# Longitudinal Tune-Up of the SSC Drift-Tube and Coupled Cavity Linac Sections*

S. Nath and G. Neuschaefer
Los Alamos National Laboratory, Los Alamos, NM 87545

*Abstract*

The drift-tube and coupled cavity sections of the SSC linac will accelerate $H^-$ beam from 2.5 MeV to 70 MeV and from 70 MeV to 600 MeV, respectively. Two different procedures, namely the phase-scan method and the Δ-t method, have been in use for setting rf phase and amplitude in existing linac structures. Applicability of these two techniques for longitudinal commissioning and subsequent tuning are examined in context to the SSC linac sections.

## I. INTRODUCTION

Amplitude and phase errors in the rf field cause the beam phase and energy centroids to be displaced from their design values. If these displacements are sufficiently large, some of the particles may be outside the acceptance bucket and be lost. Even if the displacements are not large enough to cause particle loss, particles near the edge of the acceptance separatrix are subject to nonlinear forces, which would ultimately result in a severely distorted output beam.

Consequently, turn-on procedures [1-3], based on beam measurements, have been used for proper setting of the rf amplitude and phase. We report here the simulation results for longitudinal motion of a single particle representing the centroid of the beam. Experimentally, the beam centroid energy and phase are directly measurable and thus can be compared with the single-particle predictions.

## II. Δ-t METHOD

### A. Theory

The Δ-t method requires the measurement of time (phase) differences at two predesignated points B and C, downstream of the module to be tuned, as the module is turned on and off. Point B is at the exit of the module being tuned; C is one module or further downstream from B. The time of flight (TOF) values measured at points B and C change when the module is turned on. The quantities $\Delta t_B$ and $\Delta t_C$ are defined as the displacement of these TOF differences relative to the design values e.g., $\Delta t_B$ = $Dt_B$ - $Dt_B$ (design), where $Dt_3$ is the difference in TOF with module on and off. The quantities $\Delta t_B$ and $\Delta t_C$ can be expressed in terms of the beam phase and energy displacements at the entrance and exit of the module and the geometrical parameters. Complete derivations are given in Refs. 1 and 2.

From dynamics with the tank on, the beam phase and energy displacements at the exit of the module, $\Delta\phi_B = \phi_B - \phi_B$ (design) and $\Delta W_B = W_B - W_B$ (design) can be related to the phase and energy displacements at the entrance, $\Delta\phi_A$ and $\Delta W_A$, to first order as

$$\begin{bmatrix} \Delta\phi_B \\ \Delta W_B \end{bmatrix} = M \begin{bmatrix} \Delta\phi_A \\ \Delta W_A \end{bmatrix} \quad (1)$$

where M is a 2 x 2 transformation matrix through the module. The quantities $\Delta t_B$ and $\Delta t_C$ can also be expressed in terms of the elements $m_{ij}$ of the M matrix,

$$\begin{bmatrix} \Delta t_B \\ \Delta t_C \end{bmatrix} = T \begin{bmatrix} \Delta\phi_A \\ \Delta W_A \end{bmatrix} \quad (2)$$

where elements $t_{ij}$ of the T matrix can be calculated in terms of $m_{ij}$.

### B. Phase

The objective of the Δt method is to find $\Delta\phi_A$ and $\Delta W_A$ in terms of $\Delta t_B$ and $\Delta t_C$. By inverting Eq. (2) one gets

$$\begin{bmatrix} \Delta\phi_A \\ \Delta W_A \end{bmatrix} = A \begin{bmatrix} \Delta t_B \\ \Delta t_C \end{bmatrix} \quad (3)$$

where AT = 1. Once $\Delta\phi_A$ is known, the rf phase needs to be adjusted by an amount $-\Delta\phi_A$. Within a specified tolerance, when the measured $\Delta\phi_A = 0$, the rf phase is set to the nominal operating point. An equation similar to (3) can also be written for $\Delta\phi_B$ and $\Delta W_B$. In theory, the output displacements must vanish when the input displacements are zero.

### C. Amplitude

The M matrix elements are also dependent on the field amplitude. So the rf amplitude must be known or set to the design value for the evaluation of matrix elements to be valid. There are several ways to set the rf amplitude. One way is to calculate the slope of the curve in the $\Delta t_B$, $\Delta t_C$ plane as the input phase is varied. The change in the slope $S = t_{21}/t_{11}$ as a

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function of amplitude can be calculated by numerically evaluating M for different amplitudes. An approximate value for the rf amplitude can then be obtained by noting the deviations of the measured S from the design value.

