Status of the R&D Program at the Gun Test Facility

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1. Introduction.

The Gun Test Facility (GTF) consists of a 1.6-cell S-band photocathode gun and a single
SLAC 3-m accelerating structure (booster) followed by a beam dump. The beam
components are housed in the SPEAR synchrotron injector vault in Building 140. Outside
the vault are the two XK5 klystrons/modulators that provide the rf power, and the laser
shack and control area. The laser shack contains a high-power low repetition rate
Nd:glass laser system used to produce photoelectrons from the copper cathode of the gun.
Using an earlier (borrowed) version of the laser system, first beams were produced in
1997. Completion of installation and commissioning took place in 1998, and the first
experimental results were obtained [1,2]. In 1999, the laser system was completely
replaced with a SLAC-owned, nearly duplicate, system [3].

The purpose of the GTF from the start was to demonstrate and characterize the high-
brightness beam required for the LCLS. The nominal LCLS beam at the booster exit is 1
nC of charge, 100 A, with an energy spread of $\leq 0.2\%$ and a normalized rms emittance of
1×10^{-6} m [4]. To achieve this emittance, the nominal plan is to use a charge distribution at
the cathode that is spatially and temporally uniform, with 2-mm and 10-ps FWHM
diameter and length respectively. The current LCLS R&D program was funded beginning
in mid-FY99. From the start it was determined by the LCLS Project leaders that the GTF
was the appropriate facility for conducting the injector R&D.

This technical note is a review of the current status of R&D program at the GTF with
emphasis on experimental results as of early April 2001. The data for the cathode
quantum efficiency (QE) profile, the emittance for various values of charge, a typical
quadrupole emittance scan and corresponding laser spatial profile, and information about

[1] J.F. Schmerge et al., "Photocathode rf gun emittance measurements using variable length laser pulses,"
SPIE 3614 (1999) 22.
[2] D.A. Reis, "Emittance Measurements from a Laser Driven Electron Injector," Ph.D dissertation,. U. of
Rochester (1999).
[3] The status and plans for the present laser system are the subject of a forthcoming Glass-Laser Task
Force report by P. Bolton, D. Dowell and J. Frisch.
[4] LCLS Design Study Report, SLAC-R-521 (Rev. Dec. 1998). The integrated energy spread requirement
has been upgraded to $\leq 0.1\%$ (see draft CDR).

the solenoid B_r measurement will be discussed. For this report, all of the data were obtained with laser spatial and temporal profiles that were approximately uniform and Gaussian respectively.
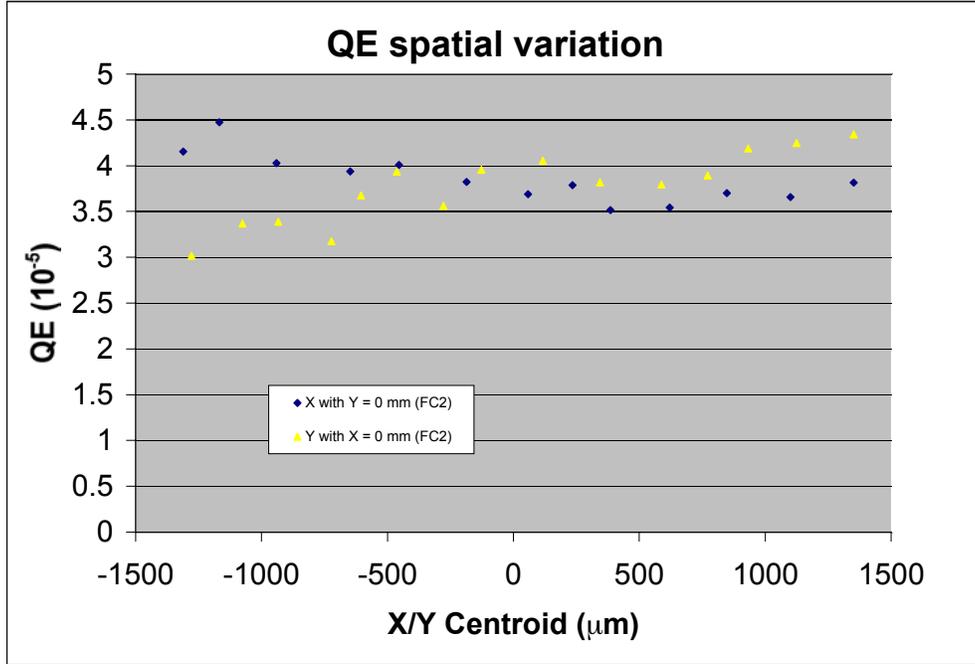

Figure 1. Quantum efficiency of the Cu cathode as a function of spatial variation.

