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Phase and Amplitude Tuning Procedures for the Fermilab Linac

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Abstract

Procedures for both coarse and fine tuning of phase and amplitude of the Fermilab linear accelerator cavities are described. Coarse tuning is accomplished by measuring the change in energy as the phase of an individual accelerator cavity is adjusted. Proper field level occurs when the peak energy change equals the design value. Phase is initially set to calculated values relative to the phase at which the energy peak is measured. Fine tuning is accomplished using the delta-t procedure developed at the Los Alamos National Laboratory.[1] Preliminary tests of the delta-t procedure on the existing 200 MeV linac show qualitative trends in agreement with theory. The procedures described in this report have been proposed for use on the upgraded linac under construction at Fermilab.[2]

I. Introduction

The objective of any procedure to set phase and amplitude in a linear accelerator is to keep the beam well centered within the longitudinal acceptance area. The beam phase and energy displacements from design values must be kept within acceptable ranges to prevent energy and phase spreading. The delta-t procedure is a method for setting the phase and amplitude within an accelerator cavity to keep the beam centered in the acceptance area. The procedure was developed at the Los Alamos National Laboratory many years ago for tuning each of 44 accelerator cavities on the LAMPF linear accelerator.[1] Recently, workers in the USSR, at the Institute of Nuclear Research, extended the analysis and utility of the procedure by treating second order effects.[3] These effects become increasingly important as the longitudinal extent of the beam bunches increases. Other recent work has examined the procedure for use on the linac of the Advanced Hadron Facility.[4]

The success of the procedure, in the form described in reference 1,

requires that the initial phase displacement and energy displacement of the beam be small enough that output displacements are linearly related to input displacements. A means for coarse setting of the phase and amplitude is therefore required to bring the displacements within this linear range where the delta-t procedure can be used. A proposal for coarse tuning is presented in the Section V of this report. Another assumption in the delta-t theory is that the beam can be accurately represented by its centroid. If the beam extent in longitudinal phase space is so large that non-linear particle motion occurs, the measurements can be seriously perturbed.[1] Finally, it is assumed that the beam current is low enough that the beam effect upon resonator fields is negligible.

This report presents the status of our on-going study of the delta-t procedure on the Fermilab linac. The linac consists of 9 cavities, each powered by a 5 MW triode amplifier, operating at a frequency of 201.2416 MHz. The delta-t procedure described here is applied only to cavities 3-9 of the existing linac. The current plan is to apply the procedure to the upgraded linac now under construction at Fermilab[2], once the procedure has been fully tested on the existing linac. For the upgrade, the last 4 Alvarez cavities of the existing linac will be replaced with 7 new side coupled cavity assemblies, powered by 7 klystrons. The delta-t procedure will be used to set the phase and amplitude of each klystron. The klystrons will be capable of 12 MW operation at 805 MHz, approximately. The goal of the upgrade is to increase the output energy of the linac from 200 MeV to 400 MeV.

At this point, most of the analysis needed to carry out the delta-procedure has been completed and is presented here. Much of the experimental hardware is still under development and only a few preliminary experiments have been performed. We will begin with a general discussion of the delta-t procedure, followed by details of its application to the existing Fermilab linac. Finally, a method for initial coarse tuning of the linac will be presented.

II. Review of the Delta-T Procedure

The procedure involves measuring the deviation from design of the changes in the times of flight of beam bunches between points along the accelerator. The measurement requires that the cavity fields be alternately turned on, then off to obtain relative times of flight. Following the description presented in reference 1, two beam monitors detect the structure of the beam at two locations downstream of the cavity being tuned. All cavities downstream of the cavity being tuned are turned off, while cavities upstream of the cavity being tuned are turned on. The cavity being tuned is alternately turned on then off. As this occurs, a change in the time of flight is measured at each of the beam monitors. The change in time of flight recorded by the monitor nearest

the exit of the cavity being tuned is designated as t_B. The change recorded by the more distant monitor is designated as t_C.

In practice, changes in times of flight are measured using a relative beam phase comparison at the fundamental frequency of the beam bunches. Because the measurements are relative, inaccuracies in absolute signal transit times are unimportant. It is only necessary that the cable electrical lengths not change on the time scale of the measurement, which is fast compared to normal thermal time constants in the system.

The theory which will be described here is a review of the original theory presented in reference 1. We will use the same notation in order to minimize confusion. The original theory will be applied in the next section to our specific situation on the Fermilab accelerator. Deviations from calculated (design) values for changes in the transit times, t_B and t_C, are designated as Δt_B and Δt_C. These deviations can be related to the phase and energy displacements at the input and exit of the cavity being tuned, and the various distances involved according to the following[1]:

$$\Delta t_B = - \frac{D_{AB}}{E_r c \eta_A^3} \Delta W_A - \frac{(\Delta\phi_B - \Delta\phi_A)}{\omega} - \frac{D_1}{E_r c} \left\{ \frac{\Delta W_A}{\eta_A^3} - \frac{\Delta W_B}{\eta_B^3} \right\} \qquad (1)$$

$$\Delta t_C = \Delta t_B - \frac{(D_2 - D_1)}{E_r c} \left\{ \frac{\Delta W_A}{\eta_A^3} - \frac{\Delta W_B}{\eta_B^3} \right\} \qquad (2)$$

where the variables are defined as follows:

D_{AB} = cavity length.

E_r = particle rest energy.

η^2 = $\gamma^2 - 1$.

$\Delta W_{A,B}$ = energy displacement from design at input, A, and exit, B, of cavity.

$\Delta\phi_{A,B}$ = phase displacement from design at input and exit of cavity.

$D_{1,2}$ = distances from end of cavity to first monitor, 1, and second monitor, 2.

The design particle is the particle for which the input phase and energy displacements are zero. In this case, the output phase and energy displacements are also zero, as are the delta-t values. For phase and energy displacements which are small, the output phase and energy displacements are linearly related to the input displacements as follows:

$$\begin{bmatrix} \Delta\phi_B \\ \Delta W_B \end{bmatrix} = \mathbf{M} \begin{bmatrix} \Delta\phi_A \\ \Delta W_A \end{bmatrix} \tag{3}$$

where **M** is the transfer matrix through the cavity being tuned. It is important to note that the transfer matrix is a function only of the cavity geometry, which is fixed, and the electric field, which is to be adjusted. Using equation 3, the delta-t values in equations 1 and 2 become functions of input phase and energy displacements according to,

$$\begin{bmatrix} \Delta t_B \\ \Delta t_C \end{bmatrix} = \mathbf{T} \begin{bmatrix} \Delta\phi_A \\ \Delta W_A \end{bmatrix} \tag{4}$$

The elements of the matrix, **T**, are written as functions of the elements of the transfer matrix in reference 1.

Since we want to determine phase and energy displacements from measurements of delta-t values, it is useful to invert equation 4, as follows:

$$\begin{bmatrix} \Delta\phi_A \\ \Delta W_A \end{bmatrix} = \mathbf{A} \begin{bmatrix} \Delta t_B \\ \Delta t_C \end{bmatrix} \tag{5}$$

Displacements at the exit of the cavity being tuned are similarly calculated as,

$$\begin{bmatrix} \Delta\phi_B \\ \Delta W_B \end{bmatrix} = \mathbf{B} \begin{bmatrix} \Delta t_B \\ \Delta t_C \end{bmatrix} \tag{6}$$

where, $\mathbf{B} = \mathbf{MA}$. From equations 5 and 6, it is clear that the important parameters related to accelerator tuning can be deduced from mesaurements of the delta-t values.

It has been assumed, however, that the electric field is known. The electric field value determines the values of the elements of the matrices, **M**, **T**, **A**, and **B**. The electric field can be estimated using one of at least three different techniques. The first technique involves measuring the slope of the curve generated in the delta-t plane as the phase is varied. The slope, S, is a sensitive function of electric field in the early cavities of the linac, and is given by,

$$S = \frac{t_{21}}{t_{11}} \tag{7}$$

where t_{21} and t_{11} are elements of the matrix, **T**.

A second technique involves measuring the slope of the curve of relative energy versus phase in the vicinity of the design phase. From equation 3, it can be seen that this slope is simply the 2,1 element (m_{21}) of the transfer matrix. The relative energy can be measured using the beam monitors, and noting that,

$$\Delta W = - E_r c \eta_B^3 \frac{(\Delta t_C - \Delta t_B)}{(D_2 - D_1)} \tag{8}$$

for energies close to design. Like the slope, S, the 2,1 element of the transfer matrix is also a sensitive function of electric field in the early cavities of the linac. Beyond cavity 6 in the Fermilab linac, m_{21} and S lose their sensitivity to the electric field, and a third technique is used.

In this case, the electric field is estimated from a measurement of the peak energy change out of the cavity as the phase is changed. The energy change can be determined, once again, from the delta-t signals, making use of equation 8.

Once the peak energy has been determined, the amplitude is changed slightly, and the change in peak energy recorded. From the difference in peak energy values, the partial derivative, $\partial W_p/\partial E$, can be determined experimentally. The quantity,

$$\frac{\partial W_p}{\partial \phi_s}\frac{\partial \phi_s}{\partial E} = -\frac{m_{21}}{\tan(\phi_s)} \tag{9}$$

is then calculated and added to the partial derivative, $\partial W_p/\partial E$, to obtain the total derivative, dW_p/dE. From this total derivative, the electric field amplitude displacement from design, ΔE can be estimated as,

$$\Delta E = \frac{\Delta W_p}{dW_p/dE} \tag{10}$$

where ΔW_p is the displacement of the measured peak energy change from the calculated value for the design particle. This technique provides a very sensitive means of determining the electric field displacement for all linac cavities. It does, however, require accurate calculations of the peak energy as a function of phase. The linear relation indicated in equation 3, between output energy and input phase, does not hold near the energy peak. A non-linear theory must be used. A description of the theory we have used in this situation is given in Section III.

To summarize the technique that has been described so far, The electric field is first determined by one of the above three methods. A correction to the electric field is made, if necessary. The cavity phase and energy displacements are determined from the measured delta-t values using equations 5 and 6. Corrections can then be made to cavity phase ($\Delta\phi_A$). The whole process is repeated until the desired accuracy is achieved. If the input energy displacement is unacceptably large, the cavities upstream of the cavity being tuned must be adjusted.

The best corrections to cavity phase may not be those that make $\Delta\phi_A = 0$, even though this seems, at first, to be the most obvious choice. There are two other factors that must be taken into account in making phase corrections. First of all, if the input energy displacement is not zero, making $\Delta\phi_A$ equal zero could result in a deleterious growth of the output energy displacement after several cavities. It is desireable that this growth not occur. This goal is

expressed mathmatically as a type of stability criterion,

$$\left| \frac{\Delta W_B / W_B}{\Delta W_A / W_A} \right| < 1 \qquad (11)$$

If this criterion is satisfied, then the beam centering within the acceptance area will improve down the linac.

Perhaps the next seemingly best choice for the phase correction is one which produces zero energy displacement at the output of the cavity. This choice would satisfy the stability criterion, making the left hand side of relation 11 equal to zero. However, the effect of measurement errors must also be considered. Large errors are produced when the line generated in the delta-t plane, by varying the cavity phase, is nearly parallel to a target line given by our choice of criteria for making phase corrections. It can be shown for the high-energy cavities in our linac, that the criterion, $\Delta W_B = 0$, defines a line in the delta-t plane that is nearly parallel to the line generated by varying the cavity phase. This criterion would not be a good choice for our high-energy cavities, since large errors in the phase setting would occur.

It seems reasonable to establish a criterion for setting the cavity phase which defines a line in the delta-t plane that is perpendicular to the line generated by varying the phase of the cavity. By varying the cavity phase until it intersects this perpendicular target line, errors should be minimized. From equation 5, the perpendicular target line is given by,

$$a_{22}\,\Delta t_B - a_{21}\,\Delta t_C = 0 \qquad (12)$$

where the a's are elements of the matrix, **A**. Using this equation, and equations 3 and 4, the stability ratio can be calculated as,

$$\left| \frac{\Delta W_B / W_B}{\Delta W_A / W_A} \right| = \left\{ m_{22} - m_{21} \frac{\left[\frac{t_{22}}{t_{11}} + \frac{t_{12}}{t_{21}} \right]}{\left[\frac{t_{21}}{t_{11}} + \frac{t_{11}}{t_{21}} \right]} \right\} \frac{W_A}{W_B} \qquad (13)$$

If the magnitude of the quantity on the right hand side of equation 13 can be made less than one, then the target line given by equation 12 will yield a

procedure which is both stable and has minimal errors. This procedure will be referred to throughout the remainder of this text as method 2.

While the errors resulting from use of method 2 are always less than the errors introduced by other methods, the stability ratio is not always less than 1. For example, it will be shown in the next section that the stability ratio is greater than 1 for the low energy cavities of the Fermilab linac. For these low energy cavities, a different method will be used. In this case, the phase is adjusted until the line generated in the delta-t plane intersects the target line given by the criterion, $\Delta\phi_A = 0$. For low energy cavities, the two lines are sufficiently close to perpendicular that only small errors occur. Better stability, compared to method 2, with acceptable errors are attained in this way. This procedure will be referred to as method 1. Which cavities are tuned using method 1 as opposed to method 2 must be determined before proceeding. This determination for the Fermilab linac is the subject of the next section.

III. The Delta-T Procedure Applied to the Fermilab Linac

In this section, the theory developed in the previous section will be applied to the specific geometry of the Fermilab linac. The most challenging aspect of this application of the theory is the development of accurate longitudinal dynamics. A major problem arose from the fact that the analysis which was used to generate the Fermilab linac geometry was performed twenty-three years ago. Details of the original analysis were not well known. The only applicable information that could be located was a set of tables generated in 1967 which listed cell lengths, betas, and transit time factors for each cell of the linac. It was not clear what theoretical dynamics were used to generate these tables, and some of the parameter definitions were unclear.

Modern theoretical dynamics were used in atempts to reproduce parameters in the tables generated in 1967. When the actual linac geometry was used in this analysis, small discrepencies in cell betas, and phases arose when compared to the original tables. For example, when the beta into the first cell of a cavity taken from the early tables was used as an initial condition for the modern dynamics code, output betas would differ by a few tenths of a percent. In addition, the discrepency from cell to cell along the cavity had a systematic character. Interestingly, we found that nearly perfect agreement could be obtained by making small adjustments in the electric field magnitude used in the modern code. After making extensive checks of our code, it was concluded that the small differences in our results, compared to those generated in 1967, were due to small, unknown differences in the theoretical dynamics used in each case.

Since delta-t values are sensitive to beam parameter differences of tenths of

a percent, the problem created by these discrepencies had to be solved before there could be any confidence in the delta-t procedure. The principle problem relates to the fact that the synchronous particle in one set of theoretical dynamics will not be a synchronous particle in a different set of dynamics. Accuracy in using the delta-t procedure depends critically upon identifying the betas and phases of a synchronous (or design) particle, since time of flight changes are relative to this particle. If a precisely synchronous particle cannot be found for a fixed geometry, then the closest thing to it must be found within the context of our modern theory.

This problem is similar to a problem encountered by the LAMPF group in their early studies of the delta-t procedure. They discovered that the linac had discrepencies in cell positions, relative to what was called for by their beam dynamics codes[5]. They had to do the best they could at correcting the situation and identifying a new "best" design particle. In our case, the best design particle was identified by minimizing the RMS variation of the phase at the centers of the cell gaps along the accelerator. The computer code used to perform this calculation is called "XYZ", and is listed in the appendix of this report.

