LEAST-SQUARES FITTING PROCEDURE FOR SETTING RF PHASE AND AMPLITUDE IN DRIFT-TUBE-LINAC TANKS*

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Abstract

Commissioning and operating a multi-tank drift-tube linac requires a procedure for setting phase and amplitude of the RF power in each tank. The Δ-t tuneup procedure has been extensively used for this (in LAMPF, for example). In this paper we present a complementary method using least-squares analysis of relative phase measurements. In this method bunch phases relative to RF power are measured at the input and output of the tank and at a reasonable drive distance downstream (or after the next tank with its RF off). The RF phase and amplitude are varied in a predetermined way; the resulting measured phase shifts are compared by least-squares fitting with their corresponding values from a beam-dynamics code simulation. The absolute calibration errors (assumed constant) of the phase sensors are the quantities which are varied to obtain the best fit. If these calibration errors are known, absolute values of RF phase and amplitude can be determined and the correct values set in the tank.

I. INTRODUCTION

Phase and amplitude set points must be found for the RF power in DTL (drift-tube linac) tanks when an accelerator is being first commissioned, tuned up, or restarted after a shutdown. For many years the Δ-t time-of-flight method[1,2,3] has been used quite successfully but for some accelerators it may be desirable to have an alternate or complementary method of adjusting RF power. This paper describes such a method and discusses its application. There is a brief discussion of the computer code that was written for this effort.

II. THE LEAST-SQUARES METHOD

A. Concept and Definitions

First, a brief description of the Δ-t method. Phase pickup sensors are required at two points downstream of the tank whose RF power is being adjusted. Usually one point is just downstream of the tank exit and the other is after the next downstream tank (whose RF power is turned off). The sensors detect beam bunch phase with respect to a reference phase. Changes in relative phase at these points, as the power in the tank is turned on and off, are converted to time-of-flight differences with and without RF power. Time-of-flight differences are also calculated by a beam-dynamics code such as PARMILA or TRACE. Experimental and calculated times-of-flight are then compared to develop information to adjust RF phase and amplitude. The RF is adjusted, then the process is repeated until the phase and amplitude are within desired tolerances.

The least-squares method also compares experimental and calculated phase measurements. There are three phase sensors (Fig. 1); one (Z_1) just upstream and one (Z_2) just downstream of the subject tank, and one (Z_3) at some appropriate drift distance further downstream. As in the Δ-t method, Z_3 can usually be placed after the next downstream tank, which is operated with no RF power. Therefore, to use this method there must be a phase sensor before the first tank, between each tank, and after a drift downstream of the last tank.

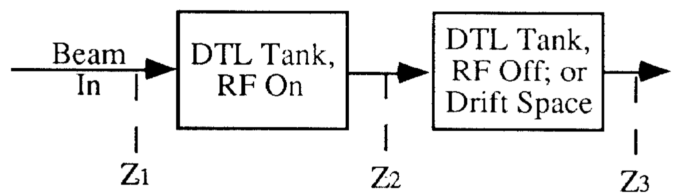

Figure 1. Placement of beam phase sensors.

The RF power is set one tank at a time starting with the lowest energy tank. The next downstream tank's RF is turned off. Beam phases Φ_1, Φ_2, and Φ_3, as measured by sensors at Z_1, Z_2 and Z_3, are defined as measured phases of the RF pickup signal from the tank when the sensor pulses induced by the beam are at their maximum. When experimental measurements are taken, the beam phase actually remains constant and the tank RF phase is adjusted. However, in this paper the tank RF phase (at the RF reference plane in the beginning of the tank) is defined as the reference phase and we assume that beam phases are measured relative to that tank phase.

Measurements of Φ_2 and Φ_3 are taken for a number of input phases Φ_1 (adjusted for Z_1 position so that beam phases at the tank bracket the input phase acceptance) and for a number of RF amplitudes (bracketing the design amplitude). Measurements of RF amplitude V, input beam energy W, and the three relative phases Φ_1, Φ_2, and Φ_3, will have unknown calibration errors which we assume will remain constant. We will henceforth refer to these constant calibration errors as **offsets** in the measurements. With known offsets, we can set the input phase Φ_1 and RF amplitude V to their desired values. The object of the least-squares method is to calculate the offsets from the phase-sensor measurements.

