# EMITTANCE MEASUREMENTS FOR THE SLAC GUN TEST FACILITY

M. Hernandez, A. Fisher, D. Meyerhofer[a], R. Miller, D.T. Palmer, S. Park, D. Reis[a],
J. Schmerge, J. Weaver, H. Wiedemann, H. Winick, D. Yeremian
Stanford Linear Accelerator Center, PO Box 4349, MS 69, Stanford, CA 94309
[a]University of Rochester, Department of Physics and Astronomy, Rochester, NY 14627

*Abstract*

The requirement of a high brightness electron source for the proposed Linac Coherent Light Source (LCLS) project at SLAC[1] has led to the development of the Gun Test Facility (GTF). The facility consists of a photocathode RF gun, emittance compensation solenoid, a single 3-meter SLAC S-band linac section, a single XK-5 klystron, low and high energy diagnostic sections and a cathode drive laser. In this paper, the specifications of the desired electron beam will be discussed along with results of PARMELA simulations to determine the optimum laser pulse shape for minimum beam emittance. The diagnostics of the GTF will be discussed and measurements will be presented which were made at the SUNSHINE Facility at Stanford to develop the instrumentation to be used at the Gun Test Facility once it is operational. Future beam diagnostics will also be discussed.

## 1 INTRODUCTION

### *1.1 Facility*

The goal of the GTF is to produce single bunches with 1 nC of charge, 10 ps(FWHM) bunch length, and a normalized emittance of 1$\pi$mm-mr. The first photocathode RF gun to be characterized was developed by a collaboration of SLAC, BNL and UCLA[2]. The laser driven copper cathode 1.6 cell RF gun is operated in $\pi$–mode at S-band with multi-pole mode suppression achieved through cavity symmeterization. In order to obtain the smallest possible emittance the beam must be quickly accelerated in the gun to reduce space charge induced emittance growth. The desired gradient in the gun is 140 MV/m which will require 12-14 MW of rf power. Immediately following the gun is an emittance compensation solenoid which enables the correction of linear space charge emittance growth. After the solenoid there are two pop-in phosphor screens for examining the beam and a toroid for current measurements. The beam is then accelerated by a single 3-meter SLAC S-band linac section for which initially 6 MW of rf power will be available, enough to accelerate the beam to 27 MeV. Future RF upgrades this summer will allow the use of a single XK-5 klystron for the linac with approximately 16 MW of RF power which should enable energies of 45-50 MeV with the single linac section. After acceleration the emittance will be measured with the standard quadrupole scan technique utilizing a phosphor screen and a wire scanner. The three screen method will also be employed. The bunch length will be determined through the use of linac phasing and possibly a streak camera. Another toroid enables measurement of the beam current. The beam is then passed through a $60^0$ bend magnet for energy analysis using a screen and finally the beam will be dumped into a Faraday Cup.

### *1.2 Gun Drive Laser*

The laser system [3] consists of an Nd:YLF oscillator and a Nd:glass amplifier which will enable generation of near Gaussians 1 ps long laser pulses. A Nd:glass oscillator will be installed which will allow pulses down to 200 fs FWHM. Temporal pulse shaping may be done in either the time domain by stacking gaussian beamlets or frequency domain through the use of amplitude or phase masks. The system is capable of producing 200 $\mu$J of UV (263 nm) on the cathode at normal incidence. This is sufficient to produce 1 nC of charge assuming a quantum efficiency of 2 $10^{-5}$. Ports on the half cell of the gun will enable the laser to also strike the cathode at grazing incidence.