The most important subroutine within this code is named "XFER". It performs the transformation of beta and phase across each cell of the linac. The theory used in this subroutine is similar to the theory used for longitudinal dynamics in the code, PARMILA. For electric fields that are symmetric about the center of the accelerating gap, the following expressions have been used,

$$\phi_e = \phi_i + l_1 \phi_i' + l_2 (\phi_i' + \Delta\phi) + \delta\phi \tag{14}$$

$$\Delta W = e E_o L \cos (\phi_o) \left[T_o - 2\pi (\frac{\beta_g}{\beta_c} - 1) T_p \right] \tag{15}$$

$$\phi_o = \phi_i + l_1 \phi_i' + \delta\psi \tag{16}$$

$$\beta_c = \beta_i + \frac{e E_o L}{2 \beta_h \gamma_h^3 W_o} \left[T_o \cos (\phi_o) + S_o \sin (\phi_o) \right] \tag{17}$$

where,

$$\phi_i' = \frac{d\phi_i}{dz} = \frac{2\pi}{\beta_i \lambda}$$

$$\Delta\phi = - \frac{2\pi \Delta W}{\lambda \beta_o^3 \gamma_o^3 W_o}$$

$$\delta\phi = - \frac{2\pi e E_o L^2}{\lambda \beta_o^3 \gamma_o^3 W_o} T_p \sin(\phi_o)$$

$$\delta\psi = - \frac{\pi e E_o L^2}{\lambda \beta_h^3 \gamma_h^3 W_o} \left[T_p \sin(\phi_o) + S_p \cos(\phi_o) \right]$$

$$\beta_o = \frac{\beta_i + \beta_e}{2} \quad , \quad \beta_h = \frac{\beta_i + \beta_c}{2} \quad , \quad \beta_g = \frac{L}{\lambda}$$

The transit time factors are defined as follows,

$$T_o = \frac{1}{E_o L} \int_{-\frac{L}{2}}^{\frac{L}{2}} E(z) \cos\left(\frac{2\pi z}{L} \right) dz$$

$$T_p = \frac{1}{E_o L^2} \int_{-\frac{L}{2}}^{\frac{L}{2}} z\, E(z) \sin\left(\frac{2\pi z}{L}\right) dz$$

$$S_o = \frac{2}{E_o L} \int_{0}^{\frac{L}{2}} E(z) \sin\left(\frac{2\pi z}{L}\right) dz$$

In the above equations, $\phi_{e,i}$ are the exit and entrance phases for the cell, ΔW is the energy change through the cell, ϕ_o is the phase at the center of the accelerating gap, β_c is the beta at the center of the accelerating gap, l_1 is the distance from the cell entrance to the center of the gap, l_2 is the distance from the center of the gap to the exit of the cell, W_o is the rest energy of the particle, and L is the cell length. The center of the accelerating gap is at z = 0. The above equations basically treat a situation in which there is a free drift to the center of the accelerating gap. At the gap center there is a stepwise transformation of the energy and phase. The particle then drifts from the gap center to the exit of the cell.

Inputs to the subroutine, XFER, include the input beta, phase at the input to the cell, and the average axial electric field. The subroutine outputs the beta and phase at the exit of each cell along a cavity, and the phase at the center of each gap. Geometric parameters for each cavity are obtained in the subroutine, GEO. The subroutine reads the cell lengths, drift tube lengths, and the cell gaps from files TXX.DAT, where XX=01-12. It also reads, from files CFXX.DAT, the coefficients for curve fits to the transit time factors, which have been obtained from an electromagnetics code such as SUPERFISH. Finally, the subroutine LSCAN finds the minimum of a function of two variables. The function is supplied as an external function subprogram. In the present case, FUNXY is the function subprogram. It calculates the RMS phase along the accelerator cavity. The file SYNC.DAT contains the phases and betas at the input and output of cavities 3-9 for the particle exhibiting the minimum RMS phase variation along each cavity. This particle will be the "design" particle for the delta-t calculations which follow. A listing of the file, SYNC.DAT is given in Table I.

Once the design particle has been identified in the program, XYZ, the transfer matrix, **M**, can be calculated. Once this matrix has been calculated, the elements of the other matrices, **T**, **A**, **B**, can be determined from a knowledge of the cavity overall length, and the distances to the beam monitors. Module and beam monitor distances are contained in file, D.DAT. The program, DTPAR, calculates all of the elements of the matrices for cavities 3-9 of the Fermilab linac. A listing of this program is given in the appendix. The program outputs the changes in the times of flight through the cavity. These are the variables t_B and t_C in the theory given in the previous section. In the experiments, we measure deviations from these values. The values for t_B and t_C , calculated in the program DTPAR, are used to set the zero in the delta-t plane in the experiments. A listing of these parameters is given in file, TAB.DAT, in Table I. Elements of the various matrices are listed in Table I in the files, M.DAT, TMAT.DAT, AMAT.DAT, and BMAT.DAT for cavities 3-9.

Having calculated the elements of the above matrices, error analysis and stability of the delta-t methods can be examined. It can be shown that for random errors in the delta-t measurements, the expected value for the square of the output energy is given by [1,4],

$$<\delta W^2> = \left[b_{21} + s_2 b_{22} \right]^2 \frac{(1 + s_1^2)}{(s_1 - s_2)^2} <\delta t^2> \qquad (18)$$

where s_2 is the slope of the line generated in the delta-t plane by varying the cavity phase, s_1 is the slope of a target line in the delta-t plane with which an intersection is sought, and $<\delta t^2>$ is the mean value of the square of the time measurement error. The quantity in the denominator in equation 18 shows that large errors occur when the slope of the target line is close to the slope of the line generated by varying cavity phase. This point was made in the previous section, using a qualitative argument. Equation 18 has been evaluated for cavities 3-9 of the Fermilab linac for target lines given by delta-t methods 1 and 2 (the definitions of method 1 and 2 were given in the previous section). Results are plotted in figure 1. It is observed in the figure that errors for both methods are comparable in cavities 3-5. Much smaller errors are recorded for method 2 in cavities 6-9.

The stability ratio given in equation 13 for method 2 has also been calculated for the Fermilab linac. The program to calculate both the stability

ratio and the uncertainty in output energy is called, DTERR. A listing of this program is given in the appendix. The stability ratios calculated using this code are shown in figure 2. The stabiltiy ratio is less than 1 in cavities 4-9, but is greater than 2.5 in cavity 3. Information contained in figures 1 and 2 suggest that method 2 would work better than method 1 in cavities 6-9. Both methods would work well in cavities 4 and 5, while method 2 is somewhat unstable for cavity 3. A prescription for conduct of the experiments is now provided.

Preliminary tests of the delta-t procedure on the Fermilab linac have been reported elsewhere[6] and will not be discussed at length in this report. Basically, these tests measured the curves that are generated in the delta-t plane as the cavity phase is varied. Module electric field and input energy were varied for each of the various curves generated in these experiments. Good qualitative agreement between theory and experiment were obtained, but no attempt was made to adjust cavity phase and amplitude. A summary of the recommended procedures to make these adjustments will be provided in the next section.

IV. Experimental Procedures for the Fermilab Linac

As discussed earlier in this report, the first step in the procedure is to measure and adjust the cavity electric field. This can be accomplished in cavities 3-5 by finding the slope of the curve generated in the delta-t plane by varying the phase of the cavity about the approximate design phase. The phase about which to measure the slope will normally be within a few degrees of the point where curves of various electric field values intersect. The slope of the line through this intersection point could be taken if there is some question regarding where to conduct the slope search.

Once the slope has been determined experimentally, its value is input to the subroutine EFSET. This subroutine provides an estimate of the electric field displacement from design using the slope data. A listing of this code is given in the appendix. If Δt_B is input to this subroutine, it will output an estimate of the input energy displacement. Corrections to the electric field should be made at this point to bring it closer to the design value.

The next step is to measure the delta-t values of the initial phase set point. These values are then input to subroutine, PHSET. This subroutine outputs an estimate of the phase and input energy displacements from design. Corrections to these displacements can then be made. The electric field measurement is repeated and additional corrections to phase and energy displacements are made until the desired accuracy is achieved or until incremental corrections reach the

limits of accuracy of the hardware. Small corrections to the input energy displacement can be made by varying the phase of the previous tank or tanks.

For cavities 6-9, the electric field displacement is estimated by measuring the peak energy change through the cavity as the cavity phase is varied. This energy change is estimated from the changes in the time of flight between the two beam monitors placed after the cavity being tuned. Equation 8 is used to calculate the energy change from the beam monitor measurements. The electric field is next changed by one or two percent and a new value for peak energy change is measured. The two values of peak energy change, and the fractional change in electric field are input to subroutine EFSET2. This subroutine provides an estimate of the electric field displacement using equations 9 and 10. Values for the peak energy change for the design particle, needed to evaluate equation 10, are calculated using the computer program WPEAK listed in the appendix. A sample plot of the output of this code is given in figure 3 for cavity 6. In this case, energy change is plotted as a function of cavity phase. A mark is placed at the location of the peak energy in the figure. The file WPEAK.LIS contains values of the peak energy and the phase displacement at which the peak occurs for cavities 5-9, as calculated in the program, WPEAK.

The next step is to generate a target line on the screen which displays the delta-t plane in the experiment. For cavities 6-9, delta-t method 2 is recommended. In this case, the target line is given by equation 12. Values for the matrix elements given in equation 12 are contained in the file, AMAT.DAT. Once the target line has been drawn on the screen, the phase of the cavity is adjusted until the measured delta-t values intersect the target line. The new phase setting occurs at this intersection. The electric field measurement is repeated and additonal adjustments of the phase are made to intersect the target line. The process continues until the desired accuracy is achieved. If the input energy displacement is known, then it is not necessary to draw and intersect the target line on the delta-t plane in the experiment. It is only necessary to know the initial delta-t values. The phase is then adjusted according to,

$$\Delta\phi_A = a_{11}\Delta t_B + a_{12}\Delta t_C + \left[a_{11} + \frac{a_{22}\,a_{12}}{a_{21}}\right]\left\{\frac{\dfrac{\Delta W_A}{a_{22}}}{s_2 + \dfrac{1}{s_2}}\right\} \qquad (19)$$

The methods described here assume that the input energy displacement is close to zero. It is very important to insure that this is the case, particularly for the early cavities. For example, figure 4 is a plot of the errors that can be produced in the electric field setting using the peak-energy-measurement

technique and method 2. From the figure, input energy displacements of only a few tenths of a percent can produce percent size errors in the electric field setting. The severity of the problem is diminished by the fact that the errors drop considerably for the higher energy cavities. Also, considering the stability ratios in figure 2, the fractional input energy displacement should decrease by approximately a factor of ten from cavity 6 to cavity 9.

V. Coarse Setting of Phase and Amplitude

Since the methods described here assume a linear relation exists between input and output phase and energy displacements, the initial displacements must not be too large. In addition, in the early cavities large displacements can lead to ambiguities in the results. A means of coarse tuning is needed. We propose here a possible technique for coarse tuning, which should be convenient and reasonably straight-forward. The technique requires measurements of the energy change through the cavity as a function of cavity phase. This energy change can be conveniently measured using a time-of-flight technique similar to the delta-t procedure. Spectrometer measurements of energy changes can also be made if this equipment is available, and if the beam can be drifted down the accelerator to the location of the spectrometer.

Focusing upon the time-of-flight procedure, phase changes at two beam monitors placed after the cavity being tuned are recorded as the cavity is alternately turned off then on. These phase changes are then converted to time changes. The change in velocity through the cavity is then calculated from,

$$\frac{\Delta v}{v_i} = \left\{ \frac{1}{1 - \dfrac{(\Delta t_2 - \Delta t_1)}{D} v_i} - 1 \right\} \tag{20}$$

where v_i is the velocity entering the cavity being tuned, and D is the distance between the two beam monitors (designated by subscripts 1 and 2) placed after the cavity being tuned. The energy change is calculated from this equation and the relation,

$$\Delta W = E_r \Delta\gamma \tag{21}$$

As can be deduced from equation 20, accurate energy change measurements can be made using the proposed time-of-flight procedure only if the velocity into the cavity being tuned is known with some degree of accuracy.

During the procedure, the amplitude is increased from zero until the peak energy change equals the calculated peak energy for the design particle. It is important to start the cavity phase scans from zero so that the number of 2π cycles of beam phase can be counted. The cavity phase is then set to the design value relative to the phase at which the peak energy occurs. Values for this relative phase and the output energy displacement (deviation from the design output energy) of the peak energy have been calculated for the Fermilab linac, and are given in the file WPEAK.LIS. The energy change through the cavity is calculated by adding the energy displacement at a given cavity phase to the energy change through the cavity for the design particle at the design phase. The energy changes for the design particle at the design phase may be calculated from the beta values given in the file, SYNC.DAT, listed in Table I.

To simulate what might be measured in the experiments, plots of output energy displacement versus phase have been generated in figures 5 and 6 for a variety of cavity electric field levels. The file, WPEAK has been used in this simulation. Results are shown for cavities 5 and 8, as examples. A full 360 degrees of phase are scanned in the figures. Recall that the total energy change through the cavity is found by adding plot values to the energy change experienced by the design particle at the design phase. The single peak in energy is a clear feature of the plots. For cavity 5, at the approximate boundaries of the acceptance region, the particle acceleration through the cavity drops rather abruptly. The drop in acceleration is not nearly as sharp in cavity 8.

It is possible, in these coarse phase and amplitude scans to determine something about the input energy into the cavity being tuned. To illustrate how this might work, figures 7-9 show the energy displacements versus phase for situations in which the input energy is varied + - 0.5 %. The curves suggest that input energy displacement may be determined by finding the phase difference between the peak and the zero energy displacement values when the energy peak has been adjusted to its design value (by varying the electric field). This phase difference is dependent upon the input energy displacement. For example, in the figure 7, the phase difference is approximately 55 degrees if the input energy displacement is zero. It is approximately 25 degrees if the input energy displacement is 0.5% high (figure 8) and it appears to be greater than approximately 70 degrees (figure 9) if the input energy is low by 0.5%.

Conclusions

The delta-t procedure outlined in this report should provide an accurate means of tuning the phase and amplitude of the linac at Fermilab, provided the input energy displacement to each cavity can be held close to zero. The coarse tuning procedure proposed here, which is performed before the delta-t procedure, is relatively simple and convenient. Equipment needed for coarse tuning is the same equipment used to perform the delta-t procedure. During coarse tuning, a bunched beam must be maintained as the phase and electric field are scanned over wide ranges.

The next logical step in the program is to implement the procedures outlined above on the existing linac at Fermilab. This practical test will provide valuable information on the procedures before they are used on the upgraded linac, now under construction. If the tests are successful, calculations similar to those presented in this report will need to be made for the parameters of the upgraded linac.

References

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

2. R. J. Noble, "The Fermilab Linac Upgrade," in the *Proceedings of the 1990 Linear Accelerator Conference*, Albuquerque, New Mexico, Sept. 10-14, 1990.

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).

5. K. R. Crandall, "Summary of 805 MHz Linac Length Corrections," Los Alamos Scientific Laboratory memorandum, March 26, 1975.

6. T. L. Owens and E. S. McCrory, "The Delta-T Tuneup Procedure for the Fermilab Linac," in *Proceedings of the 1990 linear Accelerator Conference*, New Mexico, Sept. 10-14, 1990 (Also Fermilab Report Conf-90/207).

Table I.