The measurements of Φ_2 and Φ_3 form a matrix covering all the input phases and RF amplitudes. One can calculate a similar matrix using a beam-dynamics code such as

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PARMILA by running the appropriate problems. An error value, X^2, can be found from the difference between the experimental and calculated matrices. We can avoid determining the offsets in Φ_2 and Φ_3 if we use **phase differences** ($\Delta\Phi_2$, $\Delta\Phi_3$) due to changes in input phase ($\Delta\Phi_1$), rather than the relative phases themselves, as the quantities which are squared and summed to form X^2. Any offsets in Φ_2 and Φ_3 then cancel out.

The offsets that we need to determine, then, are $\delta\Phi_1$, the offset in the relative phase Φ_1, and δW_i, the offset in input beam energy W_i, which together with the distance between Z_1 and the tank determine the offset in the RF phase in the tank; and δV, the offset in RF amplitude V. In our code we define δW and δV as fractions of design values and $\delta\Phi$ in degrees. Offsets are added to measurements to determine true values.

$$\Phi_{1,\,true} = \Phi_{1,\,measured} + \delta\Phi$$

$$W_{i,\,true} = W_{i,\,measured} + \delta W \times W_{i,\,design} \tag{1}$$

$$V_{true} = V_{measured} + \delta V \times V_{design}$$

These offsets are found as follows: A matrix of calculated phases Φ_2 and Φ_3 is constructed using a first guess (usually zero) at the set of offsets $\delta\Phi_1$, δW_i and δV in this way: A macroparticle representing the bunch is initiated at Z_1 with energy $W_i + \delta W_i$ at the first $\Phi_1 + \delta\Phi_1$ with the tank amplitude at the first $V + \delta V$. The macroparticle is tracked through the tank and phases at downstream sensor positions are stored. Another macroparticle with the next value of $\Phi_1 + \delta\Phi_1$ is tracked using the same W_i and V. After Φ_1 has been scanned, the scan is repeated using the next V and so on until a matrix of calculated phases has been built up using that particular set of offsets. X^2 is found by comparing the calculated matrix with the measured one:

$$X^2 = \frac{1}{2NM} \sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=2}^{3} (\Delta\Phi^{i,j}_{k,calc} - \Delta\Phi^{i,j}_{k,meas})^2 \tag{2}$$

where i and j indicate, respectively, RF phases and amplitudes;
N + 1 is the number of input Φ's;
N is the number of $\Delta\Phi$ measurements, $\Delta\Phi^i = \Phi^{i+1} - \Phi^i$;
M is the number of RF amplitude measurements (V's);
k is the sensor number, 2 or 3, for the Φ_k measurements;
$\Delta\Phi_{k,calc}$ is calculated by tracking through the PARMILA linac with a particular set of offsets;
$\Delta\Phi_{k,meas}$ is the corresponding measured value.

We then put in a different set of offsets, again calculate a matrix and get another value of X^2. Presumably if the second X^2 is less than the first, then the second set of assumed offsets is likely to be closer to the actual offsets in the measurements. The set of offsets that is the best fit to the actual values should produce the minimum X^2.

B. Calculational Techniques

The computer code that implements the least-squares calculation is called COMFIT. It is written in Fortran and runs in a few seconds on the Cray. The code has two subroutines that have been adapted from the PARMILA beam-dynamics code. The first uses design data on the DTL tank, previously calculated by PARMILA, at the beginning of the problem to set DTL cell parameters. The second transports a macroparticle representing the bunch through the tank and associated drifts to calculate phases at the three sensor points.

We have made several assumptions in writing this code. The first three are fundamental to the method but the others could be changed if necessary. The assumptions are:

1. The tanks are built as designed; errors in construction are ignored. Therefore given exact RF amplitude, input beam phase, and input beam energy, PARMILA can predict exact output beam phase and energy.
2. Input beam energy remains constant.
3. The macroparticle transported through the PARMILA subroutine represents the bunch centroid, and no particles are lost from the bunch during measurement. This assumption is discussed further below.
4. RF amplitude offset is the same for all amplitudes.
5. Offsets are less than about 20% in RF amplitude, 1% in beam energy and 30^{o} in input beam phase relative to the tank.
6. Phase measurements (including Φ_1) have random jitter. The RF amplitude also jitters but remains constant during a particle transit of the tank. Jitter distribution is uniform over a specified range.

DTL tank design parameters are provided to the code in tabular form. Input data also includes sensor positions, nominal input beam energy, nominal tank voltage amplitude and synchronous Φ_1, the number of steps and step sizes in the phase scan and tank voltage (although actual values of phases and voltages could be used), and the matrix of measured phase values. There are a few other input values having to do with the fitting and plotting routines. The code first generates the DTL tank in the same way as PARMILA. It then moves into the fitting subroutine which minimizes X^2.

