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AUTHOR: John T. Seeman**DATE:** May 16, 1986**TITLE:** NEW LIMITS ON RESIDUAL RTL η FROM LINAC
WAKEFIELDS**

Summary:

An SLC beam entering the Linac at Sector 2 has been damped and compressed by its associated Damping Ring and Ring-to-Linac (RTL) transport line. If the Damping Ring or the RTL is not properly tuned, then a residual η (and/or η') will be launched into the Linac where an injection $\eta(\eta')$ of zero is expected. J. Sheppard (CN-298) has calculated the effects of residual η on the apparent emittance of the beams and found that η must be kept below about 13 mm at $\beta = 6.6m$ so that no detrimental size increase occurs. He also calculated an associated limit on η' .

In this note, the additional effects of Linac transverse wakefields are combined with residual η and partially compressed bunches (presently the SLC design) to place much tighter, current dependent limits on residual η and η' . The limits are comparable to or exceed those needed at the SLC final focus. These limits will be difficult to maintain due to present experimental resolution. However, the use of Landau Damping in the Linac restores the limits to those of CN-298 but forces the use of relatively large launching angles and positions.

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Bunch Length and Energy Spectrum

The length and energy spectrum of a bunch at the entrance to the Linac can be calculated (Wiedemann, CN-117) given the length and energy spectrum of the Damping Ring beam, the compressor peak accelerating field and the RTL compression parameter (R_{36} matrix element). Table I shows these parameters for several compressor voltages. Bunch lengths in the range of 1 to 1.5 millimeters are presently of interest.

Table I

Initial energy spectra and lengths of bunches in the Linac as a function of compressor voltage.

Compressor Voltage (MV)	Energy Spectrum (%)	Bunch Length (mm)
0	0.073	5.92
22.3	0.661	2.00
25.2	0.746	1.50
28.2	0.834	1.00
31.9	0.943	0.50
33.0	0.975	0.44 (minimum)

Transverse-Longitudinal Position Correlations:

For bunches not fully compressed*, there is a strong correlation between the energy of a particular longitudinal slice in the beam and that slice's

*Due to aperture restrictions in the RTL, only under-compressed bunches are considered here. Over-compressed bunches would be severely attenuated.

longitudinal position after compression. The reason is the head remains the head after compression, and the tail the tail. The head and tail will merge longitudinally only after full compression. Furthermore, for any bunch length of interest (less than 2 mm) the resultant energy spectrum is dominated by the spread introduced by the compressor. This spectrum has a correlation with longitudinal position. Therefore, if a residual η is present at the beginning of the Linac, then the transverse position of each slice is correlated with its longitudinal position. Since no injection displacement or angle can be added to the beam to place all particles on the Linac axis, transverse wakefield enlargement effects will occur.

Simulations:

A series of single beam, one plane tracking simulations were made to determine the wakefield effects of residual η on bunches with lengths of 1 to 1.5 mm (sigma). The tracking program used twenty-five longitudinal slices (macroparticles) and incorporated the Linac FODO lattice, transverse and longitudinal wakefields given by the SLC Design Handbook (Red or Blue), RF acceleration and gaussian longitudinally weighted charge distributions. The RF phases of the bunches were always chosen to produce an energy spread of 0.2% (RMS) at 50 GeV. The position of each macroparticle represents the centroid position of all the beam particles within that longitudinal slice. The longitudinal-transverse correlation resulting from a partially compressed bunch and residual η was used to position each slice and adjust its energy (slightly) before the packet was tracked through the Linac.

A representative example of the launching conditions of a bunch with a length of 1.5 mm in the presence of a 1 mm η is shown in Figs. 1, 2 and 3.

As with all transverse wakefield calculations, the minimization of the oscillation amplitude of the bunch head is very important. Therefore, the addition of a specific launching position error correlated with a residual η error will allow the

head to be nearer the Linac axis and reduce the wakefield blowup. An example of this is shown in Fig. 4, 5 and 6 where a 1 mm η coupled with a negative 10 micron launching position error reduces the enlargement of the beam tail by about a factor of three.

Landau Damping (for example, K. Bane, SLAC-PUB-3670), is a technique which introduces an energy spread into the beam early in the Linac and removes it by the end of the Linac with the sole advantage that the transverse wakefield effects are reduced by about a factor of ten. However, the cost is several percent in beam energy. If a bunch under the influence of Landau Damping is examined part way down the Linac, its transverse longitudinal position correlation looks not very dissimilar to that in Fig. 5. Therefore, it should not come as a surprise that the use of Landau Damping and carefully chosen launching angles and positions can largely reduce the effects of residual η .

In the Landau Damping calculations below, the first twenty-four klystrons had the phase of negative 30 degrees, and the remainder had all the same phase somewhere in the range 5 to 20 degrees, chosen to make the energy spectrum proper at the end of the Linac for the bunch intensity given.

Results:

The calculated upper limits on residual RTL η as a function of beam intensity are shown in Fig. 7. The η limit was chosen such that the longitudinal slice at 1 mm behind the bunch center had a maximum excursion in one of the last 10 quadrupoles in the Linac equal to the one sigma transverse size of the beam (~ 120 microns). Note that the η limit drops below the Sheppard level above about 10^{10} particles per bunch. Depending on the launching conditions, η values in the range 0.05 to 0.2 mm can be harmful at high currents. These values are quite severe and are equal to or smaller than the requirements at the SLC final focus. With Landau Damping and deliberate injection errors, the simulations show that the limits on η can be restored to the Sheppard level.

