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# Characterization and Monitoring of Transverse Beam Tails*

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## Introduction

Low emittance electron beams accelerated to high energy in a linac experience transverse effects (wakefield, filamentation, optics,...) which produce non-Gaussian projected transverse beam distributions. Characterizations of the beam shapes are difficult because the shapes are often asymmetric and change with betatron phase. In this note several methods to describe beam distributions are discussed including an accelerator physics model of these tails. The uses of these characterizations in monitoring the beam emittances in the SLC are described here as well as in Ref. 1.

First, two dimensional distributions from profile monitor screens are reviewed showing correlated tails. Second, a fitting technique for non-Gaussian one dimensional distributions is used to extract the core from the tail areas. Finally, a model for tail propagation in the linac is given.

## Beam Profiles from an X-Y Screen

When a beam strikes a fluorescent screen, it produces a two dimensional light distribution which can be observed with a TV camera and monitor or can be digitized and processed [2].

The digitized TV picture can be projected onto the x or y axis and compared to beam shaped measured with other devices such as a wire scanner [3]. Information is lost during the projection process. In addition, size data from fluorescent screens are unique in that an image of a single beam pulse can usually be measured. Whereas, many pulses (~ 20) are needed for a wire scanner measurement.

A two dimensional image is a projection of the x, x', y, y' distributions onto the x,y plane. Information about the other variables must be obtained at locations with different betatron phase advances or by using an adjustable quadrupole upstream. For example, a measured beam projection is shown in Fig. 1 where a transverse beam tail is apparent. The orientation of the tail in phase space is not known unless further measurements are taken. However, because of the longitudinal extent of the bunch and the fact that the back of the bunch tends to be the tail as produced by wakefields, a two dimensional image provides clues to the tail orientation. The x-y view aids in deciphering the head from the tail. The transverse tails observed on this type of screen can be adjusted with upstream variables but solutions which look small usually contain a tail in the angular dimension.

## Beam Projections from Wire Scanners

In the SLC, beam sizes (projections) are now routinely measured with wire scanners. When the beams are well behaved, the projected beam size is well represented by a Gaussian. A straight forward weighted least squares fit yields reliable results. However, a beam with "tails" leads often to a very poor fit. We report here on some techniques for analyzing such cases.

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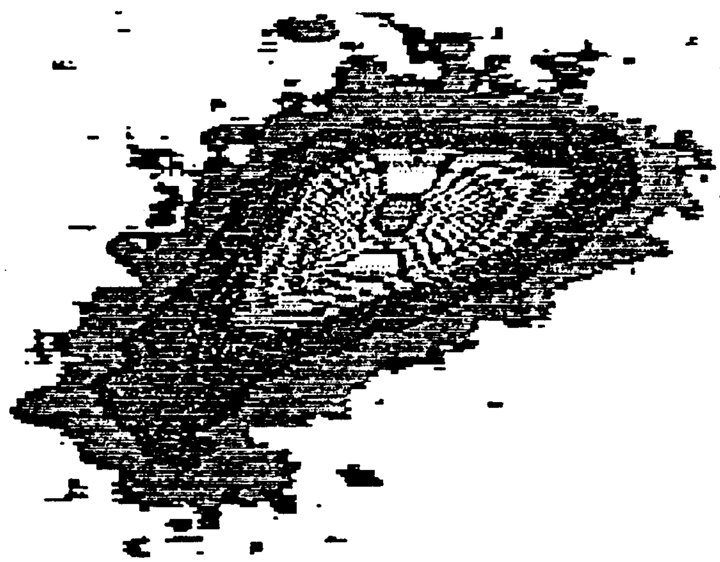

Fig. 1 Beam distribution with transverse tail measured on a screen profile monitor. This normally colored, two dimensional representation of the beam gives more information than a projection alone. The horizontal and vertical Gaussian beam sigmas are about 150 μm.

