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Abstract

The SSRL Gun Test Facility (GTF) was built to develop a high brightness electron injector for the LCLS and has been operational since 1996. Measurements at the GTF include quadrupole scan transverse emittance measurements and linac phase scan longitudinal emittance measurements. Typically the beam size is measured on a screen as a function of a quadrupole current or linac phase and the beam matrix is then fit to the measured data. Often the emittance which is the final result of the measurement is the only number reported. However, the method used to reduce the data to the final emittance value can have a significant effect on the result. This paper describes in painful detail the methods used to analyze the transverse and longitudinal emittance data collected at the GTF.

1. Introduction

The Gun Test Facility (GTF) at SLAC was constructed in 1996 to produce a high brightness electron beam capable of driving the Linac Coherent Light Source. The GTF consists of a Nd:glass laser, 1.6 cell rf gun, emittance compensating solenoid, 3 m SLAC linac section, quadrupole doublet, multiple electron beam screens and spectrometer magnet with a vertical bend. The layout is shown in Figure 1. This paper describes transverse and longitudinal emittance measurements performed at the GTF using three different electron beam screens at different longitudinal positions. A detailed description of the data analysis techniques is also included. Identical analysis was used on simulated images from the beam simulation code PARMELA with a small amount of noise added. This data was analyzed for and presented at the X-ray FEL Commissioning Workshop held at DESY Zeuthen in April 2005 so that is could be compared with alternative data analysis techniques.

Emittance measurements at the GTF are composed of four main steps listed below:

- Image Acquisition
- Compute Beam Size from Images
- Beam Transport Model
- Least Square Fit

Image acquisition is described later in this section. The steps required to reduce the images to a beam size are described in section 2 along with the specific algorithm used for GTF image analysis. The beam transport model and the least square fit used to determine the beam matrix and other fit parameters is described in section 4.

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Figure 1: The Gun Test Facility at SLAC.

The gun is a 1.6 cell, S-band rf gun with Cu cathode as shown in Figure 2. The electrons exit the gun at roughly 5 MeV and are accelerated to approximately 30 MeV through the linac and then enter the diagnostic section. The quadrupole doublet is used to focus the beam onto the screens and also for quadrupole scan emittance measurements.



Figure 2: Two views of the GTF rf gun are shown. The figure on the right is rotated 45 degrees about the beam axis. The cathode is on the left and the beam exits on the right.

The horizontal beam size was measured on all three screens as a function of quadrupole strength for horizontal emittance measurements. Temporally resolved emittance measurements were obtained by operating the linac sufficiently off crest to produce a linear energy chirp along the bunch and measuring the beam size on the phosphor screen in the dispersive region. In addition to the temporally resolved beam matrix, the slice offset angle and position can also determined as will be shown below.

Longitudinal emittance measurements were conducted by measuring the vertical beam size on the phosphor screen as a function of linac phase. As part of the longitudinal emittance measurement the beam energy is measured and the linac accelerating voltage and phase is fit to the data as well as the longitudinal beam matrix.

Electron beam images were captured on three separate screens downstream of the quadrupoles. The first is an OTR screen composed of a thin Aluminum foil stretched over a frame and inserted at a 45 degree angle with respect to the beam. The second screen is 100 μ m thick, 10 mm diameter YAG screen inserted at normal incidence with respect to the beam. A polished metal mirror roughly 1 cm downstream of the screen reflects the light out of the vacuum pipe, through a quartz window and into a camera. The third screen is labeled the spectrometer screen is mounted at 45 degrees with respect to the beam axis downstream of the spectrometer magnet in a dispersive region. The screen was manufactured at SLAC by depositing phosphor on a thin Aluminum substrate.

Analog cameras with 640 X 480 pixels were used with an 8 bit frame grabber to collect beam images for emittance measurements. A gated, intensified camera manufactured by Xybion was used to acquire images from the OTR screen due to the low signal levels from the OTR screen. The gating time was approximately 10-20 ns to reduce the dark current signal. Different optics on all three screens were used obtain the correct field of view for the particular screen. The calibration or each camera was measured by collecting images of a ruler on the bench using the identical optics and frame grabber. All the optics were locked down and the camera moved to the beamline and the position adjusted to bring the screen image into focus. The calibration for each camera/screen is listed in Table 1.

Screen	Calibration (µm/pixel)
OTR	3.99
YAG	14.8
Spectrometer	42.0

Table 1: GTF camera calibrations.

The frame grabber black and white levels are adjusted to prevent the frame grabber from saturating. The frame grabber is adjusted until the maximum pixel value is < 255 by looking at a histogram of the pixel values in an image. A variable attenuator is used to adjust the light level in the camera to avoid camera saturation. Two polarizers, one on a rotational stage, are mounted between the camera lens and vacuum window. One polarizer is rotated as the quadrupole or linac phase is adjusted to keep the maximum pixel level approximately constant.

All the currents in the magnets and various rf field amplitudes and phases are recorded for the same shot as the images. These values are used in the beamline model to determine the beam matrix. The charge is also recorded for each shot and is measured on toroids located before and after the linac. The toroids are calibrated against independent Faraday cups located before the linac and downstream of the spectrometer.