A Collection of Data Files Generated or Used By the Delta-T Programs and Referenced in this Report

```
$ TYPE SYNC.DAT
MODULE     PHASE IN      PHASE OUT       BETA IN       BETA OUT

  3     -.370184D+01  -.370016D+01  0.274682D+00  0.356964D+00
  4     -.370045D+01  -.369952D+01  0.356965D+00  0.414117D+00
  5     -.369971D+01  -.369924D+01  0.414115D+00  0.456896D+00
  6     -.370087D+01  -.370025D+01  0.456917D+00  0.491270D+00
  7     -.369903D+01  -.369881D+01  0.491279D+00  0.520408D+00
  8     -.369923D+01  -.369892D+01  0.520412D+00  0.545215D+00
  9     -.369802D+01  -.369805D+01  0.545215D+00  0.566463D+00
$
$
$ TYPE TAB.DAT
MODULE      TAB            TAC          PHASE AB      PHASE AC

  3     0.271456D-07  0.759467D-07  0.196662D+04  0.550211D+04
  4     0.119697D-07  0.335885D-07  0.867166D+03  0.243339D+04
  5     0.636528D-08  0.186077D-07  0.461145D+03  0.134807D+04
  6     0.422698D-08  0.128180D-07  0.306232D+03  0.928628D+03
  7     0.317305D-08  0.958704D-08  0.229878D+03  0.694552D+03
  8     0.242147D-08  0.730079D-08  0.175428D+03  0.528920D+03
  9     0.187558D-08  0.571578D-08  0.135880D+03  0.414091D+03
$
```

```
$ TYPE M.DAT
MODULE     M11             M21             M12             M22

  3     0.782667D+00  -.919881D+00  0.101689D+00  0.116024D+01
  4     -.518306D+00  -.325347D+01  0.205296D+00  -.642383D+00
  5     -.924054D+00  0.543904D+00  -.215194D-01  -.107007D+01
  6     -.760526D+00  0.336065D+01  -.106701D+00  -.843874D+00
  7     -.548389D+00  0.509154D+01  -.133352D+00  -.585943D+00
  8     -.329469D+00  0.631488D+01  -.141007D+00  -.333244D+00
  9     -.122018D+00  0.708665D+01  -.139368D+00  -.102785D+00
$
$
$
$ TYPE TMAT.DAT
MODULE     T11             T21             T12             T22

  3     0.164049D-09  -.856558D-09  -.260852D-08  -.397706D-08
  4     0.118436D-08  -.872424D-09  -.123588D-08  -.270881D-08
  5     0.152357D-08  0.175495D-08  -.579472D-09  -.164682D-08
  6     0.140124D-08  0.252064D-08  -.328657D-09  -.105070D-08
  7     0.123526D-08  0.258347D-08  -.211690D-09  -.700861D-09
  8     0.106234D-08  0.242642D-08  -.140255D-09  -.474777D-09
  9     0.897733D-09  0.219441D-08  -.947591D-10  -.329578D-09
$
$
$
$ TYPE AMAT.DAT
MODULE     A11             A21             A12             A22

  3     0.137768D+10  -.296718D+09  -.903608D+09  -.568275D+08
  4     0.631953D+09  -.203532D+09  -.288325D+09  -.276305D+09
  5     0.110369D+10  0.117615D+10  -.388358D+09  -.102109D+10
  6     0.163188D+10  0.391490D+10  -.510450D+09  -.217632D+10
  7     0.219810D+10  0.810252D+10  -.663920D+09  -.387412D+10
  8     0.289402D+10  0.147903D+11  -.854929D+09  -.647551D+10
  9     0.374808D+10  0.249557D+11  -.107764D+10  -.102094D+11
$
$
$
$ TYPE BMAT.DAT
MODULE     B11             B21             B12             B22

  3     0.104809D+10  -.161157D+10  -.713003D+09  0.765278D+09
  4     -.369329D+09  -.192529D+10  0.927161D+08  0.111555D+10
  5     -.104518D+10  -.658267D+09  0.380837D+09  0.881407D+09
  6     -.165882D+10  0.218051D+10  0.620426D+09  0.121096D+09
  7     -.228591D+10  0.644411D+10  0.880709D+09  -.111036D+10
  8     -.303903D+10  0.133466D+11  0.119477D+10  -.324085D+10
  9     -.393536D+10  0.239963D+11  0.155435D+10  -.658746D+10
$
```

```
$ TYPE SLOPE.DAT
TANK     SLOPE=S          dS/dE          M(2,1)       dM(2,1)/dE

  3   -.522135D+01   -.177451D+03   -.919881D+00   -.307672D+02
  4   -.736621D+01   -.711322D+02   -.325347D+00   -.921962D+00
  5   0.115187D+01   -.281154D+01   0.543904D+00   -.997426D+01
  6   0.179886D+01   -.174515D+01   0.336065D+00   -.530117D+00
  7   0.209144D+01   -.121761D+01   0.509154D+00   -.153438D+00
  8   0.228403D+01   -.860680D+00   0.631488D+00   0.169492D+00
  9   0.244278D+00   -.653983D-01   0.708665D+00   0.395586D+00
$
$
$
$ TYPE WPEAK.LIS
MODULE /WPEAK (MEV) /DEL PHI (DEG)

   5  0.320182D+01  0.551875D+02
   6  0.342375D+01  0.498125D+02
   7  0.349635D+01  0.459375D+02
   8  0.347573D+01  0.429375D+02
   9  0.338610D+01  0.408125D+02
$
```

```
$ TYPE D.DAT
  03 1.338000D-01 1.756785D+01 1.652656D+01
  04 1.338000D-01 1.689747D+01 1.668405D+01
  05 1.338000D-01 1.636593D+01 1.558367D+01
  06 1.338000D-01 1.696284D+01 1.554459D+01
  07 1.338000D-01 1.701084D+01 1.582904D+01
  08 1.338000D-01 1.686742D+01 1.587704D+01
  09 1.338000D-01 1.686742D+01 1.573362D+01
$
$
$
$ TYPE G.DAT
  03 2.012416D+08 2.600000D+00 1.000000D-06
  04 2.012416D+08 2.600000D+00 1.000000D-06
  05 2.012416D+08 2.560000D+00 1.000000D-06
  06 2.012416D+08 2.560000D+00 1.000000D-06
  07 2.012416D+08 2.560000D+00 1.000000D-06
  08 2.012416D+08 2.560000D+00 1.000000D-06
  09 2.012416D+08 2.560000D+00 1.000000D-06
$
$
$
$ TYPE S.DAT
  03 3.500000D+01 -2.121000D02 0.274682D+00
  04 2.900000D+01 -2.120200D02 0.356965D+00
  05 2.400000D+01 -2.119780D02 0.414115D+00
  06 2.200000D+01 -2.120440D02 0.456917D+00
  07 2.100000D+01 -2.119390D02 0.491279D+00
  08 2.000000D+01 -2.119500D02 0.520412D+00
  09 1.900000D+01 -2.118810D02 0.545215D+00
$
```

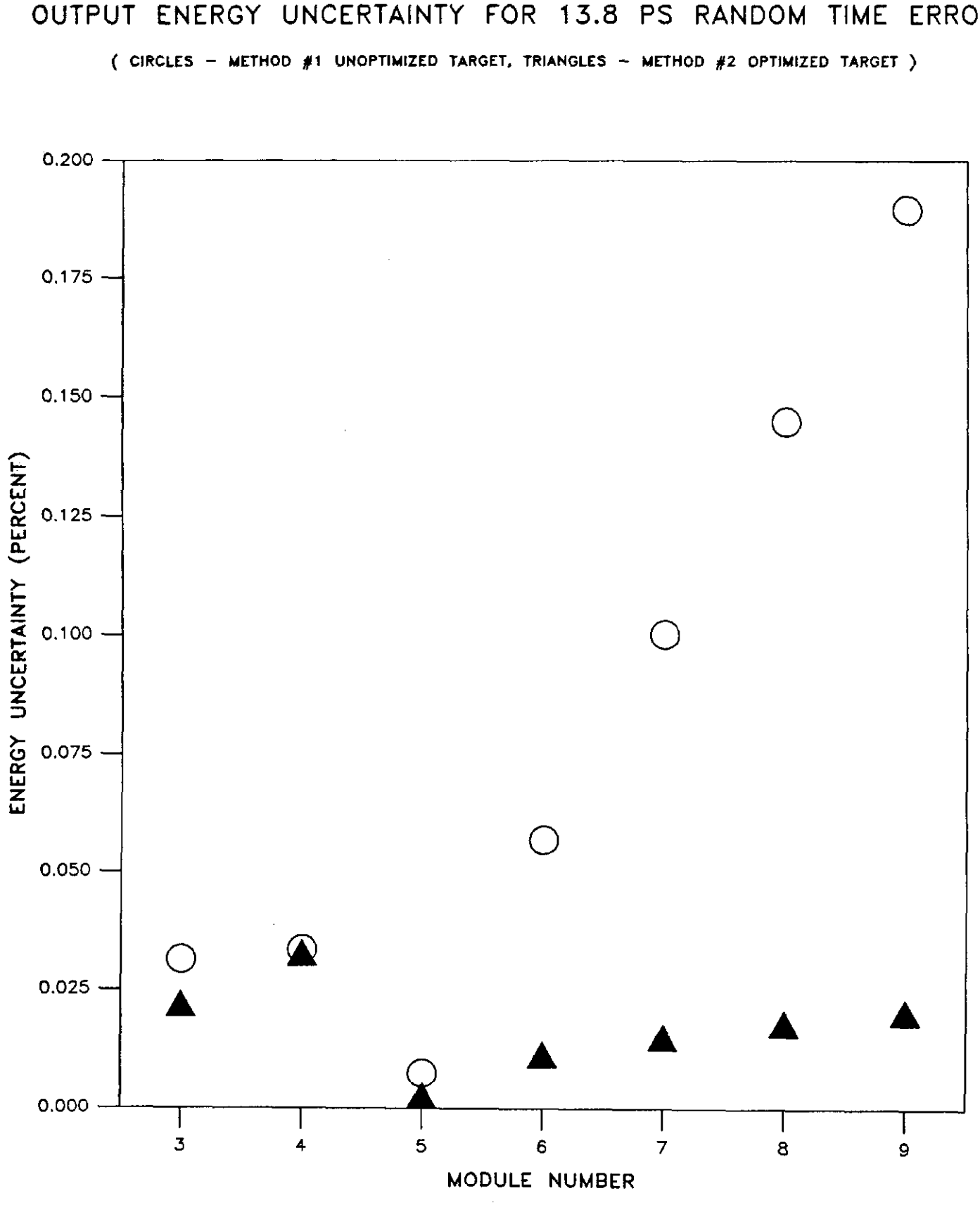
OUTPUT ENERGY UNCERTAINTY FOR 13.8 PS RANDOM TIME ERROR
(CIRCLES - METHOD #1 UNOPTIMIZED TARGET, TRIANGLES - METHOD #2 OPTIMIZED TARGET)
ENERGY UNCERTAINTY (PERCENT)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
3
4
5
6
7
8
9
MODULE NUMBER

Figure 1

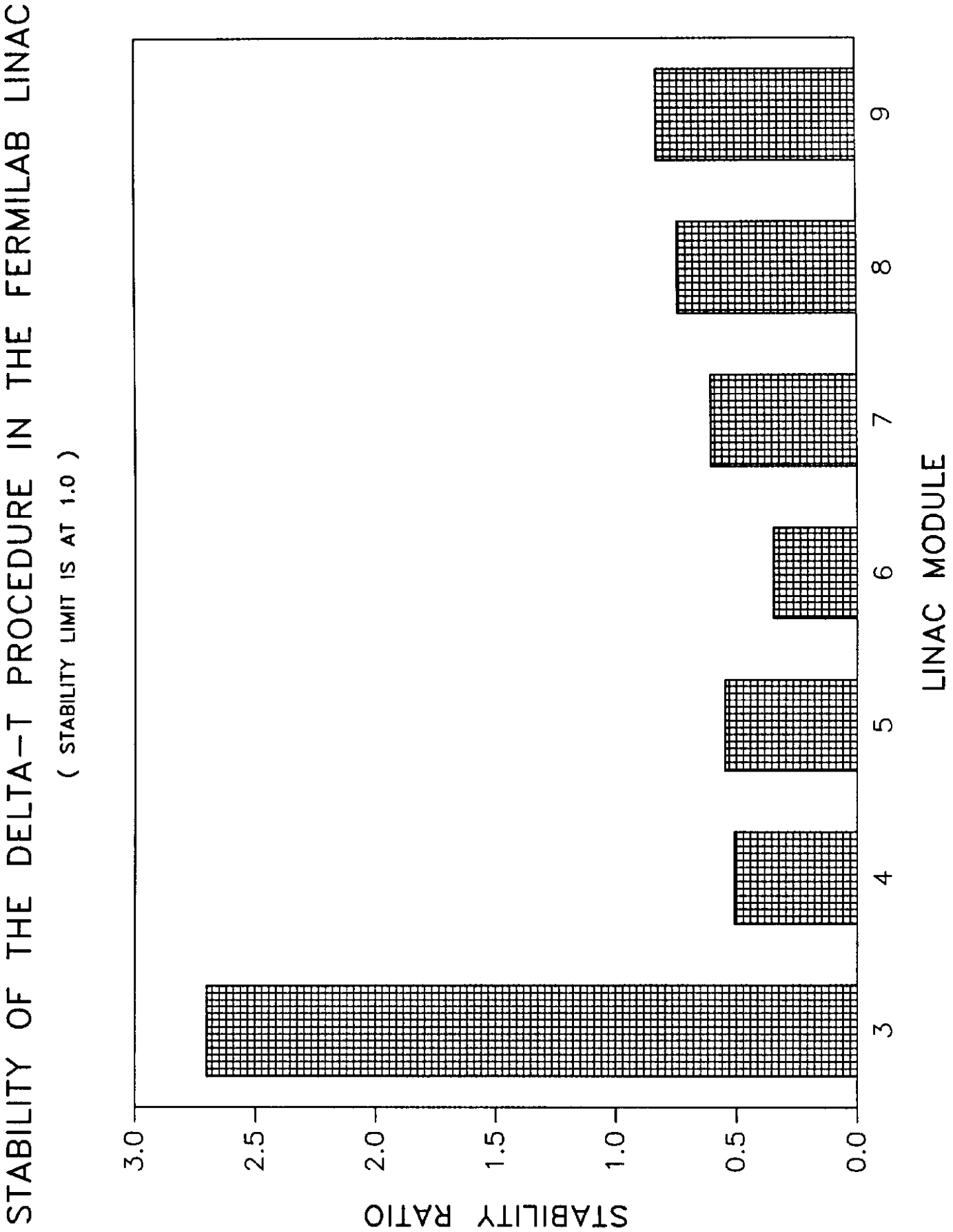
STABILITY OF THE DELTA-T PROCEDURE IN THE FERMILAB LINAC
(STABILITY LIMIT IS AT 1.0)
STABILITY RATIO
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3
4
5
6
7
8
9
LINAC MODULE