2. Cathode QE Profile.

The spatial variaion of the QE of the cathode is shown in Fig. 1. For these measurements, the glass laser is focused to a spot diameter of approximately 100 μm, and the intensity appropriately reduced to avoid the explosive emission mode [5]. The present cathode is fabricated from single-crystal Cu_{100} [6]. The cathode plug, which is about 1 cm in diameter, is brazed into the center of the back plane of the cathode cell. The braze material does not quite fill about 30° of the weld circumference. The QE of this cathode at 70 MV/m (peak field 110 MV/m, extraction phase 40°) is about 5×10^{-5} and has been fairly stable with time. The dark current has been extremely low since this cathode was first installed in the fall of 2000. The early current was on the order of 0.7 nC per rf pulse at 120 MV/m peak field at the cathode, decreasing by 2 orders of magnitude as the field

[5] X.-J. Wang, J. Appl. Phys. 72 (1992) 888.
[6] D.T. Palmer, S. Anderson and J.B. Rosenzweig, "Single Crystal Cooper Photo-Cathode in the BNL/SLAC/UCLA 1.6 Cell RF Gun," in J. Rosenzweig and L. Serafini, eds., The Physics of High Brightness Beams, World Scientific (2000), p. 439.

was reduced to 105 MV/m. Recently the dark current increased by about 50%. This increase may be related to several small potential emitter sites outside the central couple millimeters that can be observed with a HeNe laser. To first order the QE distribution is uniform. More precise measurements are planned for the near future.
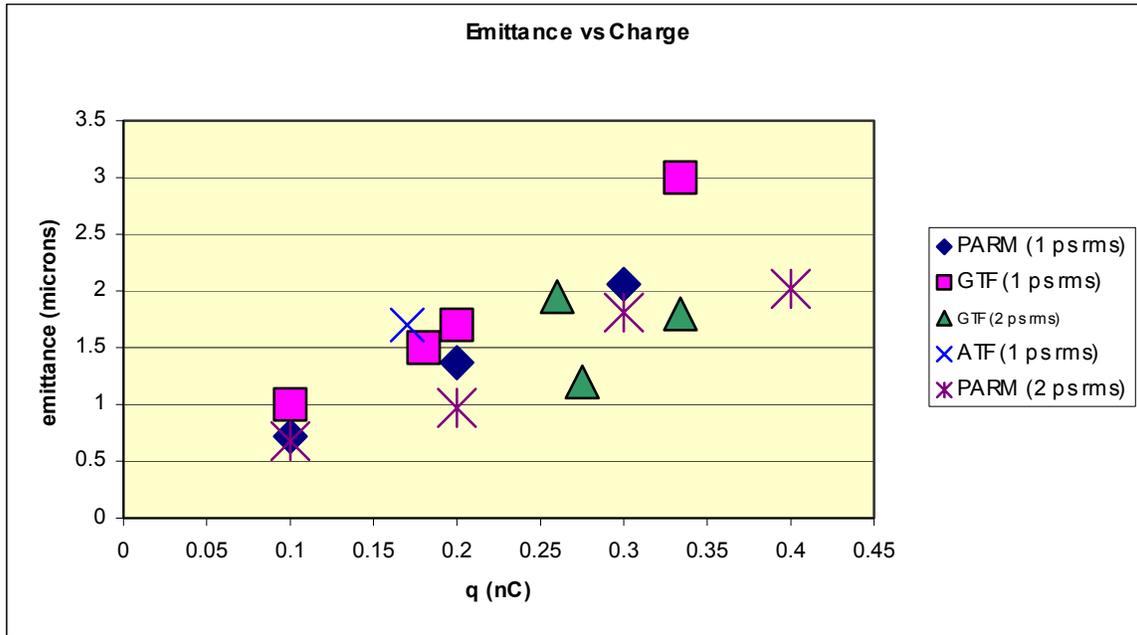
Emittance vs Charge

Figure 2. Normalilzed rms emittance measured as a function of charge for various bunch lengths.

