Characterization of E158 Beam

Joe Farrell

Office of Science, Student Undergraduate Laboratory Internship (SULI)

San Francisco State University

Stanford Linear Accelerator Center

Menlo Park, California 94025

August 8, 2003

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy's Student Undergraduate Laboratory Internship under the direction of J. Turner in the Accelerator Department of Stanford Linear Accelerator Center.

Participant: _____
Signature

Research Advisor: _____
Signature

Table of Contents

Abstract	iii
Introduction	1
Methods and Materials	3
Results	6
Discussion and Conclusions	7
Acknowledgments	8
References	9
Tables and Figures	10

ABSTRACT

Characterization of E-158 Beam. JOSEPH P. FARRELL (San Francisco State University, San Francisco, CA, 94132) JAMES L. TURNER (Stanford Linear Accelerator Center, Stanford, CA, 94025).

Stanford Linear Accelerator Center (SLAC) parity violation experiment E-158 uses a high intensity electron beam accelerated to either 45GeV or 48GeV in the SLAC Linac and requires a small energy spread, small off axis position motion, and low jitter. The purpose of our research was to better quantify the current values of energy, intensity, and position jitter as well as the relations between them and to further the understanding of the beam dynamics involved. Specifically, our method was to take data on a series of pulse lengths shorter than the experimental beam to gain information about the length dependence of the different beam parameters, effectively enabling us to create jitter, position, and energy profiles of the beam. Position was measured by beam position monitors (BPMs), intensity was measured by toroids, and energy was measured by a Synchrotron Light Monitor (SLM) as well as several energy BPMs. Data was collected using the SLAC Control Program (SCP) and analyzed using Matlab. Position jitter was found to, in general, increase linearly (10microns per 50ns) with pulse length. The peak to peak energy difference across each pulse is currently about 0.4% of the total energy, with the RMS energy jitter usually ranging from 0.013% to 0.10% for the different pulse lengths. Intensity jitter had no discernable correlation with pulse length. The slope of the linear relation between energy and intensity (beam loading relation) varied significantly with pulse length as well as with the method used to extract energy data. The position, intensity and energy profile data agree qualitatively with accepted theories and provide a more encompassing picture of the beam dynamics for E-158. The same is true, to a lesser extent, for the energy jitter and beam loading data, although some results here were unexpected.

INTRODUCTION

The purpose of the SLAC experiment E158 is to measure parity violation in Moller scattering by measuring an asymmetry in the scattering cross sections of high energy longitudinally spin-polarized electrons elastically scattering off an unpolarized electron target. The Standard Model asymmetry expected has an approximate value of 10^{-7} and is between electron bunches with opposite polarizations. Experimenters are measuring the asymmetry to an accuracy of 10^{-8} . In order to achieve this accuracy, a high intensity electron pulse is used to create large numbers of events and unwanted asymmetries between the differently polarized bunches which originate from the accelerator setup itself are minimized and controlled. First order asymmetries in the beam parameters E , x , x' , y , y' , and Intensity need to be accurately measured while higher order terms, which are considered to have a magnitude of $<1\text{ppb}$, are neglected [5]. E-158 requires very low beam jitter because it can create, amplify, and conceal these systematically caused asymmetries.

E158 is conducted by creating pulses of polarized electrons, accelerating them to the necessary energy, and colliding them into a target of liquid hydrogen. The $>80\%$ polarized electrons are photo-emitted by a 260 nanosecond long, circularly polarized laser pulse striking a SLAC designed photocathode [2] at a repetition rate of 120 Hertz. The laser used is a SLAC designed, flash lamp pumped, Ti:Sapphire laser [1]. Each laser pulse currently results in the emission about 5×10^{11} electrons, which come off the photocathode at 120 keV and are accelerated by RF pulses to a maximum energy of either 48.74GeV or 45.463GeV in the SLAC Linac. The electron bunches are then bent around a 24.5 degree turn and sent into the target.

Our work is foremost an analysis of the magnitude of energy, position, and intensity jitter for different positions along the electron pulse during the summer 2003 run of the experiment. Secondly, we quantified the current conditions of some known relations, such as beam loading, between these different forms of jitter. Also, position and energy profiles of the beam along the bunch train were

created in order to more accurately assess the importance of higher order beam asymmetries such as spot size.