Figure 2

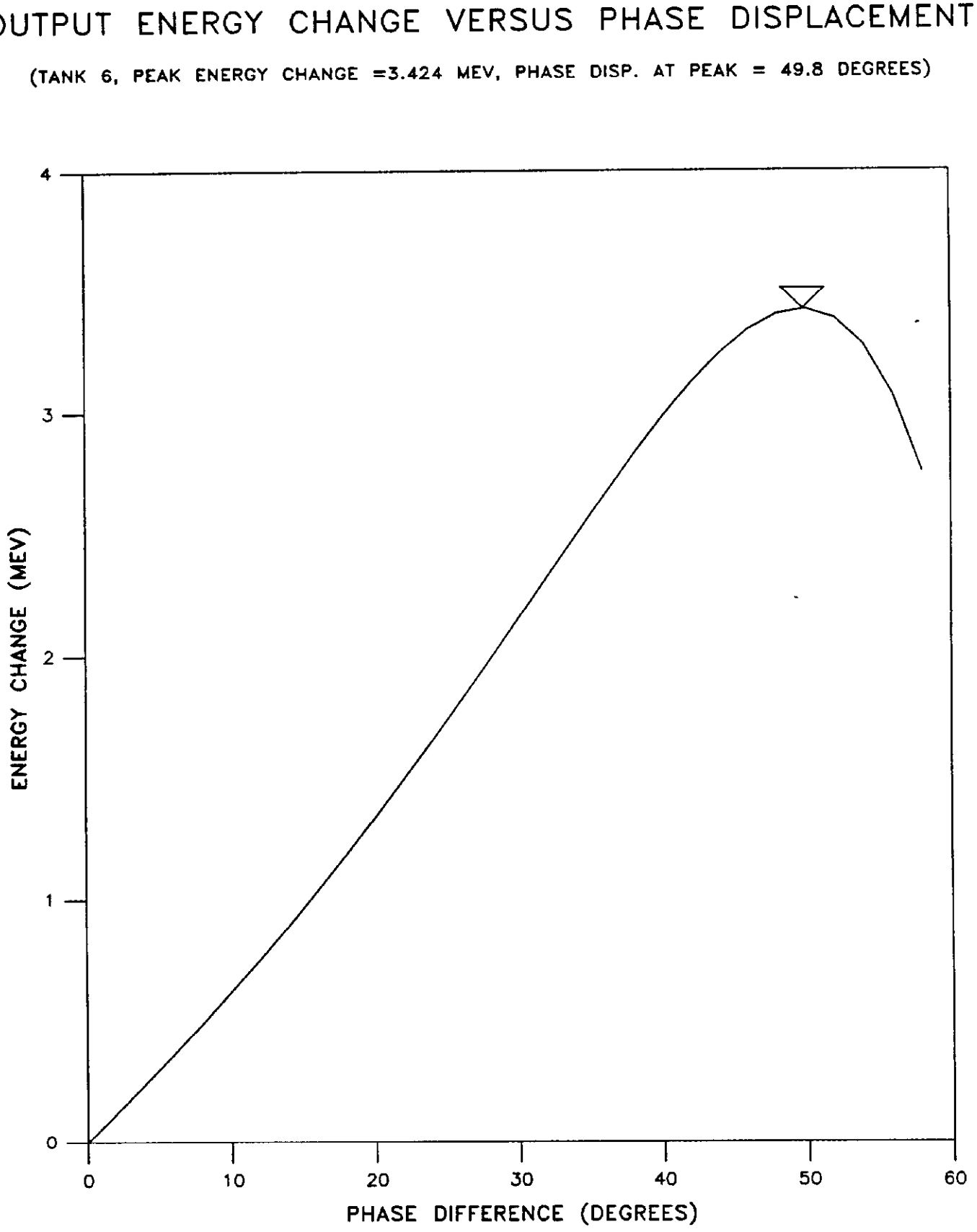
OUTPUT ENERGY CHANGE VERSUS PHASE DISPLACEMENT
(TANK 6, PEAK ENERGY CHANGE =3.424 MEV, PHASE DISP. AT PEAK = 49.8 DEGREES)
ENERGY CHANGE (MEV)
0
1
2
3
4
0
10
20
30
40
50
60
PHASE DIFFERENCE (DEGREES)

Figure 3

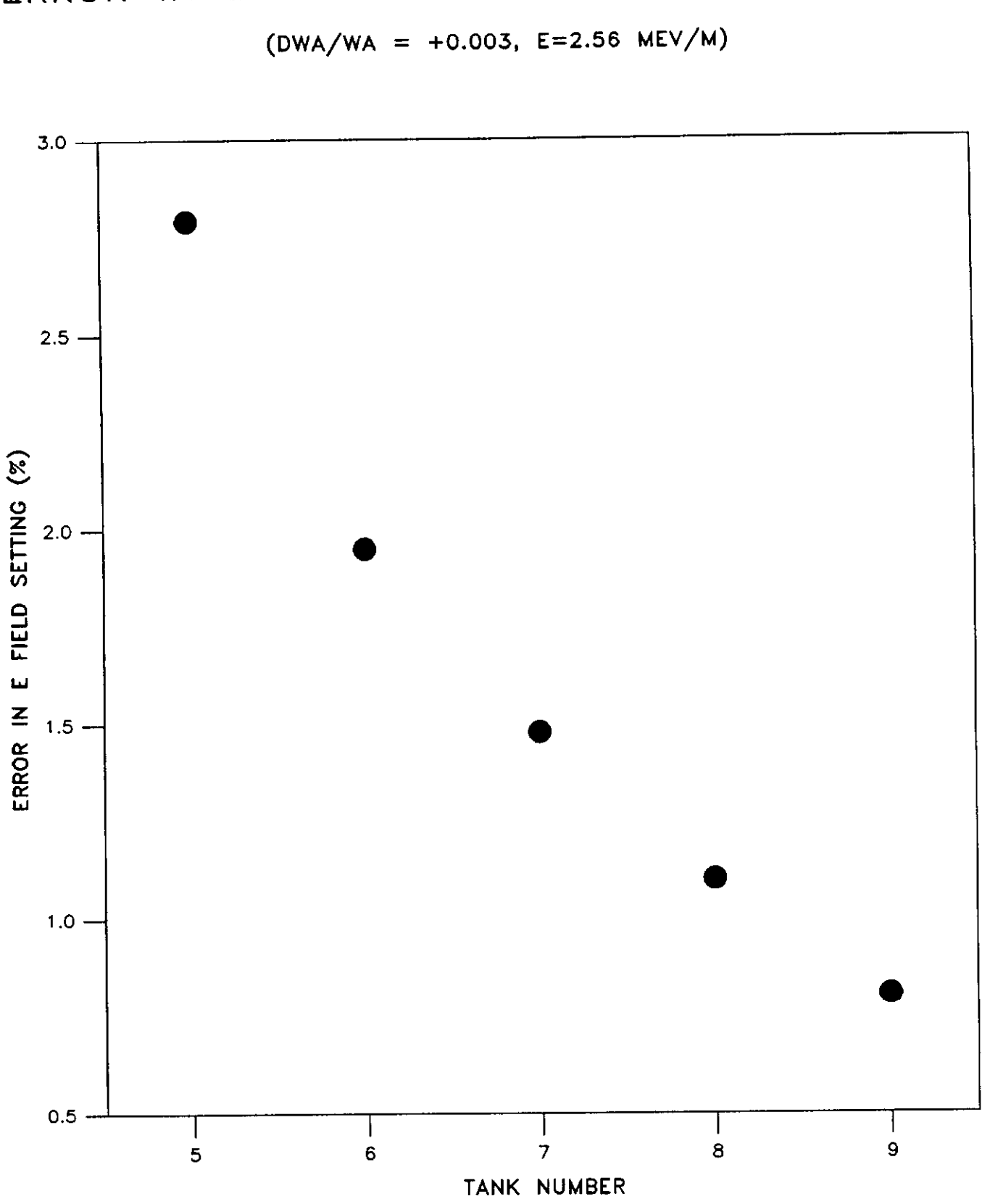
ERROR IN E FIELD SETTING USING METHOD #2
(DWA/WA = +0.003, E=2.56 MEV/M)
3.0
2.5
2.0
1.5
1.0
0.5
ERROR IN E FIELD SETTING (%)
5
6
7
8
9
TANK NUMBER

Figure 4

ENERGY DISPLACEMENT VERSUS TANK PHASE

(TANK 5, E=2.56 +10%, −10%, −20%)

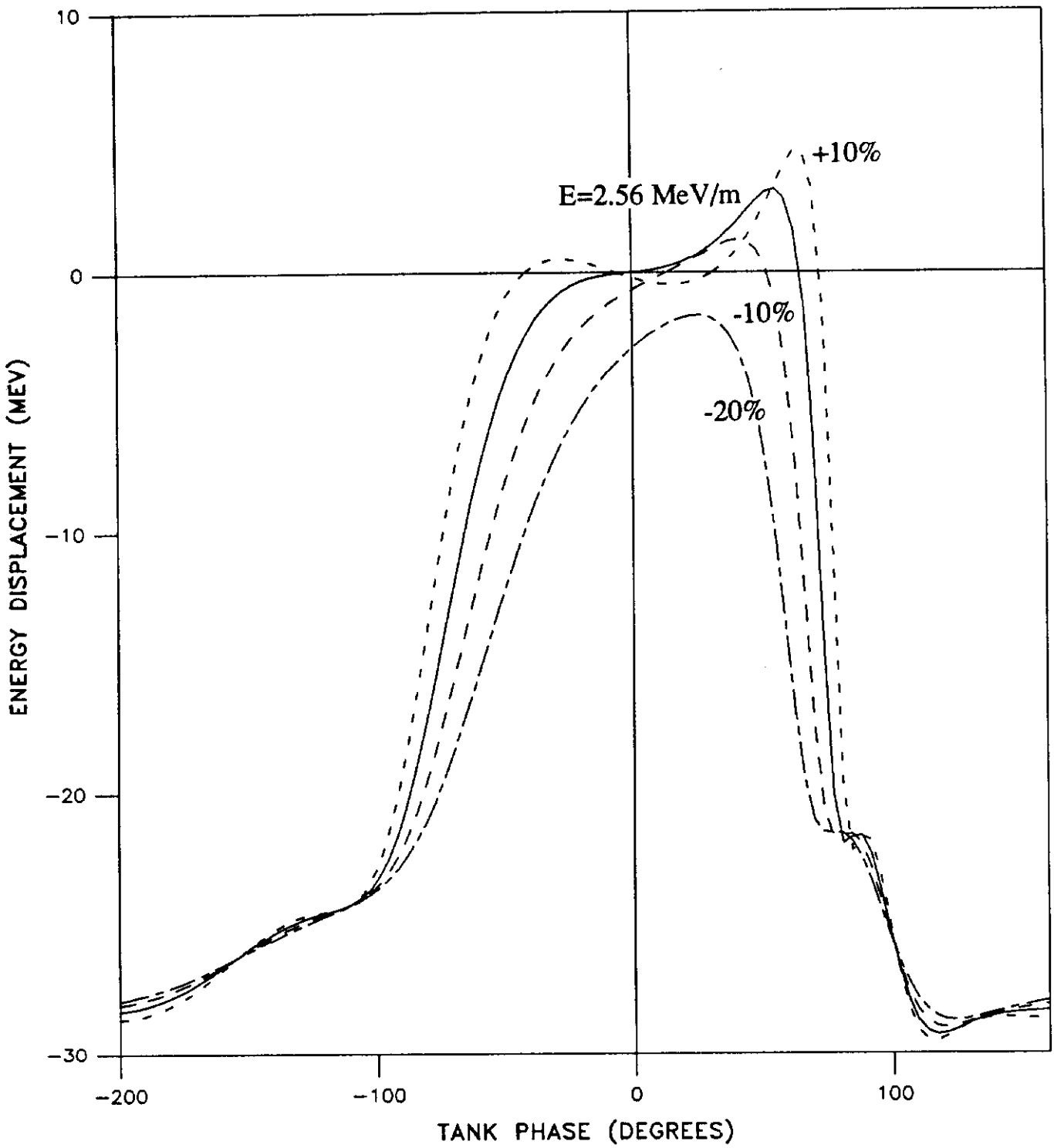

Figure 5

ENERGY DISPLACEMENT VERSUS TANK PHASE

(TANK 8, E=2.56 −10%, −20%)

