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 TITLE: WAKEFIELD DEPENDENT EMITTANCE GROWTH IN THE SLAC LINAC*

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Introduction

In this note we describe the emittance growth we can expect at bunch populations of $N = 3, 4, 5 \times 10^{10}$ in the SLC linac. We will discuss briefly the effects of injection jitter, injection drift, and coherent oscillations starting in the middle of the linac. Finally, we will discuss in a more thorough manner the effects of random misalignment errors throughout the linac.

The results we present are generated using the computer program LTRACK [K. Bane, IEEE Trans. Nucl. Sci. NS-32, 2389 (1985)]. This program is like a first order version of TRANSPORT, but it also includes the effects of the longitudinal and dipole wakefields. For the simulations the beam is cut transversely into slices, and the properties of these slices are propagated down the linac.

$$\epsilon^2 = \langle \gamma \rangle^2 (\sigma_{xx} \sigma_{x'x'} - \sigma_{xx'}^2) \quad , \quad (1)$$

with $\langle \gamma \rangle$ the average beam energy and the parameters in the parenthesis the variances of the beam distribution about its centroid. Thus, for example,

$$\sigma_{xx} = \frac{1}{N} \sum_{\ell} N_{\ell} (\sigma_{xx\ell} + \langle x_{\ell} \rangle^2) \quad (2)$$

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with N_ℓ , $\sigma_{xx\ell}$, $\langle x_\ell \rangle$, respectively, the number of particles, the position variance and the centroid of slice ℓ . The parameter ϵ is useful for characterizing the effect on beam quality of static or slowly changing errors. It is assumed that the centroid shift of the beam at the end of the linac can be corrected with the aid of a steering magnet. Let us, in addition, define the emittance factor $\bar{\epsilon}$ in a similar manner. In this case, however, the variances are calculated with respect to the axis of the machine. This parameter is useful for gauging the effects of jitters, or variations for which the centroid shift cannot or is not corrected for.

For all our calculations the wakefields used are the monopole and dipole wakefields that represent the SLAC linac accelerating structure. [K. Bane and P. B. Wilson, Proc. of the 11th Int. Conf. on High Energy Accelerators CERN (Birkhäuser Verlag, Basel, 1980), p 592.] The lattice, representing the SLC linac, was provided by M. Woodley. We assume the initial normalized emittance is 3×10^{-5} rm. Our lattice is well matched: If the beam moves on the axis of the error free version of our lattice the emittance growth found by LTRACK is at most 1-2%.

The Optimal Bunch Length

Given a beam current, what is the most desirable bunch length? If there is no energy spread in the beam then as the bunch length decreases the longitudinal wakefield effects become stronger and the transverse effects become weaker, and vice versa. As the bunch length decreases the optimal spectrum becomes wider due to the longitudinal wakefields. But, probably more importantly for the SLC, as the bunch length decreases the bunch needs to be, on average, more off-crest on the rf wave to achieve the optimal spectrum. Therefore we need more energy head room to obtain the same final energy.

Under normal operations, however, there is a significant energy spread in the beam, at least near the front of the machine, since we run the linac klystron phases in a BNS configuration. If there is an energy spread in the beam then the transverse effects don't necessarily become stronger as the bunch lengthens. The tolerance to coherent oscillations can actually increase as the bunch lengthens, at least over a finite range. However, in the SLC by the middle of the linac the beam energy spread has been greatly reduced. And consequently (as we will see below) the tolerance to coherent oscillations beginning in the middle of the linac, at high currents, rapidly becomes tighter as the bunch lengthens.

Considering all the foregoing effects we suggest that the bunch be made as short as possible, consistent with the energy head room requirements. In Table I we give the suggested bunch lengths for currents of $N = 2, 3, 4, 5 \times 10^{10}$ and the compressor settings that achieve these bunch lengths. We assume the ring voltage is 1 MV.

