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HIGH-BRIGHTNESS ELECTRON BEAM EVOLUTION IN TIME FOLLOWING LASER-BASED CLEANING OF THE LCLS CATHODE*

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Abstract

Laser-based techniques have been widely used for cleaning metal photocathodes to increase quantum efficiency (QE). However, the impact of laser cleaning on cathode uniformity and thereby on electron beam quality are less understood. We are evaluating whether this technique can be applied to revive photocathodes used for electron beam sources in advanced x-ray free electron laser (FEL) facilities, such as the Linac Coherent Light Source (LCLS) at the SLAC. Laser-based cleaning was applied to two separate areas of the current LCLS photocathode on July 4 and July 26, 2011, respectively. QE was increased by 8-10 times upon the laser cleaning. Since the cleaning, routine operation has exhibited a slow evolution of QE improvement and comparatively rapid improvement of transverse emittance, with a factor-of-3 QE enhancement over five months, and a significant emittance improvement over the initial 2-3 weeks following the cleaning. Currently, the QE of the LCLS photocathode is holding constant at about 1.2×10^{-4}, with a normalized injector emittance of about 0.3 μm for a 150-pC bunch charge. With proper procedures, the laser cleaning technique appears to be a viable tool to revive the LCLS photocathode. We present observations and analyses for QE and emittance evolution in time following laser-based cleaning of the LCLS photocathode, and comparison to previous studies, the measured thermal emittance versus QE and comparison to the model.

OVERVIEW

The Linac Coherent Light Source (LCLS), located at the SLAC, has been successfully operated for users for more than three years [1]. Its copper-cathode based photo injector has produced an ultra-low emittance electron beam [2] for the x-ray free electron laser (FEL). To date, three polycrystalline copper photocathodes have been used in LCLS injector operation since its initial commissioning [3]. The first cathode had quantum efficiency (QE), $2\text{-}3\times10^{-5}$ after some processing, sufficient for initial commissioning from early of 2007 to July 2008. The second cathode had a QE of about 5×10^{-5} and was used for about three years of operation, from July 2008 to May 2011. When the LCLS repetition rate was increased from 60 Hz to 120 Hz, its QE quickly decayed to one half its initial value within 7-10 days. For this reason, the transverse position of the drive laser on the cathode had to be moved frequently to find new high-QE spots. This movement and subsequent retuning of the photo injector occupied significant LCLS machine time, and only a limited number of laser locations on the cathode could deliver the desired low emittance electron beam for reasonably good FEL performance. The second cathode was then replaced by a third one in May 2011, but the initial QE of this third cathode was only $\sim5\times10^{-6}$, insufficient for user operations. Eventually, laser-based cleaning was initiated on the third photocathode, in order to boost the QE. Previous cleaning attempts for the third cathode, using in-situ gun hydrogen plasma cleaning [3], failed to achieve adequate QE improvement. Laser-based cleaning techniques have been used in the photo injector community for many years on metal cathodes, such as copper and Mg, to enhance QE [4-6]. A high-intensity laser beam, interacting with the cathode, may ablate the cathode surface and/or remove contamination, thereby resulting in a QE increase. However, the impact of laser cleaning on cathode uniformity and electron beam emittance are unknown at present. We evaluated whether this technique could be used to revive the LCLS photocathode for x-ray FEL facilities, which have stringent requirements on the beam emittance as well as the QE. Laser-based cleaning for the LCLS photocathode was successfully performed in July 2011, and the evolution of the QE and emittance following the cleaning will be presented.