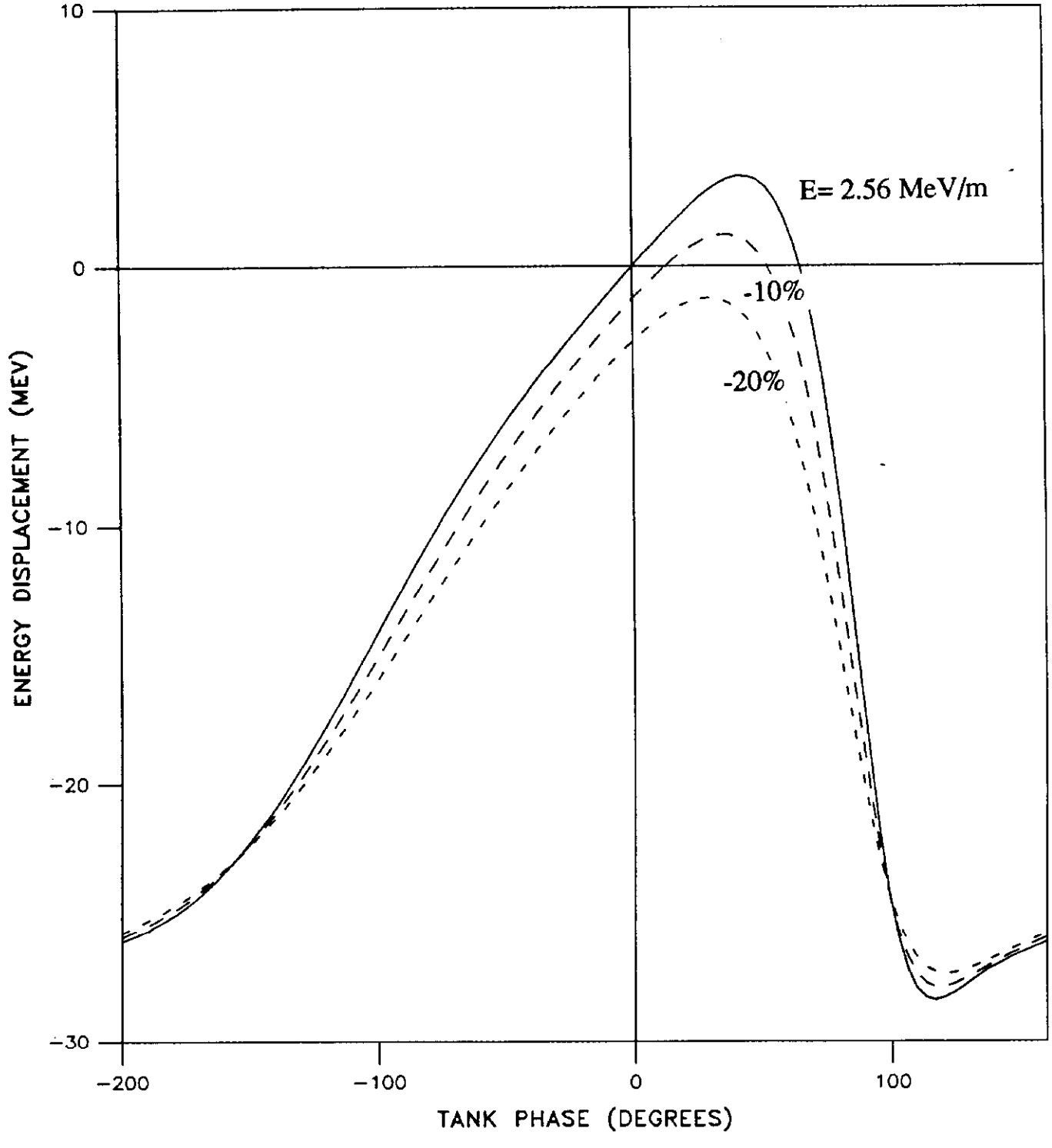

Figure 6

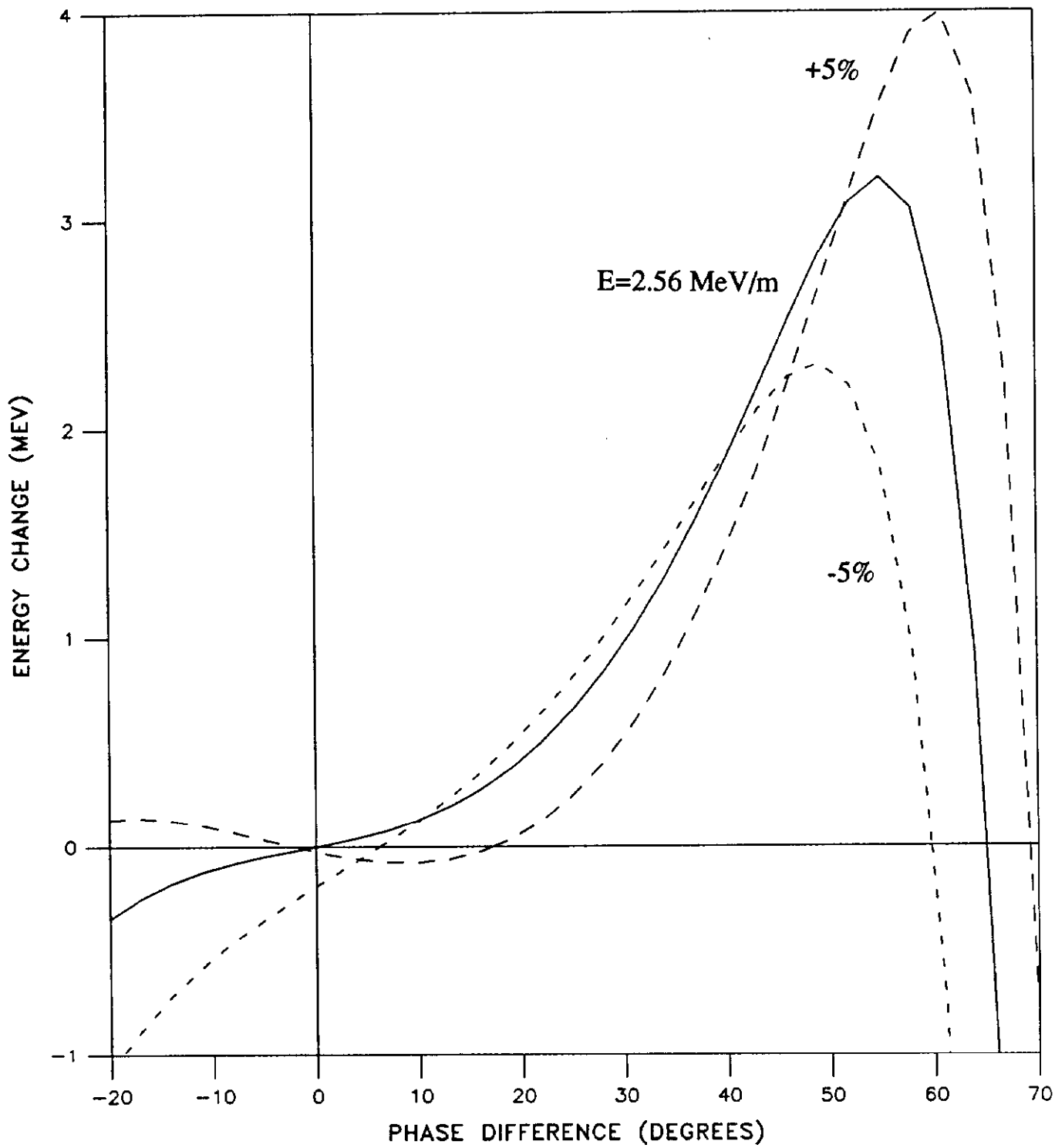
OUTPUT ENERGY CHANGE VERSUS PHASE DISPLACEMENT
(TANK 5, E=2.56 MEV/M +- 5%)
+5%
E=2.56 MeV/m
-5%
ENERGY CHANGE (MEV)
PHASE DIFFERENCE (DEGREES)
4
3
2
1
0
-1
-20
-10
0
10
20
30
40
50
60
70

Figure 7

OUTPUT ENERGY CHANGE VERSUS PHASE DISPLACEMENT

(TANK 5, E=2.56 MEV/M +- 5%, BETA IN=BETASYNC*(1.005))

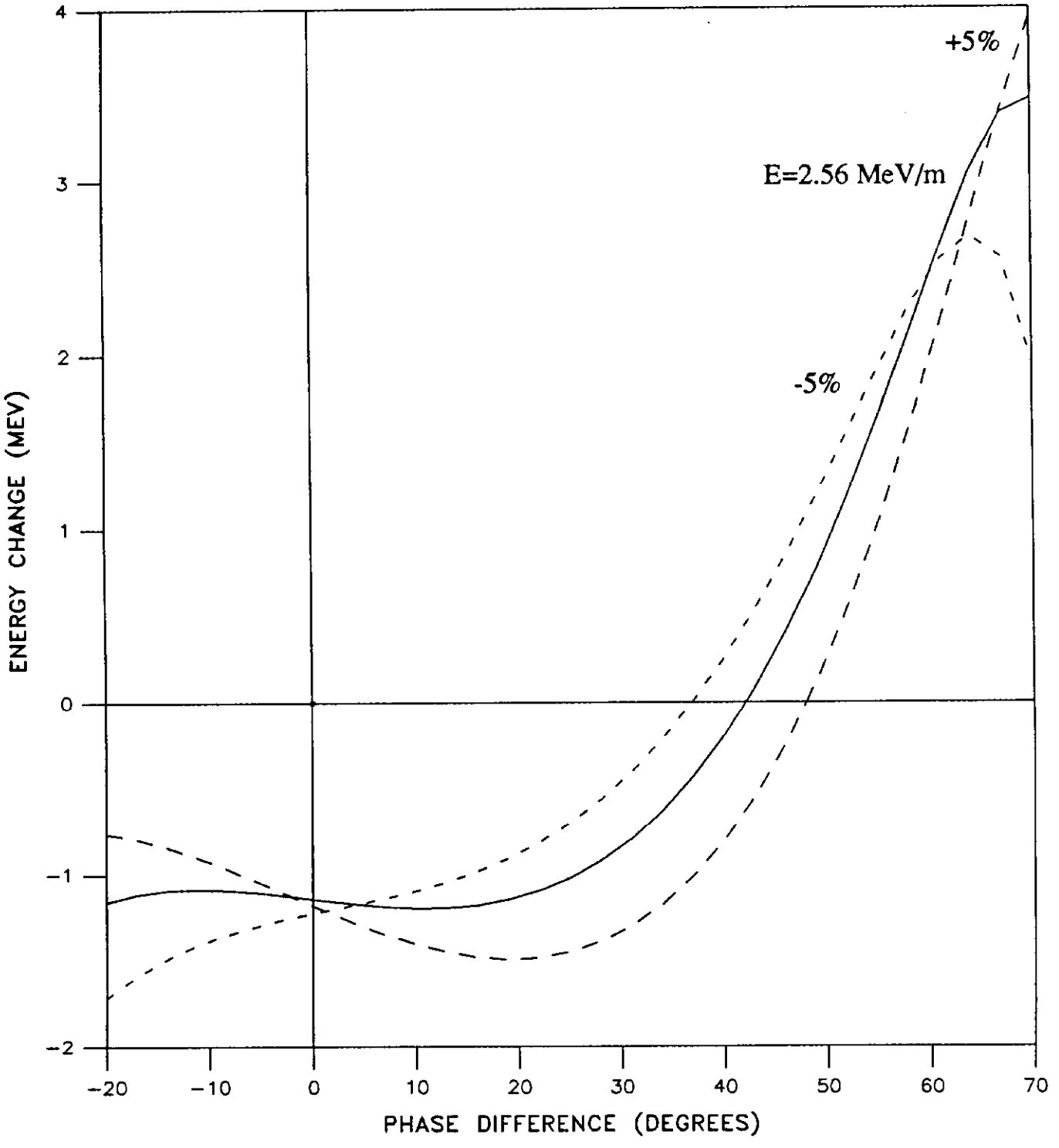

Figure 8

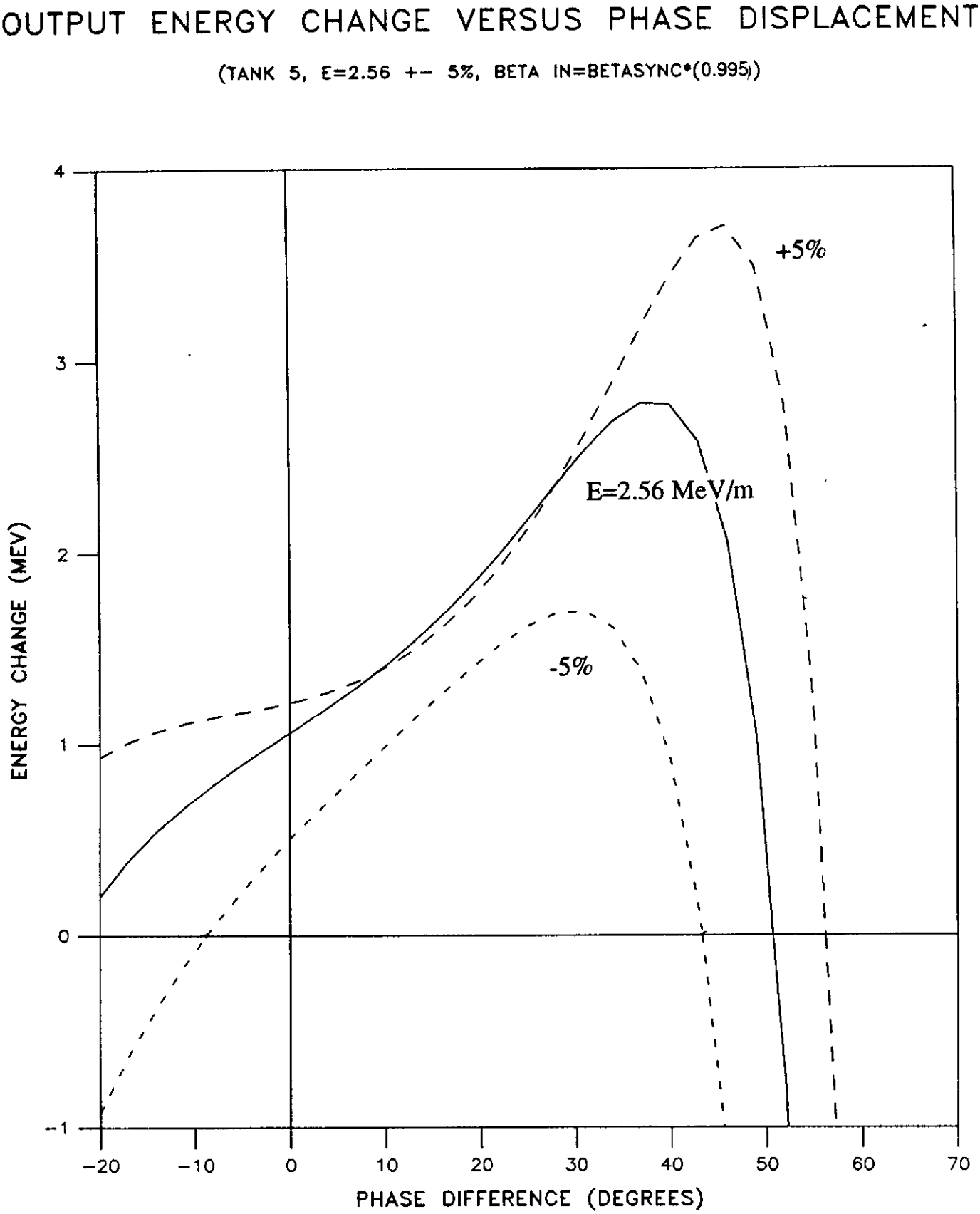
OUTPUT ENERGY CHANGE VERSUS PHASE DISPLACEMENT
(TANK 5, E=2.56 +- 5%, BETA IN=BETASYNC*(0.995))
ENERGY CHANGE (MEV)
PHASE DIFFERENCE (DEGREES)
+5%
E=2.56 MeV/m
-5%
4
3
2
1
0
-1
-20
-10
0
10
20
30
40
50
60
70

Figure 9

Appendix A.

