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Transverse Emittance Measurements from a Photocathode RF Gun with Variable Laser Pulse Length*

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Abstract

The Gun Test Facility (GTF) at SSRL was started in 1996 to develop an appropriate injector for the proposed Linac Coherent Light Source (LCLS) at SLAC. The LCLS design requires the injector to produce a beam with at least 1 nC of charge in a 10 ps or shorter pulse with no greater than 1 π mm-mrad normalized rms emittance. The photoinjector at the GTF is 1.6 cell S-band symmetrized gun and emittance compensation solenoid. Emittance measurements, reported here, were made as function of laser pulse width using Gaussian longitudinal pulses. The lowest achieved emittance to date with 1 nC of charge is 5.6 π mm-mrad and was obtained with a pulse width of 5 ps (FWHM) and is in agreement with simulation. There are indications that the accelerator settings for these results may not have been optimal. Simulations also indicate that a normalized emittance meeting the LCLS requirement can be obtained using appropriately shaped transverse and temporal laser/electron beam pulses. Work has begun on producing temporal flat top laser pulses which combined with transverse clipping of the laser is expected to lower the emittance to approximately 1 π mm-mrad for 1 nC with optimal accelerator settings.

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1 Introduction and Motivation

The proposed Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center (SLAC) is a single pass, self-amplified spontaneous emission, free-electron laser (FEL) utilizing the last third of the 3 km SLAC linac [1] and operating at a wavelength of 1.5 Å. A critical component of the LCLS is a high brightness electron source. The source must be able to produce a 1 nC beam with ≤ 1 π mm-mrad normalized rms transverse emittance and 10 ps pulse length so that the FEL can saturate in a 100 m long wiggler (assuming the pulse is compressed to 70 fs rms and the emittance grows in the linac and bunch compressors to 1.5 π mm-mrad at the wiggler entrance).

The Gun Test Facility (GTF) was constructed to develop an appropriate injector for the LCLS and is located in the Stanford Synchrotron Radiation Lab (SSRL) injector vault. The GTF consists of a photo-cathode drive laser, rf power stations, 3 m SLAC linac section, rf gun and emittance compensating solenoid as well as electron beam diagnostics to characterize the beam [2]. The first gun being characterized at the GTF is the result of a collaboration between Brookhaven National Laboratory (BNL), SLAC and the University of California at Los Angeles. The prototype 1.6 cell gun and emittance compensation solenoid was characterized at BNL [3]. Emittance measurements reported here are made as a function of laser pulse length. The GTF expects to produce lower emittance beams by controlling the laser (and thus the electron beam) pulse length and shape.

2 Drive Laser

The photocathode drive laser is a chirped-pulse amplification based Nd:glass system. The oscillator is a passively mode-locked diode pumped glass laser capable of generating <200 fs transform limited pulses [4]. The repetition rate of the oscillator is set by the cavity length and is roughly 119 MHz, the 24th subharmonic of the accelerating rf. Low timing jitter (<3 ps rms) has been achieved by using a slow photo-diode (<150 MHz) to sample the pulse train from the laser oscillator and frequency multiplying the signal in a phase-locked multiplier to generate the 2856 MHz master rf.

The pulse train from the oscillator is chirped to ~300 ps/nm in a grating pair expander, and then a single pulse is selected out at 1.25 or 2.5 Hz for amplification in a Nd:glass regenerative amplifier. The ~2 mJ, 1054 nm pulse is then compressed to as short as 1.1 ps (FWHM) using a grating pair with the opposite chirp of the expander. The pulse is frequency doubled and quadrupled in a 10 mm KD*P and 5 mm BBO crystals respectively to generate 200-300 μJ of 263 nm light. The data reported here was obtained with variable Gaussian temporal pulse widths by adjusting the chirp in the optical compressor. Pulses as short as 4.6 ps (FWHM) in the UV have been measured using a sub-picosecond resolution streak camera [5] and include ~1 ps spatial chirp across the beam. Figure 1. shows a typical measurement of the 3 UV pulse widths used in the experiments. The UV pulse is typically imaged onto the cathode at near normal incidence using an 8 m 1:1 telescope. Grazing incidence is also possible and was used for the cleaning of the cathode. Transverse shaping can be accomplished by imaging an aperture, after the quadrupling crystal, onto the cathode.