This approach assumes that the core of the beam is well represented by a gaussian, but otherwise makes no assumptions about the properties of the "tail". In particular, the functional form of the tail distribution is not needed.

Given a wire scan data set, we first fit to it with a simple Gaussian form. If the quality of fit is good as determined by a chi square cut, then the distribution is deemed to have no tail. Otherwise, we use the fitted gaussian mean to separate the data into left and right portions, and refit each one independently with Gaussians. The smaller (or better) fit is retained as being representative of beam core. Its functional value is extended into the unfitted region, and subtracted from the scan data. The residual distribution is the "tail". This tail can then be characterized by its moments relative to the fitted Gaussian mean. Two examples of this fitting procedure are shown in Fig. 2.

When the population in the tail is a significant fraction of the core or when it extends very far from the axis, the new Gaussian fit may still be unacceptably poor. This is easily cured by allowing extra iterations during partitioning of the data and refitting.

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The benefits of this approach are its simplicity, robustness and independence of tail distribution function. Reliable standard Gaussian fitting routines can be used without custom modification or additional debugging. Its convergence is essentially independent of the properties of the tail distribution function; therefore, the algorithm can be used in many situations. If a specific distribution was assumed, then the algorithm would have to be re-coded for a different functional form for each specific case.

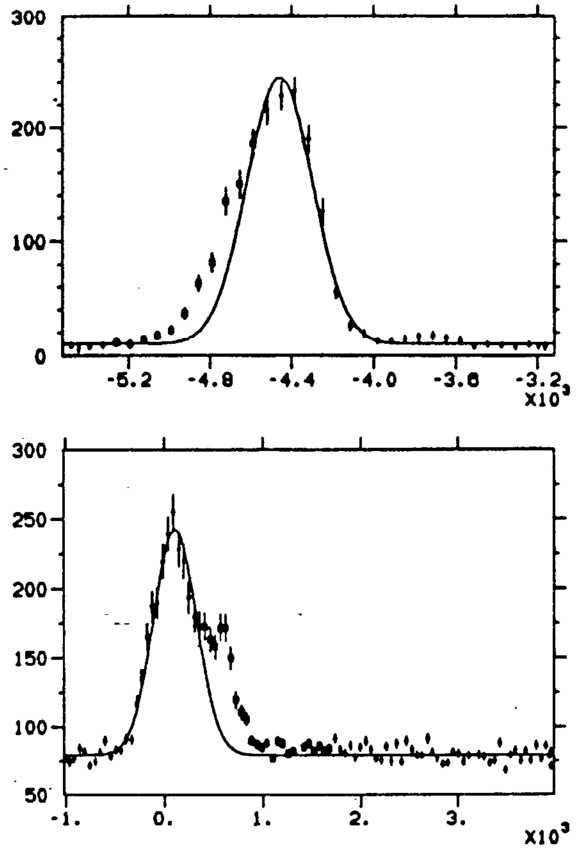


Fig. 2 Profiles fitted with a left or right core gaussian and showing a residual tail.

## Accelerator Physics Model for Tail Projection

A bunch executing a betatron oscillation in the quadrupole lattice of the linac experiences transverse wakefields in the accelerating structure. The head of the bunch drives the core and back of the bunch to ever increasing amplitudes producing a non-Gaussian tail. Simulations of this growth have been made where a bunch is divided into longitudinal slices and traced through the linac. In Fig. 3 the centroid positions of these slices are shown for a simulated SLC bunch of 5 X $10^{10}$ electrons after oscillating from an initial amplitude of about 100 microns. The (nearly) exponential growth from head to back is apparent.

The transverse particle distribution $\rho(x)$ of each slice is equal to that of the initial phase space distribution. The initial distribution for the SLC is a gaussian with width $\sigma$.