LASER CLEANING PARAMETERS AND PROCEDURES

The applied laser fluence is a key parameter in laser-based cleaning for metal cathodes. The fluence of the refocused UV drive laser (253 nm) needs to be properly chosen so that the laser can effectively remove surface contamination to enhance the QE, but will not destroy the cathode surface quality or change the surface morphology. For this application to the LCLS copper cathode, the laser fluence used for laser cleaning was determined by the "vacuum activity" in the photocathode RF gun [5]. In other words, the applied laser fluence (laser energy for a given laser spot size) had to be gradually increased until a change in vacuum pressure in the RF gun was observed. In the LCLS gun system, the nearest vacuum gauge to monitor the gun vacuum is located at a nearby RF-feed waveguide [7]. The cold cathode ion gauge on the waveguide is about 50 cm away from the cathode. Estimate shows the vacuum pressure on the cathode is 1.3-1.5 times higher than the ion gauge [8]. A pressure rise of $\sim0.5\times10^{-10}$ Torr was observed in the LCLS gun waveguide when the pulse energy of the laser illuminating the photocathode was increased to 17 μJ with a 30 μm rms spot size. With this vacuum activity, removal of cathode surface contamination was expected. The laser

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was then rastered in a 2D grid across the cathode to clean the surface, using a 30 μm step size in *x* and *y*. The gun-waveguide vacuum increased to about 7.5×10^{-10} Torr from the base value of 7×10^{-10} Torr. Note that the base vacuum on the gun waveguide was elevated to 7×10^{-10} Torr, from the typical steady-state vacuum of 3×10^{-10} Torr (with gun RF off), due to a few previous hydrogen cleanings and laser fluence-determination testing prior to the formal laser cleaning. After the first run of cleaning, the QE increased to ~1×10^{-5} from an original value of 6×10^{-6}. Two more runs followed, with laser pulse energy slightly increased to about 20 μJ, maintaining a 30-μm rms spot size. This enhanced the QE to ~4×10^{-5}, about 7-8 times before the cleaning. Table 1 gives the major parameters used for cleaning the LCLS cathode. The RF power for the gun was always turned off during the laser cleaning process. All QE data were measured at a 30° laser launch phase from zero-crossing, with 115 MV/m of peak gun electric field, using a 1 mm diameter drive laser spot on the cathode. During the QE measurements, the laser energy on the cathode was varied to produce a constant 150 pC bunch charge.

Table 1: Major parameters for the laser cleaning

Laser pulse energy (μJ)	17-20
Laser rms size on cathode, σ_x/σ_y (μm)	30 /30
Laser scan step size (μm)	30
Laser shots on each spot	60 or 120
Laser beam rate (Hz)	120
Base vacuum on the gun waveguide prior to laser cleaning (Torr)	~7×10^{-10} (RF off)
Vacuum rise on the gun waveguide during cleaning with RF off (Torr)	~0.5×10^{-10}
Gun RF power during cleaning	RF off
QE data: before/after cleaning	5×10^{-6}/4×10^{-5}
QE measured at: Laser phase from zero-crossing Peak gun accelerating field (MV/m) Laser diameter on the cathode	 30° 115 1 mm

EVOLUTION OF QE AND EMITTANCE FOLLOWING LASER CLEANING

Two separate square areas on the LCLS cathode (2 mm × 2 mm each) were processed by the laser-based cleaning technique on July 4 and July 26, 2011, using the focused drive laser beam. The focus size was σ_x=30 μm rms. Figure 1 show white-light images of the cathode before and after laser cleaning. The polycrystalline copper grain patterns are clearly seen on the cathode surface before cleaning (left plot). After cleaning, clearly, the surface reflectivity decreases as a result of laser exposure (right plot). The central top square area A shown in right plot was processed by laser cleaning on July 4, 2011 and is located at the cathode center. The lower region B was processed on July 26, 2011 and its central position has a -2.5 mm of *y*-offset from the cathode center. A 1 mm diameter spot marked with yellow circle in the area A is currently being illuminated to produce the electron beam for LCLS user operations from July 4, 2011 to now, July 21, 2012; no other areas are used during LCLS user operations. Evolution of QE and emittance for continually-used and unused spots are presented in the following sections.