3. Emittance Data.

The emittance results of the past few months are shown in Fig. 2 as a function of charge. For the "optimistic data" analysis used here, about 5-10% of the charge outside the core of the beam profile is excluded. The corresponding PARMELA simulations are also shown. These simulations are currently being revised; the results shown here should not be considered final within 20%. Within the error bars the measured 1-ps data are in pretty good agreement with the simulation results. This data was taken with a peak field of 110 MV/m. The beam was extracted from the cathode at about 40° rf phase with respect to the zero crossing. The charge was varied by changing the laser intensity while keeping the laser spatial and temporal profiles constant. Note that if the field would be increased to the CDR value of 120 MV/m, one would expect the emittance to decrease by 15-20% [7].

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[7] D.T. Palmer, "The Next Generation Photoinjector," Ph.D dissertation, Stanford U. (1998), p. 41.

The data in Fig. 2 for a 2-ps beam is somewhat inconsistent or at least one data point is an error. Still, the measured results are somewhat comparable with simulations

The recently measured emittance value from the VISA experiment at the Accelerator Test Facility (ATF) at BNL is also shown in Fig. 2. The ATF field was somewhere in the range of 100-110 MV/m. At the cathode, the beam radius was 1-mm hard edge and the rms length was about 10 ps, but the injector was operated in compression mode so that out of the booster the rms length was about 1 ps. To calculate the emittance, all data points with intensity <10% of the peak value were excluded [8]. With these differences in mind, the ATF data point is roughly consistent with the GTF results.

These recent emittance results at the GTF are vastly better than in the past. The principal reason for this progress has been a significant improvement in the spatial uniformity of the laser beam. Still more work in this direction is needed.
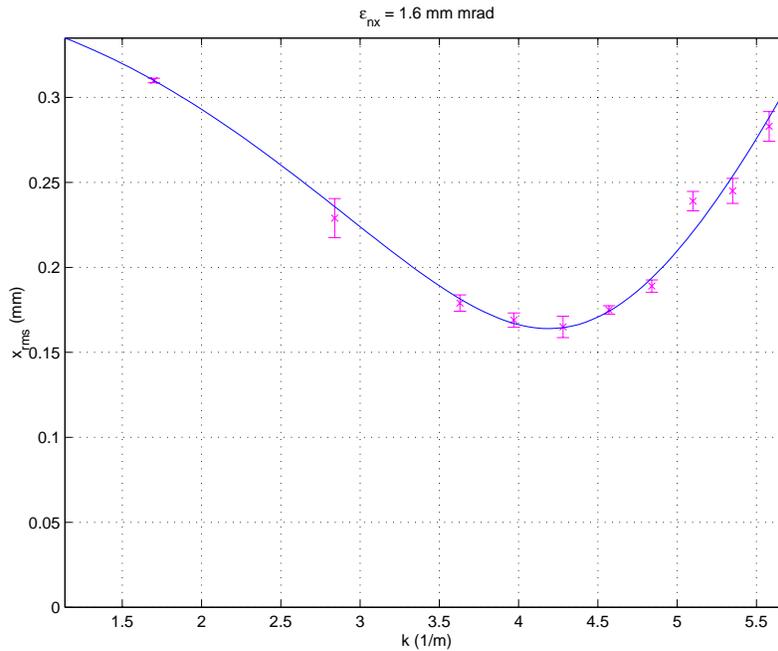

Figure 3. A typical quadrupole scan. The scan shown here corresponds to the 2 ps data in Fig. 2 for 0.275 nC.

4. Quadrupole Scan.

An example of a quadrupole scan is shown in Fig. 3. This scan corresponds to the lowest of the 2-ps data points shown in Fig. 2. The data in the scan looks fairly smooth. The error bars, which relate to repeated measurements of the spot size on the profile monitor, are narrow.

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[8] X.-J. Wang, private communication.