A Collection of Delta-T Files and Subroutines

```
      PROGRAM XYZ
C
C*********************************************************************
C
C  CALCULATES THE BEST VALUES FOR SYNCHRONOUS BETA AND PHASE
C  INPUT TO THE FIRST CELL OF EACH OF THE ACCELERATOR TANKS.
C
C  VALUES ARE CALCULATED FROM THE GEOMETRY OF THE TANK
C  AND ARE INDEPENDENT OF THE PARTICLE DYNAMICS WHICH GENERATED
C  THE GEOMETRY, ORIGINALLY.
C
C  THE BEST BETA AND PHASE ARE THOSE WHICH MINIMIZE THE
C  RMS VARIATION OF THE PHASE AT THE CENTERS OF CELL GAPS
C  ALONG THE ACCELERATOR.
C
C  THE FOLLOWING DATA FILES ARE REQUIRED:
C
C       GENL.DAT        GENERAL INPUT DATA(TANK NUMBER,FREQUENCY,ETC.)

C       TXX.DAT         TANK "XX" GEOMETRY(CELL LENGTHS,DRIFT TUBE
C                       LENGTHS,AND GAP LENGTHS)
C
C       CFXX.DAT        TANK "XX" COEFFICIENTS FOR TRANSIT TIME FACTOR
C                       FITS.
C
C  "XX" IS AN INTEGER 01-12.
C
C
C                   *** WRITTEN BY T.L. OWENS ***
C                         AUGUST 8, 1990
C
C
C*********************************************************************
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      EXTERNAL FUNXY
      PARAMETER (NC=100)
      DIMENSION PCEL(NC),BCEL(NC),PCNTR(NC)
      CHARACTER TANK*2
      COMMON/GEOM/CLN(NC),DT(NC),GAP(NC),BETAG(NC),GAMAG(NC)
      COMMON/TRNST/T(NC),S(NC),TP(NC),SP(NC)
      COMMON/PARAM/FREQ,EREST,PI,TPI,C,WAVL,TW,FNCEL
      COMMON/GEND/EF0
      OPEN(UNIT=11,FILE='GENL.DAT',TYPE='OLD')
      READ(11,2)TANK,FREQ,ESYNC,PSYNC,FNCEL
2     FORMAT(10X,A,/,4(10X,D13.6,/))
      NCEL=FNCEL
      C=2.99792458D8
      PI=3.14159265358979
      TPI=2.0*PI
      WAVL=C/FREQ
      TW=TPI/WAVL
C
C***  NEGATIVE ION REST ENERGY (NEGLECTING BINDING ENERGIES)
C***  PROTON EREST WOULD BE 938.2796.
C
      EREST=939.25
      CALL GEO(TANK)
C
```

```
C***  CALCULATE INITIAL VALUE FOR SYNC BETA AND PHASE AT TANK INPUT.
C
        BINI=CLN(1)/WAVL
        PINI=PSYNC*PI/180.0
        EF0=ESYNC
C
C*** CALCULATE THE SYNCHRONOUS BETA AND PHASE BY MINIMIZING
C*** RMS PHASE (RELATIVE TO INPUT PHASE) ALONG THE TANK.
C
        CALL LSCAN(FUNXY,BINI,PINI,0.002,BSYNC,PSYN,1.0E-6)
        WRITE(5,15)BSYNC,PSYN*180.0/PI
15      FORMAT(' BSYNC=',D12.6,' PSYN=',D12.6)
C       BTST=0.457196
C       PTST=-213.541*PI/180.0
C       CALL XFER(BTST,PTST,2.56,BCEL,PCEL,PCNTR)
C       WRITE(5,16)(BCEL(J),PCEL(J),PCNTR(J),J=1,NCEL)
C16     FORMAT(' BCEL=',D12.6,' PCEL=',D12.6,' PCNTR=',D12.6)
C       PRMSS=FUNXY(BTST,PTST)
C       WRITE(5,17)PRMSS
C17     FORMAT(' PRMSS=',D12.6)
        STOP
        END
```

```
      PROGRAM DTPAR
C
C*****************************************************************
C
C  PROGRAM TO GENERATE TABLES OF THE TRANSFER MATRICES,M , AND THE VARIOUS
C  TRANSIT MATRICES, T, A, AND B FOR ALL LINAC TANKS.  THESE MATRICES
C  ARE USED IN SUBSEQUENT CALCULATIONS OF DELTA-T PROPERTIES.
C
C  INPUT DATA FILES REQUIRED ARE:
C
C     G.DAT              GENERAL TANK DATA-TANK,FREQ,ESYNC,EPS
C     D.DAT              BPM DISTANCES DAB,D1,D2
C     S.DAT              SYNCRONOUS VALUES-NO. CELLS,PHASE IN ,BETA IN
C
C  OUTPUT DATA FILES ARE:
C
C     TAB.DAT            TAB,TAC,AND CORRESPONDING PHASES
C     SYNC.DAT           SYNCHRONOUS VALUES-BETA IN,OUT;PHASE IN,OUT
C     M.DAT              TRANSFER MATRIX,M, ELEMENTS
C     TMAT.DAT           TRANSIT MATRIX,T, ELEMENTS
C     AMAT.DAT           INVERSE OT T MATRIX
C     BMAT.DAT           B MATRIX=MA
C
C
C               ***  WRITTEN BY T.L. OWENS  ***
C                      AUGUST 21,1990
C
C*****************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (NC=100)
      DIMENSION FM(2,2),TMT(2,2),AMT(2,2),BMT(2,2)
     1,BCEL(NC),PCEL(NC),PCNTR(NC)
      CHARACTER TANK*2
      COMMON/GEOM/CLN(NC),DT(NC),GAP(NC),BETAG(NC),GAMAG(NC)
      COMMON/TRNST/T(NC),S(NC),TP(NC),SP(NC)
      COMMON/PARAM/FREQ,EREST,PI,TPI,C,WAVL,TW,FNCEL
      OPEN(UNIT=3,FILE='D.DAT',STATUS='OLD')
      OPEN(UNIT=4,FILE='S.DAT',STATUS='OLD')
      OPEN(UNIT=7,FILE='TAB.DAT',STATUS='NEW')
      OPEN(UNIT=10,FILE='SYNC.DAT',STATUS='NEW')
      OPEN(UNIT=8,FILE='M.DAT',STATUS='NEW')
      OPEN(UNIT=20,FILE='TMAT.DAT',STATUS='NEW')
      OPEN(UNIT=21,FILE='AMAT.DAT',STATUS='NEW')
      OPEN(UNIT=22,FILE='BMAT.DAT',STATUS='NEW')
      OPEN(UNIT=23,FILE='G.DAT',STATUS='OLD')
      WRITE(7,77)
77    FORMAT(' MODULE',5X,'TAB',11X,'TAC',9X,'PHASE AB',6X,'PHASE AC',/)
      WRITE(10,100)
100   FORMAT(' MODULE',4X,'PHASE IN',5X,'PHASE OUT',6X
     1,'BETA IN',5X,' BETA OUT',/)
      WRITE(8,80)
80    FORMAT(' MODULE',5X,'M11',11X,'M21',11X,'M12',11X,'M22',/)
      WRITE(20,200)
200   FORMAT(' MODULE',5X,'T11',11X,'T21',11X,'T12',11X,'T22',/)
      WRITE(21,210)
210   FORMAT(' MODULE',5X,'A11',11X,'A21',11X,'A12',11X,'A22',/)
      WRITE(22,220)
```

```
220     FORMAT(' MODULE',5X,'B11',11X,'B21',11X,'B12',11X,'B22',/)
C
C*** BEGINNING OF LOOP THROUGH TANKS
C
7       READ(3,1,END=1000)TANK,D1,D2,DAB
1       FORMAT(2X,A2,3(1X,D12.6))
        READ(23,40)ITANK,FREQ,ESYNC,EPS
        READ(4,40)ITANK,FNCEL,PHIA,BTA
40      FORMAT(2X,I2,3(1X,D12.6))
        NCEL=FNCEL
        LCEL=FNCEL+1
        C=2.99792458D8
        PI=3.14159265358979
        PHIA=PHIA*PI/180.0
        TPI=2.0*PI
        OMEGA=TPI*FREQ
        WAVL=C/FREQ
        TW=TPI/WAVL
        EREST=939.25
C
C*** READ TANK GEOMETRIC PARAMETERS
C
        CALL GEO(TANK)
C
C*** CALCULATE OUTPUT BETA AND PHASE FOR SYNCHRONOUS PARTICLE
C
        CALL XFER(BTA,PHIA,ESYNC,BCEL,PCEL,PCNTR)
        BTB=BCEL(LCEL)
        PHIB=PCEL(LCEL)
C
C*** CALCULATE PHASE SETTINGS FOR ZERO IN DELTA-T PLANE
C
        VA=BTA*C
        VB=BTB*C
        TABOF=(DAB+D1)/VA
        TABON=FNCEL/FREQ+D1/VB+(PHIB-PHIA)/(FREQ*TPI)
        DTABD=TABOF-TABON
        TACOF=(DAB+D2)/VA
        TACON=TABON+(D2-D1)/VB
        DTACD=TACOF-TACON
        DPABZ=DTABD*FREQ*360.0
        DPACZ=DTACD*FREQ*360.0
        WRITE(7,6)ITANK,DTABD,DTACD,DPABZ,DPACZ
6       FORMAT(2X,I2,2X,4(2X,D12.6))
        WRITE(10,6)ITANK,PHIA,PHIB,BTA,BTB
C
C* BEGIN CALCULATION OF TRANSFER MATRIX
C
        DELBA=BTA*EPS
        DELPA=PHIA*EPS
        BAPLS=BTA+DELBA
        BAMNS=BTA-DELBA
        GAPLS=DSQRT(1.0/(1.0-BAPLS**2))
        GAMNS=DSQRT(1.0/(1.0-BAMNS**2))
        WAPLS=EREST*(GAPLS-1.0)
        WAMNS=EREST*(GAMNS-1.0)
        DELWA=(WAPLS-WAMNS)/2.0
        PAPLS=PHIA+DELPA
```

```
        PAMNS=PHIA-DELPA
C
C*** TAKE VARIOUS DERIVATIVES W.R.T INPUT PHASE AND ENERGY
C*** TO CALCULATE ELEMENTS OF THE TRANSFER MATRIX
C
        CALL XFER(BAPLS,PHIA,ESYNC,BCEL,PCEL,PCNTR)
        BBPWA=BCEL(LCEL)
        PBPWA=PCEL(LCEL)
        CALL XFER(BAMNS,PHIA,ESYNC,BCEL,PCEL,PCNTR)
        BBMWA=BCEL(LCEL)
        PBMWA=PCEL(LCEL)
        CALL XFER(BTA,PAPLS,ESYNC,BCEL,PCEL,PCNTR)
        BBPPA=BCEL(LCEL)
        PBPPA=PCEL(LCEL)
        CALL XFER(BTA,PAMNS,ESYNC,BCEL,PCEL,PCNTR)
        BBMPA=BCEL(LCEL)
        PBMPA=PCEL(LCEL)
        GBPWA=DSQRT(1.0/(1.0-BBPWA**2))
        GBMWA=DSQRT(1.0/(1.0-BBMWA**2))
        GBPPA=DSQRT(1.0/(1.0-BBPPA**2))
        GBMPA=DSQRT(1.0/(1.0-BBMPA**2))
        WBPWA=EREST*(GBPWA-1.0)
        WBMWA=EREST*(GBMWA-1.0)
        WBPPA=EREST*(GBPPA-1.0)
        WBMPA=EREST*(GBMPA-1.0)
C
        FM(1,1)=(PBPPA-PBMPA)/(2.0*DELPA)
        FM(1,2)=(PBPWA-PBMWA)/(2.0*DELWA)
        FM(2,1)=(WBPPA-WBMPA)/(2.0*DELPA)
        FM(2,2)=(WBPWA-WBMWA)/(2.0*DELWA)
C
        WRITE(8,6)ITANK,FM
C
C*** CALCULATE THE T,A, AND B MATRICES
C
        GAMA=DSQRT(1.0/(1.0-BTA**2))
        GAMB=DSQRT(1.0/(1.0-BTB**2))
        WA=EREST*(GAMA-1.0)
        WB=EREST*(GAMB-1.0)
        EX=3.0/2.0
        ETAC=(GAMA**2-1.0)**EX
        ETBC=(GAMB**2-1.0)**EX
        DF=EREST*C
        DFA=DF*ETAC
        DFB=DF*ETBC
        TM1=(1.0-FM(1,1))/OMEGA
        TM2=FM(1,2)/OMEGA
        TM3=FM(2,1)/DFB
        TM4=(1.0/ETAC-FM(2,2)/ETBC)/DF
        TM5=DAB/DFA
C
        TMT(1,1)=TM1+D1*TM3
        TMT(1,2)=-TM2-TM5-D1*TM4
        TMT(2,1)=TM1+D2*TM3
        TMT(2,2)=-TM2-TM5-D2*TM4
C
C*** A MATRIX
C
```

```
      DET=TMT(2,2)*TMT(1,1)-TMT(1,2)*TMT(2,1)
      AMT(1,1)=TMT(2,2)/DET
      AMT(1,2)=-TMT(1,2)/DET
      AMT(2,1)=-TMT(2,1)/DET
      AMT(2,2)=TMT(1,1)/DET
C
C*** B MATRIX
C
      BMT(1,1)=FM(1,1)*AMT(1,1)+FM(1,2)*AMT(2,1)
      BMT(1,2)=FM(1,1)*AMT(1,2)+FM(1,2)*AMT(2,2)
      BMT(2,1)=FM(2,1)*AMT(1,1)+FM(2,2)*AMT(2,1)
      BMT(2,2)=FM(2,1)*AMT(1,2)+FM(2,2)*AMT(2,2)
C
      WRITE(20,6)ITANK,TMT
      WRITE(21,6)ITANK,AMT
      WRITE(22,6)ITANK,BMT
C
      GO TO 7
1000  STOP
      END
C
```

```
      PROGRAM DTERR
C
C*****************************************************************
C
C  PROGRAM TO CALCULATE THE STABILITY RATIO AND THE UNCERTAINTY
C  IN THE OUTPUT ENERGY FOR THE DELTA-T MEASUREMENTS.
C
C  REQUIRES THE VARIOUS FORMS OF THE TRANSIT TIME MATRIX
C  (T, A, B) AND THE TRANSFER MATRIX, FM.
C
C  THE STABILITY RATIO IS OUTPUT TO FILE "STAB.DAT"
C  AND THE UNCERTAINTY PER 13.8 PS TIME ERROR IS OUTPUT TO
C  FILE "METH1.DAT" FOR DELTA-T METHOD #1 (LOW ENERGY MODULES)
C  AND TO "METH2.DAT" FOR METHOD #2 (HIGH ENERGY MODULES).
C
C             WRITTEN BY T.L. OWENS
C                AUGUST 20,1990
C
C MODIFIED DEC. 12,1990
C
C*****************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION FM(2,2),T(2,2),A(2,2),B(2,2)
      OPEN(UNIT=11,FILE='M.DAT',STATUS='OLD')
      OPEN(UNIT=3,FILE='TMAT.DAT',STATUS='OLD')
      OPEN(UNIT=4,FILE='AMAT.DAT',STATUS='OLD')
      OPEN(UNIT=7,FILE='BMAT.DAT',STATUS='OLD')
      OPEN(UNIT=8,FILE='SYNC.DAT',STATUS='OLD')
      OPEN(UNIT=20,FILE='STAB.DAT',STATUS='NEW')
      OPEN(UNIT=21,FILE='METH2.DAT',STATUS='NEW')
      OPEN(UNIT=22,FILE='METH1.DAT',STATUS='NEW')
      READ(3,30)
      READ(4,30)
      READ(7,30)
      READ(8,30)
      READ(11,30)
30    FORMAT(/)
7     READ(11,1,END=1000)ITANK,FM
1     FORMAT(2X,I2,2X,4(2X,D12.6))
      READ(3,1)ITANK,T
      READ(4,1)ITANK,A
      READ(7,1)ITANK,B
      READ(8,1)ITANK,PHIA,PHIB,BTA,BTB
      WRITE(5,1)ITANK,T
      WRITE(5,1)ITANK,A
      WRITE(5,1)ITANK,B
      WRITE(5,1)ITANK,PHIA,PHIB,BTA,BTB
C
C*** SET RANDOM ERROR IN TIME MEASUREMENT TO 13.8 PICOSECONDS.
C
      TERR=1.38D-11
      EREST=939.25
      GAMA=DSQRT(1.0/(1.0-BTA**2))
      GAMB=DSQRT(1.0/(1.0-BTB**2))
      WA=EREST*(GAMA-1.0)
      WB=EREST*(GAMB-1.0)
      FNUM=T(2,2)/T(1,1)+T(1,2)/T(2,1)
```

```
        DENOM=T(2,1)/T(1,1)+T(1,1)/T(2,1)
C
C*** CALCULATE STABILITY RATIO
C
        STABR=(FM(2,2)-FM(2,1)*FNUM/DENOM)*WA/WB
        STABR=DABS(STABR)
C
C*** CALCULATE FRACTIONAL UNCERTAINTY IN OUTPUT ENERGY PER
C*** PICOSECOND ERROR IN MEASUREMENT
C
        S=A(2,1)/A(2,2)
C
C*** DWBS1 IS UNCERTAINTY SQUARED FOR METHOD #1 (LOW ENERGY MODULES)
C*** DWBS IS UNCERTAINTY SQUARED FOR METHOD #2 (HIGH ENERGY MODULES)
C
        S1=-A(1,1)/A(1,2)
        S2=-S
        DWBS1=(B(2,1)+S2*B(2,2))**2*(1.0+S1**2)/(S1-S2)**2*TERR**2
        DWBD1=SQRT(DWBS1)/WB
        DWBS=(B(2,1)-S*B(2,2))**2*(1.0/(S**2+1.0))*TERR**2
        DWBD=SQRT(DWBS)/WB
        FTANK=ITANK
        WRITE(20,2)ITANK,STABR
2       FORMAT(2X,I1,2X,E12.6)
        WRITE(21,2)ITANK,DWBD*100.0
        WRITE(22,2)ITANK,DWBD1*100.0
        GO TO 7
1000    STOP
        END
```

```
C
      PROGRAM WPEAK
C
