THE DELTA-T TUNEUP PROCEDURE FOR THE FERMILAB LINAC

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Abstract

The delta-t procedure provides a means of monitoring and setting to design values the phase and amplitude of fields within a linear accelerator. Deviations from design values of energy entering an accelerator module can also be determined. The procedure will be used to tune the upgraded linac under construction at Fermilab.[1] Results of preliminary tests of the technique on the existing 200 MeV linac show qualitative trends in agreement with analysis. Quantitative comparisons show some differences.

Introduction

The delta-t procedure was developed at the Los Alamos National Laboratory many years ago for the purpose of adjusting the phase and amplitude of the fields in each of 44 modules in the LAMPF linear accelerator.[2] Recently, workers in the USSR, at the Institute of Nuclear Research, extended the analysis and utility of the procedure by treating second order effects that become increasingly important as the longitudinal extent of the beam bunches increases.[3] Other recent work has examined use of the delta-t procedure on the linac of the Advanced Hadron Facility.[4]

The procedure entails measurements of the deviation from design of changes in the times of flight between points along the accelerator as the module fields are alternately turned on then off. Following the analysis presented in reference 2, module phase, $\Delta\phi_A$ and module input energy, ΔW_A, can be related in a linear fashion to the deviation from design of the difference in time of flight at a point just beyond the module being tuned (Δt_B) and at a point further down the accelerator (Δt_C) according to the relation,

$$\begin{bmatrix} \Delta\phi_A \\ \Delta W_A \end{bmatrix} = A \begin{bmatrix} \Delta t_B \\ \Delta t_C \end{bmatrix} \qquad (1)$$

The 2x2 matrix, A, is derived from the transformation matrix through the module. It is a function of the electric field in the accelerator gaps and the accelerator geometry. The electric field is determined using a variety of techniques. One way involves measuring the energy out of the module as input phase is changed. The ratio of energy change to phase change is equal to the (2,1) element of the transformation matrix. The known dependence of this element upon electric field then determines the electric field value. Another technique to estimate the electric field magnitude involves locating the peak in the energy change as phase is varied. The amplitude and phase location of this peak for a given electric field can be calculated using beam dynamics simulations, then compared to the measurements.

Once the electric field has been estimated and brought up to design levels, the phase and input energy displacements from design can be estimated from measurements of the delta-t values according to equation 1. Corrections to the module phase and input energy can then be made. The electric field and delta-t measurements are repeated and adjustments to field, phase and input energy are continued in an iterative fashion until the module is tuned to the desired accuracy.

Tests on the Fermilab Linac

Preliminary tests of the delta-t procedure have been performed on the 200 MeV drift tube linac at Fermilab in preparation for use on the 400 MeV accelerator upgrade. Tests have focussed on measurements of Δt_B and Δt_C as the phase is varied, as was done early on in the LANL tests, in order to understand some of the basic features of the procedure. Curves have been generated for many of the linac accelerator modules for a variety of electric fields and input energies. An example of the type of curves that are generated is given in figure 1 for the fifth accelerator module out of a total of nine

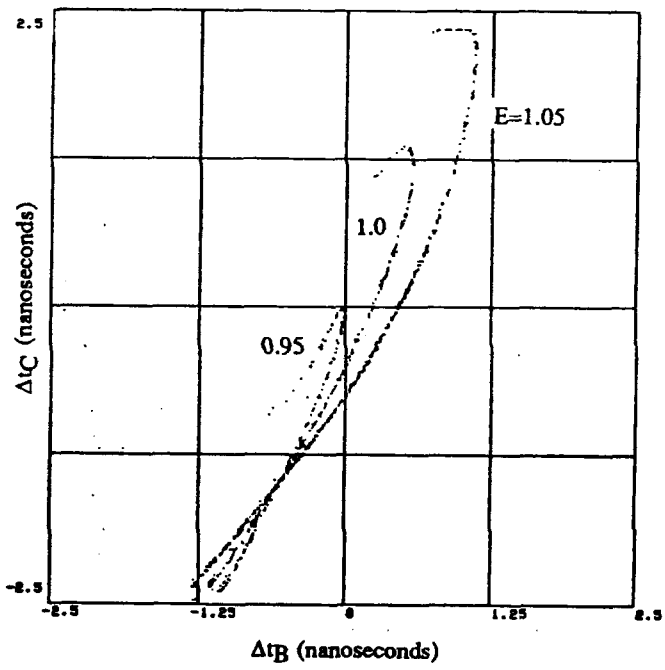

Figure 1. *Experimental measurements of delta-t values for module 5 as phase is varied. Electric field magnitude is varied ±5% about nominal (center curve).*