TOLERANCE TO COHERENT OSCILLATIONS

Injection Jitter Tolerance

At high currents, if there is no energy spread in the beam, the tolerance to coherent oscillations in the SLC linac are very tight. The tolerance to linac injection jitter at $N = 5 \times 10^{10}$, for example, would be impossible to achieve given the level of stability of the extraction kicker of the damping rings. Therefore we set the klystron phases to a BNS configuration, in order to induce an energy spread in the beam: In the front of the linac, for n_a klystrons the beam is positioned behind the rf crest at phase ϕ_a , and in the rest of the linac it is positioned in front of the crest, at phase ϕ_b . We will choose the convention that $\phi_a > 0$ is a position in front of rf crest. A condition on the overall configuration is that the final energy spread of the beam is minimal. The cost of this phase switching is a loss of some energy head room ΔE_{BNS} . Note that we have only 2 free parameters for choosing our BNS configuration.

For the currents and bunch lengths shown in Table I we have studied the tolerance to linac injection jitter as function of BNS configuration. Figure 1 shows some calculation results for $N = 5 \times 10^{10}$ and $\sigma_z = 1$ mm. For these calculations we begin the beam with initial angle $\Delta x'_0$ in an error-free linac and calculate the jitter emittance $\bar{\epsilon}$ at the end of the linac. We plot in the figure the jitter tolerance t_0 as function of ϕ_a for various values of ΔE_{BNS} . The jitter tolerance is defined as the ratio $\Delta x'_0 / \sigma_{x0'}$ that increases $\bar{\epsilon}$ by 25%. We performed a calculation at every 2° ; in Fig. 1 these results are connected by straight lines. Note that the curves all have an optimum phase.

For each current and bunch length in Table I we've chosen a BNS configuration that gives us what we believe are achievable injection jitter tolerances. The parameters of these configurations are shown in Column 5-8 of Table I; the corresponding jitter tolerance is given in Column 10. Column 9 shows the total extra energy that needs to be supplied to the beam—including the contributions of the BNS phase shifting, the higher mode losses, and the (on average) off-crest positioning of the beam that is necessary to obtain a narrow final energy spectrum. We can also calculate an injection drift tolerance t . It is defined just as the injection jitter tolerance, except the figure of merit is ϵ —the emittance with respect to the beam centroid—and not $\bar{\epsilon}$. The injection drift tolerances of the suggested configurations are given in Column 11 of Table I. For more details about calculation of the injection jitter tolerances of the SLC linac, see K. Bane, AP-76, 1989.

Tolerance to Coherent Oscillations Beginning Part Way Down the Linac*

In addition to the effects of coherent oscillations starting at the beginning of the linac we've simulated the effects of oscillations beginning at arbitrary positions along the linac. By the middle of the linac most of the beam energy spread has been removed, and the BNS damping becomes weaker. Fig. 2 gives the calculation results for $N = 1 \times 10^8$, $\sigma_z = 0.75$ mm (top); $N = 3 \times 10^{10}$, $\sigma_z = 0.75$ mm

* That this is an important problem was suggested by J. Seeman.

(middle); and $N = 5 \times 10^{10}$, $\sigma_z = 1$ mm (bottom). The left column shows the jitter tolerance t_{om} , the right column the drift tolerance t_m . These tolerances are defined as the amplitude of oscillation (given in mm in the plot) that increases ϵ (for t_m) or $\bar{\epsilon}$ (for t_{om}) by 25%. The abscissas in the plots give the linac position of the first peak of the oscillation.

It is probably the drift tolerance that is the more critical of the two for the SLC. Note that at $N = 3 \times 10^{10}$ and $N = 5 \times 10^{10}$ there is a flat minimum, roughly spanning the linac positions $s = 700$ m to $s = 2000$ m. The minimum tolerance is $70\mu\text{m}$ for the former case, and $30\mu\text{m}$ for the latter case. This tolerance is very sensitive to bunch length: at $N = 3 \times 10^{10}$ the minimum is reduced by half when the bunch length is doubled. Note also that when we repeat the calculation for $N = 5 \times 10^{10}$, but this time with no BNS damping, we find the tolerance is reduced from $30\mu\text{m}$ to $4\mu\text{m}$.

