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Measurements of Longitudinal Phase Space in the SLC Linac*

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I. Abstract

The electron and positron bunch distributions in the Stanford Linear Collider (SLC) linac have been measured using a Hamamatsu, model N3373-02, 500-femtosecond streak camera[1]. The distributions were measured at the end of the SLC linac versus the bunch compressor RF voltage. The energy spread at the end of the linac was also measured using a wire scanner. The effects of the bunch compressor on the shape of the bunch distribution are also presented.

II. Bunch Compression in the SLC Linac

In a linear collider the transverse emittance needs to be small for high luminosity. Damping rings are used to damp the emittance. The bunch extracted from the damping ring is too long for acceleration in an S-band linear accelerator. To reduce the bunch length after extraction, the bunch is compressed.

The bunch distribution in the SLC linac is determined from the distribution in the damping rings, and the bunch compressor. The bunch compression system at the SLC consists of two parts: 1) a non-isochronous transport line from the damping ring to the linac (referred to as the transport line), and 2) an S-band RF accelerating section at the beginning of the transport line (referred to as the compressor). The electron and positron damping rings have separate transport lines and compressors.

Bunch compression is determined by the relationship

$$z_f = z_i + R_{56}\frac{\Delta E}{E}$$

where R_{56} is determined by the optics in the transport line, z_i is the location of a particle in the bunch before compression, $\frac{\Delta E}{E}$ is the energy offset of a particle after the compressor, and z_f is the location of a particle in the bunch after compression.

When the bunch is extracted from the damping ring it passes through the compressor RF accelerating section where the mean of the bunch distribution is centered on the zero crossing of the compressor RF wave. The compressor voltage gives the distribution a correlated head-tail energy spread (tail of distribution is lower in energy than head). After the compressor the bunch travels through the non-isochronous transport line where the longitudinal phase space rotates. Phase space rotation occurs from the high energy particles (head) taking a longer path than lower energy particles (tail) through the dispersive transport line. The compressor voltage amplitude can be varied so that the bunch is under-compressed, fully-compressed, or over-compressed.

III. Bunch Length Measurement

The streak camera uses synchrotron light produced in the splitter magnet at the end of the linac to determine the longitudinal bunch distribution. The projections of the longitudinal distribution are saved and analyzed off-line.

The mean and σ of the projections are estimated by fitting the entire profile to an asymmetric Gaussian function

$$I(z) = I_0 + I_1 \exp\left\{-\frac{1}{2}\left(\frac{(z-\bar{z})}{(1+sgn(z-\bar{z})A)\sigma}\right)^2\right\}$$

where I_0=pedestal, and I_1=peak of the asymmetric Gaussian. The term $sgn(z-\bar{z})A$ is the asymmetry factor which parameterizes the shape of the asymmetric Gaussian. Since the shape deviates considerably from an asymmetric Gaussian, a better estimate of the bunch length is provided by the root mean square width

$$\sigma_z = \sqrt{\sum_i^N (z_i - \bar{z})^2 I(z_i)}$$

where N is the number of CCD pixels within $\pm 3\sigma$ of the mean $\bar{z}$, z_i is the location of the pixel, and $I(z_i)$ is the projection height.

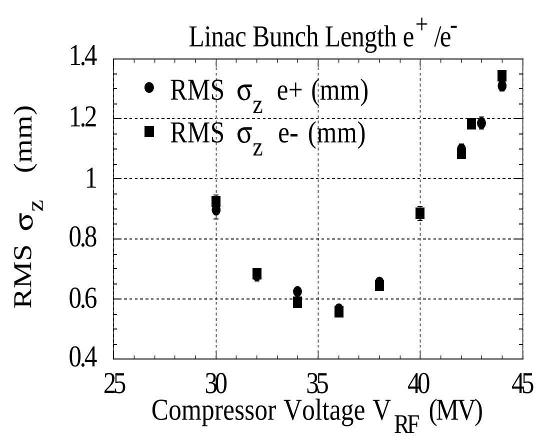

Figure 1. The bunch length as a function of the compressor voltage for the electron and positron bunch at the end of the linac.