2. GTF Image Analysis Technique

The computation of electron beam sizes is a three step process listed below:

- Background Subtraction
- Define the Region of Interest (ROI)
- Calculate Beam Size

Background subtraction is necessary to remove dark current generated at the cathode by field emission. The background subtraction also reduces any effect from ambient light or systematic camera errors such as radiation damaged pixels and baselines. In order to eliminate the dark current, background images are obtained by eliminating the drive laser pulse. At the GTF, the laser operates at 2.5 Hz and the accelerator run at 5 or 10 Hz. Thus background images are obtained in between laser shots. For the data reported here a single background image was obtained for each quadrupole current or linac phase setting. With a single background image the random noise is increased by a factor of $\sqrt{2}$. Of course this can be reduced with multiple background images. Typical background and beam images on the three screens are shown in Figure 3. No attempt is made to compensate for the shot to shot fluctuations in the background image which is most prevalent in the OTR screen images. The noise in the OTR screens is dominated by electrical noise from the fast gating electronics.



OTR Screen YAG Screen Spectrometer Screen Figure 3: The OTR, YAG and spectrometer screen images are shown left to right. A background image is shown on top and a beam image on the bottom.

After background subtraction a ROI is defined. The purpose of the ROI is to eliminate pixels that contribute only noise to the beam size computation and to limit the cumulative error caused by small offsets in the baseline.

The ROI used at the GTF is rectangular box an integral number of pixels long and wide. The dimensions of the ROI are determined by calculating the point where the horizontal and vertical projections fall below a specified fraction of the peak value. A new ROI is then computed using a projection over the old ROI and the process iterated until the ROI no longer changes. This typically requires only 2 or 3 iterations. The threshold level used for the published GTF data is 5%. Several beam images with the rectangular ROI border plotted in red are shown in Figure 4 along with the vertical projection used to determine the horizontal beam size.

The algorithm described above does not always select an ROI that completely surrounds electron beam. For example, a large tail or halo on the beam can easily be clipped. Also, a bright pixel or group of pixels separate from the beam can sometimes be selected instead of the beam. Thus it is preferred that the ROI is visually verified to properly surround the electron beam before the computed electron beam size is used in the determination of the beam matrix.



Figure 4: Two beam images from the OTR screen are shown on top with the computed ROI plotted as a red rectangle and the pixel coordinates of the ROI are shown. The vertical projection over the ROI is plotted as a red line and a Gaussian fit as a dashed line below the image. The rms beam size and standard deviation from the Gaussian fit are also shown.

The temporally resolved emittance is obtained by slicing a chirped beam image into multiple beamlets. A spectrometer screen image is shown in Figure 5 with the projected image ROI plotted in red and the ROI of each slice in yellow. Each of the 10 slice ROI's width is equal to 10% of the width of the projected ROI. The height of the slice ROI's is determined using the same algorithm described above. The energy or time axis is horizontal in the image and the horizontal beam size is on the image's vertical axis.



Figure 5: A spectrometer screen image is shown with the projected beam ROI and the ROI for 10 slices. The projected beam is 253 pixels wide by 42 pixels high. Each slice is 25 pixels wide but with different heights as determined by the ROI algorithm.

The beam size is then calculated from the pixel values distribution, $f(x_i, y_j)$, inside the ROI where i and j are the pixel coordinates. Both the rms beam size and the standard deviation using a Gaussian fit are calculated. The formula for the rms width is shown in equation 1 with the centroid x_c defined in equation 2. The Gaussian fit is determined by minimizing the error function defined in equation 3 where A_G is the amplitude and Δx_G and x_{cG} are the Gaussian width and centroid respectively.

$$\Delta x = \sqrt{\frac{\sum_{i}^{ROI} (x_{i} - x_{c})^{2} \sum_{j}^{ROI} f(x_{i}, y_{j})}{\sum_{i}^{ROI} \sum_{j}^{ROI} f(x_{i}, y_{j})}}}$$

$$x_{c} = \frac{\sum_{i}^{ROI} (x_{i} - x_{c}) \sum_{j}^{ROI} f(x_{i}, y_{j})}{\sum_{i}^{ROI} \sum_{j}^{ROI} f(x_{i}, y_{j})}$$

$$\chi^{2}_{Gaussian} = \sum_{i}^{ROI} \left(A_{G} e^{-\frac{(x_{i} - x_{cG})^{2}}{2\Delta x_{G}^{2}}} - \sum_{j}^{ROI} f(x_{i}, y_{j}) \right)^{2}$$
3

The beam sizes computed from multiple images with identical beam parameters are averaged to compute the beam size used in the emittance fitting routine. The error in the beam size is the standard deviation from the multiple measurements. The data presented in this paper uses five beam images. The same background image is subtracted from all five beam images. The appendix lists the calculated beam size for the images used to compute emittances reported in this paper.

A comparison of rms and Gaussian widths, in pixels, is shown in Figure 6 as a function of threshold level for four different randomly chosen images. The Gaussian widths are relatively independent of threshold level since the fit is not weighted and thus dominantly fits the peak of the signal. The rms width can decrease as much as 20% as the threshold level increases from 1 to 15%. Thus the Gaussian widths are more robust than the rms width calculation. However, many images, especially the longitudinal phase space data, show highly non-Gaussian distributions. Thus the rms beam size with a 5% threshold is typically chosen for analyzing GTF data. All of the beam sizes reported here, except for those in Figure 6, were calculated with a 5% threshold.



Figure 6: The x and y rms and Gaussian beam sizes as a function of ROI threshold level for four randomly chosen images are shown.

3. Emittance Calculation Technique

The computed beam sizes as a function of quadrupole current or linac phase are used to determine the transverse or longitudinal beam matrix. The three independent beam matrix parameters are fit by comparing the measured beam size to a mathematical model of the beamline. The beamline is modeled using the first order matrix presented in TRANSPORT [1].