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The beam profiles during the quadrupole scan as measured on the YAG screen (Profile Monitor #5) used for the emittance measurements are shown in Fig. 4. The three profiles (left to right) represent the low to high values of k in Fig. 3, with the middle profile corresponding to the minimum value of x_{rms}. The beam spatial profile is seen to have an oval shape. The principal axis for a given k-value is rotated with respect to its orientation for other values. Although here the ellipse at the tightest focus is nearly upright, this is not always the case for scans at other charge values.
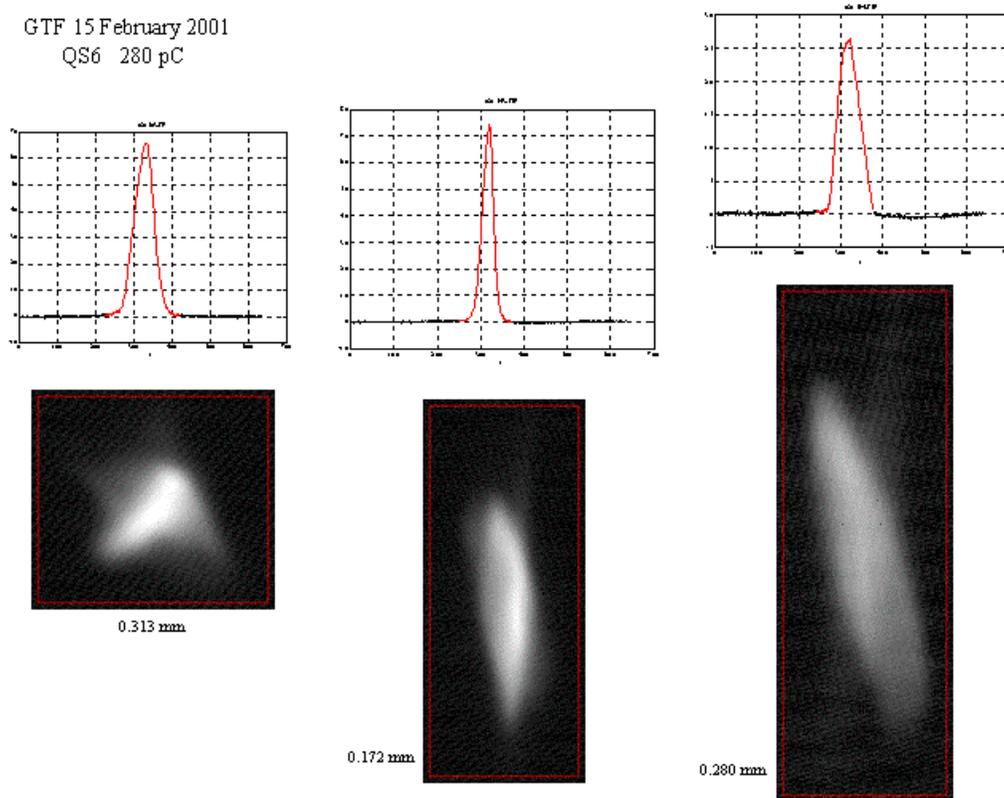

Figure 4. YAG screen profiles for the lowest, middle (minimum x_{rms}), and highest k values in Fig. 3.

Lineouts for the laser beam spatial profile on the same day as the quadrupole scan in Fig. 3 are shown in Fig. 5.

The beam profiles and other observations point to a quadrupole factor coming from the emittance-compensating solenoid that surrounds the gun or possibly from the gun rf field. But in fact any elliptical pulse shape coming from the cathode, whether it is due to the cathode QE or from the laser, will produce this kind of effect. For each tilted axis there is another shadow, roughly orthogonal, axis. This may simply be the result of the energy spread in the beam; i.e., the two axes may represent the parts of the beam that have or have not gone through the waist cross over.

It is not known if this solenoid is any different than the other solenoids used with 1.6-cell guns. The pancakes for this solenoid were wound by Elma Engineering in the Palo Alto.

The main issue is how the windings cross over. There are two windings in a pancake. The first winds down to the center, then crosses over and winds back out. If the cross over is done gradually, there would be less of a quadrupole effect, but if it's done over a space of a few centimeters (which is common in winding pancakes for other applications) the effect would be maximized. The measured focal length of the solenoid is 10-25 m for the excitation currents of about 160 A. Initial analytical calculations of the focal length based on an assumed short winding cross-over in the pancakes predict focal lengths of 10 - 20 m. More refined calculations are in progress.
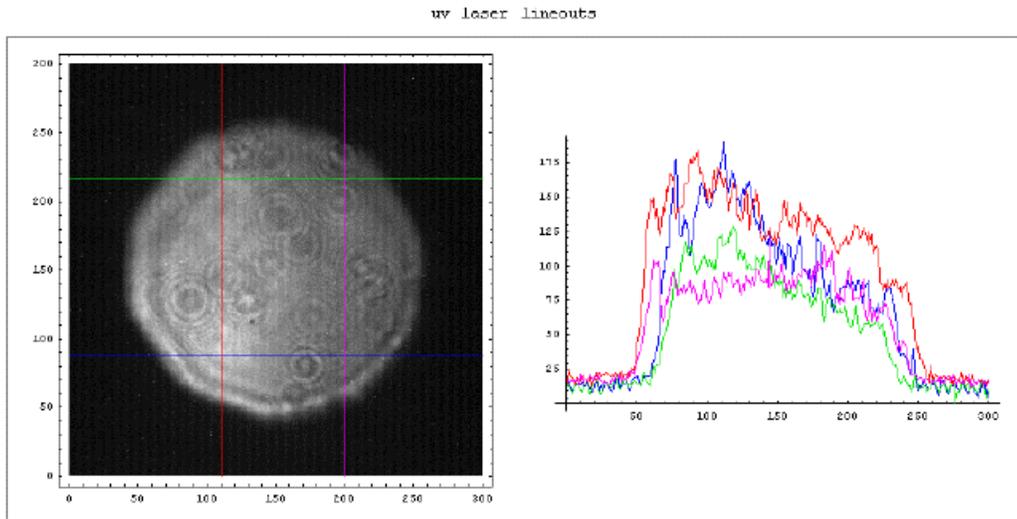