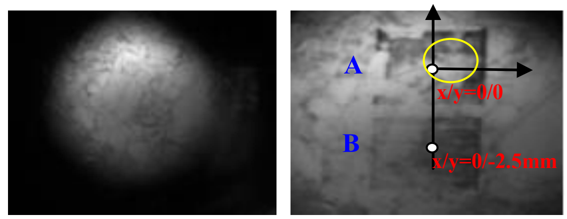

Figure 1: White light images of the LCLS cathode before (left) and after (right) laser cleaning. The x-y coordinate in the right plot is with respect to the solenoid axis.

QE Evolution

The QE measured immediately after the cleaning process was about 4×10^{-5} in the areas exposed to laser cleaning. Figure 2 shows the evolution of QE and gun waveguide vacuum from July 4, 2011 to December 15, 2011 following the cleaning process on July 4, 2011, for the spot marked with yellow circle in area A, being used for routine operations. From December 2011 to now, July 25, 2012, the QE is holding constant, about 1.2×10^{-4}. Note that the LCLS machine is always operated at a 120 Hz repetition rate for user operations. The figure shows that over time the QE increased by a factor-of-3 and reached about $1.2\text{x}10^{-4}$ after about 5 months of operation. The gun waveguide vacuum also improved, from 8×10^{-10} Torr to 6.5×10^{-10} Torr during this period. The QE for the unused-but-laser-cleaned spots in area B is also improved following cleaning on July 26, 2011. About 6 weeks later, the QE was increased to 6×10^{-5} from 5×10^{-5}. The QE was mapped again on February 2, 2012, eight months following the cleaning (Figure 3). We measured the QE of the area B, by moving the drive laser beam from -1.5 mm to +1.5 mm in the *x*-plane for different *y*-locations, -2.5 mm, -2.0 mm, and -3.0 mm, respectively. Because a 1-mm-diameter laser spot size was used to measure the QE, the full laser beam was located within the cleaned area for a laser central *x*-location ranging from -0.5 mm to +0.5 mm (Figure 3). For a central *x*-location beyond +1.5 mm or -1.5 mm, the full laser beam diameter was located completely outside the cleaned area. The data in Figure 3 show that the QE for the spots within the cleaned area had also increased from 4×10^{-5} to ~1.3×10^{-4}. The data shown in both Figures 2 and 3 suggest that the QE improvement in both areas might be related to the gun vacuum. Figure 3 also shows that the QE data for the un-cleaned areas, beyond +1.5 mm or -1.5 mm for laser central *x*-location, was still within the 10^{-6} scale. Data in Figure 3 indicates that the QE measured eight months later in the un-cleaned area was still at a very low level, although the overall gun vacuum had continuously improved.

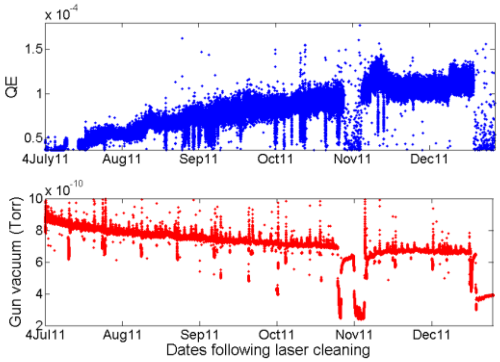

Figure 2: Evolution of QE (top) and gun waveguide vacuum (bottom) during the five months following laser cleaning, for the cathode spot being used for routine user operations.

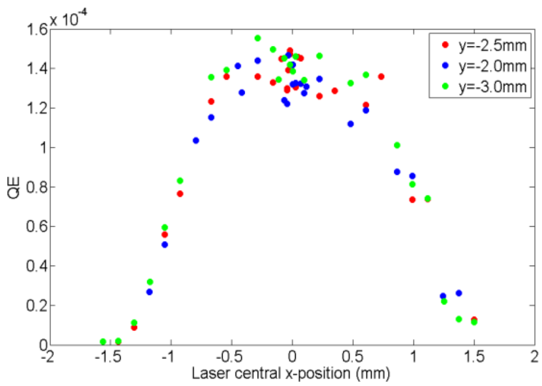

Figure 3: The QE in the area B measured eight months following laser cleaning.