The relevant beamline parameters are shown in Figure 7 including the quadrupole strength as a function of current, drift distances, and magnet lengths. The drift distance between magnets used in the Transport model is adjusted by the difference between the magnets physical length and the effective length so that the total distance in the matrix model matches the beamline distance. The first quadrupole focuses in the vertical plane and the second quadrupole focuses in the horizontal plane. The spectrometer magnet is a 60° wedge magnet with the listed bending radius, pole face rotations, and effective fringe field pole face rotation.



Figure 7: A block diagram of the GTF beamline with all the relevant beamline parameters.

The transverse beam matrix transforms along the beamline as shown in equation 4 where σ_{11} , σ_{12} , and σ_{22} are the three beam matrix parameters at the initial point and σ_{11i} , σ_{12i} , and σ_{22i} are the identical parameters at the observation point. A_i, B_i, C_i, and D_i are the total horizontal transport matrix coefficients from the starting point to the observation point and are functions of the quadrupole current. The total matrix is of course the product of the matrix for each individual element. The beam size of the ith observation can be written in terms of the transport matrix coefficients and the initial beam matrix as shown in equation 5.

$$\begin{bmatrix} \sigma_{11i} & \sigma_{12i} \\ \sigma_{12i} & \sigma_{22i} \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}^T$$

$$4$$

$$\Delta x_i^2 \equiv \sigma_{11i} = A_i^2 \sigma_{11} + 2A_i B_i \sigma_{12} + B_i^2 \sigma_{22}$$
 5

The final step is to fit the beam matrix parameters to minimize the error between the measured beam size and the beam size computed using the model. However, the error can be defined in multiple ways. Two definitions of the error function are listed in

equations 6 and 7. The first is the so called linear definition since the derivative of the error function is a linear function of the beam matrix parameters. The beam matrix parameters that minimize the linear error function can be determined by inverting a matrix. However, this error function is fitting the square of the measured beam size instead of just the beam size. The non-linear error function fits the beam matrix parameters to the measured beam size but unfortunately no analytic solution exists to minimize the error function. Instead, this error function must be minimized numerically. The published GTF data as well as the data presented here are fit with the non-linear error function since the beam size and not the beam size squared is the quantity physically measured. The beam matrix parameters from the linear fitting are used as a seed for the non-linear fit. Typically the beam matrix parameters from the non-linear fit are only a few percent different from the linear fit.

$$\chi^{2}_{\text{linear emittance}} = \sum_{i=1}^{N} \left(\frac{\Delta x_{ibcam fit}^{2} - \Delta x_{ibbcam measure}^{2}}{2\Delta x_{ibcam measure}} \sigma_{\Delta x_{ibcam measure}} \right)^{2} = \sum_{i=1}^{N} \left(\frac{A_{i}^{2}\sigma_{11} + 2A_{i}B_{i}\sigma_{12} + B_{i}^{2}\sigma_{22} - \Delta x_{ibcam measure}^{2}}{2\Delta x_{ibcam measure}} \right)^{2} \qquad 6$$

$$\chi^{2}_{\text{non-linear emittance}} = \sum_{i=1}^{N} \left(\frac{\Delta x_{ibcam fit}^{2} - \Delta x_{ibcam measure}}{\sigma_{\Delta x_{ibcam measure}}} \right)^{2} = \sum_{i=1}^{N} \left(\frac{\sqrt{A_{i}^{2}\sigma_{11} + 2A_{i}B_{i}\sigma_{12} + B_{i}^{2}\sigma_{22}} - \Delta x_{ibcam measure}}{\sigma_{\Delta x_{ibcam measure}}} \right)^{2} \qquad 7$$

With a chirped beam on the spectrometer screen it is evident that the beam has a position-time correlation or tilt. Thus in addition to fitting the beam matrix, the centroid position and angle can be fit for each slice. The centroid of each slice relative to the projected beam centroid is measured at the spectrometer screen. The error function is defined in equation 8 where x_0 and x_0 ' are the position and angle of the slice at the initial longitudinal point.

$$\chi^{2}_{centroid} = \sum_{i=1}^{N} \left(\frac{x_{i\,fit} - x_{i\,measure}}{\sigma_{x_{i\,measure}}} \right)^{2} = \sum_{i=1}^{N} \left(\frac{A_{i}x_{0} + B_{i}x_{0}' - x_{i\,measure}}{\sigma_{x_{i\,measure}}} \right)^{2}$$

$$8$$

The transport matrix used for the longitudinal measurements begins at the linac and ends at the spectrometer screen. The beam is assumed to travel at the speed of light and therefore there is no phase slippage. This assumption is not valid in the linac where the beam enters at only 5 MeV with a large energy spread. However, since all the particles slip similar amounts the net result is a small change in the definition of linac phase and the non-linear effect is ignored in the emittance analysis. Analogous to equation 5, the energy spread at the spectrometer screen can be written in terms of the longitudinal transport matrix coefficients, C_{li} and D_{li} , and the longitudinal beam matrix at the entrance to the linac as shown in equation 9.

$$\Delta E_i^2 \equiv \tau_{22i} = C_{li}^2 \tau_{11} + 2C_{li} D_{li} \tau_{12} + D_{li}^2 \tau_{22}$$
9

The beam energy is measured with the spectrometer magnet. From magnetic measurements, the beam energy is given in equation 10 as a function of spectrometer current and pixel location on the spectrometer screen. For the transverse emittance measurements the beam energy is constant and approximately 30 MeV. However, during the longitudinal measurement the energy varies sinusoidally as the linac phase is modulated. In this case the energy is fit to a sinusoid to determine the absolute linac phase and accelerating voltage. The error function is shown in equation 11 where the fit parameters are the linac voltage, V_{linac} , and the phase offset, $\Delta \theta_{\text{linac}}$. The voltage and phase are required to calculate the beam transport matrix coefficients and the phase is defined to be 0° at the maximum energy.