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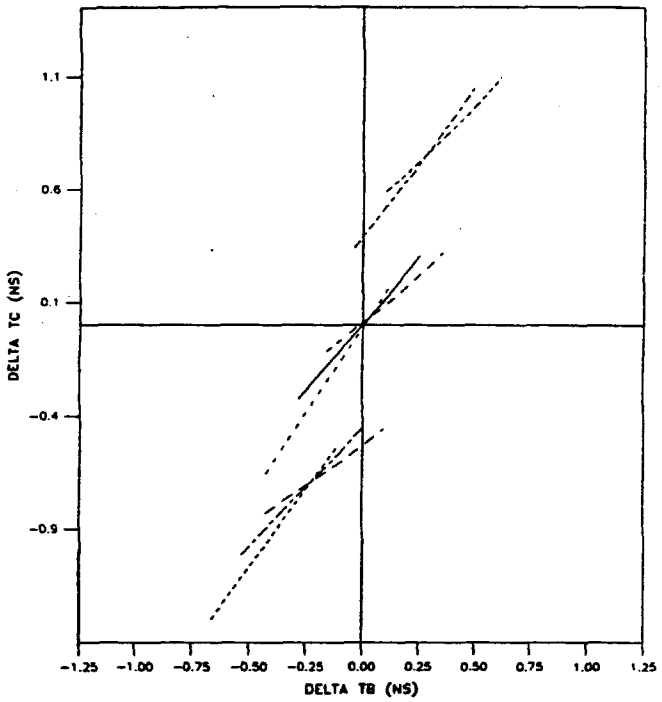

Figure 2. *Theoretical delta-t curves for module 5. For the upper curves, input beta=0.41331; for the center curves, input beta=0.41414; and for the lower curves, input beta=0.41497. Electric fields are varied ±5% about nominal within each cluster.*

modules which make up the Fermilab linac.

Computer simulations of the same type of curves for the conditions of module 5 are given in figure 2 for comparison with the experiment. We find good qualitative agreement. Basically, at a given input energy, all curves are clustered around and intersect with a single point in the delta-t plane. Separate clusters of curves occur for each input energy. As the electric field amplitude is varied, the slopes of the curves change. For a perfectly tuned module, the intersection point would lie at the origin in the delta-t plane and the curve generated by varying the phase would have a specific slope dictated by the design field setting. For module 5, the experimental curves in figure 1 indicate that the input energy into module 5 is high by a few tenths of a percent and the electric field is low by a few percent.

We have been able to vary the input energy into module 5 by adjusting the phase of module 4. A series of curves similar to the theoretical presentation in figure 2 is obtained. In figure 3, we have plotted the location in the delta-t plane of all of the points of intersection of these curves. Also plotted in figure 3 is the theoretical prediction. In agreement with theory, the points of intersection all lie on a straight line, but the slope of the line generated experimentally differs somewhat from theory, and it does not quite pass through the origin.

The source of the disagreement between theory and experiment is not known at present. Linac geometery is the only parameter that greatly affects the theoretical line generated in figure 3, according to the theory developed by Crandall.[2] The effect we are seeing is similar to what is predicted by the higher order theory described in reference 3. A careful comparison with the theory of reference 3 has not been made. Other possible reasons for the differences are currently under investigation.