## 2 EMITTANCE COMPENSATION

The emittance compensation scheme utilizes a linear lens to remove the projected emittance growth caused by linear space charge forces [4]. Consider a section of beam line which consists of a drift, a linear lens and another drift. For a slug beam, a right circular cylinder with uniform charge density, the phase space distribution of the beam can be described by a rectangle. If the beam is allowed to drift and only linear space charge effects are considered, the phase space plot of the beam becomes a rotated fan shaped distribution with increased area. The increased area indicates an increase in the projected emittance of the beam. This is due to differing rates of expansion for the electrons in various locations in the beam. Particles which are in the middle of the beam longitudinally and on the radial outer edge of the slug experience the maximum radial space charge force while those on the radial outer edges of the beam which are at the maximum longitudinal positions experience less radial space charge force. This differing force leads to a variation in the radial velocity for electrons in the beam. If the drifting beam passes through a linear lens the phase space distribution undergoes a clockwise shear due to the lens. After the lens the beam drifts and space charge forces cause differing rates of expansion for different parts of the beam which leads to a collapse of

0-7803-4376-X/98/$10.00  

the fan shaped distribution and so a reduction of the projected phase space area of the beam.

### 3 SIMULATIONS

The GTF beam has been simulated using PARMELA with the details of the gun, solenoid and linac provided by D. T. Palmer [2]. A field map from SUPERFISH is used for the gun and a POISSON field map is utilized for the emittance compensation solenoid. The field in the gun was set at 140 MV/m and the linac was run at 7-10 MV/m. The 1 nC electron beam is simulated using 10,000 macroparticles with space charge effects included. The laser spot on the cathode is $\sigma_r$=.09 cm with a maximum radial extent of $r_{max}$=2.0 cm and a pulse duration of 10 ps. Simulations for the ATF at BNL [2], which uses two linac sections indicate that a transverse Gaussian with a temporal flat top bunch should produce a normalized emittance of 1 $\pi$mm-mr RMS. Whereas simulations with a bunch which is Gaussian both transversely and temporally produces a normalized emittance of 2.5 $\pi$mm-mr RMS. Recent measurements of 5 $\pi$mm-mr RMS at BNL have been achieved [5]. Simulations of the GTF have been done with bunches which are flat top temporally and Gaussian transversely and Kapchinsky-Vladimirsky (KV) distributions, which are uniform in space with a parabolic line charge density. The transverse Gaussians were also clipped. Since the emittance compensation solenoid is capable of removing the emittance growth from linear space charge forces, the more uniform the bunch transversely the smaller the RMS emittance of the bunch. This has been observed in the simulations. From a nonlinear field energy consideration, the optimum electron distribution is a uniform distribution, such as the KV, since it leads to the least emittance growth from the thermalization of the field energy, as described in [6]. Time dependent RF also contributes to emittance growth and can be reduced by shortening the bunch. The 10 ps bunch length was chosen from requirements of the bunch compression of the LCLS. For the GTF system simulations with the KV distribution has produced .90 $\pi$mm-mr, a Gaussian clipped at $\pm$ $\sigma_r$ gave .96 $\pi$mm-mr, and the flat topped Gaussian have produced 1.12 $\pi$mm-mr normalized RMS emittances. The clipped Gaussian is more uniform than the full Gaussian and was used since it will be the most convenient to produce initially.

| Transverse | KV | Clipped Gaussian | Gaussian |
|---|---|---|---|
| Longitudinal | KV | Flat Top | Flat Top |
| $\varepsilon_{normalized}$[$\pi$ mm mr] | 0.9 | 0.96 | 1.12 |
| $\sigma_z$ [pS FWHM] | 11 | 10 | 10 |
| $B_{Solenoid}$[kG] | 2.75 | 2.82 | 2.79 |
| $E_{Linac}$[MV/m] | 7 | 7 | 10 |
| Energy[MeV] | 27.7 | 27.7 | 31.3 |

Figure 1: Parameters for PARMELA simulations of the GTF.