$$E(MeV) = \left(-1.421^{-5}I_{spect}^{3} + 1.204^{-3}I_{spect}^{2} + 0.9992I_{spect} + 0.5541\right)\left(1 + 0.0000724\left(348 - p_{centroid}\right)\right) \quad 10$$

$$\chi_{energy}^{2} = \sum_{i=1}^{N} \left[\frac{E_{i\,fit} - E_{i\,measure}}{\sigma_{E_{i\,measure}}}\right]^{2} = \sum_{i=1}^{N} \left[\frac{\left(E_{gun} + V_{linac}\cos\left(\theta_{i\,linac} + \Delta\theta_{linac}\right)\right) - E_{i\,measure}}{\sigma_{E_{i\,measure}}}\right]^{2} \quad 11$$

4. Experimental Results

The longitudinal emittance results are shown in Figure 8 which shows the measured energy and energy spread versus the linac phase along with the fits and the phase space ellipses at three positions along the beamline. The linac phase is defined as 0° at the maximum energy. The model is in excellent agreement with the measured data. Table 2 shows the longitudinal beam parameters at the linac entrance and exit with $\theta_{\text{linac}} = 8^\circ$.



Figure 8: The measured energy spread in green and energy in red are plotted on the left as a function of the linac phase. The longitudinal, rms, phase space ellipse at the linac entrance, exit, and at the spectrometer screen is plotted on the right.

Table 2: The rms beam parameters at the linac entrance and exit are shown. The exit parameters are calculated with a linac phase of 8° and gradient of 8.35 MV/m.

Beam Parameter	Linac Entrance	Linac Exit	Units
τ_{11}	0.575	0.575	ps ²
τ_{12}	-64.5	-100	keV ps
τ_{22}	7310	17600	keV ²

ει	6.84	6.84	keV ps
ε _{ln}	4.01	4.01	μm
$\sigma_{\rm E}$	85.5	133	keV
$\sigma_{E uncorrelated}$	9.02	9.02	keV
σ_t	0.758	0.758	ps
dE/dt	-112	-175	keV/ps

GTF Transverse and Longitudinal Emittance Data Analysis Technique

The longitudinal phase space is highly correlated at the linac entrance. The correlation can be removed after the linac when the phase is -14° . Alternatively it can be increased if the linac phase is $> 0^{\circ}$. The stronger correlations are used to conduct the temporally resolved transverse emittance measurements.

The sliced beam size measurements and centroid are plotted in Figure 9 along with the phase space ellipses. The centroids of each slice are measured with respect to the projected beam centroid. The Twiss parameters, offset angle, offset position and current vs time are shown in Figure 10. The measured Twiss parameters are plotted using both the Gaussian and rms beam sizes. The linac phase for these measurements was 8° so the time axis is calibrated by measuring the beam energy and using the measured correlation listed in Table 2.



Figure 9: The measured beam size (red circles) and offset (blue diamonds) for slice number 4 are plotted on the left as a function of quadrupole strength along with the fits (solid lines). The phase space at the quadrupole for all 10 slices and the projected beam (dashed line) are shown on the right. The slice phase space ellipses are plotted using the measured angle and position offsets.



Figure 10: The emittance versus time is plotted in the upper left and the α and β functions at the initial point are shown in the lower left. The current versus time is shown in the upper right based on the total charge and the charge contained in each slice. The measured offset angle and position at the initial point are shown in the lower right corner. The measurement of the projected beam is plotted at t = 0 on all graphs.

The measured beam size versus quadrupole strength is shown in Figure 11. The figure shows the projected beam size on all three screens and also the rms phase space ellipses at the entrance to quadrupole 1 from each screen measurement. There is good agreement among all three measurements. The OTR and YAG screens were measured with a linac phase of 16° which is near the minimum energy spread while the spectrometer screen measurement was conducted at a linac phase of 8° as described earlier. The beam parameters at the entrance to quadrupole 1 from all three measurements are included in Table 4. As expected the beam reaches a smaller minimum size and requires a shorter focal length the closer it is to the focusing quadrupole.



Figure 11: The measured, projected beam size versus quadrupole strength on all three screens. The rms phase space ellipses at the quadrupole are also shown.

Table 4:	Beam pa	arameters a	at the o	entrance t	o qua	drupole	1 from	the	OTR,	YAG	and
Spectrometer	r screen m	neasureme	ents.								

Beam Parameter	OTR	YAG	Spectrometer	Units
σ_{11}	0.0335	0.0426	0.0264	mm^2
σ_{12}	0.0220	0.0225	0.0157	μm
σ_{22}	0.0187	0.0148	0.0144	mrad ²
٤g	0.0120	0.0111	0.0114	μm
ε _n	0.702	0.654	0.683	μm
σ _x	183	206	162	μm
σ _x ,	137	122	120	µrad

5. Analysis of Simulated Data

In addition to using the measured electron beam images to calculate the beam matrix parameters, simulated images from PARMELA were used to test the analysis technique. The beam was simulated at three different longitudinal positions and then the data reduced to an image in x-y space at each location. The PARMELA data was binned into "pixels" with various dimensions and some random noise added to the images. The noise had a Gaussian distribution and images with different average and rms noise values were generated. Two of the images from the simulated data are shown in Figure 12.

