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Longitudinal Measurements at the SLAC Gun Test Facility*

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Abstract

The Gun Test Facility (GTF) was built to test high-brightness sources for the proposed Linac Coherent Light Source (LCLS) at SLAC. The longitudinal emittance exiting the gun has been determined by measuring the energy spectrum after the linac as a function of the linac phase. The phase-space parameters defining the beam pulse width, correlated energy spread, and slice energy spread at the linac entrance (~5 MeV beam energy) are fit to the measured energy spectra. A large, linear energy-time correlation is observed for bunch charges from 15 to 300 pC. Possible explanations for this correlated energy spread are discussed.

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The Gun Test Facility (GTF) was built to test high-brightness sources for the proposed Linac Coherent Light Source (LCLS) at SLAC. The longitudinal emittance exiting the gun has been determined by measuring the energy spectrum after the linac as a function of the linac phase. The phase-space parameters defining the beam pulse width, correlated energy spread, and slice energy spread at the linac entrance (~5 MeV beam energy) are fit to the measured energy spectra. A large, linear energy-time correlation is observed for bunch charges from 15 to 300 pC. Preliminary Parmela calculations show this correlation results from the longitudinal space charge forces in this short 2 ps long bunch.

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1. Introduction

Free electron lasers require low longitudinal emittance beams to achieve high peak current when the bunch is compressed in a bunching chicane. The use of a magnetic bunch compressor requires a good understanding of the longitudinal phase space from the RF gun. While the transverse emittance from RF guns is studied extensively, the longitudinal emittance is still poorly known.

This paper begins with a review of the experimental technique, followed by a description of the data analysis method. The final sections summarize the longitudinal emittance results and the parameters for bunch charges from 15 to 300 pC.

2. Description of the Experiment and Data

The experiment was performed at the SLAC Gun Test Facility (GTF) consisting of a 1.6 cell s-band gun of the BNL/SLAC/UCLA design followed by a 3-meter SLAC section [1]. The drive laser is a Nd:Glass CPA laser with a regenerative amplifier which provides 2 ps (fwhm) gaussian UV pulses to the cathode with an approximately uniform, 2 mm diameter transverse profile. The major beam line components are shown in Figure 1.

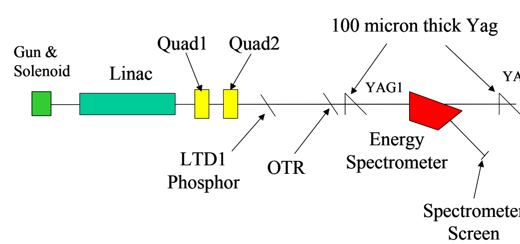

Figure 1. The GTF beamline.

This experiment uses the phase scan technique to determine the longitudinal emittance, in which the linac RF phase is varied and the beam energy spectrum is measured on the spectrometer screen.

Analysis gives the longitudinal parameters at the entrance to the linac. These are not the same as those at the gun exit, because of continued evolution of the bunch as it drifts from the gun to the linac.

3. The Longitudinal Phase Space

The data analysis assumes a longitudinal beam ellipse defined by,

$$\tau = \begin{pmatrix} \tau_{11} & \tau_{12} \\ \tau_{12} & \tau_{22} \end{pmatrix}; \tau_{11} = \sigma_t^2 ; \tau_{22} = \sigma_E^2 \qquad (1)$$

where the τ-matrix elements, τ_{11} and τ_{22}, are the rms pulse length squared and the rms energy spread squared, respectively.

The transformation of the beam matrix through the linac is given by,

$$\tau(1) = R_{linac} \tau(0) R_{linac}^T \qquad (2)$$

$\tau(0)$ and $\tau(1)$ are the beam matrices at the linac entrance and exit, respectively. Assuming the linac gives a simple $V_{linac}\cos(\phi_0)$ energy boost to the bunch, the linac R-matrix is,

$$R_{linac} = \begin{pmatrix} 1 & 0 \\ -V_{linac}\sin(\phi_0) & 1 \end{pmatrix} \qquad (3)$$

where ϕ_0 is the phase of the reference electron at the bunch center. Multiplying the matrices in Eqn. 2 gives the rms energy spread,

$$\sigma_E^2 = \tau_{22}(0) - 2\tau_{12}(0)V_{linac}\sin(\phi_0) + \tau_{11}(0)(V_{linac}\sin(\phi_0))^2 \qquad (4)$$

The experimental rms energy spread for a range of linac phases, ϕ_0, are fit with this function to obtain the three $\tau(0)$ matrix elements. The rms longitudinal emittance is defined as,

$$\varepsilon_{long} = \sqrt{\tau_{11}\tau_{22} - \tau_{12}^2} \qquad (5)$$

and expressed in units of ps-keV.

