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Over-Compression, a Method to Shape the Longitudinal Bunch Distribution for a Reduced Energy Spread*

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Abstract

In the Stanford Linear Collider the energy spread of the bunches at the end of the linac is dominated by longitudinal wakefields. A short, high current bunch with a Gaussian shape will produce a double-horned energy distribution. It can be shown that certain charge distributions with a sharp rise time (about rectangular or half-Gaussian) will give no additional energy spread due to the linac, since the generated wakefield and the rf-curvature cancel each other exactly. In this paper different methods are presented on how to achieve such distributions by using non-linear dependences in the RTL (Ring-To-Linac) compression region. A simple and effective method to achieve such a distribution is by over-compression. When not fully compressing the bunch, there are two settings of the compressor voltage, under and over-compression, which give the same core bunch length in the linac. By switching from the under to the over-compressed setting, the tails are reduced from more than Gaussian to less than Gaussian beam tails. This results in a roughly rectangular shape which will give the wakefield–rf cancellation. Simulations, measurements and their implications are discussed.

1 Introduction

At the Stanford Linear Collider (SLC) the final spot size is limited by chromatic effects. A smaller energy spread within the bunch will minimize this effect. Additionally, low energy tails give background problems if not properly collimated. Since the polarization has an energy dependent effect in the ARCs, the final control of the energy distribution or at least its measurement has become a more important issue [1].

The energy spread of a high current bunch is mostly determined by the longitudinal wakefield. The initial energy spread 0.075 % of the damping ring (DR) is rotated into bunch length and a bunch length of 7.5 mm (DR) will give an energy spread of about (linearized):

$$\sigma_E = 2\pi \frac{\sigma_z}{\lambda} E_{rf}. \tag{1}$$

With $\lambda = 105\,\mathrm{mm}$, $E_{rf} = 41\,\mathrm{MeV}$ the relative energy spread is 1.5 % at the DR energy (1190 MeV) or 0.04 % at 47 GeV. The actual measured spread is more of the order of 0.2 % which is five times bigger. For a given current and a Gaussian energy distribution in z only the bunch length and overall phase in the linac can be optimized. The result is a double-horned distribution with an energy spread of around 0.2 % [2]. What was not taken into consideration with these optimizations that the bunch shape can be also varied using the non-linearity in the bunch compressor.

It was shown in 1984 [3] that, with a special distribution in z, the generated longitudinal wakefield will exactly cancel with the rf curvature to create no additional energy spread. By reducing even the correlated part in $E - z$ (the bunch length is about twice as long than the shortest bunch) it may be possible to reach less than 0.02 % energy spread.

After describing the necessary bunch shapes, we discuss how to achieve these z-distributions. We will discuss the practical goals, the expected achievements and compare them with simulations and measurements. Besides over-compression, which is the main tool, other tools are listed which give even further control over the bunch shape and therefore energy spread.

2 Linac Bunch Distribution

In the linac, special longitudinal bunch distributions will give no additional energy spread, since the induced wakefield cancels exactly with the rf curvature. Fig. 1 shows the necessary bunch distributions, which were achieved in the following way.

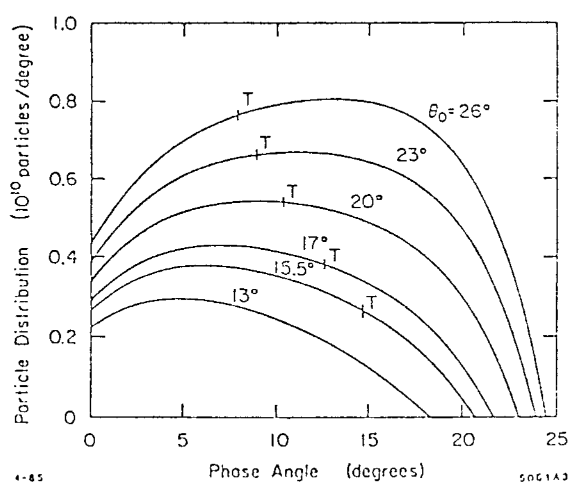

Figure 1: Linac Bunch Distributions [3]

The longitudinal wakefield cancels exactly the rf curvature for these special charge distributions. The head of the bunch is to the left and starts with a step function. The bunch length is in degrees and "T" marks the tail where $5 \cdot 10^{10}$ particles are reached. The different curves are for different starting phases θ_0 in front of the rf crest.

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The overall accelerating voltage consist of the rf voltage and the wakefield induced voltage (see [3]):

$$V(\theta) = V_0 \cos\theta - \int_0^{\theta_0-\theta} f(\theta') W_L(\theta_0 - \theta - \theta') d\theta'. \quad (2)$$

Setting the $dV/d\theta = 0$ (or const) will give no additional energy spread (or a linear relation). The necessary distribution can be expressed by a Volterra integral:

$$f(z) = \frac{V_0}{W_L(0)} \sin(\theta_0 - z) - \int_0^z \frac{\frac{\partial W}{\partial z}(z-\theta') f(\theta')}{W_L(0)} d\theta', \quad (3)$$

where θ_0 is the start phase in front of the crest. By starting 13° off the crest the bunch should be about 20° long and ends smoothly (see Fig. 1). The start is always a step-function, and if the bunch is shorter and therefore denser (e.g. 17°) it should end at about 13° (T) for $5 \cdot 10^{10}$ particles. So there are many possible distributions. Two specific ones can be described as follows: the longest possible bunch length has roughly a half-Gaussian shape and a shorter bunch has sharp rise and fall times and looks more like a rectangular bunch.