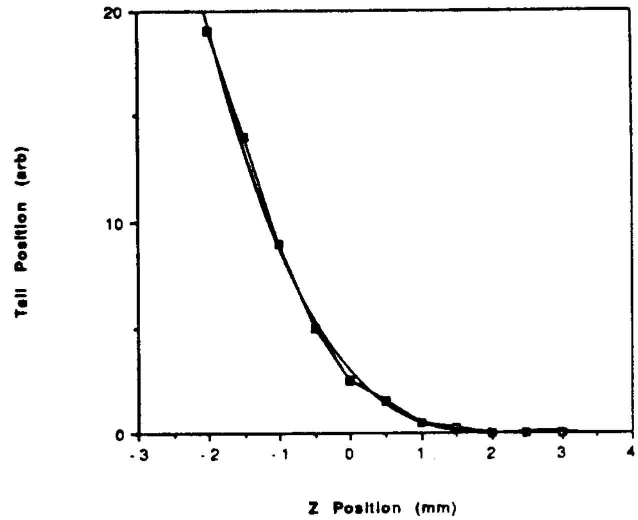


Fig. 3 Transverse slice centroid positions of a simulated SLC beam. The longitudinal head is on the right and the back of the bunch is on the left. Note the (nearly) exponential growth of the transverse position.

$$\rho(x) = \exp( - [x - x_0 ]^2 / 2 \sigma^2) / \sigma (2\pi)^{1/2} , \qquad (1)$$

where $x_0$ is the mean of the distribution. The overall distribution must be integrated over the slices with different transverse positions $x_0$.

The position $x_0$ of each slice is represented by an exponential which initiates at position $z_0$ along the length of the bunch, as in Fig. 3, and has a growth rate of $\tau$. This tail rotates in phase space with the betatron phase $\phi_i$ but has an initial phase $\phi_0$. The emittance of each slice of the beam is $\varepsilon$ and the betatron function at each profile measurement 'i' is $\beta_i$. $\sigma_i^2 = \varepsilon \beta_i$. The tail extension is scaled locally by $\sigma_i$.

$$x_0(\phi_i, z) = \sigma_i U (z_0 - z) [ \exp( (z_0 - z) \tau / \sigma_z) - 1 ]$$

$$\quad X \cos(\phi_i + \phi_0) \qquad (2)$$

where U is the unit step function. The bunch length is $\sigma_z$. The transverse distribution of each slice is given by :

$$\rho (x, \phi_i, z) = \exp(- (x - x_0(\phi_i, z))^2 /2\sigma_i^2) / (2 \pi)^{1/2}\sigma_i \qquad (3)$$

Now, the overall transverse distribution we will call f(x) is given by

$$f (x, \phi_i) = \int_{-\infty}^{+\infty} \rho (x, \phi_i, z) h ( z ) dz \qquad (4)$$

where h(z) is the longitudinal profile, usually assumed to be a gaussian as in Eqn. 1 but with length $\sigma_z$. By choosing $\phi_0$, $\tau$, and $z_0$, the beam shape can be calculated at any location over a reasonably short (less than a betatron wavelength) region of the linac. In Fig. 4 various calculated beam spots using this formalism are shown. Clearly, many different shapes can be generated.

Conversely, measured beam shapes can be analyzed to determine the tails structure of the beam and measure the effective $\phi_0$, $z_0$, and $\tau$. An oscillation was induced in the SLC electron beam with a dipole magnet and the resulting oscillation is shown in Fig. 5. The associated beam profiles are shown in Fig. 6 which cover a range in betatron phase. The beam shapes observed have a definite tail with a phase. Profiles (a) and (b) show no tails (it is in angles), but profiles (c) and (d) show large tails. Several simulated profiles from Fig. 4 closely resemble the measured shapes.

This analysis breaks down when the tail of the beam becomes quite convoluted after many oscillations or very strong wakefields. Longitudinal shapes go from banana-like into worm-like. Therefore, this analysis handles only moderately enlarged beams which covers the standard running condition of the SLC. If the shapes are much worse than shown, we would stop the program to fix them.

In the near future we plan to implement this algorithm into the online emittance package for eventual use in a feedback system for tails. This technique is properly suited for feedback as the phase of the tail is determined as well as the amplitude.

