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**Longitudinal Tuning of the
LAMPF 201.25-MHz Linac
Without Space Charge**

MASTER

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with appendixes by

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ABSTRACT

After an accelerator is operational, the simulation models, used in the design phase to study perfect linacs or those with random errors, can be specialized to study the behavior of the actual machine and optimize its performance. This is being done on the Alvarez linac at LAMPF using the PARMILA model. We have incorporated as many of the actual measured physical parameters as possible into the code, and have found it necessary to include a more comprehensive treatment of the beam dynamics to make the model and experimental observations agree. For example, it is necessary to consider longitudinal and transverse phase space together in the calculations. This report outlines the modifications to the model, the results of experiments that indicate the validity of the model, and use of the model to optimize the longitudinal tuning of the Alvarez linac.

I. INTRODUCTION

Most of the parameters of a modern linear accelerator can be selected by simulating the desired machine characteristics in a computer code and observing how the parameters affect the beam dynamics. The code PARMILA¹ is used at the Los Alamos meson physics facility (LAMPF) for the low-energy part of linacs. Collections of particles can be traced with a free choice of input distributions in the six-dimensional phase space. Random errors often are included to study the tolerances that should be imposed during manufacture or in operation.

Once a machine is built, the simulation can be put to another use, modeling the actual behavior observed. If an accurate model can be found, it can be used in many ways, for example, to understand what is happening at intermediate points unobservable in practice. A most important use is in derivation of optimum settings for the accessible variables. Often the effect of imperfections can be largely alleviated or circumvented, once it is realized that they are present and the actual measurements are used in the model. This technique has been applied successfully^{2,3,4} to longitudinal tuning of the side-coupled linac part of LAMPF,

and here is applied to the same problem in the low-energy part of the accelerator.

The first cavity, or tank, of the LAMPF linac is a 31-cell, uncompensated, zero-mode Alvarez structure that operates at 201.25 MHz, with an axial electric field distribution designed to increase linearly from input to output. The three other tanks in the Alvarez part bring the particles to 100 MeV. Each is post-coupler stabilized, with uniform field distributions. All four tanks have a design ϕ_0 of -26° . The linac is preceded by two bunchers, both operating at 201.25 MHz. The phase and amplitude of the rf in these six structures are independently adjustable; the basic problem is how to set these parameters for optimum acceleration characteristics.

The procedure⁶ for this tuning is to scan an area around the desired operating point, looking for a strongly characteristic pattern *that has been predicted by a simulation model*. When the pattern is achieved, the model tells how to make the final settings. In this instance, the model and tuning are inextricably interwoven.

At first, observing the actual linac, we could not find the predicted shapes in detail, although the general features were present. There were indications that the discrepancies occurred in the first tank. Therefore we undertook to experimentally determine the operating characteristics of the 201.25-MHz accelerator and to improve the modeling until we got agreement. This report concentrates on the first tank; the results for tanks 2-4 were easier to obtain and are used in developing the final tuning strategy.

II. MODEL DEVELOPMENT

A. The Experiment

The experiment⁶ was to map the longitudinal acceptance of the first tank of the 201.25-MHz linac. The first step is to tune the H^+ transport line so that an H^+ beam with an energy of 750 keV and peak current of 1 mA enters the linac centered on the linac axis, so that the beam centroid is $(x, x', y, y')_c = (0, 0, 0, 0)$. The measuring apparatus is a copper absorber positioned after the second tank of the linac; the rf in this tank must be delayed so the beam will not be accelerated after it leaves Tank 1. Hence the

Fig. 1.
Experimental amplitude scan of Tank 1 with Tank 2 off.

second tank acts as a beam transport system and a filter. Both bunchers in the transport line are turned off so that a dc, monoenergetic beam enters Tank 1.

Then the amplitude of the power tube is varied until no particles are transmitted through Tank 2. This generates a picture (or amplitude scan) like that shown in Fig. 1. Each amplitude scan contains information in terms of amplitude set point (ASP) below which there is no longer any transmission (hereafter called the cutoff), and the shape of the curve relating the particle transmission to the ASP. From them, we aim to determine the calibration factors that will allow setting the field to the design level.

Further information can be obtained by making an amplitude scan with Tank 2 accelerating and collecting all the particles that are transmitted through a 36-MeV copper absorber (design energy for Tank 2 is 41.2 MeV). Because the cutoff occurs at a different amplitude, one gets redundant information about the ASP which corresponds to 100% of design field. This scan is shown in Fig. 2.

Next, we turn on the main buncher with its amplitude set to give the narrowest phase spread to the beam bunch. We then phase scan Tank 1 at 105, 100, 95, 92, and 90% ASP's, where 100% is the nominal design value. This gives the picture shown in Fig. 3.

Fig. 2.
Experimental amplitude scan of Tank 1 with
Tank 2 accelerating.

Fig. 4.
Experimental phase scan of Tank 2 at left edge
of acceptance, and derivative of edge to yield a
phase profile of the bunch.

