders of magnitude of QE enhancement in the RF gun therefore cannot be explained by the Schottky effect alone. It is noticed that the high-power RF operation boosts QE at the ASTA RF gun, as shown in Fig. 3. For a new cathode installed in the ASTA RF gun, the initial QE is 3×10^{-5} for the first day of electron beam operation. Then the QE increases by 50% after a few days of RF operations. It is logical to assume the RF processing conditions the cathode by removing surface contamination. In combination with the Schottky effect, a much higher QE is observed relative to measurements in a test chamber.

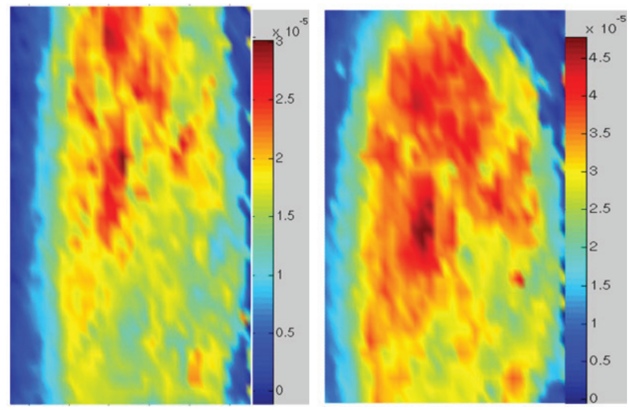

Figure 3: QE map for a new cathode in the ASTA RF gun: 3×10^{-5} of peak QE for first day with turn-on electron beam (left), 4.5×10^{-5} for a week later (right).

IN-SITU LASER-ASSISTED CLEANING DEVELOPMENTS IN THE ASTA RF GUN

Laser-based cleaning techniques have been widely used to clean metal photocathodes, such as copper and Mg, for more than two decades. A high-intensity laser beam, interacting with the metal cathodes, may ablate the cathode surface, removing surface contamination and possibly changing the cathode reflectivity, thereby resulting in a QE increase. However, the laser cleaning may change cathode's QE uniformity, thereby electron beam emittance, and also generate unwanted dark current or even deteriorate cathode's crystal quality, if the laser cleaning process is too aggressive.

The laser cleaning was performed for the present LCLS cathode in July 2011 [4]. The QE was evolved to 1×10^{-4} from 3×10^{-5} over a few months following the laser cleaning. Since then, 1×10^{-4} of the QE is essentially unchanged for three years to date for 24/7 users operation. The emittance was recovered to the normal value within three weeks following the laser cleaning. Although the previous LCLS laser cleaning was successful, two major concerns still remain. One concern is the reproducibility of the laser cleaning for different spots on the same cathodes and different cathodes. The other is the need to reduce emittance-recovery time and QE-evolution time following the laser cleaning with refinements of laser leaning process. These concerns are particularly important to deliver reliable and high quality electron beam for a high-impact machine for users, like the LCLS, which drives further studies at ASTA.

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Improvements of Laser Cleaning at the ASTA RF Gun

The laser energy for the previous laser cleaning of the current LCLS cathode performed in 2011 was fully determined by the vacuum activity in the RF gun [4]. In that case, the laser energy was set to a value for each round of the laser cleaning in order that about 0.5×10^{-10} Torr of the RF gun vacuum rise can be observed. It took 2-3 rounds of laser cleaning to increase QE to the desired value, $(3\text{-}5)\times10^{-5}$. For a better laser cleaning process, the laser energy should be set to a value with which QE is increased but with minimum gun vacuum rise. In this case, the copper crystal quality and cathode uniformity may not be affected. Ideally any minor surface change by the laser cleaning may cause a vacuum change. But in practice, observation of the RF gun vacuum rise depends on the resolution of the RF gun vacuum gauge and its controls, and the distance of the vacuum gauge to the cathode. To consider these practical factors, at the ASTA we start the laser cleaning with a laser-energy below the observable small gun vacuum activity. For example, if a small RF gun vacuum activity of 0.5×10^{-10} Torr is observed with 8 μJ of laser energy in about 40 μm rms of spot size, the actual laser energy for the first round is set to 6-7 μJ. Using this technique it was found that the QE could be reliably enhanced with only small amounts of vacuum activity.