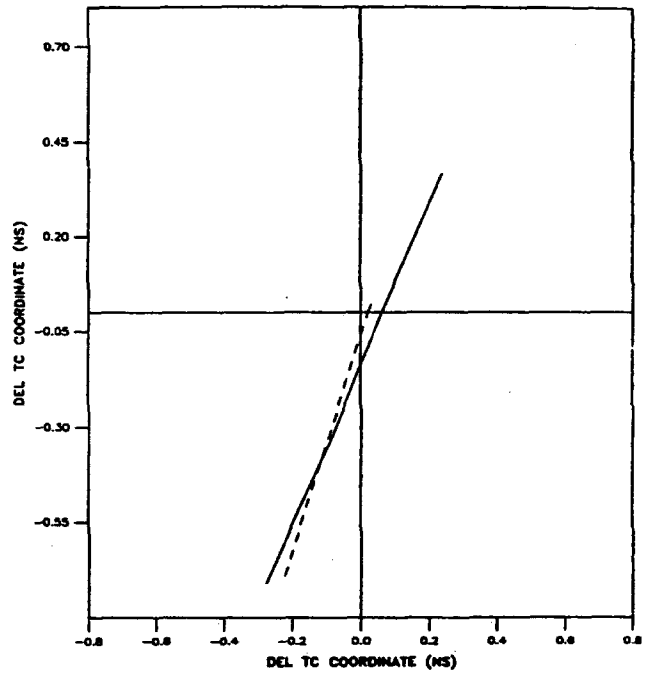

Figure 3. *Variation of the intersection points of curve clusters for module 5 as input energy is varied. Solid line - experiment, dashed line - theory.*

We have tested the technique, mentioned in the introduction, for estimating the electric field using measurements of the peak energy out of the module. In this case, electric field is estimated by comparisons between simulation and experiment. Figure 4 shows measurements of

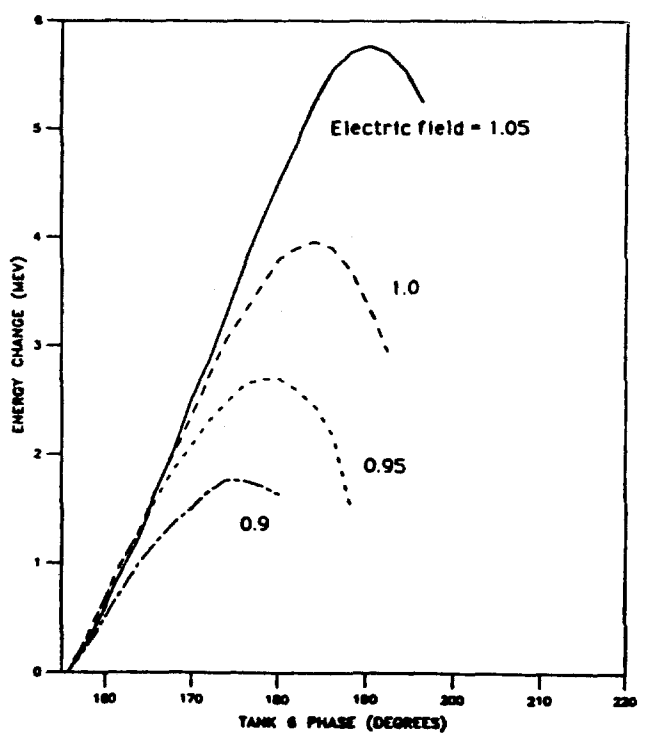

Figure 4. *Experimental measurement of particle energy increase in module 6 versus module 6 phase. Nominal phase setting is 155.7 degrees.*

the energy out of module 6 of the Fermilab linac as phase is varied. The figure demonstrates that the energy peak is highly sensitive to electric field magnitude, and should therefore provide a very accurate means of setting field magnitude within the context of the delta-t procedure. Surprisingly, we found substantial differences between the curves of figure 4 and computer simulations. Detailed comparisons indicate that the differences arise because the beam is not well centered in the rf bucket for this module.

In principle, all of the information necessary for tuning a given module is present in experimental plots like figure 1. However, we have found that the curves are all nearly parallel to one another by the seventh or eighth module in the Fermilab linac, and results become inaccurate. The procedure must be modified for these higher-energy modules, as discussed in reference 2 and in the next section.

Procedure for High-Energy Modules

Since inaccuracies in the higher-energy modules are due to the fact that the delta-t curves generated by varying the module phase are nearly parallel, we choose a procedure which seeks a target line that is perpendicular to the variable phase curves. We have reproduced the theory[2] necessary to simulate this procedure in order to determine its effectiveness on our linac. As discussed in reference 2, any procedure must be stable. The criterion for stability is that the percentage energy displacement at the output of the module must be less than the input percentage energy displacement. If this stability criterion fails, the beam will tend to walk out of the rf bucket.