The primary causes of position jitter are transverse wakefields and dispersion. Wakefields originating from beam interaction with accelerator irises create large, wagging beam tails that are unstable and tend to have high position jitter (see Figure 1) [3]. Transverse wakefields are always existent, but the net force from them is related to how far the beam centroid is off the axis in the Linac. Oscillations about the axis are unavoidable due to the fact that even a very tiny misalignment of a single magnetic element can push the beam off axis and induce an oscillation (see figure 2). Typical oscillations have a magnitude of about 1mm. Alignment corrections and ‘wakefield compensating bumps’ are then necessary to minimize this unavoidable beam tail motion. Position jitter also occurs as a function of energy jitter due to dispersion through magnetic elements along the Linac.

Intensity noise, which is a major factor in magnifying jitter in position and energy, originates, for the most part, in the laser system [1]. The focus of our research is beam dynamics in the Linac and A-Line, and as such the sources of intensity jitter were not studied in detail, only it’s relations to position and energy.

Energy jitter is typically caused by intensity fluctuations loading the RF. Beam loading is the reduction of the electric field from RF pulses due to energy loss to the passing electron pulses. This effect unavoidably reduces the magnitude of the RF between 8.5% and 14.5% (depending upon the intensity of the beam) and can also increase the energy spread across the pulse, affecting the tail the most. In order to minimize the energy spread, the phase (with respect to the RF pulses) and intensity distribution of the beam have been carefully adjusted. Fluctuations in the intensity break that balance, with, in the simplest case, increases in average intensity leading to decreases in average energy. So, a negative correlation between energy jitter and intensity jitter is expected, with the greatest effect expected in the tail of the pulse.

MATERIALS AND METHODS

All data was taken directly from the E158 experimental beam at SLAC during the time period July 20, 2003, to August 18, 2003, and, unless otherwise stated, should be considered generally indicative of the beam characteristics of the experiment during this time. Data sets were taken while beam energies were at 45.463GeV as well as 48GeV with pulse lengths of 266ns and 227ns, respectively. No significant difference in beam behavior due to beam energy was expected. Data was taken using toroids, RF and strip-line Beam Position Monitors (BPMs), photo diodes, and RF Phase detectors and was obtained either directly from oscilloscopes on location or through SCP. The Linac is divided into 30 sectors, denoted LI01-LI30. LI00 denotes the injector sector. The A-Line consists of the beam line from LI30 to the target, which includes the 24.5 degree bend and contains two micros, FB31 and AB01.

Intensity information was gathered using toroids. They are useful for getting an intensity profile of electron pulses as well as total number of electrons per pulse (see Figure 3).

Position information in the Linac was gathered using strip-line BPMs while RF BPMs were used in the A-Line. The strip-line BPMs, which are sensitive only to changes in current, and SCP were originally calibrated to measure 20ps long pulses and to differentiate between electron and positron pulses by the sign of the current change. The 266ns(227ns) E-158 electron pulse produces a sharp change in current as the head passes by and an opposite current change as the tail passes by, but nothing in between (see Figure 4). For this reason strip-line BPMs are only able to collect data on the head and tail of the beam, not the middle. Position measurements of the head of the pulse are made by setting the SCP to read positive changes in current (electron definition) and for the tail by setting the SCP to read negative changes in current (positron definition). However, head and tail measurements cannot be made simultaneously, so only average head and tail motion can be compared. ‘Head data’ and ‘tail data’ refer to data sets taken with the strip-line BPMs configured to electron definition and positron definition respectively.

When calculating position jitter due to Linac strip-line BPMs, bad data points were eliminated by cutting all points with RMS position (position jitter) greater than .3mm for head data sets and .4mm for tail data sets.

RF BPMs integrate over the entire electron pulse and give readings on the average position of the beam away from the axis of the tube. They do not give explicit data on the head and tail of the pulse, but can be used to give qualitative position profiles of the beam (see Figure 7). They generally are considered to have less systematic error than strip-line BPMs. In addition to position jitter plots, RF BPMs were used to create position and energy profiles of the beam. Two types of position profiles were made. First, direct data from RF BPMs was plotted against pulse length. However, because each point is the average position of the pulse length, these plots are not entirely indicative of the shape of the beam, so an iterative method was used on the RF data to estimate the actual position profile of the pulse. Plots using this method are called ‘adjusted position(or energy) profile plots’.