Estimates of the phase slippage give 7 to 9 degrees, which simply shift the $V_{linac}\cos(\phi)$ RF waveform by this amount in phase, as confirmed by a Parmela calculation. This shift has little effect on these results, since maximum energy gain is used to define zero RF phase. However Parmela also indicates approximately 15% change in the pulse length during acceleration in the linac which is not accounted for in this analysis.

4. The Experimental Results

Measurements of the energy spectrum for several linac phases were performed for bunch charges from 15 to 300 pC. The rms energy widths are then fit using Eqn. 4 to obtain the $\tau(0)$ matrix, giving the longitudinal emittance, bunch length, uncorrelated energy spread and correlated energy spread at the linac entrance. Because of their relevance to a companion contribution to these proceedings [2], the 15 and 300 pC data are shown in some detail. A summary of the parameters at all charges is then given.

4.1 15 pC and 300 pC Measurements

The data along with the fits are shown in Figure 2 for 15 pC and 300 pC. In general, the data fitting uses data in the region approximately 20 degrees wide, centered at the minimum energy spread phase. This is done because the energy spectra become more complex at the large phases due to the non-linear nature of the longitudinal phase space. This is a linear analysis, since it represents a simple ellipse enclosing a complex energy-time distribution, and as such will over estimate the longitudinal parameters. Previous work [3] has shown the need to include higher order terms, especially a 3rd order term to properly represent the phase space distribution. The non-linear analysis of this data is in progress.

In addition, a secondary electron bunch trailing approximately 1.5 ps behind the primary bunch was observed during the experiment. This second bunch contained 5 to 10% of the total bunch charge, and attempts to remove it were unsuccessful. Its source is being investigated.

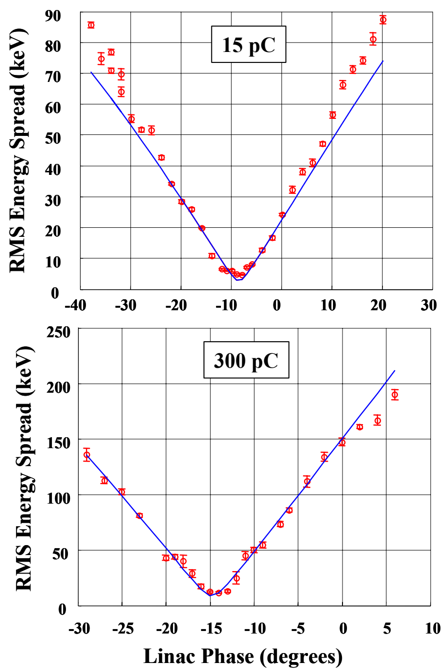

Figure 2. Top: The rms energy spread vs. linac phase for 15 pC bunch charge. Bottom: Data and fit for 300 pC. The lines are best fits for the beam matrix elements in Eqn. 5 to data in the region of minimum energy spread.

The 15 pC data in Figure 2 indicate the energy measurements are near the resolution limit of the spectrometer. This can be seen by the flattening of the minimum energy spread data at 5 keV (rms). This is consistent with the estimated resolution. The data was taken after careful optimisation of the electron optics to achieve the best resolution.

4.2 Correlated Energy Spread

Both the 15 and 300 pC data clearly show the linac phase for minimum energy spread is at –9 and –15 degrees relative to the crest. Similar phases are observed for all bunch charges. This can be seen most graphically by the longitudinal ellipses for 15, 100 and 300 pC shown in Figure 3.