Although detailed surface and material science studies for the third LCLS cathode are still pending, we assume that the cathode surface exposed to laser cleaning still retained contaminants, which were pumped out over time, causing a slow increase in the QE. However, the contaminants on the un-cleaned surface remain unchanged, and appear strongly bound to the surface, and are not removed as a result of vacuum improvement. Cathode R&D programs to further understand the detailed surface and material processes that take place during the laser cleaning are under way at the SLAC [9].

The first LCLS cathode was also processed by the laser cleanings in 2007 and 2008 but using different procedures from the current one for the third LCLS cathode. The QE of the first cathode decayed quickly during the operations following the cleaning. During the laser cleaning process in 2007, the vacuum measured on the gun-waveguide increased to about 1×10^{-8} Torr from the base vacuum of 1×10^{-9} Torr. The first cathode was laser cleaned again in 2008. The gun vacuum rise during the cleanings in 2008 was at least 2-3 times for the current cathode ($\sim0.5\times10^{-10}$ Torr). The laser fluence for cleaning the first cathode was at least twice for the third cathode. A small vacuum leak in the waveguide for the first accelerator section following the gun system was observed during the early days of the LCLS operations, which caused an additional gas load to the cathode. Similar phenomena for cleaning Mg cathode were also observed [6]. Upon the laser cleaning, the QE of the Mg cathode improved two orders of magnitudes [6] against one order for the third LCLS cathode. The laser fluence and/or laser exposed time for the cleaning was much higher than for the current third LCLS photocathode. During operation of this Mg cathode the QE following laser cleaning did not decay during the first three months of operation but did not further increase as we observed for the third LCLS cathode. The comparison of the previous cleaning results to the third LCLS cathode illustrate that the laser fluence and laser exposed time for the cleaning need be properly chosen to have a good QE evolution during operations following the cleaning.

Emittance Evolution

The LCLS injector emittance measurements are made using a quadrupole scan. After acceleration of the electron beam to 135 MeV, the beam is intercepted by a 1-µm thick aluminum screen. Here, the transverse electron beam size is measured using optical transition radiation (OTR) from the screen, which is imaged onto a digital camera. The strength of an upstream quadrupole is varied over several settings while the horizontal beam size is measured on the OTR screen. Figure 4 shows the emittance evolution from July 4, 2011, to February 2012, for the spot marked with yellow circle in area A, following laser cleaning. The location of the cathode spot is at x=+0.3 mm and y=+0.35 mm, close to the cathode center, in the area A. The emittance measured immediately after laser cleaning was about 0.75 µm for a 150 pC bunch charge. It then improved to 0.3-0.4 µm within 2-3 weeks following the cleaning process. The converged emittance was close to expectation from simulations with ImpactT [10], 0.35 µm for 150 pC. The corresponding slice emittance also improved for both 150 pC and 250 pC bunch charge, as shown in Figure 4. The emittance for an "idle" spot in area B cleaned on July 26, 2011, one not used during routine operations, centrally located at a -2.2 mm of y-offset from the cathode center, was also characterized. The emittance measured on September 6, 2011 had been converged to our expectation, $\varepsilon_x/\varepsilon_y$=0.52/0.48 µm from simulations for 250 pC [11]. About 90° of phase advance through the solenoid results in the coupling of y-plane to x-plane, which indicates the y-offset causes x-emittance growth.

The emittance improvement, compared with the value measured immediately after cleaning, is attributed to an improved, more-uniform QE emission [11]. The continuous RF conditioning during routine user operations may smooth-out a non-uniform surface created by laser cleaning.