The launching and RF conditions for the data with Landau Damping and with no-Landau-Damping but with injection offsets are listed in Table 2. Note that the deliberate injection offsets are comparable to injection errors, which cause significant enlargement for normal bunch displacements as described in the SLC Design Handbook. The displacements at low beam intensities can be quite large.

TABLE II

Launching and RF Conditions for η Limits in Fig.7

Beam Conditions		RF Phases (degrees) ($\sigma_z = 1.5mm$)		Optimized Inj. Cond. ($\beta = 6.6m$)	
Case	$N(z10^{10})$	Klystrons 1-24	Klystrons 25-232	$\Delta z(\mu m)$	$\Delta z'(\mu rad)$
without	1.0	2	2	-90	0
Landau	2.5	6	6	-33	0
Damping	5.0	8	8	-8	0
	7.5	11	14	-3	0
with	1.0	-30	5	-560	-80
Landau	2.5	-30	8	-300	-35
Damping	5.0	-30	12	-240	-27
	7.5	-30	20	-110	-13

Several observations have emerged from the simulations which give a general overview of the effects.

1. The enlargement of the beams at the end of the Linac is proportional to the residual $\eta(\eta')$ at the beginning of the Linac. This is in reality the same effect as for conventional wakefields where the beam enlargement is proportional

to the initial beam offset (angle).

2. The maximum allowed residual η_{max} without Landau Damping can be estimated from the maximum allowed conventional injection offset error x_{max} .

$$\eta_{max} \approx x_{max}/(\Delta E/E) \quad (1)$$

where $\Delta E/E$ is the energy spectrum in a partially compressed bunch.

3. For the case without Landau Damping, the deliberate injection errors (Δx and $\Delta x'$) added to the beam to partially cancel the effects of a residual η are roughly equal to the conventional injection tolerances. They have the opposite sign of the residual η .
4. The limits on residual η'_{max} can be calculated from the limits on η_{max} given the value of β .

$$\eta' \approx \eta_{max}/\beta \quad (2)$$

- 5 The variation of the wakefield effects of residual η with bunch lengths in the range 1 to 1.5 mm are not large because two effects nearly cancel. As the bunch length becomes shorter with increasing compressor voltage, the energy spectrum is enlarged, and the head and tail offsets for a given residual η are increased making the wakefield effects worse. However, the transverse wakefield force decreases roughly linearly in proportion with the shorter bunch length.
6. The tolerances on residual $\eta(\eta')$ are significantly relaxed when the bunch is fully compressed (below 0.5 mm). When fully compressed, the original head and tail coincide with the bunch center at the entrance to the Linac, and any residual $\eta(\eta')$ only adds to the apparent emittance of the bunch. The Sheppard limits then apply. Clearly, for future linear colliders, the design of the Damping Ring compression system should provide for operation with

fully compressed bunches to avoid residual η effects.

η Measurements

η is measured at the front of the Linac by adjusting the energy of the extracted damping ring beam using the compressor and observing beam position changes. The phase of the compressor is set so that the energy spectrum of the beam remains small. Total energy changes of $\pm 1\%$ are reasonable upper limits. The position changes in the Linac are measured using beam position monitors. Averaged position measurements have a best possible resolution of about $\pm 8\mu\text{m}$. Thus, the best possible resolution on η is

$$\sigma_{\eta} = \frac{\sqrt{2}\Delta K}{\Delta E/E} = 0.6\text{mm}$$

Some work is needed to achieve this level, because typical resolutions during the ten sector tests were $\pm 10\text{mm}$.

An alternative method of measuring residual η is to extract it from measurements of the required injection offsets to minimize the beam enlargement due to wakefields, as discussed above. This approach is clouded by several other effects in the Linac (such as, steering induced η) which can contribute significantly to the spot size.

Finally, η' values are measured as η values downstream in the Linac at a betatron phase shift of 90° (about 6 m).

FIGURE CAPTIONS

Fig.1. Longitudinal charge distribution of an SLC bunch with a length (σ_z) of 1.5 mm used in the simulations.

Fig.2. Energy of the macroparticles in the simulated bunch as a function of longitudinal position for $\sigma_z = 1.5\text{mm}$.

Fig.3. Transverse offsets of the bunch slices as a function of longitudinal position resulting from residual η of 1 mm and the conditions in Figs. 1 and 2.

Fig.4. Enlargement of the tail of the beam (1 mm behind the center) at the end of the Linac as a function of initial beam transverse offset in the presence of a 1 mm residual η . Note the minimum is at a non-zero offset value.

Fig.5. Optimum transverse offsets of the bunch slices versus longitudinal position given a residual η of +1 mm. The offset is negative 10 microns.

Fig.6. Transverse offsets of the slices of a bunch near the end of the Linac given by the injection conditions in Fig.5.

Fig.7. Upper limits of the allowed residual η from the RTL into the Linac as a function of bunch intensity. The limits were calculated using a partially compressed bunch ($\sigma_z = 1.5\text{mm}$) combined with transverse wakefields in the Linac. Limits on η (or η') without Landau Damping are comparable to those at the final focus when the bunch intensity is high.

LONG. PARTICLE DISTRIBUTION

Fig. 1

INITIAL ENERGY VS LONG. POSITION

Fig. 2

POSITION VS Z PLOT

Fig. 3

MAX TAIL POSITION VS INITIAL OFFSET

Fig. 4

POSITION VS Z PLOT

Fig. 5

POSITION VS Z PLOT

Fig. 6

ALLOWED DISPERSION VERSUS BEAM INTENSITY

Fig. 7