The calculated rms beam sizes using the image analysis software algorithm described earlier are then compared with PARMELA results computed from the 6-D coordinates of all the particles. Figure 13 shows the beam size on the three screens for three different beam parameters as well as the beam size calculated by PARMELA. The calculated emittance from each three screen test case and the pixel size and noise levels for each case are listed in Table 5. The emittance is calculated in identical manner as reported above except that the transport matrix is modified since the simulated data uses a three screen emittance measurement technique and the real measured data utilizes a quadrupole scan. In all cases the emittance is less than or equal to the emittance calculated by PARMELA and in almost all cases the beam size is smaller than computed by PARMELA. This is almost certainly due to the halo particles that are included in the PARMELA result but are filtered in the image analysis routine due to the 5% threshold limit.



Figure 12: Two images at screen location three generated from the simulation code PARMELA. The image on the left has 20 μ m pixel size and 60 counts of average noise level with standard deviation of 10. The image on the right has 10 μ m pixel size and 100 counts of average noise level with a standard deviation of 20. The red boxes are the ROI for each image as calculated using the algorithm described earlier.



Figure 13: The horizontal rms beam size is shown on the bottom row and the vertical rms beam size on the top row for three different sets of beam parameters. Several different test cases for each set of beam parameters were run with different pixel size, average and standard deviation noise level.

Case	ε_{nx} (µm)	$\varepsilon_{ny}(\mu m)$	Pixel (µm)	Ave noise	Rms noise
D (PARMELA)	0.76	0.76	NA	NA	NA
D1	0.68	0.69	10	60	10
D2	0.76	0.74	20	60	10
DD (PARMELA)	1.17	1.17	NA	NA	NA
DD1	0.90	0.91	10	60	10
S (PARMELA)	1.07	1.08	NA	NA	NA
S1	0.76	0.77	10	60	10
S2	0.80	0.79	20	60	10
S 3	0.72	0.77	10	60	20
S4	0.67	0.74	10	100	20

Table 5: The horizontal and vertical emittance for the various simulated test cases.

6. Conclusions

As expected the data analysis revealed that the ROI affects the calculated beam size and thus the emittance. Different algorithms used to compute the ROI will produce different emittance results. The published GTF data uses a 5% threshold limit to cut off the wings in an attempt to minimize this effect. Table 6 shows the measured projected emittance for each screen using both rms and Gaussian beam sizes. The Gaussian fits routinely produce a smaller minimum beam size and therefore lower emittance. The ratio of Gaussian to rms beam size also varies with the beam size as can be seen in the appendix. The Gaussian fit in the longitudinal data should not be trusted as the distribution is typically non-Gaussian. However, the Gaussian fits are less sensitive to the ROI.

Comparing the results of a simulated beam with PARMELA computations indicates the beam size and thus the emittance can be underestimated when compared with 100% of the particles. This is not surprising since the data analysis necessarily excludes particles far from the centroid that are indistinguishable from noise and thus will compute a lower emittance.

Measurement	rms Fit	Gaussian Fit	Units
OTR (Transverse)	0.70 ± 0.02	0.61 ± 0.01	μm
YAG (Transverse)	0.65 ± 0.01	0.61 ± 0.01	μm
Spectrometer (Transverse)	0.68 ± 0.01	0.69 ± 0.01	μm
Spectrometer (Longitudinal)	4.0 ± 0.13	1.9 ± 0.42	μm

Table 6: comparison of emittance measurements using rms and Gaussian beam sizes.

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8. Appendix

The calculated beam sizes for the images used in the analysis in this paper. The table lists both the rms and Gaussian beam size for the real projected beam images in pixels and the x and y rms beam size for the simulated images.