C. Simulated Measurements

A subroutine was included in the code to test its operation. The subroutine generates a matrix of fake "measured" phases using a specified set of offsets by running macroparticles through the tank as described above. Phase and voltage jitter can be included. The code fits this simulated data to see how closely the specified set of offsets can be reproduced. This technique was employed using a test case.

Cross-sections of the X^2 surface can be plotted by holding two of the offsets constant at specified values and plotting X^2 vs. the other offset. In the cases that have been run, these plots have shown only one minimum in the surface in the region where the input beam and RF voltage allow the macroparticle to remain in synchronization with the RF bucket. While one cross-section may show two or more minima, cross-sections in the other directions reveal that only one is a true minimum. The code's simple slope-following minimization process works well on such a surface as long as the macroparticle remains in the bucket. Since the macro-particle represents the whole bunch, results may not be good if particles are lost from the bunch. Therefore, it is important to monitor beam current through the tank; if current is lost on any phase measurement then that measurement should not be used.

If there is no jitter in V, but some jitter in Φ in the simulated measurements, the minimum X^2 (whose units are degrees^2) is near the average value of the square of the jitter, as it should be. This provides a convenient check on the code and may be useful in estimating actual jitter.

The code has some interactive graphics capability. Various views and cross-sections of the X^2 surface can be provided and various quantities can be plotted, for instance output phase vs. output energy along lines of constant V.

D. Estimated Accuracy

Accuracy using the simulated measurements has been encouraging. A hundred or so runs were made on two different DTL tanks of 2.5 MeV and 20 MeV input energy. Input phase was scanned over $\pm 40^{\circ}$ in steps of 10° and amplitude was scanned over $\pm 15\%$ in steps of 5%. Many combinations of offsets and jitter amplitudes were tried. Accuracy was found to depend upon the magnitude of offsets, jitter amplitude, the number of data points in the measured matrix, and to a small extent upon details of the fitting routine. Not enough runs have been made to determine the exact nature of these dependencies, but in general for reasonable offset values (within the assumptions listed above) and jitter (within about 2° in Φ and 2% in V) the code will reproduce offsets within 1° in RF amplitude and a few tenths of a percent in V and input beam energy. For small offsets the accuracy is somewhat better. Presumably if large offsets were found in the data, corrections would be made and new data taken.

E. Some Possible Problems, Suggested Solutions and Code Improvements

If the offset in V is linear rather than constant, the code as written is inaccurate; but if such dependence is determined from other analyses, the code could easily be modified.

Some DTL tanks may be so long that if the RF power is turned off, the beam goes unstable in transiting the tank. This could occur with permanent-magnet focusing if the zero-current phase advance per focusing period approaches 90° (envelope instability) because the beam is not accelerated and the lower beam energy causes stronger focusing than the normal accelerated beam would see. This situation could cause trouble in applying the least-squares tuneup method (and indeed, any method such as Δ-t that relies on a drift space after the tank). In such a case, if there is sufficient space between the tanks perhaps two phase sensors could be placed there. In some cases it may be possible to include a phase sensor partway down the tank so that phase can be measured before the instability sets in. If enough of the bunch remains after transiting the tank to permit phase measurement, and particle loss does not cause damage to the drift tubes, perhaps the method can be used anyway although particle loss may affect accuracy. Beam current could be reduced, minimizing damage and perhaps slowing instability buildup; an analysis taking into account reduced beam current should still give proper RF phase and amplitude settings although some corrections may be required and the settings may not be quite as accurate.

A more sophisticated minimization code such as MINUIT[4] might provide more information on the X^2 surface, including determination of the valid limits of the phase scan and estimation of sensitivities and jitter in all the offsets.

III. CONCLUSIONS

On the basis of the tests described above, we suggest that the least-squares method be tested with actual measurements. If no obvious uncorrectable difficulties are encountered then perhaps the method can help to determine measurement errors in the RF setting process, providing information on correct settings of RF amplitude and beam phase in DTL tanks.

IV. ACKNOWLEDGEMENT

Discussions with Ken Crandall of AccSys Corporation helped greatly in simplifying the least-squares method of DTL tuneup and in adapting the method to use phase differences, the type of experimental data that is likely to be the easiest and most accurate to measure.

V. REFERENCES

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