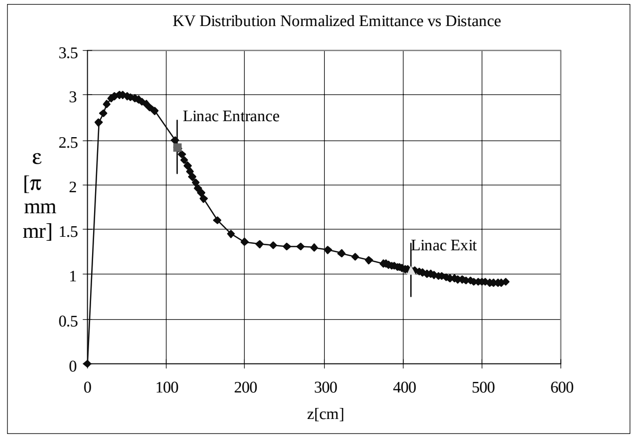


Figure 2: Plot of normalized emittance vs. distance along the GTF for the KV distribution from PARMELA.

### 4 MEASUREMENTS

Since the GTF is under construction, the SUNSHINE facility at Stanford campus was utilized to test the instrumentation for emittance measurements. SUNSHINE [7] consists of a 1.5 cell S-band RF gun with a thermionic cathode, an alpha magnet for bunch compression and one SLAC type linac section for acceleration. Existing instrumentation includes toroids and Faraday Cups for current measurements, phosphor screens for profile measurements, and bend magnets for energy measurements. Normal operation of the machine produces a 1.5 $\mu$s macropulse with about 200 pC of charge per microbunch, the alpha magnet allows bunch compression down to 100 fs rms after acceleration. Instead of accelerating the beam it can be directed straight through the Alpha magnet after degaussing to a low energy beam line (2-3 MeV.) This portion of the beam line was used to test emittance instrumentation. After the beam exits the gun it is focused by four quadrupole magnets. A dipole is then used in conjunction with a set of slits to set the energy spread of the beam. Measurements were done at $\pm$ .1, .2, .3 .4 percent energy spread. This enabled minimization of chromatic effects in the final doublet used to perform the quad scan. Ideally, a double bend achromat would have been used to minimize the horizontal dispersion of the beam, however existing instrumentation did not allow this. The beam profile was observed with a screen made from SLAC chromate. Finally, the beam was dumped into a Faraday Cup to determine the current. The image of the beam was captured using a Pulnix CCD camera and DataTranslation 8-bit frame grabber synchronized to the beam. A neutral density filter and a remotely controllable iris were used to control saturation of the camera. The beam was focused to the smallest possible spot and the iris and frame grabber ADC were adjusted to keep the maximum pixel value less than 255. The quadrupole was then re-standardized and the current was raised incrementally and images of the beam were captured. The data was analyzed off line by least squares fitting of the widths of the beam profiles with the values for the beamline parameters. The widths of the beam profiles were obtained by fitting to a Gaussian distribution from which the sigma of the profile was obtained. The fits were quite good as expected since the beam is generated by a thermionic cathode. The resolution of the system was determined to be 50 μm/pixel and 60 μm/pixel horizontally and vertically respectively. The resolution of the system is ultimately limited to the response and granularity of the screen. The resolution of this type of screen is approximately 50 μm/pixel [8]. The camera was placed as close as possible to the screen, this gives higher resolution but radiation effects must be considered. The resolution given above was for a setup in which a 45 degree mirror was used to reflect the image of the beam to the camera which was located behind 2-4 inches of lead to provide shielding from the source point. The wire scanner has the potential for 10 μm resolution. However the lower beam current densities (about 10 pC per macropulse depending on the slit settings), for the energy filtered beam only allowed integrated measurements over the macropulse. This served to debug electronics and motion control of the system. Also a high impedance amplifier was shown to improve signal levels. Future plans are to move the wire scanner to the high energy part of the beam line where higher current densities are available. The 1 nC beam of the GTF is expected to produce sufficiently high current densities for the wire scanner.