Information about the energy of the beam is determined in two ways. First, as the beam is directed around the 24.5 degree turn following the Linac, higher energy electrons are deflected slightly less through the bend magnets than lower energy ones, creating large position differences (up to 20mm) that can be measured by either a strip-line BPM (AB01 1790 in the x direction) or any of several RF BPMs. A linear dispersion relation (see Figure 5 and Table 1) is used to relate position jitter to energy jitter, requiring only the geometry of the bending magnets and mean energy of the beam. This gives a measurement of the pulse-to-pulse energy jitter with a maximum error of 10%. These BPMs are referred to as energy or dispersion BPMs. Secondly, position differences of synchrotron light emitted as the beam rounds the turn can, through a similar relation, be used to determine the mean energy as well as energy spread throughout each individual pulse. Because the RF BPMs average over the whole pulse, we expect the values of energy data from RF BPMs to be about half that of values of tail data from 1790x.

Data sets on a series of different pulse lengths (74ns, 132ns, 200ns, 266ns) were taken on July 30 and again on July 31 with a beam energy of 45GeV while another set (60ns, 74ns, 132ns, 168ns, 200ns,

227ns) was taken on Aug 18 with a beam energy of 48GeV, each run taking about ten to twenty minutes of experimental beam time. During these runs, the physical length and overall intensity of the beam were reduced by changing the triggering of a Pockels cell in the laser system. The motivation for doing this was primarily that, due to the limitations of the strip-line and RF BPMs, exact values of position, position jitter, and energy jitter information about the middle of the 266ns pulses were unobtainable. Readings on shorter pulse lengths were considered to be effective analogies to the middle of the 266ns or 227ns pulse. Head data sets are used as the 0ns readings.

A SCP macro was used to take all needed data for the different pulse lengths. A total of 120 strip-line BPMs in the Linac, one strip-line energy BPM, eight RF BPMs in the A-Line measuring energy, position, and angle, four toroids in LI00, four toroids in AB01, four photodiodes, one beam phase monitor, and a phase monitor on the first klystron were used. We took data on 120 pulses for each pulse length. Originally, it was assumed that the different pulse lengths did not affect the behavior of the head of the pulse, so head data was only taken at 266ns pulses. This decision cost us pulse length data from the RF BPMs, which weren't triggered properly during tail data runs. The data taken on Aug 18 contained head data sets (thus good RF data) for all pulse lengths. Also, during a period of high jitter on July 31, we took two data sets of only 266ns pulse lengths.

We took data on different pulse lengths in order to investigate how known correlations in the jitter as well as overall beam behavior changed with pulse length. In effect, we constructed jitter and position profiles of the pulse, which directly relate to the behavior of the experimental beam and can potentially tell us more about the motion of the beam down the accelerator.

Technical Information for SLAC Physicists

The SCP macro used is titled A_BEAM_JITTER and is located in the BPMOBUFR panel under the ESA panel type. Tail data sets were calibrated with 'SuperAsset' calibration located in BPM Calibration Panel while head data sets were calibrated with CIDESA. The triggering delays used on shorter pulses are given in Tables 2-3. All data sets are stored in PHYSICS1_DATA:[FARRELL] on the

SLAC network. The .m files used to analyze the data are located in groups/ad/dropboxes/jturner/farrell on the SLAC network.

RESULTS

Figures 8, 9 and 10 show averaged RMS energy jitter as a function of pulse length for all data sets. Energy jitter data taken from the dispersion strip-line BPM 1790x and the dispersion RF BPM 1240x are compared. In general, energy jitter ranged from .02% in the head (0ns) to .08% in the tail for 1790x readings and significantly less than that for 1240x, as expected. Figure 41 shows a Synchrotron Light Monitor (SLM) mean energy profile and a profile of the energy spread throughout the beam. The peak-to-peak mean energy change was about 200MeV, which is about 0.44% of the total energy. The energy spread ranged from 50 to 100 MeV. This data was taken only for a 266ns pulse and was compiled and averaged automatically by the SCP. Figure 42 shows a similar plot taken on Aug 18 using adjusted 1240x data. Here the peak-to-peak energy change is around 80MeV. The energy profile of the beam is expected to fluctuate significantly with small changes in injector tuning or phasing of the beam with respect to the RF, so the difference in these two readings is not abnormal.