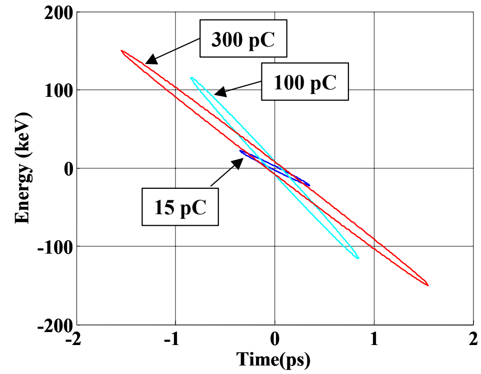

Figure 3. Relative orientation of the longitudinal phase space ellipses for 15,100 and 300 pC bunch charges.

Preliminary analysis using Parmela indicates much of this correlation results from the longitudinal space charge forces in the short 2-ps long bunch. However, another possibility is that the RF fields in the 0.6 and full cells of the gun are not equal [4]. The 0.6 cell field needs to be approximately 20% lower than the full cell field to account for this correlation. To investigate this effect, the gun is now removed from the experiment and its field distribution will be mapped using the bead drop technique. In addition, an RF probe will be installed in the 0.6λ cell to allow measurements of the field balance during gun operation.

5. Summary of Results and Conclusions

The dependence of the longitudinal emittance, bunch length and uncorrelated energy spread upon bunch charge are shown in Figures 4, 5 and 6. The emittance and bunch length are seen to grow linearly with charge. This strong growth is driven by the short, 2 ps (fwhm) laser pulse used in these experiments. At 200 pC for example, the 2 ps laser pulse produces 100 amperes peak current at the cathode and a peak surface current density of over 3000 amperes per cm^2. The strong longitudinal space charge force overwhelms the RF compression seen at low charge, as shown in Figure 5.

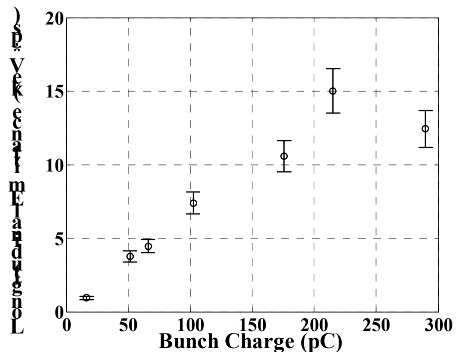

Figure 4. The rms longitudinal emittance vs bunch charge.

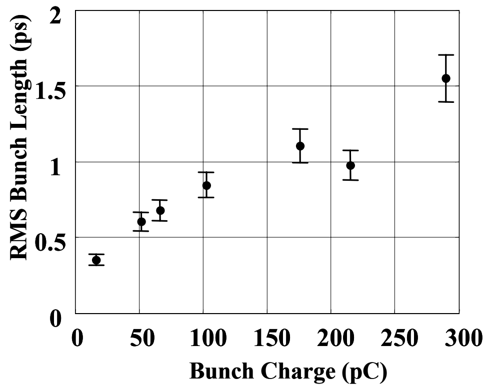

Figure 5. The rms length vs. charge. The bunch shows compression below and elongation above 100 pC. The laser phase is 30 degrees relative to the zero crossing of the RF field. The laser pulse length is 0.85 ps (rms).

6. Conclusions

A large correlated energy spread has been measured for bunch charges between 15 to 300 pC. Preliminary Parmela analysis suggests this is due to strong longitudinal space charge forces. However another possibility is an unbalance of the RF fields between the 0.6λ and 1.0λ gun cells. Both effects are being investigated. In addition, a smaller, second bunch trailing the main bunch by approximately 1.5ps is also observed. Efforts are in progress to understand its origin.

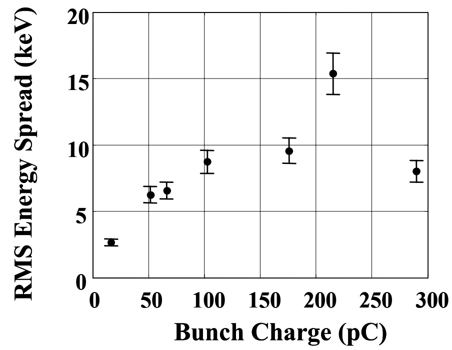

Figure 6. The bunch rms energy spread vs. charge.

7. Acknowledgements

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8. References

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