Fig. 3.
Experimental phase scan of Tank 1 at different amplitudes of its rf field.

The next step is to make a phase scan of Tank 2 and then differentiate the left edge. This gives the

picture in Fig. 4. The derivative of the left edge gives the phase profile of the bunch.

All of the above steps are then repeated at injection energies of 720, 730, 740, 745, 750, 755, 760, 770, 780, and 790 keV. The H^+ beam transport line is as shown in Fig. 5. Because there are four bends, the bending magnets have to be changed for each energy to keep the beam centroid at (0,0,0,0).

Next, the rf heads in Tank 1 are moved to change the gaps in the first and last cells of the tank. This is the mechanism for setting the tilted field distribution in the tank. The heads were moved five times to give six field distributions on which all the above data were taken. The range of field distributions thus obtained is shown in Fig. 6.

Finally, the rf heads were returned to their starting positions and the amplitude scans were repeated over the entire range to check reproducibility.

The detailed experimental approach and procedure are given in App. A. This lengthy experiment was carried out by the machine operators in the operations group.

B. Data Analysis

1. The Problem. There are four sets of information to be analyzed: accelerator structure, quadrupole magnet measurements, the experimental data, and the simulated experiment calculated using the PARMILA model.

This is a massive amount of data, and we had to find a convenient way to handle it. We decided to use the computer language APL, which has several features superbly suited to data analysis: high-level

Fig. 5.

The H^+ injector, beam transport line, and entrance to the 201.25-MHz linac.

Fig. 6.

Range of axial field distributions in Tank 1 achieved by changing the gap lengths of the first and last cells.

vector manipulations, bookkeeping features that simplify analysis, and interactive format. When these features are combined with a graphic terminal, the result is a very sophisticated, on-line, data analysis tool that makes the analysis problem tractable.

2. Accelerator Structure Data. Analysis of the bead-pull data requires many steps to get relative axial electric field distributions for different geometrical configurations (called tilts) of the rf end walls. This has been reported elsewhere.⁷ Our analysis was to determine how best to characterize the field distributions for incorporation into PARMILA.

We have bead-pull information for nine tilt conditions. One way to characterize the data is to add average cell-by-cell structure on to a smoothed curve. The structure was determined by doing a cubic least squares fit to the field distribution for each tilt and then averaging the resultant set of deviations. Because the effects of perturbations in a tilted tank are not well enough understood, it is not clear that the above procedure is valid. From the data, we could not decide that it was valid so we rejected this approach. We finally chose simply to use the field distribution as measured.

The relative fields must be tied to the field strengths in PARMILA. The fields in the tank are controlled to a constant level during actual operation by use of a probe in cell 26. Thus we force the bead-pull fields to agree with the PARMILA fields in cell 26 and scale the values in the rest of the cells accordingly. As there is a positive bump in the field distribution in cell 26, this procedure has the effect of making the average field in the tank lower than design as Fig. 7 shows. To remove this effect in later calculations, we tied the fitted value of the measured field in cell 26 to the PARMILA value.

We also included actual measurements of gaps and drift tube lengths (see App. B). The effect of these quantities on dynamical parameters is discussed in Sec. II.C.2.

3. Magnet Data. The magnet-operating currents were measured, and the corresponding gradients were obtained using interpolating polynomial fits to the magnet calibration curves. The difference between mechanical and magnetic center was also measured. Details are given in App. B.

4. Experimental Data Calibration Factors. Most of the data analysis was done to compare the experimental and PARMILA-generated data and to improve the code to make the two sets of data agree. We concentrated on achieving agreement in the am-

Fig. 7.

The effect of a positive error in field at Cell 26, where the field level is controlled operationally, on the setting for the average field level.

plitude scans with the bunchers off, to minimize the number of unknowns. The first problem was to get the calibration factors needed to convert the raw data into units that could be compared directly to the PARMILA data. The raw data are expressed in the machine control computer data-system-count units for detected current versus ASP. The PARMILA data are in number of particles transmitted versus per cent of design field.

In trying to relate ASP to per cent of design field, we first used a calibration of the power delivered to Tank 1 as a function of ASP. Given the cutoff at 750 keV as a per cent of design field from the model, and the cutoff from the experiment at 750 keV in ASP, one should be able to use the calibration curve to determine what ASP corresponds to 100% of design field. This method did not yield good results.

We therefore made a linear least squares fit to the cutoffs in ASP versus the calculated cutoffs as a per cent of design field over the entire energy spectrum using the cutoffs from only one tilt (Fig. 8) and allowing an energy calibration offset. The resultant linear equation could then be used to convert all the experimental data from ASP to per cent of design field. This produced much better agreement, and was the essence of the method used in the final analysis described below.

The reason for the difference between this field/ASP relation and the one resulting from the delivered power calibration is not understood. Possibly details of the magnetic control probe interaction with nearby fields are responsible. There are nine of these rather crudely built probes along

Fig. 8.

