PROCEDURES FOR SETTING RF PHASE AND AMPLITUDE IN SSC DRIFT-TUBE-LINAC TANKS*

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Abstract

A procedure to accurately set RF power phase and amplitude in each tank is required for commissioning and operating the multi-tank SSC DTL (drift-tube linac). In this paper we describe and compare the Δt and the least-squares methods of determining correct phase and amplitude. Simulation results and probable advantages and problems with each method are presented and discussed. The Δt tuneup procedure is used for other linacs (at LAMPF, for example), but the least-squares procedure has not yet been tried except in simulation; it could provide a complementary or alternate technique to Δt.

Introduction

The SSC linac has severe limits on emittance growth. Longitudinal emittance growth must be kept low by proper longitudinal matching into each tank. This is accomplished by setting RF phase and amplitude to the correct set points when the linac is commissioned, tuned up, or restarted after a shutdown. The Δt method [1, 2, 3, 4] has been used quite successfully. The phase-scan method [5] is a good way to begin the tuneup. The least-squares method [6] may also be useful although it has never been tested in practice. We present a brief description of these methods and discuss their application to the SSC DTL.

Methods

Definitions and Concepts

In setting phase and amplitude, or "tuning up" the RF of a linac tank, for simplicity we define the tank RF phase (at the RF reference plane in the beginning of the tank) as the reference phase and we assume that beam phases are measured relative to that tank phase, although in practice a different phase reference will probably be used.

We use **A** to indicate a phase reference near the beginning of the tank being set. Conceptually, input beam phase, Φ_A, and energy, W_A, is measured at A; actually, there may or may not be a sensor there. Usually there are two phase sensors measuring the phase of the output beam. **B** is a phase sensor near the end of the tank and C is a sensor downstream of B, after a drift space, a matching or transport section, or downstream tank(s) with RF off.

We use the term **offset** in the least-squares method for the constant, systematic difference between actual and measured values of a quantity. We want to find the offsets in Φ_A, W_A, and V, the RF amplitude. Knowing the offsets in Φ_A and V allows us to set these quantities to desired values. If W_A is not correct, we can retune previous tanks or we can try to compensate by adjusting RF in the current tank. If Φ_A, W_A, and V, and our computer model, are correct, then the beam output phase Φ_B and energy W_B should be correct.

When discussing the Δt method, we use Δ to indicate the difference between measured and design values of a quantity. However, in discussing the least-squares method, $\Delta\Phi_B$ and $\Delta\Phi_C$ are changes in phase at B and C resulting from a change in phase $\Delta\Phi_A$ at A.

Jitter is random error or noise in the measurements.

Procedures, Measurements and Analyses

A simple version of the phase-scan method is often used for setting phase and amplitude in single cavities or short tanks where beam-energy change is small. Φ_A, measured at A, is shifted in steps over a range of 2π with W_B measurements every step. To get an absolute value of W_B by time-of-flight, phase-scan requires that phase differences between B and C be known accurately; if it is sufficient to measure ΔW_B , this may not be necessary. A plot of W_B vs Φ_A is obtained. The highest value of W_B is W_A +TV where T(W) is the transit-time factor; the lowest is W_A - TV; thus V and W_A can be found and the desired Φ_A can be set. If only ΔW_B is known, W_A cannot be found by phase-scan. No simulation is required to analyze phase-scan data for simple cases.

Another form of phase-scan [5] uses an absorber-collector that detects accelerated beam. Current from the absorber-collector is plotted against Φ_A as Φ_A is scanned across the longitudinal acceptance. The acceptance can be mapped vs. Φ_A and V. This is a useful method for initial tuning. Like the Δt and least-squares methods, this form of phase-scan depends upon a correct model that gives the proper transformations through the tank.

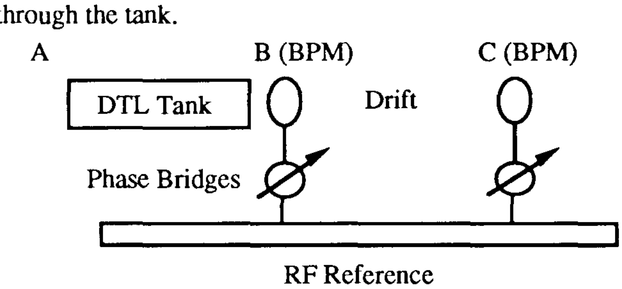

Fig. 1. In the Δt method, the phase of the beam through Beam Position Monitors B and C is measured relative to the reference line. The DTL tank is turned on and off and the difference in phase is measured at each BPM. The change in phase can also be measured as a function of tank phase to determine the amplitude set point.

The Δt method was proposed in 1970 by Crandall and Swenson [1] and described in detail in a subsequent report [2]. It is a way of measuring the difference of the energy and phase

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centroids from that of the design phase and energy. Fig. 1 shows a representation of the measurement system.