Figure 11 shows intensity jitter, which ranged from 0.57% for the head to 0.77% for the 74ns tail and averaged at 0.68%. Also, intensity jitter was found to have a strong linear relationship with laser intensity jitter with correlation coefficients reaching 0.95. All intensity values used were obtained from toroid 60 (TORO 60) in sector AB01.

Figures 12 and 13 plot the pulse length dependence of RMS position (position jitter) in the Linac. Figure 12 uses an average of the July 30, 31 data and Figure 13 uses the Aug 18 data. These position values were obtained from the 122 strip-line BPMs in the Linac. The July 30/31 data show an approximately linear increase in position jitter. For all data sets the tail of the pulses (227ns or 266ns) had at least twice the jitter as the head (0ns). Figures 14 –15 qualitatively show the difference between head and 266ns tail position jitter. Figures 16-18 show position jitter as read by RF BPMs in the A-Line. Unlike the Linac readings, here the jitter decreases as pulse length increases. Figure 19 shows the jitter profile of BPM LI09 901 in the Y direction, which had unusually high jitter. The jitter stays constant at

about .05mm until about halfway through the pulse where it climbs to .3mm, an increase of a factor of nine. Figures 20 and 21 show how the position/intensity and energy/intensity relationships change with pulse length for BPM LI09 901 Y. Figures 22-29 show position profiles for RF BPMs in the A-line while Figures 30-33 show adjusted position profiles for the same RF BPMs.

Correlation plots between energy jitter and intensity jitter, also called beam loading plots, were made for each set of data. The correlation is linear, and Figures 34-38 qualitatively show its pulse length dependence as well as compare plots made using 1790x data and 1240x data both taken on Aug 18. Figures 39-40 summarize the pulse length dependence for the beam loading slope, again comparing the 1790x and 1240x data from Aug 18. Most notable is the strange character of the 1790x plot, which has several positive points (a negative correlation was expected) and a point with an extremely large magnitude. The 1240x plot predictably has all negative values and the magnitude gets larger with pulse length.

We also found strong correlations between position and energy, position and intensity, and energy and beam phase. These and other relations haven't yet been adequately analyzed, however.

DISCUSSION AND CONCLUSIONS

The known increase of position jitter with pulse length has been further quantified for this run and has been put at nearly 0.2 microns per ns for both x and y in the Linac during low jitter conditions. The Aug 18 results of Linac position jitter showed a large jump in jitter near the middle of the pulse but the head and tail of the pulse had jitter values very close to the July 30/31 data. All three RF BPM jitter readings unexpectedly show a decrease in jitter with increases in pulse length, a result that conflicts with position jitter data in the Linac.

Position and energy profile plots as well as adjusted position and energy profile plots provide E-158 experimenters with data that is useful for them to assess the asymmetries caused by spotsize and other higher order terms.

The fact that intensity jitter exhibited no discernable pulse length dependence coupled with the strong dependence on laser intensity jitter supports the notion that almost all intensity jitter originates

prior to the Linac. We can then assert that intensity jitter is the independent variable in pulse length dependent relations involving it.

Results on the pulse length dependence of the energy jitter and energy/intensity relationship were, in general, as expected. RF BPM measurements showed steady increases in energy jitter and steady increases in the magnitude of the negative beam loading slope. This supports the simplified beam loading theory discussed in the introduction. However, the 1790x data had some extremely high jitter readings as well as repeated positive beam loading slopes, indicating an increase in beam energy with increased intensity. These results are not in agreement with the 1240x data. We have concluded that the 1790x energy readings for shorter pulse lengths are probably not accurate.

Also, the 74ns spike that appeared in several position, position jitter, and energy jitter plots was probably an isolated fluctuation in beam behavior and not indicative of normal running conditions.

