SLAC-PUB-9540
September 2002

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Abstract

A goal of the Gun Test Facility (GTF) at SLAC is to investigate the production of high-brightness electron beams for the Linac Coherent Light Source (LCLS) X-ray FEL. High brightness in the rf photocathode gun occurs when the time-sliced emittance is nearly the same as the cathode thermal emittance and when the slices are all lined up, i.e., their Twiss parameters are nearly identical. In collaboration with the BNL Source Development Lab (SDL), we have begun a systematic study of the slice emittance at GTF. The technique involves giving the bunch a near linear energy chirp using the booster linac and dispersing it with a magnetic spectrometer. Combined with knowledge of the longitudinal phase space, this establishes the energy-time correlation on the spectrometer screen. The slice emittances are determined by varying the strengths of the quadrupoles in front of the spectrometer. Spectrometer images for a range of quadrupole settings are then binned into small energy/time windows and analysed for the slice emittance and Twiss parameters. Results for various gun parameters are presented.

Submitted to 24th International Free Electron Laser Conference,
Argonne National Laboratory, Argonne, IL, 9/9/2002 - 9/13/2002

*Work supported by Department of Energy contract DE-AC03-76SF00515

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Abstract

A goal of the Gun Test Facility (GTF) at SLAC is to investigate the production of high-brightness electron beams for the Linac Coherent Light Source (LCLS) X-ray FEL. High brightness in the rf photocathode gun occurs when the time-sliced emittance is nearly the same as the cathode thermal emittance and when the slices are all lined up, i.e., their Twiss parameters are nearly identical. In collaboration with the BNL Source Development Lab (SDL), we have begun a systematic study of the slice emittance at GTF. The technique involves giving the bunch a near linear energy chirp using the booster linac and dispersing it with a magnetic spectrometer. Combined with knowledge of the longitudinal phase space, this establishes the energy-time correlation on the spectrometer screen. The slice emittances are determined by varying the strengths of the quadrupoles in front of the spectrometer. Spectrometer images for a range of quadrupole settings are then binned into small energy/time windows and analysed for the slice emittance and Twiss parameters. Results for various gun parameters are presented.

PACS codes: 29.25.Bx,29.27.Ac,41.60.Cr,41.85.Ar

Keywords: Photoinjectors; Transverse Emittance; Slice Emittance; Free Electron Lasers

1. Introduction

The SASE free electron laser requires a bright, low-emittance, high-peak current electron beam best generated by a RF photocathode gun. The RF gun, utilising the concept of emittance compensation with a solenoid field to achieve low transverse emitttance, relies critically upon the alignment of the relative phase-space orientation each temporally short slice of the electron bunch. Unfortunately, there are few measurements of the slice emittance and fewer still verifications of emittance compensation. This work describes experimental results demonstrating that the solenoid affects not only the slice alignment, but also the slice emittance and relative phase space displacements. These three factors combine to produce the observed projected emittance.

In this paper the transverse emittance is determined for both projections and slices. The projected emittance is obtained from time-integrated bunch profiles measured with the usual view screen in a field-free drift after a quadrupole lens. The well-established quadrupole scan technique is used to extract the beam matrix parameters. The slice emittance is the transverse emittance of a short time interval (or slice) of the microbunch. In these experiments the slice emittance is measured using an energy-dispersed beam with a linear energy-time correlation or chirp. This chirp is combined with the quadrupole scan technique to determine the emittance for ten slices along the bunch [1].

This paper presents experimental results from the SLAC Gun Test Facility (GTF), which determine the

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slice parameters and illustrate how these individual slice emittances combine to produce the projected emittance. A detailed comparison for bunch charges of 15 pC and 300 pC illustrates the differences of low- and high-charge beam characteristics, and highlights the need for time-resolved measurements to diagnose and optimise the beam parameters. The data demonstrates a principal cause of large projected emittance is the relative offset of the slices in transverse phase space.

2. Brief Description of the GTF Experiment

The GTF beamline is given in Figure 1 showing the major components used in these experiments. Further details can be found in previous publications [2].

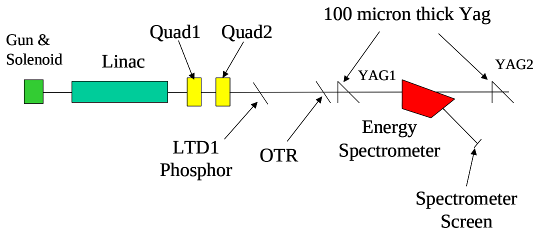

Figure 1. Schematic drawing of the Gun Test Facility beam line.