	image	OTR rms Gaussian	YAG rms Gaussian	Spectrometer (Transverse) rms Gaussian	Spectrometer (Longitudinal) rms Gaussian	Simulated Data image x rms y rms
	0001.tif 0002.tif	57.683 64.514 62.858 68.924 55.220 62.824	24.716 25.520 25.051 26.696 22.844 24.121	7.558 7.551 7.715 7.877 7.571 7.671	66.952 77.979 65.735 77.246 60.050 79.075	d1_WS01.tif 11.46 11.70 d1_WS02.tif 5.15 5.14 d1_WS02.tif 10.00 10.01
NAME Conto Conto <thc< td=""><td>0004.tif 0005.tif</td><td>56.498 64.901 58.460 65.114</td><td>24.166 25.958 22.847 24.546</td><td>7.657 7.721 7.834 7.907</td><td>69.252 79.785 69.168 79.121</td><td>d2_WS01.tif 5.68 5.84 d2_WS02.tif 3.11 2.86</td></thc<>	0004.tif 0005.tif	56.498 64.901 58.460 65.114	24.166 25.958 22.847 24.546	7.657 7.721 7.834 7.907	69.252 79.785 69.168 79.121	d2_WS01.tif 5.68 5.84 d2_WS02.tif 3.11 2.86
	0101.tif 0102.tif	46.263 49.161 44.436 50.232	19.933 22.306 20.998 23.276	6.974 6.869 7.406 7.127	61.640 70.601 64.745 73.276	d2_WS03.tif 4.99 5.02 dd1_WS01.tif 11.74 12.27
	0103.tif 0104.tif	43.090 46.608 49.239 50.209	20.113 22.747 18.865 20.404	6.686 6.661 7.092 6.784	60.688 68.574 60.119 68.384	dd1_WS02.tif 5.67 6.79 dd1_WS03.tif 13.49 11.09
	0201.tif	46.904 53.079 37.570 46.612 37.399 41.398	20.005 21.363 18.749 19.937 19.311 20.558	6.242 6.138 5.958 5.948	54.130 63.500 55.673 65.489	s1_WS01.tif 11.06 11.53 s1_WS02.tif 4.82 4.88 e1_WS03.tif 12.76 12.82
	0203.tif 0204.tif	36.690 40.810 35.864 39.527	17.798 18.668 18.164 19.242	6.268 6.113 6.523 6.350	56.491 65.147 57.237 66.405	s2_WS01.tif 6.05 6.01 s2_WS02.tif 2.46 2.47
	0205.tif 0301.tif	42.267 44.982 29.695 31.309	17.480 18.150 13.628 14.521	6.283 6.066 5.776 5.333	57.510 65.229 52.823 59.954	s2_WS03.tif 6.49 6.37 s3_WS01.tif 11.76 11.83
	0302.tif 0303.tif	28.809 30.324 28.477 30.082	12.704 13.476 13.980 14.464	5.532 5.348 5.568 5.388	51.238 58.635 53.735 61.887	s3_WS02.tif 4.48 4.78 s3_WS03.tif 12.75 12.80
	0305.tif 0401 tif	30.927 34.585 19.451 20.991	13.327 14.280 9.365 9.757	5.667 5.406 4.647 4.503	46.755 57.255 54.335 61.538 48.697 54.338	s4_WS01.til 11.44 11.22 s4_WS02.til 4.19 4.82 s4_WS03.til 12.72 12.70
	0402.tif 0403.tif	20.311 21.607 20.606 22.251	9.800 9.871 10.939 10.243	4.812 4.511 4.639 4.442	48.821 55.403 48.160 53.809	
	0404.tif 0405.tif	18.731 19.887 20.329 21.605	9.910 10.391 9.385 9.603	4.496 4.389 4.309 4.272	46.381 53.091 47.040 53.575	
	0501.tif 0502.tif 0503.tif	15.582 15.200 16.118 15.508 14.986 15.102	6.976 6.799 7.200 7.006 7.104 7.024	3.853 3.432 4.109 3.461 3.915 3.495	39.930 44.847 40.492 45.069 41.690 45.989	
	0504.tif 0505.tif	14.653 14.204	7.378 7.327 7.800 7.757	4.061 3.568 3.928 3.457	42.561 46.223 41.821 46.697	
	0601.tif 0602.tif	12.056 9.596 11.770 9.641	5.385 4.985 5.762 5.504	3.576 2.997 3.436 2.957	33.637 36.724 34.121 36.816	
	0603.tif 0604.tif	12.955 9.706 11.699 9.436	5.942 5.593 5.843 5.240 5.424 4.085	3.425 2.943 3.408 2.921 3.630 3.035	34.153 36.159 35.321 37.170 35.350 26.830	
	0701.tif 0702.tif	13.017 10.704 13.149 10.825	4.939 4.229 4.709 4.199	3.152 2.848 3.109 2.807	30.618 33.533 32.501 33.550	
Nome Nome <th< td=""><td>0703.tif 0704.tif</td><td>12.506 9.500 11.993 10.012</td><td>4.964 4.231 5.372 4.433</td><td>3.091 2.773 2.970 2.699</td><td>32.393 33.867 33.348 34.861</td><td></td></th<>	0703.tif 0704.tif	12.506 9.500 11.993 10.012	4.964 4.231 5.372 4.433	3.091 2.773 2.970 2.699	32.393 33.867 33.348 34.861	
	0705.tif 0801.tif	14.269 14.915	4.729 4.119 3.880 3.321	3.173 2.906 2.969 3.000	33.448 34.214 27.200 29.159	
BACK BACK <th< td=""><td>0803.tif</td><td>14.233 14.347 13.754 14.445 13.743 14.237</td><td>4.303 3.471 4.004 3.388 3.979 3.333</td><td>2.908 2.964 2.895 2.995 2.971 3.030</td><td>20.002 27.001 29.793 29.505 29.430 30.206</td><td></td></th<>	0803.tif	14.233 14.347 13.754 14.445 13.743 14.237	4.303 3.471 4.004 3.388 3.979 3.333	2.908 2.964 2.895 2.995 2.971 3.030	20.002 27.001 29.793 29.505 29.430 30.206	
Book Book <th< td=""><td>0805.tif 0901.tif</td><td>15.198 15.596 24.319 21.096</td><td>4.509 3.480 3.900 3.095</td><td>2.946 3.004 3.544 3.725</td><td>27.747 30.114 20.655 20.784</td><td></td></th<>	0805.tif 0901.tif	15.198 15.596 24.319 21.096	4.509 3.480 3.900 3.095	2.946 3.004 3.544 3.725	27.747 30.114 20.655 20.784	
	0902.tif 0903.tif	18.863 20.511 16.919 17.404	3.970 3.304 3.810 2.996	3.496 3.701 3.474 3.670	22.124 20.998 22.495 22.070	