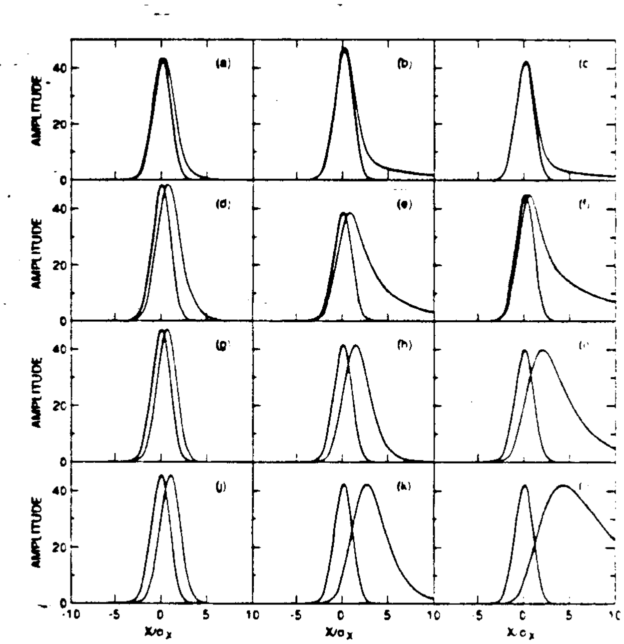


Fig. 4 Calculated transverse bunch projections showing the effects of different input conditions with the rate of tail growth $\tau$ and the place $z_0$ along the bunch where the exponential growth starts. Large $\tau$ (horizontal axis) makes long thin tails and a $z_0$ closer to the front of the bunch (vertical axis) makes a broader shoulder.

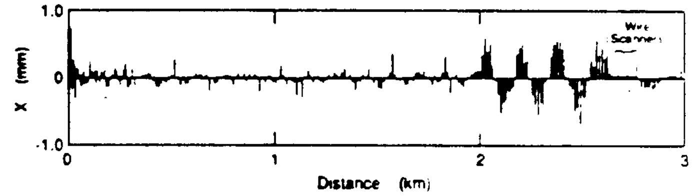


Fig. 5 Induced horizontal oscillation (measured) in the SLC linac which generated the beam tails in Fig. 6

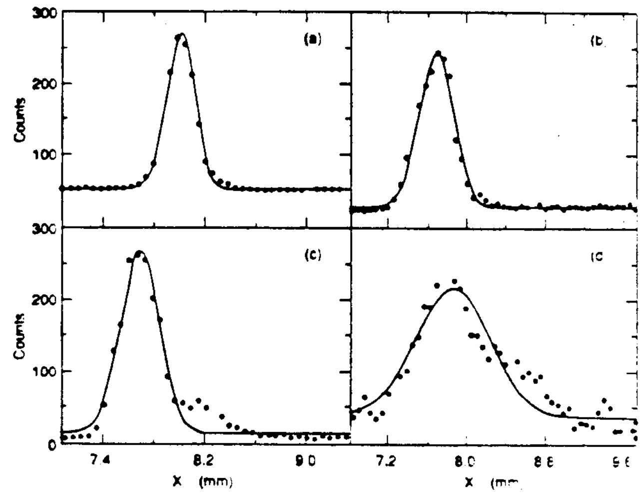


Fig. 6 Measured beam profiles (47 GeV) for the betatron oscillation in Fig. 5. The projections were taken with four wire scanners spaced at 0, 22.5, 90., and 112.5 degrees in betatron phase. Note the similarities of these profiles with those calculated in Fig. 4.

## Acknowledgments

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## References

1) J. Seeman et al., 'Summary of Emittance Control in the SLC Linac', SLAC-PUB-5437 and Proc. of US PAC San Francisco (1991).
2) F. J. Decker, 'Beam Size Measurement at High Radiation Levels', SLAC-PUB-5481 and US PAC San Francisco (1991).
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