The projected emittance data is obtained at four locations by using the quadrupole doublet and four separate view screen locations designated by the screen material: optical transition radiation (OTR), YAG:Ce [3] (YAG1), (YAG2) and the phosphor spectrometer screen. An additional phosphor screen, LTD1, is used to determine the beam's entrance position and angle trajectory into the spectrometer dipole. Projected emittances are measured at all four locations while the slice emittance is obtained using the spectrometer screen.

Resolution studies compared emittances measured on both the OTR and YAG1 screens which are separated by only 11 cm. Data for a 500-micron thick YAG screen gave twice the value as obtained using OTR, and analysis showed the 500-micron YAG resolution was approximately 70 microns (rms) for charges below 200 pC.

Because of these results, YAG1 was replaced with one 100-microns thick. An additional, second 100-micron crystal, YAG2, was installed at the end of the beam line. The YAG2 screen, being further from the quadrupoles, sees a larger beam waist than YAG1. Thus the YAG2 resolution requirement is relaxed compared to YAG1. Also, YAG2 is approximately the same distance from the quadrupole as spectrometer screen. This arrangement allows extensive cross checks of the data's accuracy. Low-charge emittance comparisons between OTR and the new 100-micron YAG1 and YAG2 screens are in excellent agreement. The resolution of the 100 micron screens is estimated to be less than 30 microns (rms).

The slice analysis also requires knowledge of the bunch energy-time correlation, the spectrometer energy resolution, and an understanding of the non-bend plane optics. Therefore the longitudinal emittance is measured in conjunction with the slice data, to obtain the energy-time correlation [4]; and beam-based techniques, as well as, magnetic field measurements are used to determine the spectrometer optics.

3. Experimental Results

Data were collected at low and high bunch charge to investigate the effects of space charge and wakefields. The analysis at 15 pC and 300 pC is presented. The drive laser pulse length is 2 ps (fwhm) and an approximately uniform 2 mm diameter on the cathode. The laser was phased 30 degrees from the gun's zero field phase.

3.1 15 pC Results

A summary of the 15 pC data analysis is given in Figure 2. The top panel shows one of the spectrometer screen images acquired during the quadrupole scan when the beam is near a waist. The center panel gives the instantaneous peak current obtained by projecting the top image onto the energy axis and converting energy to time with the results of the longitudinal emittance analysis [4].

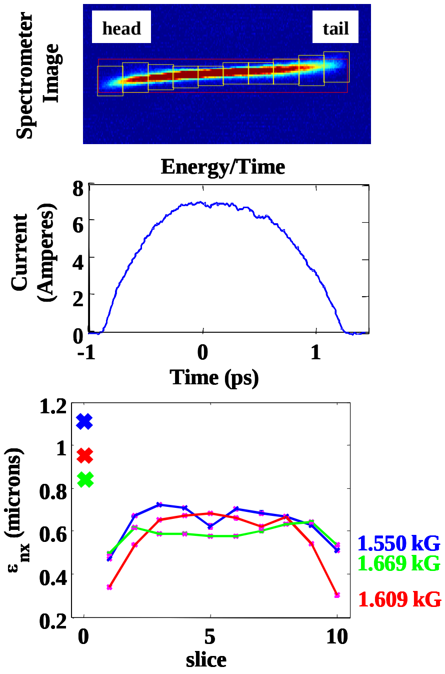

Figure 2. Slice and projected emittances for 15 pC bunch charge. The top image is of the spectrometer screen with the bunch energy chirped in the horizontal direction. The regions used for the 10 slices are outlined with yellow boxes. The bunch is sliced into equal time intervals. The instantaneous beam current is given in the center panel. The slice and projected emittances are plotted in the bottom panel. The projected emittances are given as Slice 0. The values refer to the solenoid fields.

The bunch length is observed to be shorter than the 2ps (fwhm) drive laser uv pulse due to compression in the gun. The full dependence of the longitudinal parameters is given in a companion contribution to these proceedings. [2]

Slice and projected emittances are in the bottom panel. Slice 0 is the projected quantity and is found from summing the image inside the red box to obtain the transverse profile for each quadrupole strength. Slice emittances are shown for three solenoid fields with the slices defined by the ten equal time intervals as indicated. Each box selects electrons contained in a 220 fs wide time slice.