Changes in phase at B and C are measured as RF power in the tank is turned on and off (in practice, the RF is shifted in and out of synchrony with the beam pulse). These changes are converted to time-of-flight differences t_B and t_C at B and C. Corresponding time-of-flight differences for the design particle or bunch are calculated by a beam-dynamics code such as PARMILA or TRACE. The differences between measured t_B and t_C, and design t_B and t_C, are Δt_B and Δt_C. Similarly, the differences between measured and design beam energy and phase are ΔW and $\Delta\Phi$. In the linear region, the equations relating Δt measurements to the beam differences ΔW and $\Delta\Phi$ are:

$$\Delta t_B = -\frac{D_{AB}}{E_r c (\beta\gamma)_A^3}\Delta W_A - \frac{(\Delta\Phi_B - \Delta\Phi_A)}{\omega} \qquad (1)$$

$$\Delta t_C = \Delta t_B - \frac{D_{BC}}{E_r c}\left[\frac{\Delta W_A}{(\beta\gamma)_A^3} - \frac{\Delta W_B}{(\beta\gamma)_B^3}\right] \qquad (2)$$

where D_{AB} and D_{BC} are distances between positions,
E_r is the particle rest mass,
β and γ are standard relativistic notations,
c is light-speed,
ω is the RF angular frequency.

These equations are taken from reference [2] and fully described there. Δt does not depend upon absolute phase measurements or phase differences between sensors, but only upon phase shifts at each sensor, a more accurate measurement.

The least-squares method was the concept of T.P. Wangler. He proposed that the transformation through the tank with different values of input variables Φ_A, W_A, and V, and output variables Φ_B and Φ_C, forms a system of equations with unknown constants (the offsets in the input variables) that can be found by least-squares techniques. Phase measurements Φ_B and Φ_C are taken as V and Φ_A are varied over a range around the expected operating point. We can avoid determining offsets in Φ_B and Φ_C if we use phase differences ($\Delta\Phi_B$, $\Delta\Phi_C$) resulting from changes in input phase ($\Delta\Phi_A$), rather than the phases Φ_B and Φ_C themselves. Any offsets in Φ_B and Φ_C then cancel out as in the Δt method. Measurements of $\Delta\Phi_B$ and $\Delta\Phi_C$ are taken over the input phase and RF amplitude steps. $\Delta\Phi_B$ and $\Delta\Phi_C$ are calculated for the same phases and amplitudes using a beam-dynamics code, adding offsets to the calculational input variables V, W_A and Φ_A. An error value, X^2 (Equation 3), can be found from the difference between measured and calculated phase values:

$$X^2 = \frac{1}{2NM}\sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=B,C}(\Delta\Phi_{k,calc}^{i,j} - \Delta\Phi_{k,meas}^{i,j})^2 \qquad (3)$$

where i and j indicate, respectively, RF phases and amplitudes;
N is the number of $\Delta\Phi$ measurements at each amplitude;
M is the number of RF amplitude measurements (V's);
$\Delta\Phi_{k,calc}$ is calculated by tracking particles through the tank with PARMILA using a particular set of offsets;
$\Delta\Phi_{k,meas}$ is the corresponding measured value.

A new X^2 can be found by changing the offsets in V, W_A and Φ_A and recalculating. If the new X^2 is less than the old, presumably the new offsets are closer to the correct values than the old. Minimizing X^2 gives the best guess at the correct offsets.

The least-squares method requires considerable calculation because a matrix of simulations (covering many input phases and amplitudes) is calculated for each particular set of offsets. This could be several dozen cases per set of offsets. The minimization algorithm must search over three dimensions; many different sets of offsets must be tried and therefore efficiency is important. The present code uses the "simplex" algorithm [7] and with single-particle simulations converges within one or two minutes on a Sun Sparc2 computer.

In all three methods (phase-scan, Δt and least-squares) phases are measured modulo 2π. This could be a source of error in long drifts and the analysis must take this into account. This problem may be more likely to be encountered when using the Δt method because it requires drifting through two tanks, and because there are two quite different drift velocities to measure; power-off and power-on.

Application to the SSC DTL

Phase-scan Method

The phase-scan technique will probably be used to set RF phases in the RFQ-DTL matching-section buncher cavities. Phase-scan results and x-ray gap-voltage measurements will provide amplitude set points. Current plans call for the SSCL Beam Position Monitor to be used to measure the relative phase between the beam and the RF reference line for all the tune-up methods.

Phase-scan is not adequate for DTL tank 1 although stepping through input phases will probably provide the first beam through the tank. Tank 1 is very sensitive to offsets in W_A and V. These offsets couple strongly in their effect on the output beam; for instance, an offset in W_A is multiplied by factors of -2 to 3 (nonlinearly) as V changes from 94% to 106% of its correct value (after tank 1 the problem is not as severe). W_A can be adjusted over a range of about ±50 KeV without significant penalty by properly phasing the matching-section bunchers. The value of $\delta W_B/\delta\Phi_A$ around the design Φ_A can provide information about V, but interpretation is unambiguous only if W_A and Φ_A are accurately known.