EMITTANCE GROWTH CAUSED BY ALIGNMENT ERRORS IN THE LINAC

The SLC linac lattice is essentially a sequence of FODO cells with acceleration sections filling the space between quads. Near the beginning of the acceleration sections are correctors, and in the quads are position monitors. First with the orbit uncorrected the monitors are read; then the correctors are adjusted to correct the orbit errors. However, since the quads are not perfectly aligned with respect to the acceleration sections and since the monitors have reading errors there will always be residual orbit errors, even in a corrected machine.

The most recent estimate of alignment errors (supplied to me by C. Adolphsen and J. Seeman) are quad offset errors with an rms of $100\mu\text{m}$, monitor reading errors (with respect to the quad centers) with an rms of $100\mu\text{m}$, and acceleration section offset errors (at each end) with an rms of $300\mu\text{m}$. The quad offset and monitor read errors can be added in quadrature to give a total effective offset of $140\mu\text{m}$. For our simulations we will take the whole length of acceleration section between adjacent quads to be of one rigid piece. Offsetting each end independently with an rms of $300\mu\text{m}$ in effect is equivalent to offsetting the two ends the same with an rms of $300/\sqrt{2} = 210\mu\text{m}$. The relative importance of the quad offset and the acceleration section offset errors depends on the beam current, the lattice and the klystron phase profile in the linac. At low currents, for example, the acceleration section offsets have no effect while the quad offsets still do. We find that in our case, for $N = 3 - 5 \times 10^{10}$, the relative importance of the acceleration section offset errors to the quad offset/monitor read errors is given by the ratio of the square of the corresponding rms offsets, i.e. by $45/20 = 2.2$. We see that the acceleration section misalignments dominate over the quad offset/monitor read errors.

In the simulations to be presented we will take as errors the quad offset, monitor read, and acceleration offset errors discussed above. To correct the orbit we use only those monitors that are positioned in the focusing quads, just as is done in the actual operation of the linac. Beginning at

the front of the linac we correct, at high currents, to one monitor at a time. Then finally we choose one of two methods to further improve the final beam quality. We adjust either (1) the launch of the beam (x_0, x'_0) or (2) two correctors at the beginning of Sector 22, until the emittance ϵ at the end of the linac is minimized. Note that for our simulations the errors are normally distributed, but truncated at $\pm 2\sigma$. Note also that for every example that will be shown the sequence of error seeds is the same. Figure 3 displays the simulation results for $N = 3 \times 10^{10}$, $\sigma_z = 1$ mm, $\phi_a = -20^\circ$ and $n_a = 56$. Note that this bunch length is not exactly that given in Table 1. In Fig. 3 we plot histograms of the final emittance growth [$\delta\epsilon = \epsilon/\epsilon_0 - 1$] in units of percent growth. With the beam launched on axis [Case (a)] the median growth $\delta\epsilon_{\text{med}} = 30\%$; with the launch optimized [Case (b)] $\delta\epsilon_{\text{med}} = 6\%$ with 2 correctors in Sector 22 optimized [Case (c)] $\delta\epsilon_{\text{med}} = 4.5\%$. We note, in addition, the total span of results is in Case (a) 150%, in Case (b) 33%, in Case (c) 11%.

Figure 4 displays information about the amplitude of the optimized launch of Case (b) [the left column] and the amplitude of the optimized Sector 22 kicks for Case (c) [the right column]. The top histograms give the distribution of these optimizing corrections. The amplitudes are normalized to the beam size at the front of the linac [for Case (b)] or to the beam size in Sector 22 [for Case (c)]. The median value for Case (b) is 0.64, for Case (c) 0.85. Note that a value of 1 corresponds to a 250 μm oscillation in Case (b), a 120 μm oscillation in Case (c).

