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Beam-Beam Simulations with Non-Gaussian Distributions for SLC and SLC-2000*

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Abstract

Due to various upstream beam manipulations, the longitudinal bunch shape at the interaction point of the Stanford Linear Collider (SLC) is highly non-Gaussian. In this paper, we report beam-beam simulations with realistic longitudinal bunch shapes for the present SLC parameters and for the SLC-2000 luminosity upgrade. The simulation results allow us to estimate the luminosity enhancement due to the pinch effect and to find optimum parameter settings for the bunch compressor and the linac.

1 INTRODUCTION

Many linear-collider beam-beam simulations performed in the past have assumed simplified longitudinal beam distributions at the interaction point, usually a Gaussian and, sometimes, a uniform distribution. However, real bunch distributions are neither Gaussian nor uniform.

At the Stanford Linear Collider, the first and only linear collider in the world, the longitudinal distribution at the interaction point (IP) is clearly non-Gaussian. The longitudinal bunch shape at the SLC IP is determined by a variety of effects [1]: bunch-lengthening in the damping rings, (over)compression, rf curvature and second-order momentum compaction in the ring-to-linac transfer lines, rf curvature and longitudinal wake fields in the linac, and, finally, another bunch compression or expansion plus synchrotron radiation in the collider arcs. As a result of all these effects, the bunch distribution at the interaction point (IP) differs markedly from the idealized distributions usually considered. There is, in fact, some evidence that luminosity predictions derived from Gaussian-bunch simulations compare poorly with SLC observations [2].

A study of non-Gaussian beam-beam collisions is further motivated by the proposed luminosity upgrade SLC-2000 [3], for which, due to stronger bunch-length compression in the arcs (necessary to reduce the hourglass effect for the smaller $\beta_y^\star$), the distortion of the IP distribution will be even more pronounced.

In this paper, we report recent simulation results of beam-beam collisions, both for the present SLC and for the SLC-2000 upgrade. The simulations are based on realistic IP bunch distributions including all the effects in longitudinal phase space mentioned above, and starting with the potential-well distorted beams in the damping rings. The purpose of these simulations is: (1) to provide an estimate of the expected luminosity and of the pinch effect for real, non-Gaussian bunches, (2) to determine settings of compressor voltage and linac phase which are optimized for maximum luminosity, and (3) to provide guidance for the operation of two newly installed IP bunch-length monitors [7, 8]. Table 1 lists nominal IP beam parameters for the present SLC and for the SLC-2000 upgrade, which will be assumed in the remainder of this paper.

parameter	SLC-1996	SLC-2000
$\gamma\epsilon_x$ (m)	5.9×10^{-5}	4.0×10^{-5}
$\gamma\epsilon_y$ (m)	1.9×10^{-5}	1.1×10^{-5}
$\theta_x^\star$	350 μrad	550 μrad
$\theta_y^\star$	350 μrad	500 μrad
$\beta_x^\star$	5.4 mm	1.47 mm
$\beta_y^\star$	1.7 mm	0.5 mm
δ_{rms}	0.1%	0.2 %
N	3.5×10^{10}	3.5×10^{10}
$\sigma_x^\star$	1.9 μm	810 nm
$\sigma_y^\star$	600 nm	250 nm

Table 1: Nominal IP beam parameters for the 1996 SLC and for the SLC-2000 upgrade.

2 OPTIMUM BUNCH SHAPE FOR THE SLC

The longitudinal bunch distribution at the SLC IP is calculated with the program LITRACK [4], by which we model the longitudinal dynamics in the damping rings and in all downstream systems. This distribution is used as an input to the beam-beam program Guinea-pig [5]. Other input parameters, including the angular divergence and the spot size, are taken from Table 1. We have performed a series of simulations to study the dependence of the IP bunch shape and luminosity on the linac phase and bunch compressor voltage.

Figure 1 illustrates how a change of the average linac phase ϕ affects the IP bunch shape. Displayed is the longitudinal beam distribution for three different linac phases, with the center figure representing the nominal case. In this report, the phase ϕ is measured with respect to the crest of the linac rf, with $\phi < 0$ (or $z < 0$) to the front of the bunch.

In Fig. 2, the IP bunch length, energy spread and luminosity enhancement factor are shown as a function of the linac phase, for a constant compressor voltage V_c. The luminosity enhancement factor H_D is defined as the ratio of the effective luminosity L and the geometric luminosity L_0, where the latter is calculated from the IP beam size without collision. The enhancement factor can be larger than 1 due to the pinch effect (mutual focusing of the two beams by each other) or smaller than 1 due to the hourglass ef-

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fect (*i.e.*, the angular divergence of the two beams). During SLC operation, the injection time is continually adjusted in order to compensate for diurnal drifts of the linac-rf reference phases. Usually, this adjustment is done by minimizing the beam energy spread at the end of the linac. This is not necessarily the best choice in regard to the pinch effect, although Figs. 2 (a) and (d) suggest that it is not too far from the optimum. For comparison, the luminosity enhancement for a Gaussian bunch, one with the same rms length, is also shown in Fig. 2 (a), by the dotted line. In this particular case, the enhancement factors for Gaussian and real distributions are almost identical.