Δt Method

Δt cannot be used for tank 1 because the beam will not propagate through the tank if the RF power is off. However, it can be used for following tanks. To simulate the Δt method for the SSC DTL, a model is needed to relate ΔW_A and $\Delta\Phi_A$ to ΔW_B and $\Delta\Phi_B$. A linear approximation based on reference [8] is used to calculate the elements of a matrix equation:

$$\begin{pmatrix}\Delta\Phi_B \\ \Delta W_B\end{pmatrix} = M \begin{pmatrix}\Delta\Phi_A \\ \Delta W_A\end{pmatrix} \qquad (4)$$

This equation is used to adjust Φ_A and, through the dependence of the matrix elements on amplitude, V. The measurement-adjustment process is continued until W_B and Φ_B are as close as possible to desired values.

As an example, Equations (1) and (2) were programmed in MATHEMATICA for analysis of tank 2. The resulting Δt_B - Δt_C plot (Fig. 2) shows the sensitivity to an offset in W_A.

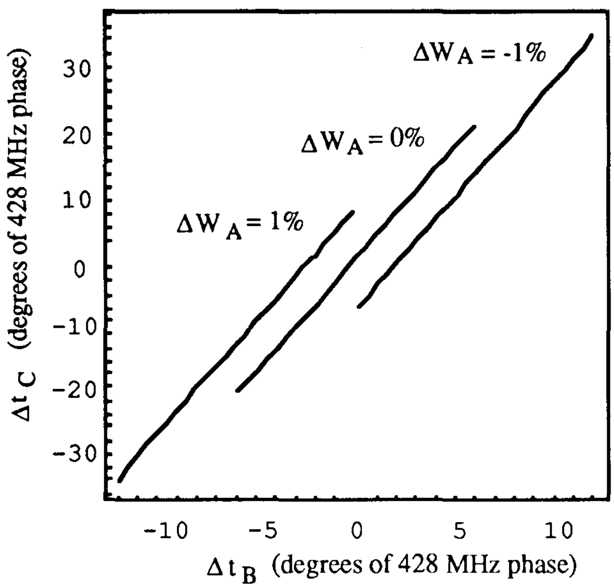

Fig. 2. Parametric plot of Δt_B and Δt_C for variations of the input phase, $\Delta\Phi_A$, from -5° to 5° for various input energies, W_A. Plot shown is for the second DTL tank.

Least-Squares Method

The untested (in practice) least-squares method works well in simulation for DTL tanks 1 and 4, for which calculations have been done. As W_A, Φ_A and V are moved away from design values in multiparticle simulation, beam is lost longitudinally from the bucket and not accelerated, though particle transmission remains high. The output beam becomes a continuous beam of low-energy particles with a high-energy bunch component superimposed. The phase of the high-energy bunch can be detected if the accelerated, bunched beam is more than about 2.5 mA. Because (unlike Δt) the least-squares method does not assume linearity, offsets can be calculated if phase can be measured over only a few RF phase and amplitude settings. It is preferable that the design point be near or inside the region covered by the steps in Φ_A and V. However, even if this condition is not met, the procedure will give an estimate of the offsets that will allow the next iteration to converge to the desired operating point.

A problem with least-squares on tank 1 is that single-particle simulations do not give the same phase results as multiparticle simulations except very close to the design point. We believe that least-squares will still converge to the correct offsets using single-particle simulation but this has not yet been tested. If not, multiparticle simulation must be used, the method will require more computer time, and some thought should be given to speeding up the calculation. Perhaps a higher-order transformation could be empirically fit to the multi-particle simulations. This problem does not exist for tank 4 of the DTL; there, single- and multi-particle calculations give essentially the same results. Tanks 2 and 3 have yet to be simulated for least-squares but are not expected to be as difficult as tank 1. Both least-squares and Δt can probably be used on these tanks because the beam retains a significant bunch structure without RF power.

Tank 1 may provide the most sensitive measurement of the energy out of the matching section; least-squares, combined with absorber-collector phase-scan, might be a way of measuring W_A with good accuracy after tank 1 is installed.

Measurement jitter, or random measurement error, in both phase and voltage affects the accuracy of results in all three methods. Simulations show that in least-squares for tanks 1 and 4, phase jitter of <0.5° rms and amplitude jitter of 0.5% rms give good results (within 1° and 1% on offsets). An interesting characteristic of least-squares is that if there is no amplitude jitter, phase jitter can be estimated from the normalized minimum X^2 value.

Conclusions

The SSC must develop an accurate procedure for setting RF phase and amplitude in the DTL tanks, both for initial turn-on and for normal operation. Several techniques are available for our use. The phase-scan and Δt methods have been proven effective on other linacs and will certainly be used on the DTL. The least-squares method works well in simulation, and will be tried for the first time on an actual machine; perhaps it will prove to be a useful tool. Our next steps will be extensive simulations using each method, preliminary adaptions of the selected methods to the control system programs, and extension of this effort to plans for setting RF in the Coupled-Cavity Linac.

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