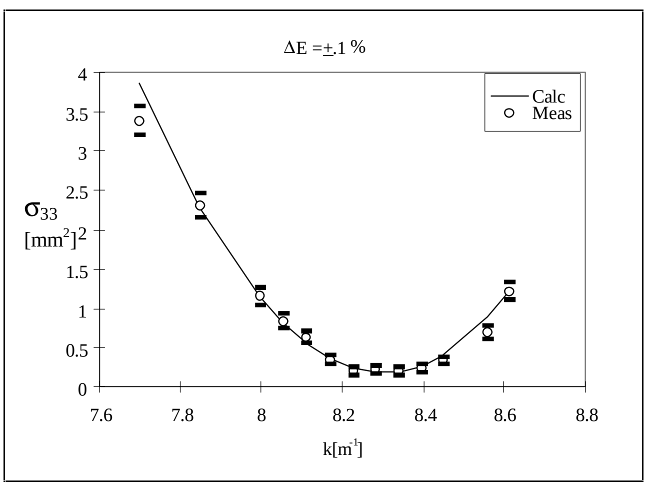


Figure 3: Plot of measured and calculated $\sigma_{33}$ versus quadrupole strength for the SUNSHINE facility. Where $\sigma_{33}$ is the square of the vertical beam size.

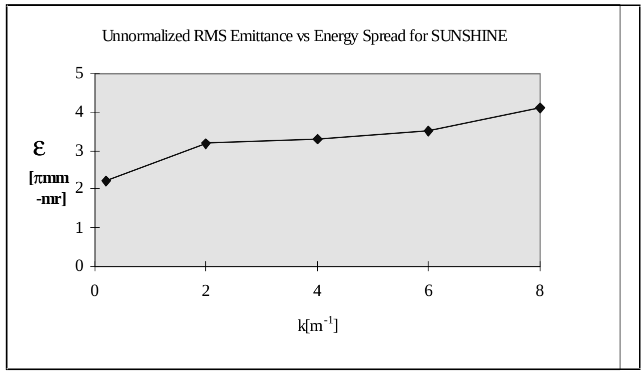


Figure 4: Plot of unnormalized RMS emittance vs. energy spread for SUNSHINE. The energy of the beam was 3.1[MeV] for all measurements.

## 5 FUTURE INSTRUMENTATION

As is evident in the simulations of the GTF, the emittance of the beam will increase due to space charge effects if it is allowed to drift after acceleration. In order to eliminate these effects on the measurements, single shot emittance measurements using TR will be investigated. If OTR intensities are insufficient, Coherent TR will be used since it will have greater intensity. Either masks and a room temperature pyroelectronic bolometer or movable bolometers would be used to determine the divergence of the TR. Low energy emittance measurements will be made with a pepper pot or slits. Also a low energy beam line is being considered. This would require the temporary removal of the linac so that a double bend achromat could be installed.

## 6 ACKNOWLEDGEMENTS


The authors would like to acknowledge the entire SSRL staff ant the collaborators at ANL, BNL, UCLA, and the University of Rochester for the support. This work supported under the Department of Energy contract DE-AC03-76SF00515.


## REFERENCES


[1] R. Tatchyn et al, Nucl. Instr. and Meth., A 375, p. 274, 1996

[2] D.T. Palmer et al, Proc. of SPIE, vol. 252, p. 514, 1995

[3] J. Schmerge et al, Proc. of SPIE, vol. 2988, 1997.

[4] B.E. Carlsten: ‘New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator,’ Nucl. Instrum Methods Phys. Res., vol. A285, p. 313, 1989.

[5] D.T. Palmer et al, Proc. of SPIE, vol. 2988, 1997.

[6] ‘Theory And Design Of Charged Particle Beams’, by M. Reiser, John Wiley & Sons, 1994.

[7] P. Kung, HC Lihn, D. Bocek, and H. Wiedemann, Phys. Rev. Lett. **73**, 967 (1994).

[8] S. Yencho and D.R. Walz: ‘A High-Resolution Phosphor Screen Beam Profile Monitor,’ IEEE Trans., 32:2009-2011, 1985.