NUME NUME <th< td=""><td>0904.tif 0905.tif</td><td>19.232 20.687 19.128 19.928</td><td>3.860 3.197 3.893 3.031</td><td>3.510 3.758 3.471 3.665</td><td>22.624 20.652 22.651 21.834</td><td></td></th<>	0904.tif 0905.tif	19.232 20.687 19.128 19.928	3.860 3.197 3.893 3.031	3.510 3.758 3.471 3.665	22.624 20.652 22.651 21.834	
Note Above Above <tha< td=""><td>1001.tif 1003.tif</td><td>20.946 19.557 24.612 25.265 23.459 26.093</td><td>4.633 4.259 4.300 4.009 4.485 4.157</td><td>4.370 4.656 4.308 4.643 4.308 4.664</td><td>19.506 17.654 19.795 18.286 18.916 17.083</td><td></td></tha<>	1001.tif 1003.tif	20.946 19.557 24.612 25.265 23.459 26.093	4.633 4.259 4.300 4.009 4.485 4.157	4.370 4.656 4.308 4.643 4.308 4.664	19.506 17.654 19.795 18.286 18.916 17.083	
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	1101.tif 1102.tif	29.119 32.917 26.079 28.297	5.504 5.670 5.608 5.678	5.293 5.768 5.291 5.853	14.489 10.042 14.857 9.576	
1920 1920	1103.tif 1104.tif	28.372 30.248 28.397 31.716	5.362 5.126 5.540 5.800	5.314 5.800 5.156 5.647	14.370 9.538 14.194 11.276	
151.01 15.101 15.101 15.10 15.00 15.00 151.01 15.00 15.00 15.00 15.00 151.01 17.00 17.00 7.00 15.00 151.01 17.00 7.00 15.00 15.00 151.01 17.00 7.00 15.00 15.00 151.01 17.00 7.00 15.00 15.00 151.01 17.00 7.00 15.00 15.00 151.01 17.00 7.00 15.00 15.00 151.01 17.00 7.00 15.00 15.00 152.01 15.00 15.00 15.00 15.00 152.01 15.00 15.00 15.00 15.00 152.01 15.00 15.00 15.00 15.00 153.01 15.00 15.00 15.00 15.00 153.01 15.00 15.00 15.00 15.00 153.01 15.00 15.00 15.00 15.00 153.01 15.00 15.00 15.00 15.00 153.01 15.00 15.00 15.00 15.00 153.01 15.00 15.00 15.00 153.01 15.00 <	1201.tif 1202 tif	35.239 40.667 33.946 39.721	6.925 7.180 6.609 7.068	6.250 6.869 6.053 6.521	10.850 6.442 10.634 5.089	
10506.526.507.508.509.509.50103247.948.807.747.7010.777.50103247.948.807.747.7411777.50103247.948.807.747.7511777.50103247.948.807.747.7511777.50103248.907.7411777.501177103248.907.758.755.56103248.907.758.752.56103248.907.758.752.561032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.771032411.977.728.762.77	1203.tif 1204.tif	36.431 38.768 33.808 40.990	6.699 7.115 6.688 6.970	6.169 6.650 6.138 6.703	10.631 4.866 10.550 6.426	
135.4175.47.547.547.547.547.547.547.54135.47.547.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.547.54135.47.547.547.547.547.54135.47.547.547.547.547.54	1205.tif 1301.tif		6.492 6.920 7.715 8.163	6.148 6.600 7.174 7.649	10.844 5.846 10.877 4.735	
135.07.207.207.207.207.207.20145.015.0015.002.60145.015.002.60145.015.002.60155.01	1302.tif 1303.tif 1304.tif		8.115 8.797 7.896 8.838 7.858 8.691	7.265 7.768 7.182 7.826 7.154 7.743	10.971 7.024 9.911 3.908 11.770 7.366	
No. </td <td>1305.tif 1401.tif</td> <td></td> <td>7.919 8.866 9.504 10.498</td> <td>7.326 7.932</td> <td>11.747 7.429 5.834 2.555</td> <td></td>	1305.tif 1401.tif		7.919 8.866 9.504 10.498	7.326 7.932	11.747 7.429 5.834 2.555	
No.0.1010.402.402.40103.11.1014.203.33103.21.1014.203.33103.31.1024.203.34103.41.1041.304.203.44103.41.1041.304.203.44103.41.1041.304.203.44103.41.1024.203.44103.41.1014.203.20103.41.1024.203.20103.41.1014.203.20103.41.1024.203.20103.41.1016.206.31103.41.1016.206.31103.41.1016.206.31103.41.1016.206.31103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.1016.207.20103.41.101 <td< td=""><td>1402.tif 1403.tif</td><td></td><td>9.571 10.556 9.609 10.395</td><td></td><td>7.605 3.564 5.601 2.560</td><td></td></td<>	1402.tif 1403.tif		9.571 10.556 9.609 10.395		7.605 3.564 5.601 2.560	
	1404.tif 1405.tif		9.610 10.701 9.136 10.247		6.448 2.988 6.637 2.967	
INDE1.582.4d4.502.5015231.5271.5282.37915241.5273.6475.64715241.5284.6205.64715241.5204.5205.64715241.5204.5205.64715241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.506.47115241.5205.507.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.3015241.5207.301524	1501.tif 1502.tif 1503.tif		11.414 12.057 12.303 12.692 11.672 12.571		4.249 3.383 4.492 2.714 4.687 3.354	
Hole12.4412.374.625.62Hole12.3113.074.645.32Hole12.3113.074.645.32Hole12.3113.074.645.32Hole12.3115.076.386.40Hole14.7715.076.386.40Hole12.3115.076.386.40Hole13.076.396.40Hole12.3115.076.386.40Hole12.3115.076.396.40Hole12.3115.076.396.40Hole12.3115.076.306.40Hole12.3115.076.307.09Hole12.3113.076.307.09Hole12.3113.076.307.09Hole12.3113.078.307.09Hole12.3113.078.307.09Hole12.3113.078.307.09Hole12.3113.078.307.09Hole12.3113.087.097.09Hole12.3113.087.09Hole12.3113.097.09Hole12.3113.097.09Hole12.3113.097.09Hole12.3113.097.09Hole12.3113.097.09Hole12.3113.097.09Hole12.3113.097.09Hole13.09 </td <td>1504.tif 1505.tif</td> <td></td> <td>11.589 12.448 11.314 12.296</td> <td></td> <td>4.087 3.304 4.582 2.984 4.272 3.379</td> <td></td>	1504.tif 1505.tif		11.589 12.448 11.314 12.296		4.087 3.304 4.582 2.984 4.272 3.379	