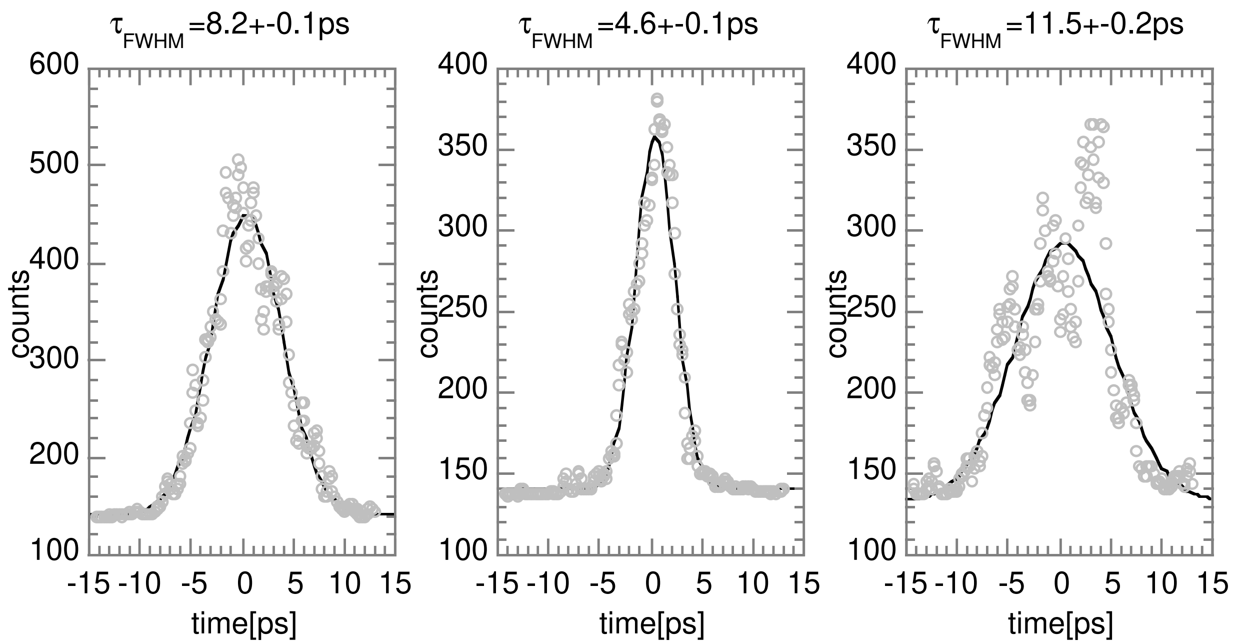

Figure 1: Streak camera output of 3 different UV pulses with Gaussian fits. The different pulses lengths are obtained by varying the chirp in the compression stage.

3 Timing Jitter Measurements

Typical measurements of the timing jitter at the GTF were conducted using a double balanced mixer as a phase bridge to measure shot to shot variations in the phase of different rf signals relative to the 2856 MHz master clock derived from the laser. It was found that the total jitter between the rf gun and this master clock was about 0.5 ps rms over a few minutes with negligible contributions from the klystron and its drive. It is believed that this jitter comes from a shot to shot change in the difference between the drive frequency and the gun resonance and could be produced from either $\sim$100 Hz noise in the laser oscillator or $\sim$0.1 °C change in the gun temperature.

The jitter between the 2856 MHz master clock and the 119 MHz from the laser was measured with a fast sampling scope and found to be stable to $<$2 ps rms where the upper limit is set by the trigger jitter of the scope. The amplified laser pulse was found to be stable to $<$2 ps rms by phase comparing the bandpass filtered output of a photodiode to the 119 MHz again using a double balanced mixer. While no direct measurement of the jitter in arrival time of the laser at the cathode have been made, we can estimate the jitter to be $<$3 ps rms (assuming the above measurements are uncorrelated). However, the long term drift between the laser and the gun can be on the order of tens of ps in the course of a day. In principle this could be eliminated with a slow feedback system on the laser cavity length, the gun temperature, or on the laser injection phase.