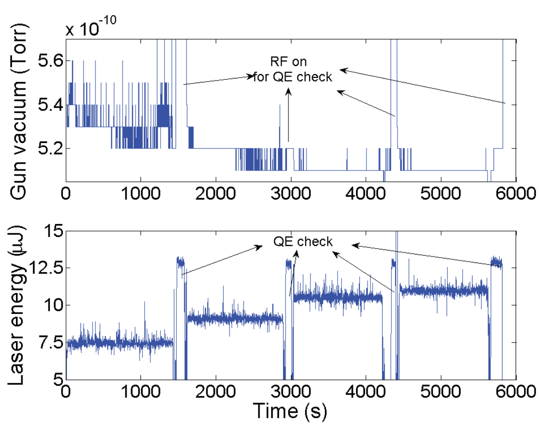

Figure 4: Laser energy and gun vacuum activities for the laser cleanings at ASTA.

Laser energy for subsequent rounds is increased in small, 0.5-1 μJ step. Typical RF gun vacuum activity and laser energy for each round are shown in Fig. 4. The vacuum activity during the laser cleaning for each round at the ASTA is much less than at the LCLS [4]. The laser cleaning raster step size is 30 μm for 40 μm of the focused laser size. For three of the four cathodes installed in the ASTA gun, about ten 1.2 mm × 1.2 mm areas each cathode are processed by the laser cleaning. QE increases to $(3\text{-}5)\text{x}10^{-5}$ after a few rounds of laser cleaning. The QE and emittance evolutions following the laser cleaning are consistent and reproducible for different areas and cathodes. Table 1 lists the standard laser cleaning parameters developed at the ASTA, in comparison to the previous laser cleaning recipe for the LCLS cathode. Note the required laser energy for the laser cleaning is proportional to the laser pulse length. The laser fluence for the single laser shot at ASTA is less than at the LCLS. The laser shots for the laser cleaning at the ASTA are only half the previous cleaning at the LCLS. The integrated laser fluence for laser cleaning at the ASTA is much less than the previous cleaning at the LCLS. It results in a much better QE evolution and quicker emittance recovery following the laser cleaning at the ASTA than the previous cleaning at the LCLS.

Table 1: Laser Cleaning Parameters at ASTA and LCLS

	ASTA (LCLS)
Laser pulse energy (μJ)	7-10 (17-20)
Laser size on cathode (μm)	40 (30)
Laser scan step size (μm)	30 (30)
Laser shots on each spot	60 (120)
Laser pulse length (ps)	1.6 (3)
Base gun vacuum range with RF power off (Torr)	$4\text{-}12\times10^{-10}$ $(4\text{-}7\times10^{-10})$
Gun vacuum rise during the cleaning (Torr)	$<0.25\times10^{-10}$ (0.5×10^{-10})
Gun power during cleaning	RF off
QE after cleaning	$3\text{-}5\times10^{-10}\,(4\times10^{-5})$

QE and Emittance Evolution Following the Laser Cleaning

Using the standard laser cleaning process, the QE can be reliably increased to $(3\text{-}5)\times10^{-5}$ from 10^{-6}- 2×10^{-5} after 3-8 rounds of the gentle cleaning. Following the laser cleaning, the QE is gradually increased, and eventually evolved to $>1\times10^{-4}$ over 2-3 weeks, as illustrated in Fig. 5, much shorter than a few months for previous LCLS cleaning. It shows all five areas A-E cleaned by the intensive laser have similar QE evolution over time, while the QE of the center area, which is not exposed to the laser cleaning, is kept unchanged over the time as expected. Note that the five areas A, B, C, D and E are cleaned on different dates, on 10th, 18th, 25th, 32nd and 32nd respectively, as illustrated in the plot.

At ASTA, the beam energy is determined by measuring the beam rotation angle through the solenoid, and the beam size is measured at a YAG screen downstream of the solenoid. The measured beam energy is 5.5 MeV, with which the space charge dominates the beam. Thus, only the intrinsic emittance with very low charge 1-2 pC can be measured using the solenoid scan. The measured intrinsic emittance for non-cleaned center area at ASTA is about 0.7 μm per mm-rms, close to the measured value in the LCLS, 0.9 μm per mm-rms. It indicates the emittance measurements at ASTA are reliable. Figure 6 shows the measured intrinsic emittance before the cleaning, immediately after the cleaning, and next day after the laser cleaning. For the emittance measurements, laser spot

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on the cathode is 1 mm in size with about 3 mm offset in x-plane from the cathode center. The intrinsic emittance is increased immediately following the laser cleaning but in the next day the emittance is recovered to the one before the cleaning. The High power RF operation helps to smoothen out the surface's non-uniformity thereby improving the emittance. The emittance recovery time at the ASTA is only 1-2 days, much shorter than 2-3 weeks for the previous cleaning at the LCLS. The fewer laser cleaning fluence for the ASTA results in a better QE and emittance evolution than the previous laser cleaning at the LCLS.