We have repeated the calculations for $N = 4 \times 10^{10}$, $\sigma_z = 0.75$ mm, $n_a = 64$ and $\phi_a = -15^\circ$. The emittance growth histograms are shown in Fig. 5 for the Cases (a) on axis launch, (b) optimized launch and (c) optimized kicks in Sector 22. The median emittance growths are respectively $\delta\epsilon_{\text{med}} = 46\%$, 17%, and 6%. Fig. 6 shows the distributions of the final optimizing adjustments for Case (b) [the left two plots] and Case (c) [the right plots]. The amplitudes are again normalized to the beam size at the front of the linac [Case (b)] and at Sector 22 [Case (c)]. The median amplitude for Case (b) is 0.53, for Case (c) 0.46.

Fig. 7 gives a representation of final phase space for one example collection of alignment errors, an example that yields an emittance growth that is equal to the median value of the histograms of Fig. 5. The vertical axis is given in units of mr, the horizontal axis in units of mm. In the plots 19 slices represent the beam from $z = 2.5\sigma_z$ to $z = 2.0\sigma_z$. We plot the 1σ ellipse and centroids [‘+’] for all slices. Note that when we compute the emittance each slice is weighted by the charge distribution. For this example the emittance growth is (a) 60%, (b) 20%, and (c) 9%.

Finally, we have repeated the calculations for $N = 5 \times 10^{10}$, $\sigma_z = 1$ mm, $n_a = 96$ and $\phi_a = -12^\circ$. Fig. 8 gives the distribution of emittance growth when the beam is launched on axis. The median value is 107%. Fig. 9 gives the results after launch optimization. The median value $\delta\epsilon_{\text{med}} = 29\%$. The size of the optimizing adjustments is shown in the plot on the right. The median amplitude is 0.96. Fig. 10 gives the results obtained using the Sector 22 kicks. This time $\delta\epsilon_{\text{med}} = 17\%$ and the median amplitude of correction is 0.48.

J. Seeman once proposed distorting the waveguides down the linac in a manner that adds a

component of the betatron oscillation frequency to the existing random errors. With the proper choice of amplitude and phase the emittance growth can be reduced. We've simulated this correction scheme for the previous example. The results are given in Fig. 11. After correction $\delta\epsilon_{\text{med}} = 28\%$; the median amplitude of correction is 0.26, with respect to the beam size. We note that the histogram is similar to the one in Fig. 9. For our parameters it appears that whether we add a betatron oscillation to the beam or add it to the alignment of the waveguides, we achieve the same effect.

Acknowledgements

The type of simulation results presented here have been reported over the last two years at SLC Linac meetings. The author has learned much about the SLC Linac from J. Seeman and the other members of the linac group. In addition, the author notes that D. Ritson, and more recently C. Adolphsen, also have written programs similar to LTRACK, and have presented their simulation results at SLC Linac meetings.

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Table I: Suggested Bunch Length and BNS Set-up for Different Currents

$N/10^{10}$	σ_z/mm	V_{comp}/MV	$(\sigma_E/E)/\%$	ΔE_{BNS}	$\phi_a/^\circ$	n_a	$\phi_a/^\circ$	$\Delta E_{tot}/\text{GeV}$	Injection t_0 t	Middle of linac $t_m/\mu\text{m}$	Emittance growth due to alignment errors, median value (%) $(x_0, x'_0) = 0$ $(x_0, x'_0)_{opt}$ Sector 22 kicks
2	0.75	29.8	0.16	1.57	-20.	48	14.8	2.55	0.54 1.13		
3	0.75	30.8	0.25	2.51	-20.	56	21.6	4.23	0.50 0.91	75.	30. 6. 4.5.*
4	0.75	31.4	0.35	2.83	-15.	64	27.1	5.37	0.31 0.50		46. 17. 6.
5	1.00	30.2	0.39	2.97	-12.	88	28.4	5.30	0.22 0.37	30.	
5	1.00	30.2	0.39	3.50	-12.	96	31.6	5.83	0.28 0.47	30.	107. 29. 17.

* Note: The 3×10^{10} alignment error results were for a bunch with a slightly different length, 1.00 mm.