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The streak camera measurement consists of taking 30 longitudinal profiles at compressor voltage settings 2 MV apart. Plotted in figure 1 is the mean RMS bunch length and the root mean error for currents of I=3.4×10^{10} and 3.3×10^{10} particles per bunch for the electrons and positrons respectively. The accelerating RF voltage in the damping rings during this measurement was 820 and 880 kV for the electron and positron rings respectively.

A compressor voltage setting of 30 MV gives a bunch distribution that is under-compressed, 36 MV is a fully-compressed, and 42 MV gives an over-compressed distribution. The longitudinal distribution of the positrons and electrons (see figures 2 and 3) is a sum of 30 plots where the means of the distribution are shifted to a common origin.

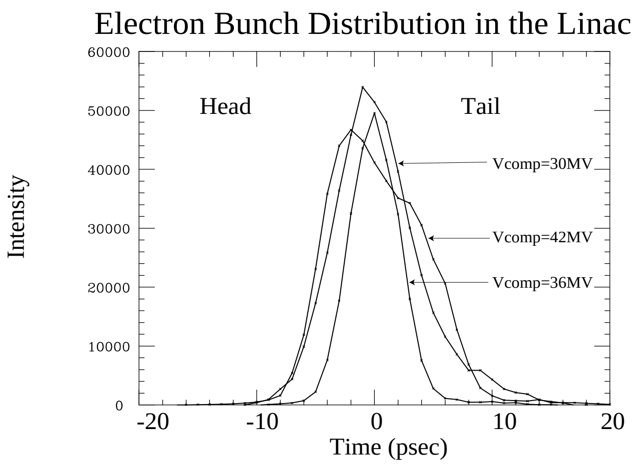

Figure 2. The electron bunch distributions at the end of the linac for compressor voltage settings of 30, 36, and 42 MV.

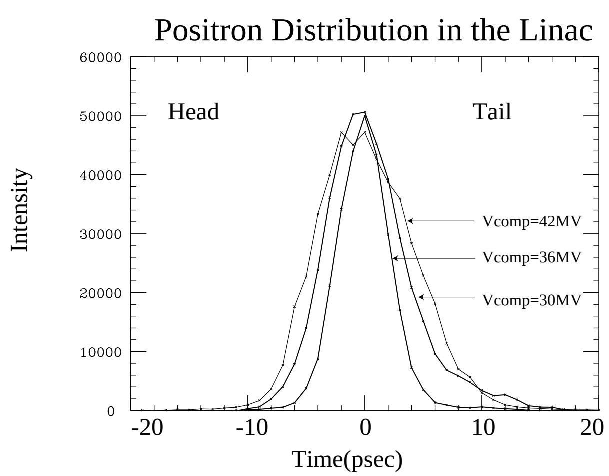

Figure 3. The positron bunch distributions at the end of the linac for compressor voltage settings of 30, 36, and 42 MV.

The systematic errors using the streak camera are discussed in reference 2. The dispersion in the glass optics limits the resolution of the streak camera as seen in figure 4. The effect of the dispersion can be minimized by using a narrow band (10nm FWHM) interference filter.

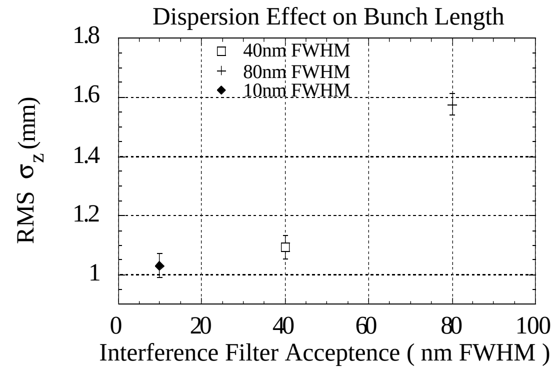

Figure 4. The electron bunch length at the end of the linac as a function of interference filter acceptance.

IV. Energy Spread

A. Ring to linac transport line

The energy spread in the transport line determines the degree of compression. It is determined by the compressor's voltage. A linearized expression for the energy spread is

$$\frac{\sigma_E}{E} = 2\pi\left(\frac{\sigma_z}{\lambda E}\right)V_{rf}$$

where σ_z is the damping ring bunch length, $\lambda = 105\text{mm}$ is the S-band wavelength, V_{rf} is the RF voltage amplitude, and E is the beam energy (1.19GeV). During the 1994 run the compressor voltage amplitude was 43 MV and the bunch length out of the linac is 7.0mm. This results in an energy spread of 1.5% in the compressor transport line. The energy aperture in the transport line at the high dispersion regions is $\pm 2.5\%$ which results in current losses for the high and low energy tails.