This study gives E-158 experimenters a more telling account of the beam jitter for this run, giving them information about the interior of the beam that was not previously known. Comparisons of data taken through different methods, such as the energy jitter and beam loading plots, allowed for detection of previously unknown systematic errors. Also, RF position profiles will enable experimenters to assess the systematically caused asymmetry more accurately. In general, most results were as expected, however, the position jitter results from the RF BPMs are unexpected and need to be analyzed further. Future work would also include using this data to attempt to distinguish between dispersion and transverse wakefield effects in regard to position jitter.

ACKNOWLEDGMENTS

I would like to thank the SULI program for giving me the opportunity to have this experience, which has given me a much clearer picture of how physics research is conducted. I would also like to thank my mentor Jim Turner for his dedication and Mike Woods, Jym Clendenin, and Franz-Josef Decker for their guidance along the way.

REFERENCES

- [1] J.L. Turner, A. et al., "A High-Intensity Highly-Polarized Electron Beam for High-Energy Physics," EPAC'02, Paris, June 2002.
- [2] A. Brachmann et al., "SLAC's polarized electron source laser system for the E-158 parity violation experiment," SLAC-PUB-9145, Mar 2002.
- [3] J. Seeman, "Linear Collider Accelerator Physics Issues regarding Alignment," *Stanford 1989, Proceedings, Accelerator alignment* 257-262, 1989.
- [4] F.-J. Decker, et al., "High Power Beam at SLAC," PAC'01, Chicago, June 2001.
- [5] M. Woods, et al., "Run 1 Systematic Error for Beam Asymmetry Corrections," E158 TechNote 45, March 2003.

Tables

Table 1. Values of eta for different BPMs

BPM	type	eta (mm)
1790x	strip-line	-5060
1020x	RF	-650
1240x	RF	-420
2420x	RF	-88

Table 2. Trigger Delays for July 30, 31 datasets

Trig 310	BPM e+ delay
142	266
76	200
8.6	132
-58	74

Table 3. Trigger Delays for Aug 18 datasets

Trig 310	BPM e+ delay
-58	60
-44	74
17	132
50	168
84	200
109	227

Figures

Figure 1. Characterization of growing of wakefield induced tails as the pulse travels down the Linac. Depiction is of a short (rms length is about 1mm) “micro”-bunch in one rf bucket. In contrast, the E-158 beam is a train of about 800 micro-bunches with bunch spacings of 0.3 nanoseconds, but the effect is similar. Taken with permission from ‘Linear Collider Accelerator Physics Issues Regarding Alignment’ by John T. Seeman [3].

Figure 2. Position oscillations of electron pulses as they accelerate down the Linac taken on July 29. These are on the order of about 1mm.

Figure 3. Toroid reading showing the trapezoidal intensity distribution used to minimize energy spread during beam loading. Intensity jitter is evident along the top of the pulse.

Figure 4. Strip-line BPM reading of the changing current as the 266ns E-158 electron pulse passes by. At $t = 0$ the front of the pulse passes by and the BPM detects an ‘electron pulse’, while at $t = 266$ ns the current drops to zero and the BPM reads a ‘positron pulse’. This figure can be thought of as the derivative of Figure 3.

Figure 5.

Figure 6.

Figure 5-6. RF BPM scope traces for x and y of two BPMs located near the injector (Figure 5) and two located near the target (Figure 6.). Top two traces are x and the bottom two traces are y for both Figures. The rf bpm signals are proportional to the integral of position offset times charge for the duration of the pulse, and then the signals decay with a time constant of a few 100 ns after the beam signal passes. Thus, a perfectly centered beam gives no signal; a beam with a simple offset will give a triangular shaped pulse. A beam whose offset changes during the train (due to a tilt or banana shape) will show some curvature in the pulse shape.

$$dE = \frac{E}{\eta} dx$$

Figure 7. Linear dispersion relation used to convert displacement to energy. η is a constant derived from the geometry of the system E is the mean energy, and dx is measured by a BPM.

Figure 9. RMS energy jitter from RF BPM 1240x the pulse from BPM 1790x on Aug 18. The high reading at 74ns was unexpected and is probably a systematic hiccup.

Figure 8. RMS energy jitter as a function of time in

on July30/31. Note there is no jump in the middle of the pulse and the magnitude is significantly less than the 1790x values, as expected.

