Jefferson Lab
Center for Injectors and Sources

JLAB-TN-22-013

High-voltage quantum-efficiency scans at the UITF

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April 2022

Measuring the quantum-efficiency distribution of our photoelectron guns traditionally involves manually changing the electrode voltages. Although it would be natural and convenient to perform such measurements remotely in the usual gun configuration, the variable orbit of the extracted beam poses a challenge. Interpolating the magnet settings on a grid of empirically found setups is a simple solution that works without any extra instrumentation. We describe a first attempt at exploring its feasibility and usefulness in an example implementation.

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1 Introduction

Laser-driven photoelectron guns such as those installed at CEBAF and at the UITF employ photocathodes with a certain chemical composition and surface structure designed to convert photons into free electrons. The constant of proportionality between the two, η, is called *quantum efficiency* (QE):

$$\eta = \frac{\text{number of electrons}}{\text{number of photons}} = \frac{I}{P}\frac{hc}{e\lambda} \tag{1}$$

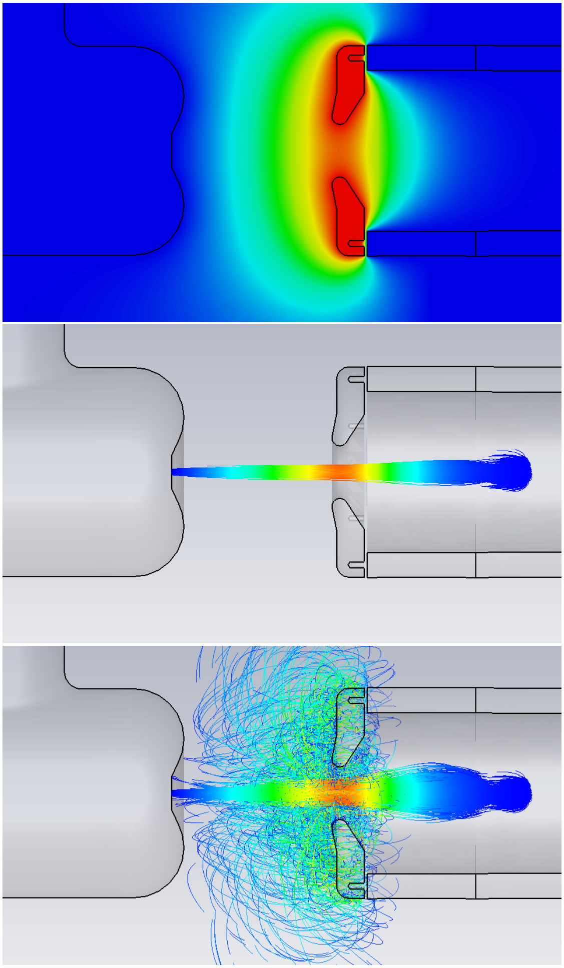
with the electron current I, the laser power P, and the laser wavelength λ. When this quantity is measured by comparing the beam current with the incident laser power, it amalgamates the intrinsic properties of the photocathode—e.g., energy bands—with extrinsic properties of the setup such as accelerating voltage, beam transmission loss (in case the current is measured on the receiving side), etc. To what extent this is harmful, or even beneficial, depends on the application, i.e., whether it is fundamental research on cathodes or accelerator operation, where one needs to know the actual current the cathode can deliver. As photocathodes are subject to various damage mechanisms reducing the QE over time[1], some of which are localized (primarily ion back-bombardment), others less so (e.g., chemical reactions with static residual gas), we benefit from a routinely applicable method to determine the QE as a function of laser spot position, called a *QE scan*.

[1] R. R. Mammei et al. "Charge lifetime measurements at high average current using a K_2CsSb photocathode inside a dc high voltage photogun." In: *Phys. Rev. ST Accel. Beams* 16 (3 Mar. 2013), p. 033401. DOI: `10.1103/PhysRevSTAB.16.033401`, J. Grames et al. "Charge and fluence lifetime measurements of a dc high voltage GaAs photogun at high average current." In: *Phys. Rev. ST Accel. Beams* 14 (4 Apr. 2011), p. 043501. DOI: `10.1103/PhysRevSTAB.14.043501`

Traditionally, QE scans are performed with the cathode grounded and the anode biased positively; this way, the "beam" is collected on the anode instead of being transmitted into the beam line, so one does not have to account for a spot-position-dependent orbit. While conceptually simple, this method comes with certain caveats:

- Our high-voltage supplies cannot ground the output, so the process involves opening the valve to the preparation chamber and mechanically moving the cathode transfer manipulator into the gun to ground the cathode by touching the puck from behind. Moreover, the anode cable needs to be unplugged to supply the bias through a battery, though this is an implementation issue, not a fundamental one. All these steps take time and effort, require an access of the injector enclosure, and introduce wear and potential for human error.