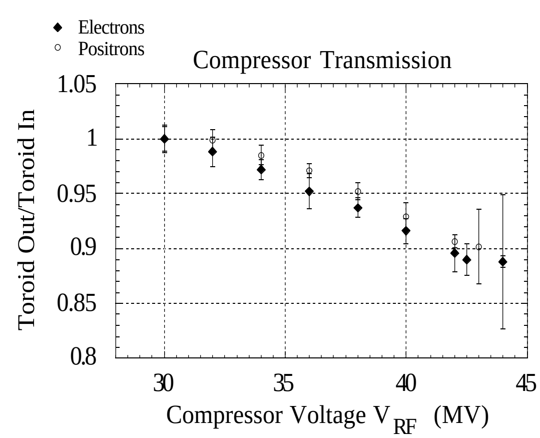

Figure 5. Electron and positron compressor transport line transmission as a function of compressor RF voltage.

Transmission through the positron and electron transport lines was measured versus compressor voltage with a toroid at the entrance and exit of the transport line. The ratio of the toroid readings (figure 5) determines the current loss. An over-compressed bunch results in a current loss of about 10% over an under-compressed bunch.

B. End of Linac

The energy spread at the end of the linac is determined from the RF amplitude in the linac, the phase of the bunch on the RF accelerating wave, and the energy loss due to longitudinal wake fields. The bunch has a longitudinal distribution in z and the energy of a particle at location z is given by[3]

$$E(z) = E_{inj}(z) + \sum_{i}^{N} E_i \cos(\frac{2\pi z}{\lambda} + \varphi_i) - E_{wake}(z).$$

Where N is the number of accelerating sections, $E_{inj}(z)$ is the energy of the particle entering the linac, E_i is the maximum RF amplitude from an accelerating section, φ_i is the phase with respect to the crest of the RF wave, λ is the S-band wavelength, and $E_{wake}(z)$ is the energy loss or gain due to the longitudinal wake fields.

The energy spread at the end of the linac is minimized if

$$\frac{dE(z)}{dz} = 0$$

Minimizing the energy spread is done by shaping the initial distribution with the bunch compressor and by adjusting the beam phase φ_i. The distribution that gives the minimum energy spread can be shown to be an over-compressed distribution[4,5].

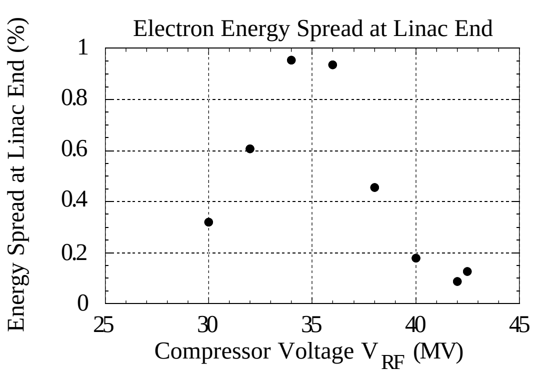

Figure 6. The minimized electron energy spread at the end of the linac as a function of compressor voltage.

The energy spread measurement at the end of the linac was made by a wire scanner at a location where the dispersion is large. The wire scanner measures the transverse bunch size, and the energy spread is determined from the Twiss parameters. At each compressor voltage the energy spread was minimized by adjusting the phase of the bunch φ_i. Once the energy spread was minimized, it was measured using the wire scanner. The energy spread (see figure 6) is approximately 0.09% when minimized with an over-compressed bunch distribution (42 MV).

V. Conclusion

The measurements of the bunch distributions and the current losses in the compressor transport line for positrons and electrons are in excellent agreement with each other. The advantage of a greatly reduced energy spread from over-compression far outweighs the 10% current loss in the transport line. The reduced energy spread allows for a lower tolerance on chromatic issues in the SLC arcs as well as the interaction region. The current losses in the transport line suggest that further investigation into increasing the aperture should be done for future high current running.

VI. Acknowledgment

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VII. REFERENCES

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