Figure 10. RMS energy jitter as a function of time in the pulse from BPM 1790x on July 30/31.

Figure 11. RMS Intensity jitter as a function of pulse length. Note that there is little change with varying pulse lengths.

Figure 13. RMS position jitter analogous to Figure 12 strip-line BPMs in both x and y as a function of time in the pulse taken on July 30/31. They both vary close to linearly with nearly the same slope.

Figure 12. RMS position jitter averaged over all Linac

taken on Aug18 and averaging over all 122 Linac BPMs. The middle of the pulse has high jitter, but the head and tail have very similar values to Figure 12.

Figures 14 –15. Qualitatively show the difference between head and tail jitter along the Linac.

Figure 16. Position Jitter Profile from Aug 18 data for RF BPM 1010, which is at the start of the A-Line. The large spike and low tail jitter results are unexpected. Again, we see an abnormal spike in the 74ns data.

Figure 17. Position Jitter Profile from Aug 18 data for RF BPM 3115, which is located 40m upstream of the target. Again, the falling jitter values with pulse length are unexpected.

Figure 18. Position Jitter Profile from Aug 18 data for RF BPM 4160, which is located 1m upstream of the target. The 74ns spike persists.

Figure 19. Jitter Profile for high jitter strip-line BPM Y LI09 901

Figure 20. Profile indicating how the strong correlation between position and Intensity jitter changes with time in the pulse for BPM Y LI09 901.

Figure 21. Profile indicating how the correlation between position and Energy jitter changes with time in the pulse for BPM Y LI09 901.

Figures 22 –25. Position profiles in Y taken using RF BPMs in the A-Line. Points are position averages of entire pulse length, so these graphs are not entirely indicative of pulse shape. The 3115 plot should be comparable to the purple (second to bottom) scope trace (which is a 3115 trace) and the 4160 plot can be compared with the bottom trace (a 4160 trace). The 74ns spike appears again on the 4160Y plot.

Figures 26 –29. Position profiles in X taken using RF BPMs in the A-Line. The top scope trace (yellow) is of 3115 while the second trace from the top is of 4160.

Figures 30-33. A iterative process was used on RF position data to give more accurate position readings for RF BPMs 3115 and 4160. The 74ns spike appears again in several of these plots. It probably should not be considered indicative of normal beam behavior.

3115x

4160x

3115y

4160y

Figures 34 – 38. Intended to qualitatively show the dependence of the energy/intensity correlation on pulse length. All y-axes are RMS energy jitter and all x-axes are RMS intensity jitter. Plots were made using energy data from strip-line BPM 1790x as well as RF BPM 1240x and comparisons are made. Some 1790x plots show enormous positive slopes that are not expected. This, coupled with the fact that 1240x readings show only a steadily increasing negative slope, lead to the thought that there is some reoccurring systematic error in the 1790x data.

Figure 34. Head (0ns) reading from 1790x. There is very little correlation.

Figures 35-36. 74ns. The 1790x data has an extremely large positive slope. These two data sets are contradictory.

1240x 1790x tail

Figures 37-38. 227ns pulse tails. 1790x data now has a comparable slope to 1240x data (-.05647 vs -.0772).

Figure 39. Averaged Beam Loading Slope dependence on pulse length using energy measurements from strip-line BPM 1790x. The positive slopes of the 74ns, 132ns and 168ns tails were unexpected. It's possible that there is a reoccurring systematic error.

Figure 40. Averaged Beam Loading Slope dependence on pulse length using energy measurements from RF BPM 1240x. These results are quite different from those of Figure 23 (i.e. there are no positive or extremely large slopes) and were taken from the same data sets.

Figure 41. SLM Energy Profile and energy spread (width) along the length of the pulse. Data was taken at the end of July with a mean energy of 45GeV. This profile is dynamic and can be significantly changed with changes in injector tuning or phasing of the beam with respect to the RF. At the time this data was taken the peak-to-peak energy change was about 150MeV-200MeV and the energy spread along the pulse was around 50MeV – 100MeV.

Figure 42. Adjusted Energy Profile using RF BPM 1240x data taken on Aug 18 at an energy of 48GeV. Peak to peak energy change is about 80MeV.