A constant offset under these shapes will give not a perfect cancellation but a perfect E vs z slope. This gives the freedom of having a longer linac bunch in the SLC, while the $E-z$ correlation is used in the ARCs to compress the bunch length for the right final focus bunch length.

Since a step function distribution is difficult to achieve, a practical charge distribution might have a little slower rise time, overshoots somewhat, but then has the right charge distribution.

3 Bunch Shaping in the RTL Compression Region

The final energy distribution at the end of the SLC has many contributions from different parts of the accelerator and can be influenced by adjusting parameters in the longitudinal phase space. In the ring-to-linac (RTL) transport line the bunch sits on the zero-crossing of the rf in the compressor cavity, which results in a energy-length correlation (linear for short bunch lengths). Then the beam goes through a high dispersion region with a R_{56}-term of about 600 mm. This compresses the bunch length to the desired linac bunch length of about 1.3 mm (σ) at 29 MeV compressor amplitude; the shortest length of about 0.5 mm at 34 MeV is too short for the linac at higher currents. In the over-compressed scenario, the same core bunch length of 1.3 mm is achieved with a compressor amplitude of 40 MeV. The non-linear shape of the rf is important for long DR bunch lengths. Under-compression gives long tails, while over-compression folds the tails on top of the core, resulting in a shape which has even less tails than a Gaussian. Besides the advantage of less tails (reduced backgrounds), a 2.5 (1.3 mm/0.5 mm) times sharper rise time might get a 2.5 times smaller energy spread at the end of the linac (rough estimate). Fig. 2 gives a comparison of a 10 mm long DR bunch (1993) for under- and over-compression.

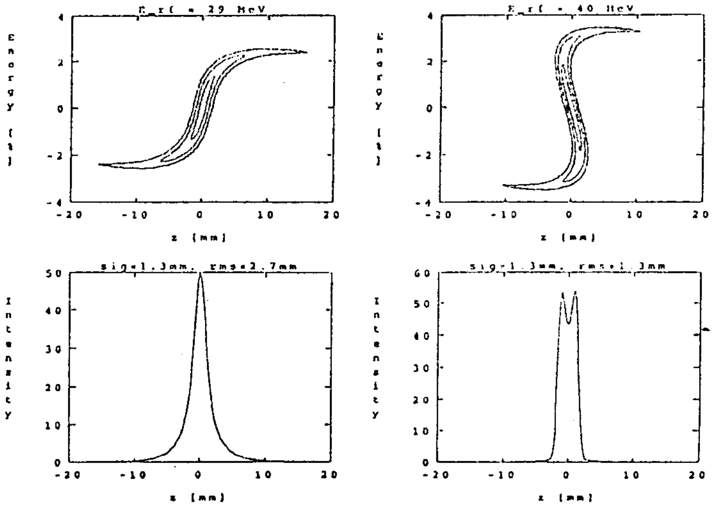

Figure 2: Under- and Over-Compression of the RTL Bunch Length

Below or above a compressor setting which will give the shortest bunch length, there are values e.g. 29 and 40 MeV giving the same core bunch length of 1.3 mm, but dramatically different bunch shapes. The bunch shape with over-compression is more rectangular or even double-humped. That gives a smaller energy spread later in the linac. There are also much less tails, since they are folded on top of the core.

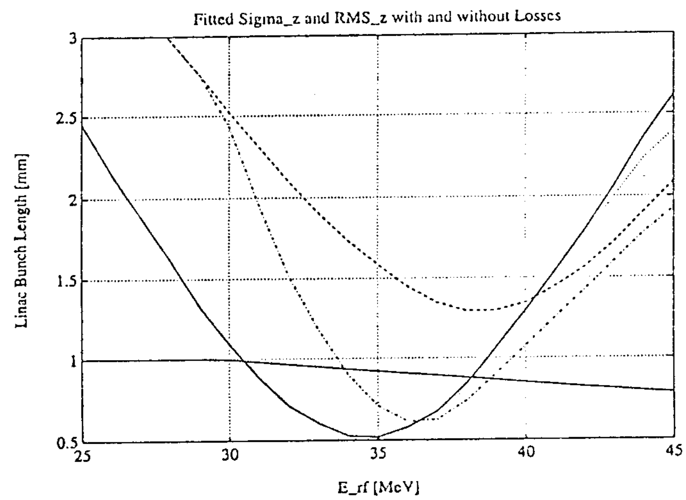

Figure 3: Bunch Length versus Compressor Amplitude

The linac bunch length is plotted for different compressor settings for a 10 mm DR bunch length. The solid curve gives the sigma of a fitted Gaussian, while the dashed curve is the rms-value (dash-dotted with losses). The losses for a ±2.5 % energy acceptance in the RTL mainly affect the tails (solid near 1) and reaches about 15 % at 40 MeV. In the under-compressed case (less than 34 MeV) the rms is very high indicating the tails, while in the over-compressed case the rms is even smaller than the fitted sigma.