- While the collection efficiency of the anode is generally assumed to be less than 1, it may also be a function of spot position, distorting the QE map in addition to dividing it by a calibratable factor. Simulating the collection efficiency is not trivial: the very-low-energy particles are sensitive to small external fields, and secondary emission, potentially to high order, plays a significant role. The focusing action of the anode leads to very complicated electron trajectories, even for the primary particles, involving multiple reflections at potential barriers on both sides of the anode, see Figure 1.



← Figure 1: CST simulation of the potential distribution and particle trajectories with the cathode grounded and the anode biased to 250 V (cut-plane view). The color scale corresponds to electric potential (top) or particle energy (middle and bottom), respectively. Secondary emission is turned on. The trajectories are shown at $t = 100\,\text{ns}$ (middle) and $t = 150\,\text{ns}$ (bottom). Even neglecting external fields and other potential effects such as ionization, this situation is too complicated to model correctly, so the collection efficiency is hard to predict.

- The effective QE of GaAs cathodes is voltage-dependent due to the external field counteracting the surface barrier (similar to the Schottky effect), and it is also current-dependent due to surface photovoltage[2]. Deplorably, both effects depend on the NEA value, which may be position-dependent.

The last two points are not trivial to disentangle, suggesting a scan at low voltage may not tell the full story.

[2] G. Mulhollan et al. "Photovoltage effects in photoemission from thin GaAs layers." In: *Physics Letters A* 282.4 (2001), pp. 309–318. DOI: 10.1016/S0375-9601(01)00202-X, S. Friederich, K. Aulenbacher, and C. Matejcek. "Vacuum lifetime and surface charge limit investigations concerning high intensity spin-polarized photoinjectors." In: *Journal of Physics: Conference Series* 1350.1 (Nov. 2019), p. 012045. DOI: 10.1088/1742-6596/1350/1/012045

2 High-voltage QE scans

As the very purpose of electron guns is to deliver a beam through their anode aperture, it seems counterintuitive having to radically change the electrode potentials just to be able to measure the current while scanning the laser spot. However, the problem with operating the gun in its usual configuration is that the orbit of the extracted beam is heavily dependent on its origin, i.e., the laser spot position[3], so the beam will generally end up being lost in unpredictable ways instead of being collected by a cup. Clearly, even if we found a way to measure the cathode current (rather than the extracted beam current) accurately enough, dumping beam on random surfaces close to the gun is not the most productive of ideas. To make QE scans work in gun mode, we therefore need a way to make the orbit reasonably independent of the laser spot position.

[3] This dependency is not a design deficiency of our guns and cannot be removed. Even if, hypothetically, the cathode-anode field had perfect radial symmetry and, unlike the current guns, were designed not to be radially focusing, the orbit would still be displaced, albeit not tilted.

Given a sufficient number of BPMs and correctors, especially between the gun and the first lens, intuition suggests one should be able to devise a piece of code that will automatically steer to an identical orbit for any spot position; in fact, the Injector Steering Script at CEBAF is designed to do just that. While this particular implementation of the steering script can only carry out single spot moves, it should not be hard to programmatically map out the (x, y) space and save the resulting magnet settings as a look-up table.

At the UITF, where the desire for gun-mode QE scans recently arose, there is only one corrector between the gun and the first lens, making it impossible to fully compensate for both tilt and displacement of the orbit at the same time. Moreover, the only BPM upstream of the first cup is located after the first lens and even after the 15° bend. A purely programmatic solution to the problem therefore cannot be found. However, for any given laser spot position, one can empirically find magnet settings that will transmit the beam into the first cup without any loss. Centering in all lenses (of which there are three on the way to the first cup, see Figure 2) provides a methodical way to do this: even though accurate focusing without emittance degradation is not crucial, each lens to center in acts as a BPM of sorts and thereby adds enough optimization criteria to make the problem well-defined.