The slice emittances at 1.669 kilogauss are in good agreement with the thermal emittance measured by scanning the gun solenoid field in a modified quadrupole scan technique [5].

Data were collected for a range of solenoid current to illustrate the principal of emittance compensation. However a somewhat different behavior is observed even at this low charge. In particular, the slice emittance depends upon the solenoid field, an effect also seen in the 300 pC data.

3.2 300 pC Results

At 300 pC the experimental situation is very different from the 15 pC case, as shown in Figure 3. First the chirped beam image indicates a wake-like transverse displacement of the tail. Second the slice emittances are now more strongly dependent upon the solenoid field, especially for the front half of the bunch. Third, the optimum solenoid field for lowest emittance is very different for projected and slice quantities. And fourth, the 300 pC bunch has elongated approximately 1.4 times the initial drive laser pulse length.

The relative orientation of the slice ellipses in phase space is quantified with the mismatch factor, ζ, given by [6],

$$\zeta \equiv \frac{1}{2}(\beta_0\gamma - 2\alpha_0\alpha + \gamma_0\beta) \geq 1$$

where α_0, β_0 and γ_0 are the Twiss parameters for a reference ellipse, given in this case by the projected ellipse, and α, β and γ are the beam parameters for each slice. A mismatch of unity corresponds to perfect alignment of the slices.

A comparison of the 300 pC emittances with the slice mismatch, shows again that the best slice emittance occurs at a different solenoid current than that for the

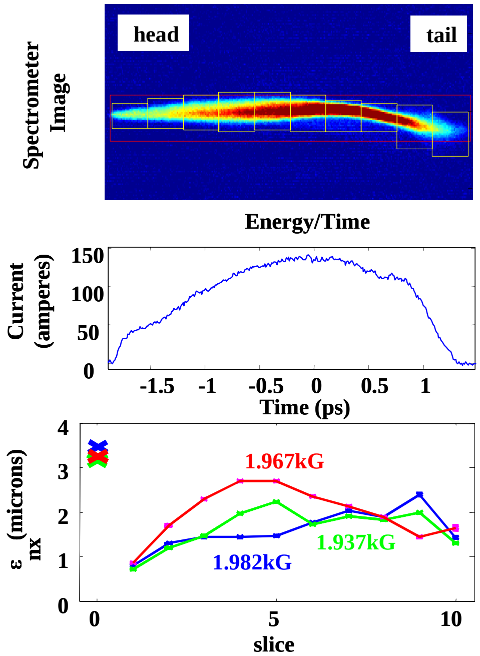

Figure 3. Slice and projected emittances determined for 300 pC bunch charge. The slice time width is 330 fs. These data show an inverse relation between the best slice and projected emittances when optimising with the solenoid.

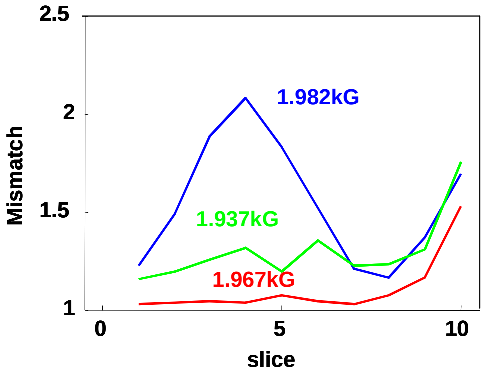

Figure 4. The mismatch the 300 pC slice emittances. The mismatch factor's reference is the projected emittance at that solenoid field. The mismatch factor appears to be anti-correlated with lowest slice emittance.

best alignment of the ellipses. Further work will confirm that slice ellipse displacement in phase space accounts for the bulk of the higher projected emittance.

4. Conclusions

The projected emittance is the result of three basic phenomena: 1. Mismatch between the slice ellipse parameters, 2. Position and angle offsets of each slice's ellipse in phase space, and 3. The emittance of the individual slices. Of these only the first is considered by standard emittance compensation theory. The other two are always present, but rarely considered, either in theory or experiment. However this work shows they can dominate the projected emittance, even to the extent that emittance compensation effects are evident only by the analysis of the slice data.

5. Acknowledgements

SLAC is operated by Stanford University for the Department of Energy under contract number DE-AC03-76SF00515.

6. References

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