C*********************************************************************
C
C  PROGRAM TO GENERATE CURVES OF ENERGY CHANGE VERSUS PHASE
C  DISPLACEMENT FROM SYNCHRONOUS VALUES AT THE OUTPUT OF EACH TANK.
C  THE MAXIMUM ENERGY DISPLACEMENT AND THE CORRESPONDING PHASE
C  DISPLACEMENT ARE FOUND.
C
C  INPUT DATA FILES:
C
C       WPEAK.DAT
C       SYNCS.DAT       RANDOM ACCESS FILE CREATED FROM FILE "SYNC.DAT"
C                       CONTAINING SYNCHRONOUS PHASES AND ENERGIES
C                       AT THE INPUT AND OUTPUT OF TANKS.
C
C  OUTPUT FILES:
C
C       WPEAK.OUT       CONTAINS PLOT VALUES, ENERGY DISPLACEMENT VERSUS
C                       PHASE (FROM SYNCHRONOUS VALUES).
C
C       WDIF.OUT        CONTAINS PLOT VALUES FOR ENERGY CHANGE DEVIATION
C                       FROM SYNCHRONOUS VALUES. THIS IS THE
C                       QUANTITY THAT WOULD BE MEASURED IN PRACTICE
C
C       WPEAK.MAX       CONTAINS THE PEAK ENERGY CHANGE AND PHASE AT PEAK
C                       (FOR WPEAK.OUT FILE ONLY CURRENTLY).
C
C  USES SUBROUTINES GEO AND XFER.
C
C  NOTE:  OUTPUT IN WPEAK.OUT IS DISPLACEMENT FROM SYNCHRONOUS ENERGY OUT
C         NOT THE DEVIATION IN THE OUTPUT/INPUT DIFFERENCE FROM SYNC VALUES.
C
C
C               ***   WRITTEN BY T. L. OWENS   ***
C                        OCT. 17,1990
C
C*********************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION DWB(200),PHI(200),BCEL(100),PCEL(100),PCNTR(100)
     1,DWABS(200)
      CHARACTER TANK*2
      COMMON/PARAM/FREQ,EREST,PI,TPI,C,WAVL,TW,FNCEL
      OPEN(UNIT=8,FILE='WPEAK.OUT',STATUS='NEW')
      OPEN(UNIT=3,FILE='WPEAK.DAT',STATUS='OLD')
      OPEN(UNIT=7,FILE='WPEAK.MAX',STATUS='NEW')
      OPEN(UNIT=20,FILE='WDIF.OUT',STATUS='NEW')
C
C*** OPEN RANDOM ACCESS FILE TO OBTAIN SYNCHRONOUS PARAMETERS
C
      OPEN(UNIT=4,FILE='SYNCS.DAT',ACCESS='DIRECT',FORM='FORMATTED'
     1,STATUS='OLD',RECL=62)
      READ(3,11)ITANK
11    FORMAT(10X,I2)
      READ(3,12)FREQ,EF0,FNCEL,PINT,FNPTS,TOLPH,DPINI,DBINI
12    FORMAT(10X,D12.6)
```

```
C
C*** CONVERT INTEGER TANK NUMBER TO CHARACTER VARIABLE
C*** ASCII FOR INTEGERS 0-9 IS 48-57.
C
        IC10=ITANK/10
        IC1=ITANK-IC10
        TANK=CHAR(IC10+48)//CHAR(IC1+48)
        READ(4,6,REC=ITANK-2)ITNK,PHIA,PHIB,BTA,BTB
6       FORMAT(2X,I2,2X,4(2X,D12.6))
C
C*** EREST USED BY LANL (SWAIN).
C
        EREST=939.301
        PI=4.0*DATAN(1.0D0)
        TPI=2.0*PI
        RD=180.0/PI
        DR=PI/180.0
        PINT=PINT*DR
        TOLPH=TOLPH*DR
        C=2.99792458D8
        WAVL=C/FREQ
        TW=TPI/WAVL
C
C*** GENERATE TANK PARAMETERS.
C
        CALL GEO(TANK)
        PHINC=PINT/FNPTS
        NPTS=FNPTS
        PSTRT=PHIA+DPINI*DR
        BSTRT=BTA*(1.0+DBINI)
        IFLAG=0
        GSOUT=DSQRT(1.0/(1.0-BTB**2))
        GSIN=DSQRT(1.0/(1.0-BTA**2))
        GIN=DSQRT(1.0/(1.0-BSTRT**2))
        DWINI=EREST*(GIN-GSIN)
C
C*** OBTAIN POINTS FOR DWB VERSUS PHI PLOTS
C
        DO 15 I=1,NPTS+1
        CALL XFER(BSTRT,PSTRT,EF0,BCEL,PCEL,PCNTR)
        GOUT=DSQRT(1.0/(1.0-BCEL(FNCEL+1)**2))
C
C*** DWB IS ENERGY DIFFERENCE BETWEEN OUTPUT AND SYNCHRONOUS OUTPUT ENERGY.
C
        DWB(I)=EREST*(GOUT-GSOUT)
C
C*** DWABS IS DEVIATION FROM SYNC ENERGY CHANGE OF THE TOTAL ENERGY
C*** CHANGE THROUGH THE MODULE.
C*** THIS IS THE QUANTITY THAT WOULD BE MEASURED IN PRACTICE.
C
        DWABS(I)=DWB(I)-DWINI
        PHI(I)=PSTRT
        WRITE(8,51)(PHI(I)-PHIA)*RD,DWB(I)
51      FORMAT(2X,E12.6,2X,E12.6)
        WRITE(20,51)(PHI(I)-PHIA)*RD,DWABS(I)
        PSTRT=PSTRT+PHINC
        IF(I.LE.2.OR.IFLAG.EQ.1)GO TO 15
        IF(DWB(I).LT.DWB(I-1).AND.DWB(I-1).GT.DWB(I-2))THEN
```

```
          P1=PHI(I-2)
          P3=PHI(I)
          D1=DWB(I-2)
          D3=DWB(I)
          IFLAG=1
        END IF
15      CONTINUE
        IF(IFLAG.EQ.0)THEN
          WRITE(5,52)
52        FORMAT(' WPEAK DOES NOT LIE IN PHASE INTERVAL SELECTED
     1 ---- INCREASE SEARCH INTERVAL.')
          GO TO 1000
        END IF
C
C*** FIND PEAK IN ENERGY CURVE.
C
        IFLG=1
        ITMAX=50
C
C*** IF TOLPH IS 0 THEN SKIP THE MAX FINDER
C
        IF(TOLPH.EQ.0.0)GO TO 1000
        DPHI=(P3-P1)/2.0
        DWST=D1
        PSTRT=P1
30      PSTRT=PSTRT+DPHI
        IF(DABS(DPHI).LT.TOLPH)GO TO 900
32      CALL XFER(BSTRT,PSTRT,EF0,BCEL,PCEL,PCNTR)
        GOUT=DSQRT(1.0/(1.0-BCEL(FNCEL+1)**2))
        DWBB=EREST*(GOUT-GSOUT)
        IF(DWBB.LT.DWST)THEN
          DPHI=-DPHI/2.0
        END IF
        DWST=DWBB
        IFLG=IFLG+1
        IF(IFLG.GT.ITMAX)THEN
          WRITE(5,33)
33        FORMAT(' WPEAK> MAX FINDER DOES NOT CONVERGE')
          GO TO 1000
        END IF
        GO TO 30
C900    WRITE(7,37)(PSTRT-PHIA)*RD,DWBB
900     WRITE(7,37)(PSTRT-PHIA)*RD,DWBB-DWINI
37      FORMAT(2X,E12.6,2X,E12.6)
C
C*** WRITE PHASE AND ENERGY CHANGE THROUGH TANK AT MAX ENERGY.
C
        WRITE(5,37)(PSTRT-PHIA)*RD,DWBB-DWINI
1000    STOP
        END
C
```

```
      PROGRAM SLOPE
C
C*** PROGRAM CALCULATES THE SLOPE OF LINE IN DELTA-T PLANE
C*** AND THE DERIVATIVE OF THE SLOPE WRT E. ALSO CALCULATES
C*** DERIVATIVE OF 2,1 ELEMENT OF THE M MATRIX.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION TMT(4),TMTS(4),FM(4),FMS(4)
      OPEN(UNIT=4,FILE='TMAT99.DAT',STATUS='OLD')
      OPEN(UNIT=7,FILE='TMATSV.DAT',STATUS='OLD')
      OPEN(UNIT=3,FILE='M99.DAT',STATUS='OLD')
      OPEN(UNIT=11,FILE='MSV.DAT',STATUS='OLD')
      OPEN(UNIT=8,FILE='SLOPE.DAT',STATUS='NEW')
      WRITE(8,5)
5     FORMAT(' TANK','    SLOPE=S','        dS/dE','         M(2,1)'
     1,'     dM(2,1)/dE'/)
      READ(4,3)
      READ(7,3)
      READ(3,3)
      READ(11,3)
3     FORMAT(/)
2     READ(4,1,END=1000)ITANK,(TMT(I),I=1,4)
      READ(3,1)ITANK,(FM(I),I=1,4)
      READ(11,1)ITANK,(FMS(I),I=1,4)
1     FORMAT(2X,I2,4(2X,D12.6))
      READ(7,1)ITANK,(TMTS(I),I=1,4)
      SLPS=TMTS(2)/TMTS(1)
      SLP=TMT(2)/TMT(1)
      IF(ITANK.EQ.3.OR.ITANK.EQ.4)THEN
      DSLP=(SLPS-SLP)/0.026
      DM=(FMS(2)-FM(2))/0.026
      ELSE
      DSLP=(SLPS-SLP)/0.0256
      DM=(FMS(2)-FM(2))/0.0256
      END IF
      WRITE(5,1)ITANK,SLPS,DSLP,FMS(2),DM
      WRITE(8,1)ITANK,SLPS,DSLP,FMS(2),DM
      GO TO 2
1000  STOP
      END
```

```
C
      SUBROUTINE XFER(BSTRT,PSTRT,EF0,BCEL,PCEL,PCNTR)
C
C*****************************************************************
C
C  CALCULATES BETA AND PHASE AT THE INPUT TO EACH CELL OF
C  A LINAC TANK (NOT THE PHASE AT THE GAP CENTER).
C
C  INPUTS ARE:
C       BSTRT   BETA INTO FIRST CELL
C       PSTRT   PHASE INTO FIRST CELL (RADIANS)
C       EF0     TANK ELECTRIC FIELD (MEGAVOLTS/METER)
C
C  OUTPUTS ARE:
C       BCEL    ARRAY CONTAINING BETA VALUES AT EACH CELL INPUT
C       PCEL    ARRAY CONTAINING PHASE VALUES AT EACH CELL INPUT
C       PCNTR   ARRAY CONTAINING PHASE AT THE CENTER OF EACH CELL
C
C  NOTE: IF THERE ARE N CELLS, THE OUTPUT BETA AND PHASE OF THE
C        TANK WILL BE CONTAINED IN BCEL(N+1) & PCEL(N+1), RESPECTIVELY.
C
C                   *** WRITTEN BY T.L. OWENS ***
C                         AUGUST 8, 1990
C
C*****************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (NC=100)
      COMMON/GEOM/CLN(NC),DT(NC),GAP(NC),BETAG(NC),GAMAG(NC)
      COMMON/TRNST/T(NC),S(NC),TP(NC),SP(NC)
      COMMON/PARAM/FREQ,EREST,PI,TPI,C,WAVL,TW,FNCEL
      DIMENSION BCEL(NC),PCEL(NC),PCNTR(NC)
      BINI=BSTRT
      PINI=PSTRT
      NCELLS=FNCEL
      CPR=TW*EF0/EREST
      DWSUM=0.0
      DBTASUM=0.0
      GAMAI=DSQRT(1.0/(1.0-BINI**2))
      WINI=EREST*(GAMAI-1.0)
      PI0=PINI+PI
      BCEN=0.0
      BAV=BINI
      GAV=DSQRT(1.0/(1.0-BAV**2))
      BCEL(1)=BINI
      PCEL(1)=PINI
C
C*** MAIN LOOP
C
      DO 6 J=1,NCELLS
      FL1=(DT(J)+GAP(J))/2.0
      FL2=(DT(J+1)+GAP(J))/2.0
      P1=TW/BINI*FL1
C
C*** LOOP TO DETERMINE CENTRAL BETA
C
      JFLAG=0
7     FPR=CPR*CLN(J)**2/(BAV*GAV)**3
```

```
C
C*** LOOP TO SOLVE TRANSCENDENTAL EQUATION FOR CENTRAL PHASE
C
        IFLG3=0
33      PI0S=PI0
        T1=FPR/2.0*(TP(J)*DSIN(PI0S)+SP(J)*DCOS(PI0S))
        PI0=PINI+P1-T1
        IFLG3=IFLG3+1
        IF(IFLG3.EQ.1)GO TO 33
        IF(ABS(1.0-PI0/PI0S).LT.1.0E-10)GO TO 30
        IF(IFLG3.EQ.20)GO TO 32
        GO TO 33
32      WRITE(5,34)
34      FORMAT(' ETRAN> CENTRAL PHASE DOES NOT CONVERGE-EXITING')
        GO TO 1000
30      CONTINUE
C
C*** END LOOP
C
        BCENS=BCEN
        BCEN=BINI+EF0*CLN(J)/(2.0*BAV*GAV**3*EREST)
     1*(T(J)*DCOS(PI0)+S(J)*DSIN(PI0))
        BAV=(BINI+BCEN)/2.0
        GAV=DSQRT(1.0/(1.0-BAV**2))
        JFLAG=JFLAG+1
        IF(JFLAG.EQ.1)GO TO 7
        IF(ABS(1.0-BCEN/BCENS).LT.1.0E-10)GO TO 8
        IF(JFLAG.GT.20)GO TO 9
        GO TO 7
9       WRITE(5,100)
100     FORMAT(' CENTRAL BETA VALUE DOES NOT CONVERGE-EXITING')
        GO TO 1000
C
C*** END LOOP
C
8       CONTINUE
        PCNTR(J)=PI0
        DWTRM=TPI*(BETAG(J)/BCEN-1.0)*TP(J)
        DW=EF0*CLN(J)*DCOS(PI0)*(T(J)-DWTRM)
        DWSUM=DWSUM+DW
C
C*** LOOP TO SOLVE FOR FULL GAP BETA
C
        IFLAG2=0
        DBTA=2.0*(BCEN-BINI)
10      BBAV=BINI+DBTA/2.0
        GGAV=DSQRT(1.0/(1.0-BBAV**2))
        DBTAS=DBTA
        DBTA=DW/(BBAV*GGAV**3*EREST)
        IFLAG2=IFLAG2+1
        IF(IFLAG2.EQ.1)GO TO 10
        IF(ABS(1.0-DBTA/DBTAS).LT.1.0D-10)GO TO 11
        IF(IFLAG2.EQ.20)GO TO 14
        GO TO 10
14      WRITE(5,15)
15      FORMAT(' ETRAN> FULL GAP AVERAGE BETA DOES NOT CONVERGE')
        GO TO 1000
11      CONTINUE
```

```
C
C*** END LOOP
C
        DBTASUM=DBTASUM+DBTA
        F2=TW/((BBAV*GGAV)**3*EREST)
        T2=FL2*(P1/FL1-F2*DW)
        T3=F2*EF0*CLN(J)**2*TP(J)*DSIN(PI0)
        PHIE=PINI+P1+T2-T3
156     PINI=PHIE-TPI
        BINI=BINI+DBTA
        BCEL(J+1)=BINI
        PCEL(J+1)=PINI
        GAMAI=DSQRT(1.0/(1.0-BINI**2))
        WINI=EREST*(GAMAI-1.0)
6       CONTINUE
C
C*** END OF MAIN LOOP
C
1000    RETURN
        END
```

```
C
      SUBROUTINE GEO(TANK)
C
C*********************************************************************
C
C  GENERATES GEOMETRIC PARAMETERS FOR THE TANK INCLUDING
C
C    CLN        CELL LENGTH
C    DT         DRIFT TUBE LENGTH
C    GAP        CELL GAP
C    BETAG      GEOMETRIC BETA
C    GAMAG      GEOMETRIC GAMMA
C    T,S        FIRST ORDER TRANSIT TIME FACTORS
C    TP,SP      SECOND ORDER TRANSIT TIME FACTORS
C
C  TANK IS THE TANK NUMBER (01-12) - MUST BE DECLARED 'INTEGER*2'
C  IN CALL FROM MAIN PROGRAM.
C
C  CLN,DT,GAP ARE CONTAINED IN FILE 'TXX.DAT' XX=01-12
C  COEFFICIENTS FOR TRANSIT TIME FITS ARE CONTAINED IN 'CFXX.DAT'.
C
C
C                *** WRITTEN BY T.L. OWENS ***
C                      AUGUST 8, 1990
C
C*********************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (NC=100)
      DIMENSION TC(4),SC(4),TPC(4),SPC(4)
      COMMON/GEOM/CLN(NC),DT(NC),GAP(NC),BETAG(NC),GAMAG(NC)
      COMMON/TRNST/T(NC),S(NC),TP(NC),SP(NC)
      COMMON/PARAM/FREQ,EREST,PI,TPI,C,WAVL,TW,FNCEL
      CHARACTER TANK*2,TFILE*7,CFITS*11
      TFILE='T'//TANK//'.DAT'
      CFITS='CF'//TANK//'.DAT'
      NCEL=FNCEL
      OPEN(UNIT=11,FILE=TFILE,TYPE='OLD')
      READ(11,1)(CLN(J),DT(J),GAP(J),J=1,NCEL+1)
1     FORMAT(3(2X,F6.5))
      CLOSE(UNIT=11)
      OPEN(UNIT=11,FILE=CFITS,TYPE='OLD')
      READ(11,3)(TC(J),SC(J),TPC(J),SPC(J),J=1,4)
3     FORMAT(4(2X,F8.5))
      CLOSE(UNIT=11)
C
C*** GENERATE TRANSIT TIME FACTORS, GEOMETRIC BETA, AND GEOMETRIC GAMMA