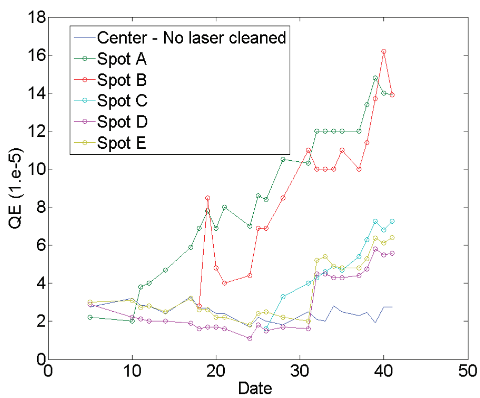

Figure 5: QE evolution for the areas with and without laser cleaning. Areas A, B, C, D and E are exposed to the laser cleaning while the center area is not cleaned by intensive laser.

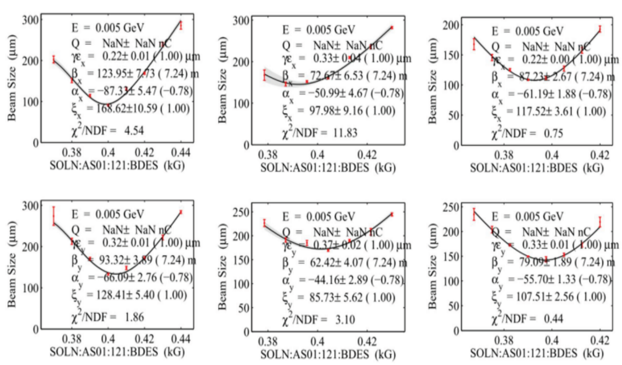

Figure 6: Intrinsic emittance 0.22-µm (x)/0.32-µm (y) before laser cleaning (left), 0.33-µm (x)/0.37-µm (y) immediately after laser cleaning (middle), and 0.22-µm (x) /0.33 -µm (y) on the second day after laser cleaning (right).

Laser Pointing Requirements for the Laser Cleaning

Reasonable good laser pointing stability on the cathode is required for the application of laser cleaning technique to the cathode cleaning. The focused laser size for the laser cleaning of the ASTA cathodes is about 40 µm rms. According to the standard laser cleaning procedures, QE starts to be increased when the laser energy is increased to 7 µJ with continuous 60 shots for each location. However, for one time the QE was not changed at all, even if the laser energy had been increased to 28 µJ with nominal 60 shots for each location. Eventually QE was increased through doubling laser shots for each location. Later, we realized the laser pointing stability on the cathode was bad during the laser cleaning, about 10 µm rms double the normal pointing jitter, as shown in Fig. 7. The bad laser pointing causes the failure of the laser cleaning. Melting the cathode surface needs certain amount of laser shots. Unstable laser pointing significantly reduces the actual laser shots for the same location. The laser cleaning works again with the nominal laser shots, when the laser pointing stability is improved to the normal value. According to the observations, laser pointing stability $\Delta\sigma_{x,y}/\sigma_{x,y}$ is required better than 10% to make laser cleaning work. This laser pointing requirement can be met readily for laser user facilities.

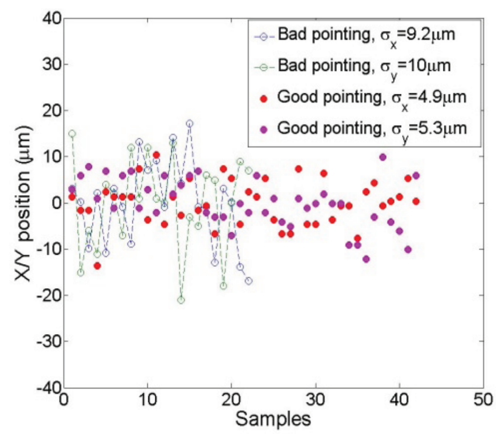

Figure 7: Laser pointing stability requirements during the laser cleaning. Laser cleaning fails with the bad laser pointing.