TSF WITH N=5E10 SIGZ-1.0MM XOP- SIGXOP- 50.D-6RAD

Fig. 1

$N = 1.08 \times 10^8$
 $\sigma_z = 0.75 \text{ mm}$

jitter tol, mm

drift tol, mm

+ solution of

$$= 1 + \frac{1}{2} \left(\frac{x}{\sigma_x} \right)^2 = 1.25$$

$N = 3 \times 10^{10}$
 $\sigma_z = 0.75 \text{ mm}$

$N = 5 \times 10^{10}$
 $\sigma_z = 1 \text{ mm}$

Fig. 2

$$N = 3 \times 10^{10}, \sigma_z = 1 \text{ mm}$$

$$\varphi_a = -20^\circ \quad \mu_a = 56$$

errs: { quad offset = 100 $\mu\text{m rms}$
monitors read (wrt to quad) = 100 $\mu\text{m rms}$
all offset (each end) = 200 $\mu\text{m rms}$

Fig. 3

$N = 3 \times 10^4$

Distribution
of corrections:

Kicks are
normalized
to beam size

AO CHRX CO

AO CHRXEM CO

Fig. 4

Note: at Sep. 22 v = 1.1

XO AO CHRXEM CO

$$N = 4 \times 10^{10}$$

EP% 4D

NTOT=	36	NOUT=	0
XBAR=	68.859	XRMS=	66.439
XMIN=	5.474	XMAX=	304.850
XFAC=	1.000	ICOL=	4
XMED=	46.065	XRMB=	42.715
NB=	23

EP% 4D

NTOT=	36	NOUT=	0
XBAR=	24.008	XRMS=	26.885
XMIN=	2.531	XMAX=	130.860
XFAC=	1.000	ICOL=	3
XMED=	17.153	XRMB=	14.165
NB=	25

EP% CHR4DEM.C

NTOT=	86	NOUT=	0
XBAR=	8.837	XRMS=	10.404
XMIN=	2.124	XMAX=	66.148
XFAC=	1.000	ICOL=	0
XMED=	6.082	XRMB=	6.517
NB=	23		

Fig. 5

Fig. 6

11/01/91 13:22:53
 11/01/91 11:16:58
 11/01/91 13:22:53
 11/01/91 11:16:58

A median example

$$N = 4 \times 10^{10}$$

Fig. 7

$5 \times 10^{13} / \text{cm}^2$

$\Delta E_{\text{Boj}} = 3.5 \text{ GeV}$, $\chi_a = -12^\circ$, $\chi_b = 9^\circ$

NTOT-	39	NOUT-	0
XBAR-	146.653	XRMS-	136.877
XMIN-	6.999	XMAX-	720.980
XTAC-	1.000	ICOL-	4
XMED-	107.370		
NB-	24	XRMB-	89.171

NTOT-	38	NOUT-	0
XBAR-	49.742	XRMS-	88.247
XMIN-	3.573	XMAX-	881.480
XTAC-	1.000	ICOL-	8
XMED-	28.692		
NB-	24	XRMB-	80.808

Fig. 8

12 Sep 70
Line Meeting

adjust x, y, z at beginning of Line

NTOT=	38	NOUT=	0
XBAR=	49.742	XRMS=	58.247
XMIN=	3.373	XMAX=	331.430
XFAC=	1.000	ICOL=	3
XMED=	28.592	XRMB=	30.836
NB=	24		

$$N = 5 \times 10^{10}, \Delta E = 1 \text{ meV}, \alpha_a = 96, \varphi_a = -12^\circ$$

erm { 300 acc section offsets
100 quad offsets
100 monitor offsets

Fig. 9

NTOT=	69	NOUT=	0
XDAR=	26.727	XRMS=	23.141
XMIN=	2.433	XMAX=	115.590
XFAC=	1.000	ICOL=	3
XMED=	16.857	XRMB=	14.343
NS=	45

adjust tide at bay sector 22 (Eman bungs)

Fig. 10

11

NTOT=	35	NOUT=	0
XBAR=	42.631	XRMS=	42.637
XMIN=	2.894	XMAX=	220.000
XFAC=	1.000	ICOL=	3
XMED=	27.601	XRMB=	25.043
NB=	23		

add betatron component
to acc. section misalignment, (T. Seeman)

Fig. 11

END

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