Figure 5. Laser beam line-profiles at the virtual cathode. There are 4 profiles on the right corresponding to the color coded lines through the cathode shown on the left. The cathode axes and the abscissa for the profiles are in pixels (9 μm per pixel). The ordinate for the profiles is in arbitrary units.

5. Solenoid Field Asymmetries.

E. Colby suggested a measurement of B_r as a function of azimuthal angle at the exit of the solenoid. The resulting data is shown in Fig. 6. A Hall probe on a controlled mount was placed between the downstream iron end-plate of the solenoid and the vacuum chamber and rotated azimuthally. It was found that there is a perturbation in the field at 270°. The original magnetic measurements data also shows such a perturbation at the downstream edge. This perturbation is consistent with a quadrupole term having a focal length of about 25 m.

6. Conclusion.

Despite the presence of a small quadrupole component, the GTF data now appears to be within the "ball park" of what is expected for the LCLS. Emittance measurements with a uniform temporal distribution are in progress. Plans for modifying the laser system to allow generation of 1-nC beams are underway.
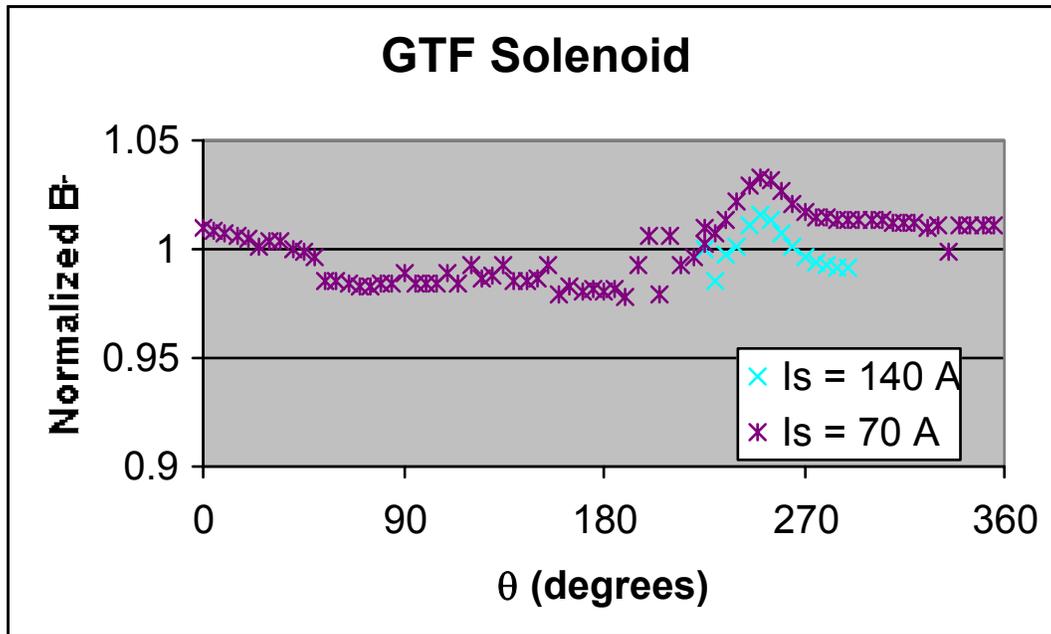

Figure 6. B_r at the downstream end of the solenoid measured as a function of the azimuthal angle using a Hall probeplaced between the end plate and the beam line vacuum chamber.