Discussion of the Laser Cleaning Process and the QE Evolution

Laser cleaning was thought as pure chemical processing to remove surface contaminations, thereby reducing work function and increasing the photoemission. During the process, the reflectivity was thought unchanged. Reducing work function increases the intrinsic emittance. Relations of QE to work function ϕ_w and intrinsic emittance ε_x are expressed by the following equations [5]:

$$QE(\omega) = \frac{1-R(\omega)}{1+\dfrac{\lambda_{opt}(\omega)}{\lambda_{e-e}(\omega)}} \frac{\left(h\nu-\phi_{eff}\right)^2}{8\phi_{eff}\left(E_F+\phi_{eff}\right)}$$

$$\frac{\varepsilon_n}{\sigma_x} = \sqrt{\frac{h\nu-\phi_{eff}}{3mc^2}}$$

with $\phi_{eff} = \phi_w - 0.037947\sqrt{E_0}$, where R is the cathode optical reflectivity = 0.43, hν is the photon energy, about 4.91 eV for 253 nm of wavelength, λ_{opt} is the photon absorption length of 116 angstroms, λ_{e-e} is electron-electron mean-free path about 22 angstroms, E_f is the

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Fermi energy, about 7 eV, ϕ_{eff} is the effective work function, mc^2 is the rest mass energy of electron, E_0 is the applied RF electric field on the cathode, expressed by $E_{peak}\bullet\sin(\varphi)$ in units of MV/m, E_{peak} is gun's peak accelerating gradient, 110 MV/m, φ is the gun phase from zero-crossing, 15° for intrinsic emittance measurement. Substituting these parameters into Eqs. 1 and 2, the intrinsic emittance should be changed by about 20% when the QE doubles from 6×10^{-5} to 1.2×10^{-4}. For the LCLS, the intrinsic emittance is expected to have been changed from 0.9 µm/mm-rms to 1.08 µm/mm-rms, when the QE doubles from 6×10^{-5} to 1.2×10^{-4}. However, no noticeable change of intrinsic emittance is observed at the LCLS, as shown in Fig. 8, when the QE is increased by a factor of 2 following the laser cleaning. The result indicates the laser cleaning process may not change the work function. Instead, the images of LCLS [4] and ASTA cathodes using the white light, as illustrated in Fig. 9, suggest that the reflectivity for the laser cleaned areas is decreased after the laser cleaning. The two squares subject to the laser cleaning have lower reflectivity than other areas without laser cleaning. It is believed a change in the reflectivity of cathode surface is one of the major factors for the observed QE enhancement following the laser cleaning.

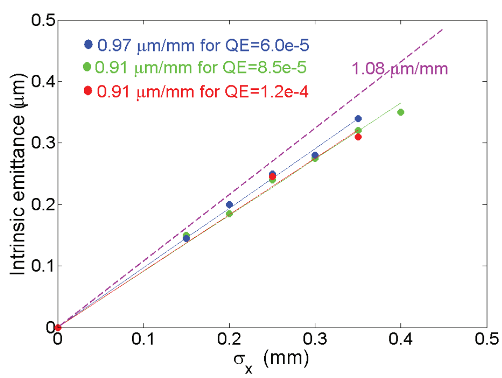

Figure 8: Measured intrinsic emittance with the different QE following the laser cleaning at the LCLS.

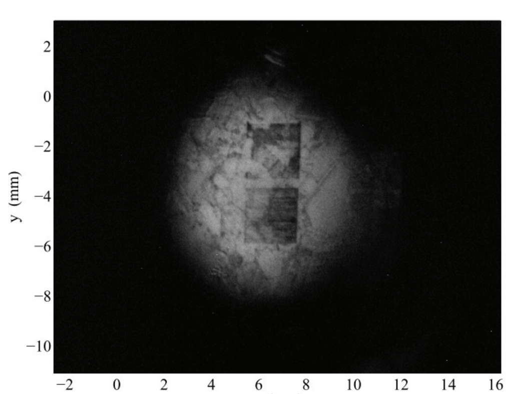

Figure 9: Image of the copper cathode using the white light. Two square areas are processed by the laser cleaning.

SUMMARY

LCLS cathodes have to be exposed to air for the installation in the RF gun due to the lack of loadlock system. Experimental studies indicate that the plasma cleaning for the cathodes in the test chamber results in a very low initial QE in the LCLS RF gun. All four cathodes, without the plasma cleaning in the test chamber, have reliably demonstrated initial QE>4×10^{-5} in the ASTA gun. Laser cleaning procedures are improved at the ASTA, resulting in a better QE and emittance evolution than the previous cleaning at the LCLS. Physics of the laser cleaning process and its QE evolution is discussed. It is believed that the work function is not changed during the laser cleaning process and the QE evolution over time. The change of cathode surface reflectivity is considered as one of factors for the QE enhancement for the laser cleaning. A more complete picture of understanding the complex laser-cleaning process is under investigation.

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