The second way is to measure the change in the output energy as a function of the input phase, i.e., $d(\Delta W_B)/d(\Delta\phi_A)$, which is the matrix element $m_{21}$. The calculated variation of $m_{21}$ as a function of amplitude can then be used for setting the amplitude to the design value. Yet another way is to compare the measured peak position and peak energy gain of the energy vs phase curve with numerically simulated curves for different rf amplitudes. The amplitude and the $\Delta t$ phase measurements are repeated iteratively until the module is set to the desired accuracy.

*D. Uncertainty*

For a given uncertainty $\delta t_B = \delta t_C = \delta t$ in the measurement of $\Delta t_B$ and $\Delta t_C$ and assuming that the errors in the measurements are uncorrelated, the uncertainty in $\Delta\phi_A$ can be written from Eq. 3 as

$$\delta\phi_A = \pm \delta t \left[ (a_{11})^2 + (a_{12})^2 \right]^{1/2} \qquad (4)$$

Similar expressions give uncertainties in $\Delta\phi_B$, $\Delta W_A$, and $\Delta W_B$.

*E. Simulation Results*

For CCL dynamics calculation, we use a model with the following design parameters. It accelerates the beam from 70.0 MeV to 616 MeV. The entire CCL is divided into 11 modules. Each module has 6 tanks with 20 cells in each tank. An unramped accelerating field EoT = 6.5 MV/m and design phase $\phi_s = -30°$ are used. The frequency is taken as 1284 MHz while the beam structure is assumed to be at 428 MHz. We further assume that the $\Delta t$ pickup loops are placed after every module and that the experimental uncertainty in the measurement of $\Delta t$ is 3.25 psec ($\pm$ 0.5° at 428 MHz).

The calculated uncertainties in the input and output phases and energy displacements are shown in Figure 1. The phase uncertainty does not exceed $\simeq \pm 2°$. The energy uncertainty gets somewhat larger towards the end modules, attaining a value of $\simeq \pm$ 0.04% for $\Delta W_A$ at module 11. These values are, however, well within the longitudinal acceptance limit of the CCL.

For the DTL section, we use the design reported in Ref. 4. It consists of 4 tanks with a space of $3\beta\lambda$ between the tanks to accommodate microstrip probes, magnets and diagnostics. To examine how far down in energy one can apply the $\Delta t$ method, the beam is tracked through the tanks (using TRACE 3D) with successive tanks turned off. The result is summarized in Table 1. For tanks 1 and 2, the $\Delta t$ method is not applicable because the beam is lost radially when the rf is turned off as is needed for $\Delta t$ measurement. The bunch width at the exit of tank 4, with tank 3 rf turned off, is still quite large. For tank 4, however, the phase width is small enough for $\Delta$-t method to be applicable. Thus, the phase-scan method (to be described in the next section) has to be used for tanks 1, 2 and 3. For the sake of completeness, we also examine the applicability of the phase-scan method to tank 4.

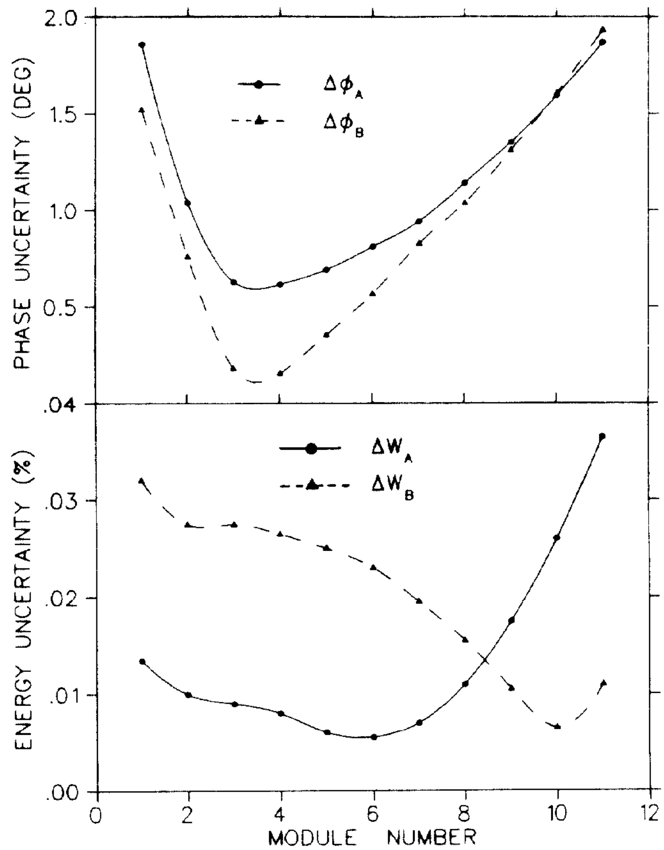


**Figure 1.** Uncertainties in the input (A) and output (B) phases and energy displacements, assuming a 3.25 pico-second (0.5° at 428 MHz) uncertainty in the measurement of $\Delta t_B$ and $\Delta t_C$.