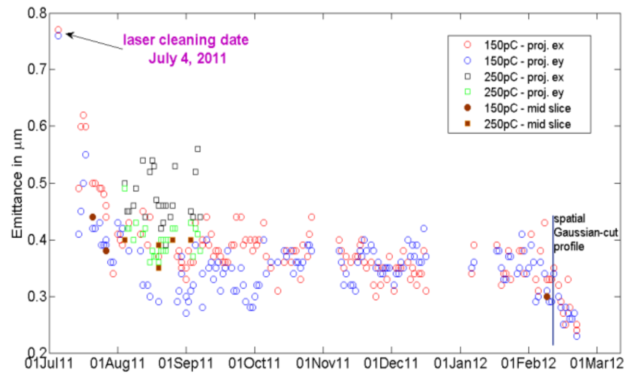

Figure 4: Emittance evolution for the spot with yellow circle: the emittance improvement after February 9, 2012 is due to use of a Gaussian-cut laser spatial profile [12].

Thermal Emittance versus QE

An S-band transverse RF cavity, located upstream of the OTR screen, is used to streak the beam vertically across the screen, in order to time-resolve the horizontal emittance. The horizontal emittance measurement is then "sliced up" into a number of bins in time (thirteen for example). The thermal emittance is taken from the core time-sliced emittance measurements at 20 pC as a function of laser spot size, assuming that space charge forces and other emittance-growth sources are negligible for this charge. Figure 5 shows a comparison of the thermal emittance for the previous copper cathode, which was never laser-cleaning processed, and the current copper cathode, processed by laser cleaning. For the previous copper cathode, the measured thermal emittance was 0.9 µm/mm-rms [13], as shown in Figure 5 (slice emittance divided by laser rms beam size). For the current cathode, processed by laser cleaning on July 4, 2011, the thermal emittance measured a week after cleaning was much worse than the normal value. This is now understood, since it appears to take 2-3 weeks for the emittance to evolve to a normal value following laser cleaning, as described in the previous section. A few measurements taken months later, for the same spot on the cathode, following laser cleaning, as shown in Figure 5, illustrate that the thermal emittance values for the current cathode with cleaning were: 1) close to the thermal emittance of the previous cathode, and 2) close to each other, despite exhibiting different QE values (up to a factor of 2), which does not agree with theoretical predictions [14]. According to the model, the "theoretical" thermal emittance is always correlated to the measured QE. However, the recent data shows thermal emittance is independent of, rather than correlated to, the measured QE. Some residual contamination that changes the QE may not modify the work function, and thereby the cathode thermal emittance. We conclude that the theoretical model does not completely describe the photoemission process.

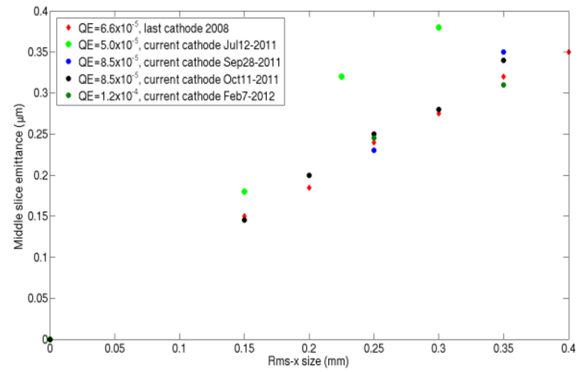

Figure 5: Thermal emittance for the previous cathode (red squares), which was never laser-cleaning processed, and the current cathode, which was processed by the laser cleaning.

CONCLUSION

QE was increased by 8-10 times upon the laser cleaning. Since laser cleaning was performed on the LCLS cathode, routine operations have shown a slow improvement of the QE and comparatively rapid improvement of the transverse emittance, with a factor-of-3 QE enhancement over five months and a significant emittance improvement over the initial 2-3 weeks following cleaning. Currently, the LCLS photocathode QE is holding constant at about 1.2×10^{-4}, with a normalized injector emittance of about 0.3 µm for a 150-pC bunch charge. Similar evolution of both QE and emittance for two cleaning areas is observed. Discussions on the QE evolution and comparison to previous studies are presented. With proper procedures, the laser cleaning technique appears to be a viable tool to revive LCLS photocathodes for x-ray FEL operation. In addition, measurements show that LCLS thermal emittances for different QE values are close to each other, which suggests that cathode surface contamination impacting QE may not modify the work function, and thereby the thermal emittance.

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