Figure 5 shows the degree to which our linac is stable. Plotted here is the ratio of the output percentage energy error to input percentage energy error (the stability ratio) for modules 3-9. Any value below one in the figure is stable. We have found that the procedure is quite stable for modules 4-9, but is unstable for earlier modules.

Figure 6 is a plot of the uncertainty in the output energy for one picosecond error in the delta-t measurements for modules 3-9 of the Fermilab linac. We have assumed that errors in the measurements are random. Larger errors in output energy can be produced if there are systematic errors in the time difference

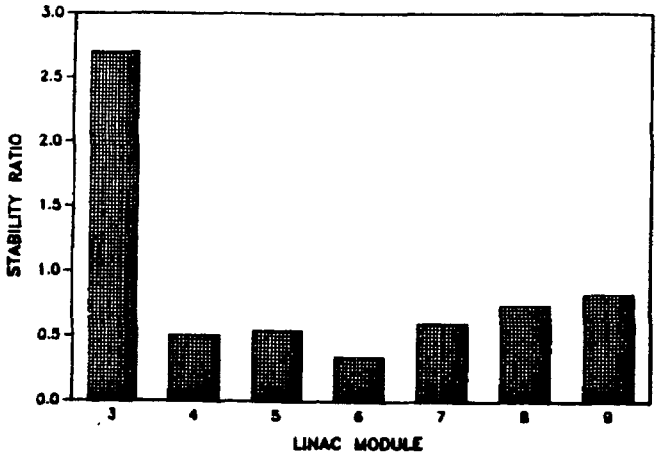

Figure 5. *Ratio of output percentage energy displacement to input percentage energy displacement (stability ratio) for the high-energy delta-t procedure in the Fermilab linac. Stability limit is unity.*

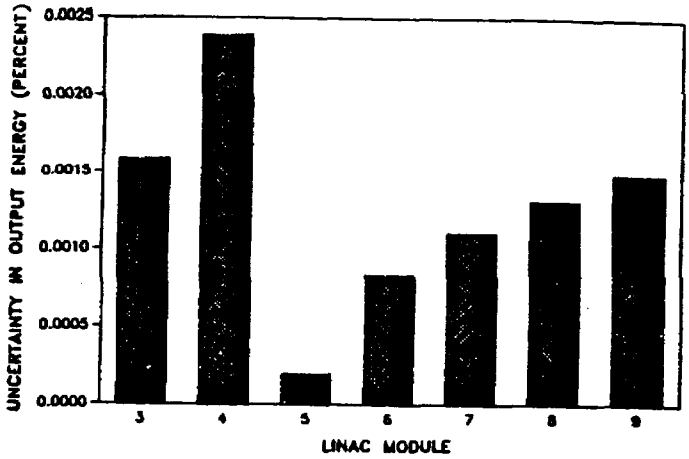

Figure 6. *Uncertainty in output energy for the high-energy delta-t procedure in the Fermilab linac. One picosecond random errors in delta-t measurements are assumed.*

measurements. We anticipate total random errors on the order of 13.8 picoseconds. From figure 6, uncertainties are expected to be less than approximately 0.02 % for each of modules 5-9 of the Fermilab linac, which should allow the beam to be well centered in the rf bucket using this procedure.

Summary

The delta-t procedure appears to be a potentially accurate and stable technique for setting the phase and electric field magnitude in the Fermilab linac. Some differences between theory and experiment have been found. Resolution of these differences would improve the accuracy of the technique.

References

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2. K. R. Crandall, "The Delta-T Tuneup Procedure for the LAMPF 805 MHz Linac," LANL Report LA-6374-MS, June, 1976.

3. G. A. Dubinski, A. V. Reshetov, Y. U. Senichev and E. N. Shapashnikova, "New Features of the Delta-T Procedure For An Intensive Ion Linac," in *1988 Linear Accelerator Conference Proceedings*, Newport News, VA, Oct. 3-7, 1988 .

4. G. R. Swain, "Use of the Delta-T Method For Setting RF Phase and Amplitude in the AHF Linac," in *Proceedings of the Advanced Hadron Facility Accelerator Design Workshop*, Feb. 20-25, 1989 (Also LANL Report LA-11684-C).