**Table 1**

Beam Dimensions with rf Turned Off

| Tank On | Tank Off | Bunch Dimension $\Delta\phi$ (deg) | $\Delta Z$ (cm) | (X or Y) (mm) | Comment |
|---|---|---|---|---|---|
| | 1 | — | — | — | beam lost in tank 1 |
| 1 | 2 | ± 131.0 | ± 4.5 | 5.6 | at the end of tank 2 |
| 1 | 2, 3 | — | — | — | beam lost in tank 3 |
| 1, 2 | 3 | ± 40.2 | ± 2.1 | 2.2 | at the end of tank 3 |
| 1, 2 | 3, 4 | ± 91.3 | ± 4.7 | 3.4 | at the end of tank 4 |
| 1, 2, 3 | 4 | ± 24.0 | ± 1.5 | 2.1 | at the end of tank 4 |

## III. PHASE SCAN METHOD

The phase-scan method, as the name suggests, is a procedure to set the amplitude and phase by comparing the experimentally observed output beam-bunch energy and phase with the simulated design values as the input phase is varied. Unlike the Δ-t method, the module (tank) being set does not need to be turned off and on alternately, which makes it the only reliable method available for use at the lower energy section of linac structures, when the beam cannot be transported through a rf module (DTL tank) with the rf turned off.

Theoretical single-particle predictions representing the beam centroid are generated with PARMILA. Input variables for the DTL are injection phase, energy, and relative rf amplitude (1.00 being the design value). A set of curves may be generated by plotting the output energy (normalized to the synchronous energy) vs input phase, output phase vs the input phase, and normalized output energy vs the output phase.

Figure 2 shows the simulated scaling of the output energy with respect to the output phase in tank 1 for different rf amplitudes. All the curves for different rf amplitudes are presented in one plot where the axes for each simulated curve have been shifted by appropriate amounts to make the points of inflexion for each curve coincide. This is done to facilitate a least squares fit of the experimental data points to the simulated curves for various rf amplitudes. The accuracy of the experimental data depends on 1) the relative signal-strength from the microstrip detectors, and 2) the energy resolution of the measurement. For a given signal-strength above the noise level, the absolute energy resolution obtainable with two microstrip probes separated by a distance of $2\beta\lambda$ are given in Table 2.

**Table 2**

Absolute Energy Resolution

| Location | Between Tanks 1 & 2 | Between Tanks 2 & 3 | Between Tanks 3 & 4 | $2\beta\lambda$ apart after Tank 4 |
|---|---|---|---|---|
| ΔW (keV) | ± 20.9 | ± 51.6 | ± 79.2 | ± 108.4 |

The curve providing the best fit to the experimental data-points determines the amplitude. The phase can be readily set once the amplitude is fixed to the nominal design value. Similar plots show that the method is applicable to tanks 2 and 3. But in tank 4, the simulated curves with ±5.0% relative amplitude-variance do not differ significantly, and hence may not be very useful in setting the rf amplitude within the desired accuracy.

## IV. CONCLUSIONS

Our initial study shows that the first three tanks of the DTL can be tuned using the phase-scan method. Two microstrip probes separated by an appropriate distance dictated by the desired resolution or alternatively a suitably designed spectrometer can be used for absolute energy measurement. The fourth tank of the DTL, and the CCL modules can be tuned using the Δ-t method. The energy and the phase uncertainty for the CCL modules are less than ±0.04% and ±2°, respectively, if phase measurements can be done with an uncertainty of ±0.5°. An error study with the above noted bounds should give the propagation of energy and phase uncertainty from tank to tank and finally to the output end of the DTL and the CCL. The effect of the estimated tuning errors on the emittance growth is expected to be very small.

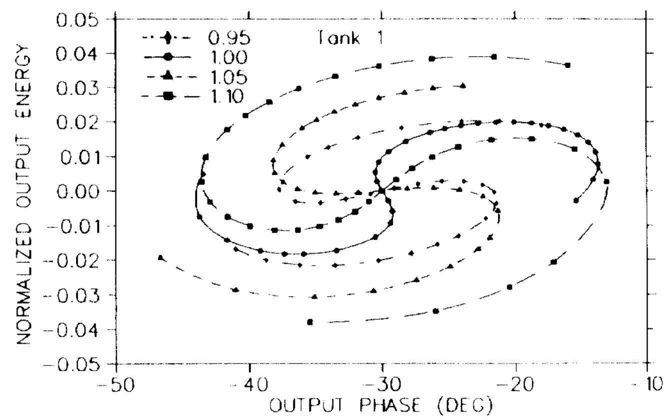


**Figure 2.** Normalized output energy as a function of the output phase for different DTL rf amplitudes in Tank 1.

## V. ACKNOWLEDGEMENTS


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## VI. REFERENCES


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