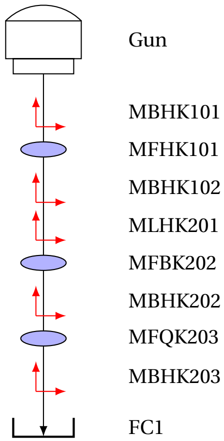
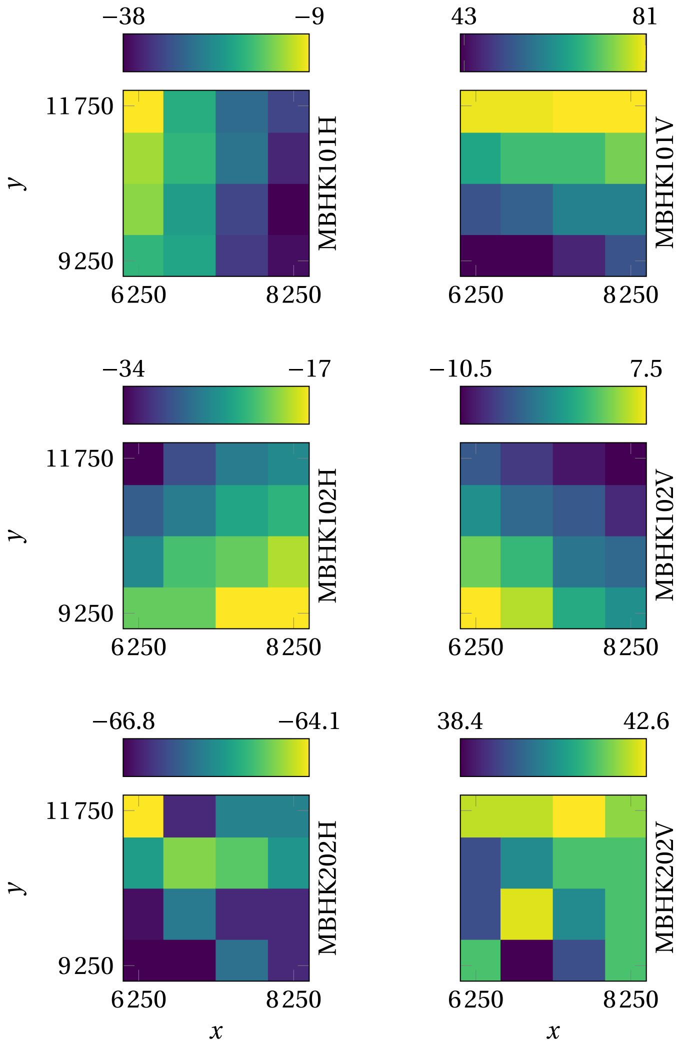


Figure 2: UITF beam line components relevant to this study. Each lens is followed by a viewscreen, allowing one to center the beam in the respective lens by optimizing for minimum centroid motion in response to a change in focal length. More details in the UITF Quick Reference Drawing, version 14: `https://wiki.jlab.org/ciswiki/images/9/9c/UITF_quick_reference_rev.14.pdf`

While it would be prohibitively tedious to perform an empirical setup for each grid point of a QE scan, it makes sense to assume that the response to a laser spot move is linear enough to be approximated through interpolation given a suitable number of points. Figure 3 shows a map of magnet settings obtained in March 2022. Interpolating these maps with a two-dimensional spline enables us to set up the magnets for any laser spot position inside the area of interest. The parameters of these splines are the only information needed to perform a QE scan in gun mode. Extrapolating these maps to points further away from the center, while not inconceivable, may be of limited usefulness because the beam setup is hard to verify and points of very low QE are of little practical relevance.

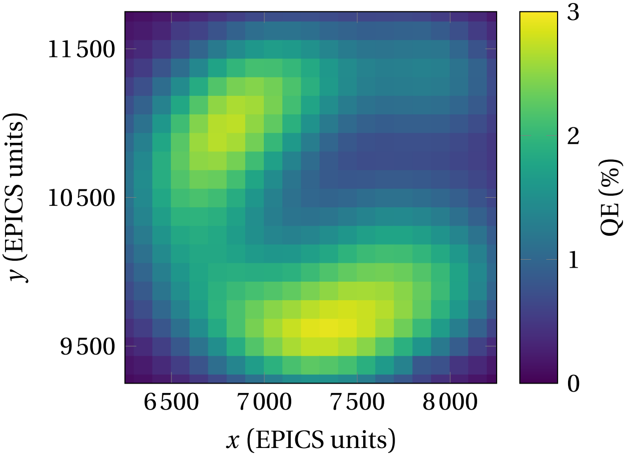


← Figure 3: Map of empirical magnet setups as a function of spot position. x and y are given in the natural units of the (x, y) stage, which roughly correspond to micrometers. The color denotes $\int B \mathrm{d}l$ in μT m. Naturally, the required corrector strengths are highest close to the gun and decrease as we go downstream. MLHK201 and MBHK203 are not shown as their values do not need to be varied.