4 Electron Beam Measurements

Because of the low quantum efficiency ($\sim 5 \cdot 10^{-6}$ electron/photon) and large scale (∼100%) non-uniformity of our copper cathode, we elected to clean the cathode *in-situ*. A relatively high intensity ($\sim 2 \cdot 10^{9}$ W/cm^2) laser pulse was incident on the cathode in the presence of ∼100 MV/m electric field after attempts to clean the cathode without the presence rf power failed. During the cleaning process ∼1 μC of charge is extracted from the cathode in ∼50 ns depleting the stored energy in the gun. The enhanced emission during this process appears to be the same as previously reported [6] and was achieved by focusing the laser onto the cathode at grazing incidence to roughly 1 x 1/3 mm^2. The cathode was "cleaned" by continuously scanning the laser across an area of roughly 5 x 3 mm^2 along the short axis of the laser at a rate of 22 shots/mm while maintaining the enhanced emission throughout each pass and with an overlap of 1/3 mm between passes. The cleaning resulted in a larger quantum efficiency (typically $2\text{–}3 \cdot 10^{-5}$ at our normal operating conditions) and a more uniform cathode (large scale). However, the dark current (field emission) from the cathode also increased by roughly an order of magnitude. The cleaning process has qualitatively been seen as a micro-roughening of the cathode surface and may explain the increase in dark current by creating areas of increased localized field. It is believed that the increase in the quantum efficiency may be from removal of copper oxide from the cathode surface in addition to the localized field enhancement.

The electron yield/photon was measured as a function of the laser phase (Schottky scan) on a Faraday cup just after the emittance compensation solenoid. Assuming a 100% collection efficiency this is equivalent to the quantum efficiency. A typical scan is shown in figure 2. The data was obtained at a single solenoid setting for phases below 100°, but due to a significantly decreased energy and increased energy spread, the solenoid had to be varied for phases above 100° to optimize charge collection on the Faraday cup. The scan is used to determine the operating phase by observing where emission first takes place. Due to the finite duration of the laser pulse, the error in determining this phase is on the order of the pulse duration. For the emittance scans, the zero phase was taken to be a few degrees into emission. The Schottky scan can also be used in determining the thermal emittance of the electron beam. Following the formalization given in [7] we can estimate the thermal emittance to be $\sim 0.2\ \pi$ mm-mrad (from the data presented in figure 2. and assuming a 1 mm radius spot at the cathode). Because of uncertainties in the charge collection, only data taken at the constant solenoid fields are used in the calculation.

The horizontal emittance of the electron beam was measured using the standard quadrupole scan technique. While measurements were made at peak currents of up to 200 A at an energy of 35 MeV, simulations using the envelope equation with space charge [8] have indicated no appreciable increase in the calculated emittance. The screen material used was SLAC chromate [9]. The image was acquired with an 8-bit CCD Pulnix camera and DataTranslation frame grabber both synchronized to the electron beam. The beam was focused to the smallest possible spot and an image was acquired. The image was examined for saturation of the camera which was controlled by using a set of crossed polarizers between the lens and the camera. This allowed intensity control without changing the depth of field