C
      NCEL=FNCEL
      DAB=0.0
      DO 4 I=1,NCEL
      DAB=DAB+CLN(I)
      BTG=CLN(I)/WAVL
      BETAG(I)=BTG
      GAMAG(I)=DSQRT(1.0/(1.0-BTG**2))
      BTS=BTG**2
      BTC=BTG*BTS
      T(I)=TC(1)+TC(2)*BTG+TC(3)*BTS+TC(4)*BTC
```

```
      S(I)=SC(1)+SC(2)*BTG+SC(3)*BTS+SC(4)*BTC
      TP(I)=TPC(1)+TPC(2)*BTG+TPC(3)*BTS+TPC(4)*BTC
      SP(I)=SPC(1)+SPC(2)*BTG+SPC(3)*BTS+SPC(4)*BTC
4     CONTINUE
      RETURN
      END
```

```
C
      DOUBLE PRECISION FUNCTION FUNXY(FX,FY)
C
C*** FUNXY IS THE RMS PHASE (SQUARED) ALONG THE TANK
C*** AT THE CENTER OF THE GAP.
C
C    INPUTS ARE:
C        FX     BETA INTO TANK
C        FY     PHASE INTO TANK
C
C                ***  WRITTEN BY T.L. OWENS  ***
C                       AUGUST 8, 1990
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (NC=100)
      DIMENSION BCEL(NC),PCEL(NC),PCNTR(NC)
      COMMON/GEND/EF0
      COMMON/PARAM/FREQ,EREST,PI,TPI,C,WAVL,TW,FNCEL
      NCEL=FNCEL
      CALL XFER(FX,FY,EF0,BCEL,PCEL,PCNTR)
      PRMSS=0.0
      DO 1,I=2,NCEL
1     PRMSS=PRMSS+(PCNTR(I)-PCNTR(1))**2
      FUNXY=PRMSS
      RETURN
      END
```

```
C
      SUBROUTINE EFSET(ITANK,DTBI,SLOPE,DWA,DE)
C
C*********************************************************************
C
C  SUBROUTINE TO CALCULATE THE ELECTRIC FIELD DISPLACEMENT FROM
C  DESIGN BASED UPON A MEASUREMENT OF THE SLOPE OF THE LINE
C  GENEREATED IN THE DELTA-T PLANE, NEAR THE INTERSECTION OF
C  CURVE CLUSTERS (DESIGN PHASE IS USUALLY WITHIN A FEW DEGREES
C  OF THIS INTERSECTION).  AN ESTIMATE OF THE INPUT ENERGY
C  DISPLACEMENT IS ALSO GIVEN BASED UPON THE DELTA-TB VALUE AT
C  THE POINT OF INTERSECTION.
C
C  INPUTS:
C       ITANK   TANK NUMBER (3-9)
C       DTBI    DELTA-T OF INTERSECTION (SECONDS)
C       SLOPE   SLOPE OF THE LINE GENERATED IN THE DELTA-T PLANE
C               BY VARYING THE TANK PHASE.
C
C  OUTPUTS:
C       DWA     ENERGY DISPLACEMENT (FRACTION) INTO TANK.
C       DE      FIELD DISPLACEMENT (FRACTION)
C
C  INPUT FILES:
C       SLOPER    -     RANDOM ACCESS FILE CONTAINING:
C               -ITANK  TANK NO.
C               -SLP    SLOPE OF SYNCHRONOUS PARTICLE.
C               -DSLP   DERIVATIVE OF SLOPE WRT E FIELD.
C               -FM     2,1 ELEMENT OF TRANSFER MATRIX
C               -DFM    DERIVATIVE OF 2,1 ELEMENT OF TRANSFER
C                       MATRIX.
C
C       GTANKR    -     RANDOM ACCESS FILE CONTAINING:
C               -ITNK   TANK NUMBER.
C               -EF     E FIELD (MV/M).
C               -DAB    TANK LENGTH (METERS).
C               -BTA    TANK INPUT BETA.
C
C            ***  WRITTEN BY T. L. OWENS  ***
C                    JAN. 8, 1991
C
C*********************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      OPEN(UNIT=4,FILE='SLOPER.DAT',ACCESS='DIRECT',FORM='FORMATTED'
     1,STATUS='OLD',RECL=62)
      OPEN(UNIT=8,FILE='GTANKR.DAT',ACCESS='DIRECT',FORM='FORMATTED'
     1,STATUS='OLD',RECL=62)
      READ(4,1,REC=ITANK-2)ITNK,SLP,DSLP,FM,DFM
1     FORMAT(2X,I2,4(2X,D12.6))
      READ(8,2,REC=ITANK-2)ITNK,EF,DAB,BTA
2     FORMAT(2X,I2,2X,D12.6,2X,D13.7,2X,D12.6)
      WRITE(5,1)ITNK,SLP,DSLP,FM,DFM
      WRITE(5,2)ITNK,EF,DAB,BTA
      C=2.99792458D+8
      DE=(SLOPE-SLP)/(DSLP*EF)
      GMA=DSQRT(1.0/(1.0-BTA**2))
      DBB=-DTBI*BTA*C/DAB
```

```
DWA=DBB*GMA*(GMA+1.0)
RETURN
END
```

```
C
      SUBROUTINE PHSET(ITANK,DTB,DTC,DPA,DWA)
C
C*********************************************************************
C
C  SUBROUTINE TO  CALCULATE THE PHASE AND ENERGY DISPLACEMENTS
C  FROM DESIGN VALUES.
C
C  INPUTS:
C       ITANK   TANK NUMBER (3-9).
C       DTB     DELTA-TB VALUE IN SECONDS.
C       DTC     DELTA-TC VALUE IN SECONDS.
C
C  OUTPUTS:
C       DPA     PHASE DISPLACEMENT (DEGREES).
C       DWA     ENERGY DISPLACEMENT (FRACTION).
C
C  INPUT FILES:
C       GTANKR.DAT      -       RANDOM ACCESS FILE CONTAINING:
C        -ITNK          TANK NUMBER.
C        -EF            E FIELD (MV/M).
C        -DAB           TANK LENGTH (M).
C        -BTA           INPUT BETA.
C
C       AMATR.DAT       -       RANDOM ACCESS FILE CONTAINING:
C        -ITNK          TANK NUMBER.
C        -A11-A22       ELEMENTS OF THE A MATRIX.
C
C
C
C                ***   WRITTEN BY T. L. OWENS   ***
C                           JAN 9, 1991
C
C*********************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      OPEN(UNIT=4,FILE='AMATR.DAT',ACCESS='DIRECT',FORM='FORMATTED'
     ,STATUS='OLD',RECL=62)
      OPEN(UNIT=8,FILE='GTANKR.DAT',ACCESS='DIRECT',FORM='FORMATTED'
     1,STATUS='OLD',RECL=62)
      READ(4,1,REC=ITANK-2)ITNK,A11,A21,A12,A22
1     FORMAT(2X,I2,2X,4(2X,D12.6))
      READ(8,2,REC=ITANK-2)ITNK,EF,DAB,BTA
2     FORMAT(2X,I2,2X,D12.6,2X,D13.7,2X,D12.6)
      WRITE(5,1)ITNK,A11,A21,A12,A22
      WRITE(5,2)ITNK,EF,DAB,BTA
      PI=4.0*DATAN(1.0D0)
      C=2.99792458D8
      EREST=939.301
      DPA=(A11*DTB+A12*DTC)*180.0/PI  !PHASE DISPLACEMENT IN DEGREES
      GMA=DSQRT(1.0/(1.0-BTA**2))
      WA=EREST*(GMA-1.0)
      DWA=(A21*DTB+A22*DTC)/WA        !ENERGY DISPLACEMENT FRACTION
      WRITE(5,3)WA
3     FORMAT(' WA=',D12.6)
      RETURN
      END
```

```
C
      SUBROUTINE EFSET2(ITANK,WP1,WP2,ECHNG,DE)
C
C*********************************************************************
C
C  SUBROUTINE TO CALCULATE THE ELECTRIC FIELD DISPLACEMENT FROM
C  DESIGN VALUES FOR TANKS 5-9, USING DELTA-T METHOD # 2.
C
C  INPUTS:
C       ITANK   TANK NUMBER.
C       WP1     INITIAL PEAK IN ENERGY VRS PHASE CURVE.
C       WP2     ENERGY PEAK FOR SLIGHTLY DIFFERENT E FIELD
C       ECHNG   CHANGE IN E FIELD (E2-E1)/E1 (FRACTION).
C
C  OUTPUTS:
C       DE      ELECTRIC FIELD DISPLACEMENT FROM DESIGN (FRACTION).
C
C  INPUT FILES:
C       SLOPER.DAT      -       RANDOM ACCESS FILE CONTAINING:
C        -ITNK          TANK NUMBER.
C        -FM21          2,1 ELEMENT OF THE TRANSFER MATRIX.
C
C       WPEAKR.LIS      -       RANDOM ACCESS FILE CONTAINING:
C        -ITNK          TANK NUMBER.
C        -WPS           PEAK ENERGY CHANGE FOR SYNCHRONOUS PARTICLE.
C        -DPHS          PHASE DISPLACEMENT OF PEAK ENERGY.
C
C                    ***   WRITTEN BY T. L. OWENS   ***
C                              JAN. 9, 1991
C
C*********************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      OPEN(UNIT=4,FILE='SLOPER.DAT',ACCESS='DIRECT',FORM='FORMATTED'
     1,STATUS='OLD',RECL=62)
      OPEN(UNIT=9,FILE='WPEAKR.LIS',ACCESS='DIRECT',FORM='FORMATTED'
     1,STATUS='OLD',RECL=62)
      READ(4,1,REC=ITANK-2)ITNK,SLP,DSLP,FM21,DFM21
1     FORMAT(2X,I2,4(2X,D12.6))
      READ(9,3,REC=ITANK-4)ITNK,WPS,DPHS
3     FORMAT(2X,I2,2(2X,D12.6))
      WRITE(5,1)ITNK,SLP,DSLP,FM21,DFM21
      WRITE(5,3)ITNK,WPS,DPHS
C
C*** DWP IS THE TOTAL DERIVATIVE OF PEAK ENERGY WRT E.
C*** 0.624869352 IS TAN(-32 DEGREES).
C
      DWP=(WP2-WP1)/ECHNG+FM21/0.624869352
      DE=(WP1-WPS)/DWP
      RETURN
      END
```

```
C
      SUBROUTINE LSCAN(FUNXY,XIN,YIN,FIN,XSOLN,YSOLN,TOL)
C
C*****************************************************************
C
C  FINDS THE MINIMUM OF A FUNCTION OF TWO VARIABLES IN THE VICINITY
C  OF THE POINT (XIN,YIN).  FUNXY (X,Y) IS THE USER SUPPLIED FUNCTION.
C  THE CALLING PROGRAM MUST CONTAIN THE STATEMENT "EXTERNAL FUNXY".
C  USES THE LATTICE METHOD TO SEARCH FOR THE MINIMUM.
C
C  INPUTS:
C    XIN        INITIAL ESTIMATE OF X SOLUTION
C    YIN        INITIAL ESTIMATE OF Y SOLUTION
C    FIN        SIZE OF INITIAL SEARCH GRID [X,Y*(1+-FIN)]
C    TOL        TOLERANCE ON THE SOLUTION
C
C  OUTPUTS:
C    XSOLN      X VALUE OF THE MINIMUM OF FUNXY
C    YSOLN      Y VALUE OF THE MINIMUM OF FUNXY
C
C
C                 ***  WRITTEN BY T.L. OWENS  ***
C                        AUGUST 8, 1990
C
C*****************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(3),Y(3)
      MAXIT=1000
      INDX=1
C
C*** RENAME INPUTS TO PREVENT THEM FROM BEING OUTPUT BY SUBROUTINE.
C
      FINC=FIN
      XINI=XIN
      YINI=YIN
      VMIN=FUNXY(XINI,YINI)
      ISAV=2
      JSAV=2
C
C*** SETUP NEW 3 X 3 GRID
C
200   X(1)=XINI*(1.0-FINC)
      X(2)=XINI
      X(3)=XINI*(1.0+FINC)
      Y(1)=YINI*(1.0-FINC)
      Y(2)=YINI
      Y(3)=YINI*(1.0+FINC)
      XINC=X(3)-X(2)
      YINC=Y(3)-Y(2)
C
C*** CHECK NEW GRID FOR MINIMUM
C
      DO 1 I=1,3
      DO 2 J=1,3
      VALU=FUNXY(X(J),Y(I))
C     WRITE(5,77)I,J,VALU
C77   FORMAT(' I=',I2,' J=',I2,' VALU=',D12.6)
```

```
        IF(VALU.LT.VMIN)THEN
          VMIN=VALU
          ISAV=I
          JSAV=J
        END IF
2       CONTINUE
1       CONTINUE
110     CONTINUE
C
C*** TEST FOR CONVERGENCE
C
        IF(DABS(FINC).LT.TOL)GO TO 900
100     IF(INDX.GT.MAXIT)THEN
          WRITE(5,101)
101       FORMAT(' LSCAN> TOO MANY ITERATIONS IN FINDING MINIMUM-EXITING')
          GO TO 1000
        END IF
C       WRITE(5,22)X(2),Y(2),XINC,YINC,VMIN
C22     FORMAT(' X=',D12.6,' Y=',D12.6,' XINC=',D12.6,' YINC=',D12.6
C     1,' VMIN=',D12.6)
C
C*** NEXT SCAN FOR MINIMUM DEPENDS UPON THE PREVIOUS MINIMUM
C*** POSITION (ISAV,JSAV) IN THE 3 X 3 GRID.
C
        GO TO (3,4,5)ISAV
3       GO TO (6,7,8)JSAV
4       GO TO (60,70,80)JSAV
5       GO TO (600,700,800)JSAV
C
C*** STATEMENTS 6,7,8,60,80,600,700,800 SET PARAMETERS FOR THE
C*** NEXT SCAN IN DO LOOPS AFTER STATEMENT 10
C
6       FX=-1.0
        FY=-1.0
        INB=1
        INE=3
        JNB=2
        JNE=3
        JJ=1
        II=1
        GO TO 10
7       FX=0.0
        FY=-1.0
        INB=2
        INE=1
        JNB=1
        JNE=3
        JJ=1
        II=1
        GO TO 10
8       FX=1.0
        FY=-1.0
        INB=1
        INE=3
        JNB=1
        JNE=2
        JJ=3
        II=1
```

```
        GO TO 10
60      FX=-1.0
        FY=0.0
        INB=1
        INE=3
        JNB=2
        JNE=1
        JJ=1
        II=1
        GO TO 10
80      FX=1.0
        FY=0.0
        INB=1
        INE=3
        JNB=2
        JNE=1
        JJ=3
        II=1
        GO TO 10
600     FX=-1.0
        FY=1.0
        INB=1
        INE=3
        JNB=2
        JNE=3
        JJ=1
        II=3
        GO TO 10
700     FX=0.0
        FY=1.0
        INB=2
        INE=1
        JNB=1
        JNE=3
        JJ=1
        II=3
        GO TO 10
800     FX=1.0
        FY=1.0
        INB=1
        INE=3
        JNB=1
        JNE=2
        JJ=3
        II=3
        GO TO 10
C
C*** IF THE CENTER OF THE 3 X 3 GRID IS AGAIN THE MINIMUM THEN
C*** REDUCE THE GRID SPACING BY A FACTOR OF TWO AND RESUME SEARCHES.
C
70      XINI=X(2)
        YINI=Y(2)
        FINC=FINC/2.0
        INDX=INDX+1
        GO TO 200
C
C*** NEW POINTS ARE SCANNED IN THE FOLLOWING LOOPS IF THE PREVIOUS
C*** MINIMUM IS NOT IN THE CENTER OF THE GRID.
```

```
C
C*** POINTS ALREADY CALCULATED ARE SKIPPED.
C
10      DO 61 IJ=1,3
        X(IJ)=X(IJ)+FX*XINC
61      Y(IJ)=Y(IJ)+FY*YINC
        ISAV=2
        JSAV=2
        DO 62 I=INB,INE
        VALU=FUNXY(X(JJ),Y(I))
        IF(VALU.LT.VMIN)THEN
          VMIN=VALU
          ISAV=I
          JSAV=JJ
        END IF
62      CONTINUE
        DO 63 J=JNB,JNE
        VALU=FUNXY(X(J),Y(II))
        IF(VALU.LT.VMIN)THEN
          VMIN=VALU
          JSAV=J
          ISAV=II
        END IF
63      CONTINUE
        INDX=INDX+1
        GO TO 100
900     XSOLN=X(2)
        YSOLN=Y(2)
1000    RETURN
        END
$
```