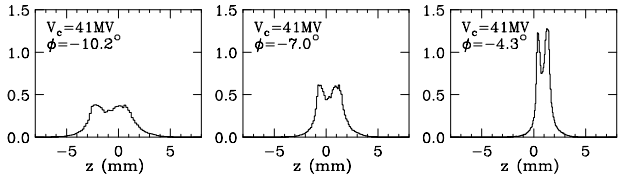

Figure 1: IP bunch shape for different linac phases. The vertical axis gives the instantaneous current in units of kA.

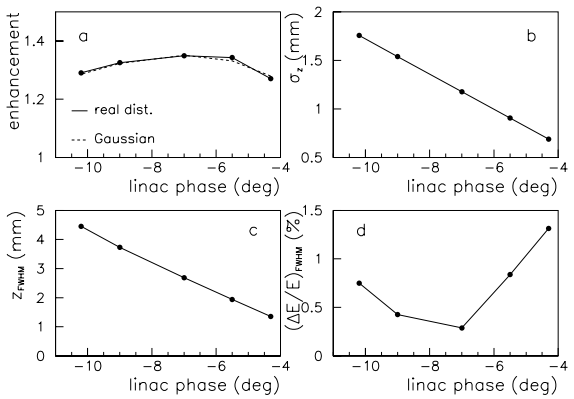

Figure 2: Luminosity enhancement (a), rms bunch length (b), FWHM bunch length (c) and FWHM energy spread (d) as a function of the linac phase, for the 1996 parameters.

The second parameter that can substantially affect the IP distribution is the voltage of the compressor rf. Examples of IP distributions for different compressor voltages are depicted in Fig. 3, where in each case the linac phase is adjusted to minimize the final energy spread. Figure 3 shows that a too small compressor voltage may result in a very spiky distribution, which is unlikely to show a large pinch effect. The nominal rf voltage is 41 MV (center case of Fig. 3), which yields an rms bunch length in the linac of about 1.2 mm. Figure 4 displays simulation results which illustrate how the IP bunch length, the energy spread and the luminosity vary with the compressor voltage, again minimizing the energy spread. For comparison, the dotted line in Fig. 4 (a) shows the luminosity enhancement for a Gaussian distribution of equal rms length. The clear difference between the dotted and solid lines demonstrates that a Gaussian is not always a good approximation.

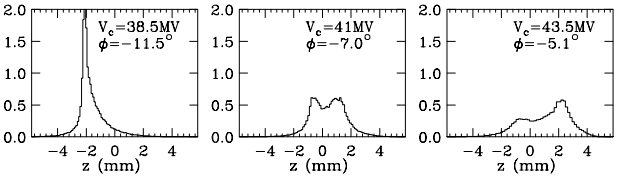

Figure 3: IP bunch shape for different compressor voltages. The vertical axis gives the instantaneous current in units of kA.

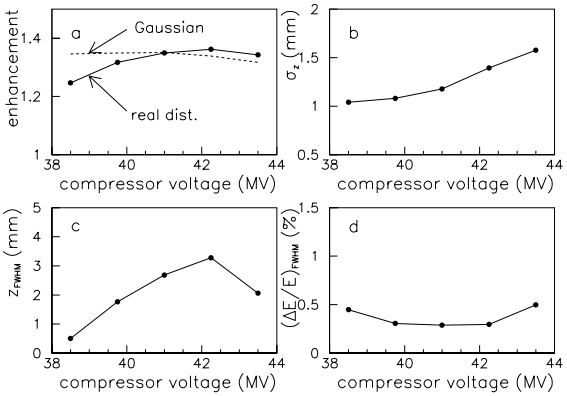

Figure 4: Luminosity enhancement (a), rms bunch length (b), FWHM bunch length (c) and FWHM energy spread (d) as a function of the compressor voltage for the 1996 parameters.

3 BUNCH LENGTH MONITORING

To optimize the luminosity enhancement, for the 1997 SLC run two novel bunch-length monitors have been installed in the SLC final focus: 1) a laser-heterodyne monitor based on the laser-wire system [8], which can be used to measure the entire Fourier transform of the beam profile; 2) a broadband rf monitor, which detects signals in 4 different frequency ranges (8–11.6 GHz, 11.6–19 GHz, 19–110 GHz, 59–110 GHz) and which will provide continuous information about the bunch length. Figure 5 displays the expected signals in the four channels of the rf monitor for various linac phases and compressor voltages equivalent to those considered in Figs. 2 and 4. The signals are calculated by performing a fast fourier transform of the bunch distribution and then integrating over the different frequency ranges. As expected, channel 4 is the most sensitive to the bunch length. In the 1997/98 SLC run, the signal of this channel will allow us to constantly monitor the IP bunch length of electron and positron beams, and, thus, to ascertain that the linac and compressor are set up properly for maximum pinch effect.