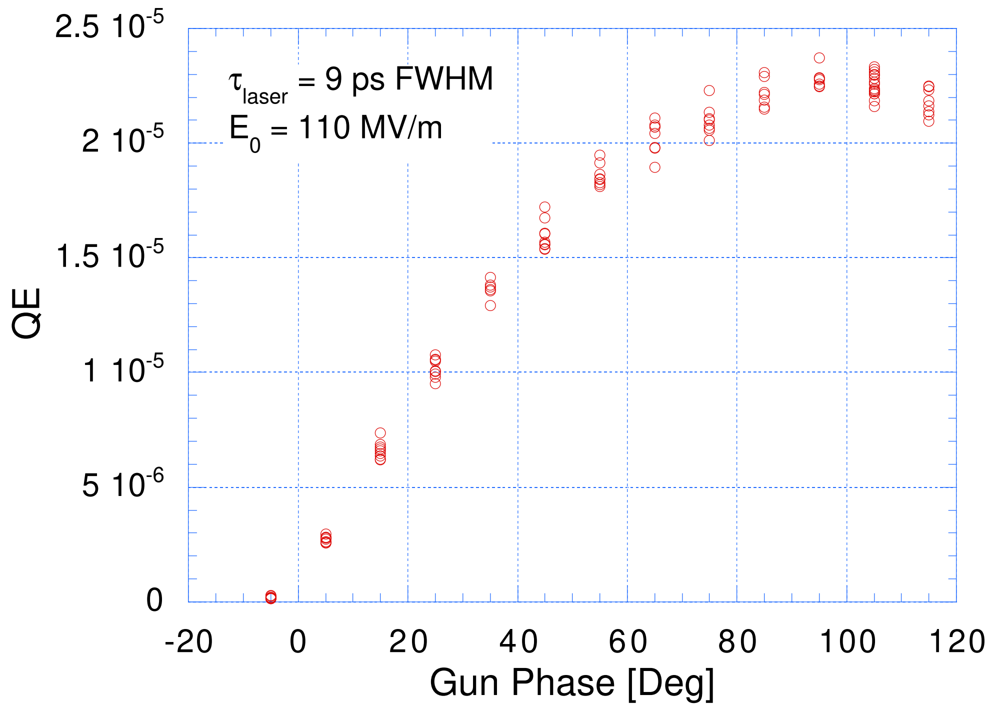

Figure 2: A typical schottky scan from which the laser phase relative to the gun and the thermal emittance can be estimated. The quantum efficiency is determined from the charge measured on the Faraday cup (with the average dark-current background subtracted) and is normalized to the number of laser photons.

of the system. The lens used was a microscope objective with an adjustable zoom. A set of 127 μm diameter wires on the screen were used for calibration purposes. The lens was set to give a calibration of 8 μm per pixel to allow a compromise between capturing the full variation of the beam size and maximizing the resolution of smallest spot size. Once it was determined that the scan would be free of saturation, the quadrupole was standardized. Five images of the beam and a background shot (taken with the rf on, but the laser off) were taken at each quadrupole setting. The following signals were logged for each shot: the field probe in the full cell of the gun, a Joule meter sampling the laser energy incident on the cathode, the phases of the laser and the linac, a toroid upstream of the screen, and the image of the electron beam. Quad scans were performed at various solenoid settings to try to find the magnetic field which produced the best emittance compensation [10] for a given set of running conditions. The background subtracted images of the beam were analyzed off line and the rms widths of the beam profiles were found using the peak in the distribution as the center.

Emittance measurements were made with 1 nC of charge using a transverse Gaussian pulse with sigmas of 1.3 and 0.8 mm for x and y respectively, at a laser phase of 50° and at 35 MeV. Lengthening the laser pulse from 5 ps (FWHM) to 9 ps (FWHM) reduced the emittance from 8.3$\pm$0.7 π mm-mrad at a solenoid field of 2.2 kG to 6.4$\pm$0.7 π mm-mrad at a solenoid field of 2.0 kG respectively as shown in figure 3. This is believed to be due to the reduction of space charge forces by lengthening the electron bunch. Measurements were also made with a laser pulse length of 11 ps (FWHM) using a transverse Gaussian pulse with sigmas of 1.3 and 0.8 mm for x and y respectively, at a laser phase of 50° and at 35 MeV which produced 6.6$\pm$0.2 π mm-mrad at a solenoid field of 2.0 kG. However, only 0.7 nC of charge was available, so this data was not included in figure 3. Conversely, for a lower charge of 0.4 nC with a transversely clipped beam (1 sigma) the 5 ps laser pulse produced an emittance of 6.3$\pm$0.4 π mm-mrad at a solenoid field of 2.0 kG while the 9 ps bunch produced 8.6$\pm$0.4 π mm-mrad at a solenoid field of 1.9 kG both at 35 MeV. These measurements were only performed once and will be repeated during the next experimental run. However, individual quad scans which were repeated were consistent within the uncertainty of the measurement process.