Besides over-compression there are the other possibilities to shape the z- distribution: (i) phase offset in the RTL, which will concentrate more particles to the head of the bunch which has the advantage of a sharper rise (step function desired), (ii) a positive T_{566} has a similar effect in the middle of the rf, (iii) the non-symmetric distribution due to potential well distortion in the DR can be used, (iv) a pre-rotation in the DR [4] can exchange energy spread to bunch length a little bit to get more or less of the non-linear rf behavior, (v) scraping in the RTL (Fig. 3).

Fig. 4 shows the distribution for a under- and over-compressed bunch on the linac rf and the corresponding energy distribution. Especially remarkable is the fact that the low energy tails are much less in the over-compressed case. The energy spread itself is difficult to quantify: An rms-value will overestimate the tails, FWHM gives a good core number, but might represent only a small part of the beam. Here an rms number within 0.5 % of the center is used for comparison.

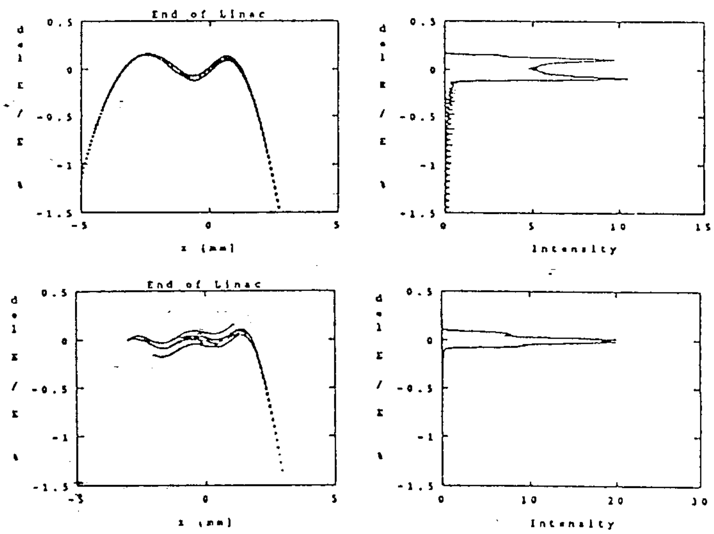

Figure 4: Energy versus z Distribution on the Linac RF and Energy Distribution

The distributions of the under- and over-compressed RTL cases were simulated and put into the linac with its longitudinal wakefield. The barely visible contour line at 1, 2, and 3 sigma indicate the bizarre shape in the over-compressed case. Instead of a simple double horned distribution in energy, the over-compressed case has more horns which are closely together giving a smaller energy spread of about 0.10 % compared to 0.15 %. The smaller tails are even more significant.

4 Measurements

At the end of the linac in the BSY (beam switch yard) the beams are bend into the ARCs and the energy distribution can be measured at a dispersive point (Fig. 5). The bunch length and distribution was measured with a 500 fs (FWHM) resolution streak camera and confirmed the sharp rise and fall times in the over-compressed case.

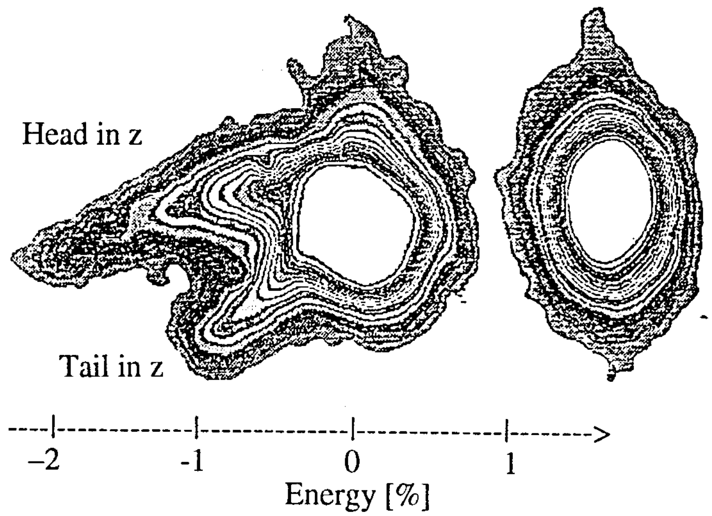

Figure 5: Beam Distributions at a Dispersive Point

A profile monitor in the BSY shows the full energy distribution. Here the core is saturated, but tails down to -2 % are visible with under-compression (left) and no tail with over-compression (right).

5 Conclusion

Over-compression is an easy way to shape the longitudinal bunch distribution so that a small energy spread results in the linac. Additional schemes can improve this even further. The reduction of low energy tails has largely improved the background situation in the detector and some polarization questions. Due to these advantages, over-compression is used as the operating mode of the SLC since the beginning 1994.

Acknowledgement

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References

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