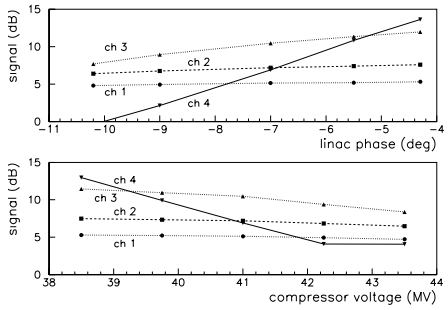

Figure 5: Predicted signal in the 4 channels of the newly installed RF bunch-length monitor [7], as a function of the linac phase and the compressor voltage (same horizontal scale as in Figs. 2 and 4, respectively).

4 LUMINOSITY ENHANCEMENT AT SLC-2000

In simulation studies for SLC-2000, we have used the parameters listed in the right-hand column of Table 1, and we have considered four different values of the compressor rf voltage. For each compressor voltage, we have varied the linac phase ϕ within a certain range constrained by the resulting energy spread (see Fig. 6). Given the present SLC-2000 final-focus energy acceptance of 0.6% [3], the optimal compressor voltage is $V_c \approx 40$ MV and the luminosity enhancement is 20–30%. However, if the energy acceptance can be increased to 1.4%, a shorter IP bunch length and an enhancement up to 60% would become possible, with a compressor voltage $V_c = 41$ MV. Our simulation results for the 1996 SLC and SLC-2000 are summarized in Table 2.

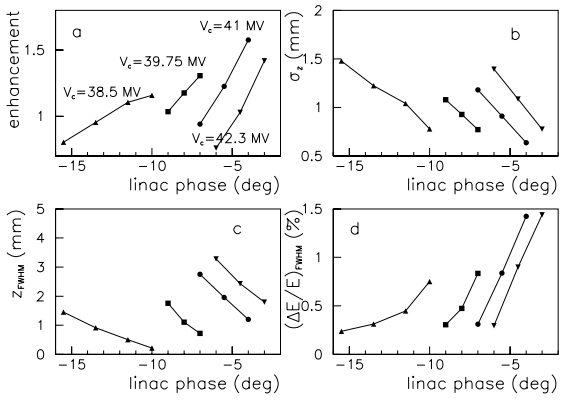

Figure 6: Luminosity enhancement (a), rms bunch length (b), FWHM bunch length (c) and FWHM energy spread (d), as a function of the linac phase for SLC-2000, considering four different compressor voltages: 38.5 MV (triangles), 39.75 MV (squares), 41 MV (rectangles), and 42.25 MV (inverse triangles).

parameter	SLC-1996	SLC-2000
ϕ	-7°	-4°
V_c	41 MV	41 MV
σ_z	1.18 (1.0) mm	0.64 (0.5) mm
L_0	110 Zs/hr	640 Zs/hr
L	150 (149) Zs/hr	998 (1073) Zs/hr
H_D	1.35 (1.34)	1.56 (1.68)
θ_x	0.62 (0.62) mrad	1.18 (1.29) mrad
θ_y	509 (532) μrad	616 (661) μrad
$< \frac{dE}{E} >$	0.039 (0.042) %	0.53 (0.61) %
σ_E	49 (54) MeV	441 (482) MeV
N_γ/electron	0.68 (0.68)	1.77 (1.80)
$< E_\gamma >$	25 (26) MeV	141 (154) MeV

Table 2: Predicted luminosity, spent-beam and photon-beam characteristics for the 1996 SLC and SLC-2000, obtained in beam-beam simulations with realistic distributions using the program Guinea-pig [5]. The symbol L_0 (L) denotes the luminosity without (with) pinch and hourglass effect, and H_D is the enhancement factor L/L_0, which, in the simulation, was optimized by adjusting the linac phase for a constant compressor voltage of 41 MV. The values given in parentheses are results for a Gaussian distribution (see also [6]). The last two rows refer to the beamstrahlung photons.

5 CONCLUSION

Using realistic longitudinal bunch distributions, we have determined the optimum compressor setting and the optimum linac phase for the 1996 SLC and for the SLC-2000 upgrade. We find that, in most cases, the Gaussian approximation to the bunch shape gives nearly the same luminosity enhancement factor as the actual bunch shape. For the 1996 SLC parameters, the maximum enhancement due to the pinch effect is about 30%, while for SLC-2000 an enhancement of 20–30% is expected for the present final-focus design optics, which may be increased to 60% with an improved final-focus energy bandwidth.

Acknowledgement
We thank O. Napoly for stimulating discussions.

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