The operating parameters for the data reported here were not optimum from theoretical considerations but were considered necessary from an operational point of view. Optimal emittance compensation is anticipated for fields around 140 MV/m [11]. However, the field in the gun was limited to 110 MV/m to avoid occasional arcs which tripped off the rf system. The laser phase which produces the maximum charge emitted from the gun (see figure 2) is not at the same phase which produces a bunch with the maximum energy (for fixed field level in the gun and laser power on the cathode). Since we were interested in producing a high charge, in most cases the laser phase was chosen closer to the peak in the Schottky scan than is ideal. Future measurements of the effect of laser phase on emittance are planned. PARMELA [12] simulations indicate that, for the present distance between the gun and linac, more efficient emittance compensation is achieved for a lower linac gradient yielding a final beam energy of 26 MeV. This is believed to be due to better matching of the rf focusing in the linac at the lower gradient. In fact, the lowest emittance measured for 1 nC of charge

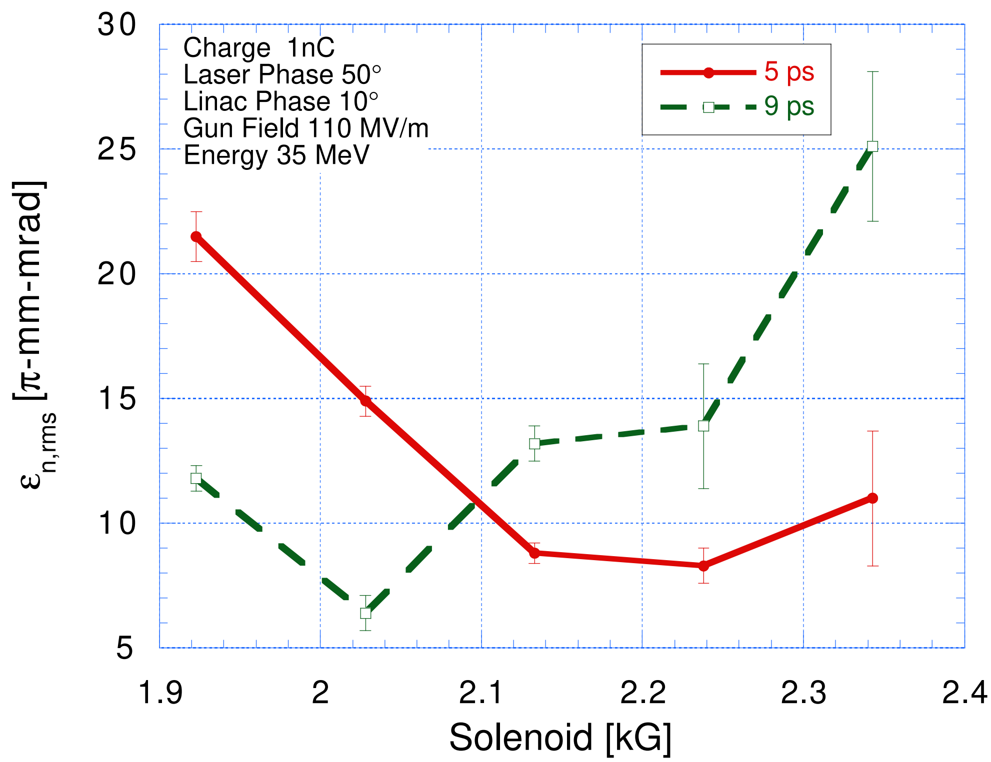

Figure 3: Emittance as a function of solenoid field with 1 nC of charge for two different laser pulse lengths. The laser phase is referenced to the zero-crossing in the cathode-cell of the gun, and the linac phase is referenced to the crest in the linac. The gun field is the maximum on axis accelerating field.

was 5.6±0.2 π mm-mrad at 26 MeV at a laser phase at 60° and solenoid field of 2.0 kG. However, it was found that for a higher gradient, the energy spread of the electron beam was smaller, which made the determination of the phase of the bunch with respect to the rf in the linac more precise and enabled greater consistency in tuning the beam. Therefore, the energy of the beam was chosen to be 35 MeV for most of the measurements despite the expected lower emittance at reduced linac gradients.

According to PARMELA simulations, altering the temporal laser profile from a Gaussian pulse shape to a flat top pulse shape will reduce the emittance to the level required by the LCLS [11]. Work is currently underway to produce temporal flat-top laser pulses by use of a Michelson interferometer based pulsed stacker (similar in design to [13]) or by the use of a mask in the Fourier plane of the optical compressor.

Acknowledgments

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