NO.813.814.623.844.23NO.814.6315.034.544.53NO.814.6315.034.544.57NO.814.6315.705.564.57NO.814.5415.705.564.57NO.814.5415.705.567.76NO.814.5415.705.567.76NO.814.5415.705.567.76NO.814.5415.705.567.76NO.814.5415.705.567.76NO.814.5415.705.567.76NO.814.5415.705.567.76NO.814.5415.702.567.76NO.814.5415.702.567.76NO.814.5415.702.567.76NO.814.542.562.557.76NO.814.542.562.557.76NO.814.542.562.557.76NO.814.542.562.557.76NO.814.542.562.557.76NO.814.542.562.557.76NO.814.542.562.567.76NO.814.542.562.567.76NO.814.542.562.567.76NO.814.542.562.567.76NO.814.542.562.567.76NO.814.542.562.567.76 <td>1601.tif 1602.tif</td> <td></td> <td>12.449 13.370 12.871 14.538</td> <td></td> <td>4.632 5.197 4.690 5.496</td> <td></td>	1601.tif 1602.tif		12.449 13.370 12.871 14.538		4.632 5.197 4.690 5.496	
Index1.4.001.8.004.5.008.001702.011.4.071.5.736.5.608.171703.011.4.071.5.736.5.608.171703.011.7.141.6.046.5.078.601803.011.7.141.6.046.5.078.601803.011.7.141.6.041.5.177.6.801803.011.7.141.6.041.5.177.6.801803.011.7.141.6.041.5.177.6.801803.011.7.141.6.041.5.177.6.801803.011.7.141.6.051.5.241.6.051803.011.7.141.6.051.5.241.5.001803.011.7.141.6.051.5.241.5.001803.011.7.141.5.001.5.241.5.001803.011.7.141.5.001.5.241.5.001803.011.7.141.5.002.5.511.5.121803.011.7.141.5.002.5.512.5.121803.011.7.141.5.002.5.121.5.101803.011.7.141.5.102.5.122.5.121803.011.7.141.5.102.5.122.5.121803.011.7.141.5.102.5.122.5.121803.011.7.141.5.102.5.122.5.121803.011.7.141.5.102.5.122.5.121803.011.7.141.5.122.5.122.5.121803.011.7.141.5.122.5.122.5.1218	1603.tif 1604.tif		13.308 14.562 12.313 13.873		3.945 4.238 4.647 5.233	
No.1.4.0001.5.0716.5476.82175.8.81.5.0716.5476.547175.8.81.5.076.5476.547175.8.91.5.076.5476.547175.8.91.5.077.598175.8.91.5.077.598175.8.91.5.077.598175.91.5.077.598175.91.5.077.598175.91.5.077.598175.91.5.077.598175.91.5.07	1605.tif 1701.tif 1702.tif		12.938 13.921 14.050 15.993 14.757 15.573		4.837 5.609 5.353 6.457 5.386 6.460	
TYDER7.5.7.46.5.7.46.5.7.46.5.7.46.5.7.46.5.7.47.5.7.46.5.7.47.5.7.4 <th7< td=""><td>1703.tif 1704.tif</td><td></td><td>14.099 15.701 14.361 15.376</td><td></td><td>5.647 6.812 5.226 6.387</td><td></td></th7<>	1703.tif 1704.tif		14.099 15.701 14.361 15.376		5.647 6.812 5.226 6.387	
No. I6.1657.781105.446.5027.80105.456.5027.80105.456.5027.80105.456.5027.80105.456.5027.80105.456.5036.503105.456.5036.503105.456.5036.503105.456.5036.503105.456.5036.503105.456.5036.503105.456.5036.503105.456.5036.503105.457.786.503105.457.786.503105.457.5037.503105.45 <td>1705.tif 1801.tif</td> <td></td> <td>17.414 16.674</td> <td></td> <td>5.578 6.840 5.514 6.447</td> <td></td>	1705.tif 1801.tif		17.414 16.674		5.578 6.840 5.514 6.447	
No. I0.177.8631901.9.66419.2441902.9.66419.2441903.8.61819.2441903.8.61819.2441903.8.61819.2441903.8.61919.2441903.8.61919.2441903.8.61919.2441903.19.27225.7182003.19.27225.552004.19.56925.552004.19.56925.552004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.19.56025.572004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5727.472004.29.5729.572004.29.5729.572004.29.5729.572004.29.5	1802.tif 1803.tif				6.195 7.781 5.505 6.615	
100.20.66610.24100.30.2632.0451100.40.2032.0451200.41.17712.571200.51.17712.571200.51.17712.571200.51.15702.571200.51.15702.571200.51.15702.571200.51.15712.528210.51.15712.529210.51.15712.571210.51.15712.571210.51.15712.571210.51.15712.571210.51.15712.571210.51.15712.571210.51.15712.591210.51.15712.591210.51.15712.591220	1804.tif 1805.tif 1901.tif				6.1// 7.698 5.902 7.260 8.924 16.137	
19.5.di9.2.6.32.0.8.52002.414.5.62.0.0.8.52003.413.5.02.0.5.52004.413.5.02.0.5.52004.413.5.02.0.5.52004.413.5.02.0.5.52004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.415.5.03.0.7.22004.414.3.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.414.5.13.0.5.12004.420.5.13.0.5.12004.420.5.13.0.5.12004.420.5.13.0.5.12004.420.5.13.0.5.12004.420.5.13.0.5.12004.420.5.13.0.5.1 <td>1902.tif 1903.tif</td> <td></td> <td></td> <td></td> <td>9.665 19.264 8.619 16.786</td> <td></td>	1902.tif 1903.tif				9.665 19.264 8.619 16.786	
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[1] Transport, SLAC -91, Rev UC-28, 1977.