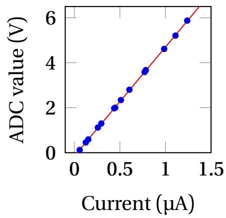
We devised a simple Python script that, given the spline parameters as an input file, will scan the laser spot over the grid covered by the splines with some granularity (e.g., 20 × 20 points), set the magnets accordingly, and read the cup current from the respective picoamperemeter[4]. Being non-real-time code that relies on a slow control system connected to hardware with poor capabilities

[4] Cup current readout is implemented by setting the record to `Passive` with no monitor deadband, `PROC`ing it, and waiting for the asynchronous monitor signal. One would expect the current to be updated synchronously each time, but in fact we need to measure at least twice and discard the first point sometimes; I do not know why.

for asynchronous readbacks, this program needs to conservatively account for delays and is therefore slower than the traditional, low-voltage method. This is, however, not a fundamental problem and could be improved upon. Currently, the total time per data point is a conservative 3 s, so a 20 × 20 scan takes about 20 min plus some overhead. The result of such a scan is shown in Figure 4.

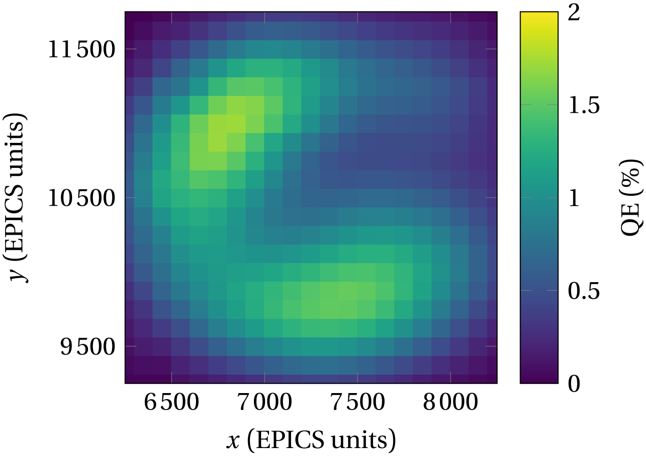


← Figure 4: Example high-voltage QE scan with 21 × 21 points. The units of the axes roughly correspond to micrometers.



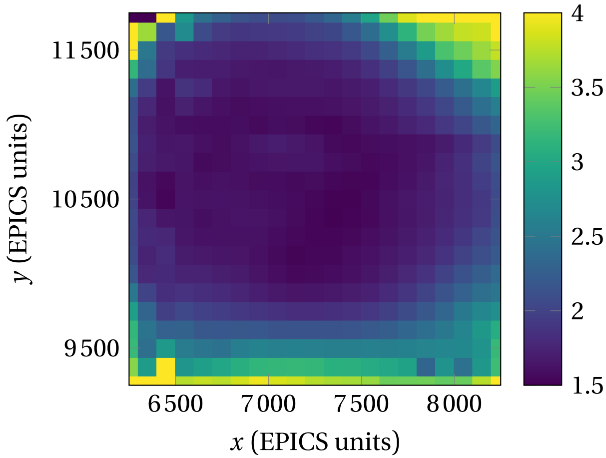
↑ Figure 5: Calibration of ADC gain and offset. The points were extracted manually from archiver traces recorded during a low-voltage QE scan. $y(x) = ax + b$ with $a = 4.85(1)\,\mathrm{V\,\mu A^{-1}}$ and $b = -0.147(8)\,\mathrm{V}$. As the ADC is unipolar and b is negative, currents below b/a, i.e., 30 nA, cannot be measured.

For comparison, a low-voltage QE scan was performed immediately afterwards; its result is shown in Figure 6. Unfortunately, apart from the physics being different, the two methods also measure the current in different ways: the QE Tool, which is used to perform the low-voltage scans, relies on an ADC connected to the voltage output of the anode picoamperemeter. Figure 5 shows the calibration function used to align the two data sets.



← Figure 6: Low-voltage scan performed using QE Tool immediately after the scan shown in Figure 4. The data were adjusted for the ADC calibration shown in Figure 5 and interpolated with a two-dimensional spline to match the grid coordinates used in Figure 4.

It behooves us to compare the two methods quantitatively; however, because the voltage dependency of the QE may be specific to the cathode, this comparison is unlikely to be useful for future calibration. Figure 7 shows the ratio between high-voltage and low-voltage QE as a function of grid position. We see that the ratio tends to be around 1.6 for the major part of the active area, whereas it increases sharply toward the edge of the active area.



← Figure 7: Ratio between high-voltage and low-voltage scans (Figures 4 and 6).

As a result of the interaction between the applied field and the surface barrier voltage[5], the effective QE of an NEA cathode is generally assumed to depend on the extraction voltage V as

$$\eta = a\left(1 + \sqrt{bV}\right) \tag{2}$$

with sample-dependent constants a and b. As shown in Figure 8, this dependency holds for the range of voltages we realistically have access to in high-voltage gun mode. The fit function gives a ratio of 1.58(1) between 180 kV and 0.25 kV, consistent with the observation from Figure 7. Because equation 2 only includes cathode surface effects and no specifics of where and how the beam is collected, this agreement suggests the collection efficiency of the anode may actually be close to 1 and all differences between high-voltage and low-voltage QE are caused by the difference in extraction field strength. This makes sense from an eletrostatic point of view, seeing as all other surfaces are negatively biased with respect to the anode and therefore should be unable to collect the charge.

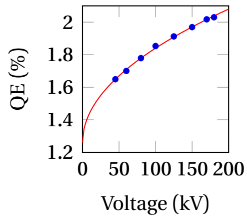


Figure 8: Measured voltage dependence of extracted current at (6800, 10 100), laser power about 0.8 mW. $y(x) = a(1 + \sqrt{bx})$ with $a = 1.26(1)\,\%$ and $b = 0.0021(1)\,\%\,\mathrm{kV}^{-1}$. See https://logbooks.jlab.org/entry/3991005.

[5] G. Mulhollan et al. "Photovoltage effects in photoemission from thin GaAs layers." In: *Physics Letters A* 282.4 (2001), pp. 309–318. DOI: 10.1016/S0375-9601(01)00202-X

3 Caveats and Outlook

Ideally, one could activate a calibration cathode with a large active area to determine a map of magnet settings for the whole parameter space, which should be a property of the beam line only and not depend on the cathode; however, our limited experience suggests that the beam orbit is not reproducible between cathode activations for reasons that may have to do with the puck transfer process, the shape of the active area, or something else entirely. Magnetic hysteresis of the beam line[6] may also contribute to reproducibility issues. Until this is fully understood, the calibration measurement must be repeated following a puck transfer, which limits the applicability of the method. On the other hand, recording an orbit calibration map after a puck transfer may well be worth it if one wants to perform a large number of QE scans between activations.

[6] M. Bruker. *2I field sleuthing*. Feb. 2022. URL: `https://logbooks.jlab.org/entry/3985810`

To reduce noise in either method (low- or high-voltage scan), it is advisable to keep the laser power from fluctuating during the scan by setting up a feedback loop from the laser power pickoff to the attenuator. Assuming the divider ratio of the pickoff remains constant over the course of the scan, the impact of any remaining fluctuations on the measured QE is mitigated by recording the pickoff value for each data point. It should, however, be noted that the high-voltage method potentially has a better signal-to-noise ratio than the low-voltage method because one can choose a higher laser power and beam current (within reasonable limits due to the vacuum load emitted by the cup). This comes with the side benefit of allowing us to compare QE maps at very different currents[7], potentially allowing insight into the impact of ion damage on the surface-charge limit.

[7] M. Bruker. *High-current QE scan*. Apr. 2022. URL: `https://logbooks.jlab.org/entry/3990865`

The spatial resolution of both methods is the same as it is limited by the fact that the measured QE distribution is a convolution of the true distribution with the Gaussian laser spot profile, which is not negligible compared to the active area of the cathode and therefore masks any tiny features of the true QE distribution. In theory, the true distribution could be computed through deconvolution provided that the laser profile be known, but the sizes compare so unfavorably that it would need to be known with unrealistic accuracy (shape error at the sub-percent level) in order for deconvolution to be viable in practice, especially given that noise in the data cannot be completely avoided.