Linear least squares fit to amplitude scan cutoff data for Tilt 1.

the tank. During the experiment, the voltage detected by a crystal detector at each probe was carefully measured at each field tilt setting. The results bore only qualitative resemblance to the axial field distribution measured by bead pulls at low power. Having no reason to suspect that the high-power axial fields differed from those at bead-pull power level (see Sec. C.3), we concluded that the probes did not indicate axial field distributions reliably on either an absolute or relative basis.

Next it is necessary to relate the experimental transmission to the PARMILA transmission. The correct way to do so would be to measure the current at the linac entrance and compare it to the current transmitted through Tank 2. This transmission ratio could then be compared directly to the percentage of particles transmitted in PARMILA. The transmission at the end of Tank 2 was measured, but the current measurement at the linac input was inaccurate, so the relation between experimental and PARMILA data was indeterminate. We resolved this problem by normalizing the experimental data to agree with the PARMILA data at 100% of design field for each energy. We then iterated on this normalization by using a gain factor that varied from 0.90 to 1.06 and chose the gain factors that gave the best fit to the data.

The last step necessary to relate the experimental and PARMILA data was to relate the experimental tilt to the bead-pull tilt conditions by calibrating the movements of the tank heads. Details are given in App. C. The experimental tilts were produced under high-power conditions by moving one rf head by Δf and then moving the other to restore the frequency. The bead pulls included data at the intermediate steps (one head moved) as well as at frequency-conserving movements. Physically, the first experimental tilt corresponded to the first bead-pull tilt, and the last experimental tilt was not quite so shallow as the last bead-pull tilt. This fact should be noted because it is a criterion used for evaluating the data analysis results.

5. Method. Now we can compare the experimental data to the PARMILA data. At the outset, we will allow for a possible discrepancy between the Cockcroft-Walton (C-W) energy reading and the actual beam energy at injection.

The PARMILA output can be put into a matrix with injection energy as one coordinate and per cent of design field as the other. The numbers in the matrix are the number of particles transmitted for a given injection energy and per cent of design field. To allow for an energy offset in the C-W, one must be able to interpolate along the energy axis in this matrix. The matrix is very sparse in the cutoff region, making interpolation difficult. The curves were extended below cutoff by determining the slope of each amplitude scan at cutoff and then linearly extending the function. The slope was determined using Lagrangian interpolation (see App. D) on the cutoff and the three adjacent points. This method filled the matrix and allowed smooth interpolation.

The experimental data were put into a similar matrix, with ASP horizontally and energy vertically, and the raw counts of transmission being the function represented.

Thus, we have all the data in a form that will facilitate a systematic search for the C-W energy offset that will make the experimental and theoretical data agree best. First, we use the curve of per cent of design field at cutoff versus energy (Fig. 9) to determine what set of data to fit to the ASP (Fig. 8). This set assumes no energy shift in the C-W, and the fit yields a slope and intercept that relate ASP and per cent of design field. Then we assume C-W energy shifts (ΔE) of 2, 4, 6, and 8 keV and generate the associated slope and intercept. Next we interpolate along the energy coordinate in the theoretical matrix for the given set of ΔE 's. Then for a given injection energy, we fit a cubic spline to the amplitude scan for both the experimental and theoretical data. These two fits are then compared point by point, and a sum of the squares of the deviations is accumulated. At this step, the two sets of data are normalized, without using the iterative fitting to find the best gain factors, as discussed in Sec. II.B.4. The results are obtained as the sum of squares of errors versus ΔE .

The region where the function is minimized is determined by inspection and then searched in detail on a finer mesh. This procedure is continued until the location of the minimum is known to a tenth of a kilovolt. Then the normalization (gain factor) for each energy is allowed to float between 0.90 and 1.06 by steps of 0.02 and then by steps of

Fig. 9.
Variation of amplitude scan cutoff field with injection energy, for Tilt 1.

0.01 around each minimum. This gives the final set of parameters that characterize the fit.*

C. The Model

1. Transverse Effects on the Longitudinal Tuning Problem. The PARMILA code we used originally was written for design studies in which errors usually were treated as randomly distributed within some bound. At the outset of our study, it had been upgraded to include the effects of quadrupole misalignments and measured axial electric field distributions. At this stage, artificial phase and energy discrimination had been used to determine particle transmission. Closer investigation showed that Tank 2 transported very low energy

*J. is an example of the power of APL that the coding for the complete analysis takes less than 175 lines.

particles. This led us to discard the energy and phase discrimination loss mechanism and leave radial impingement on the drift tubes as the only loss mechanism.

PARMILA allows single particle, as well as multiparticle, calculations. Although we are concerned mainly with the longitudinal behavior of the beam, we cannot neglect the transverse influence on this behavior. Calculationally, it is very difficult to populate this six-dimensional phase space well. The main problems are the amount of memory in the computer and the long computer time required to study a large collection of particles.

We studied how the transverse phase space population affected the longitudinal behavior by populating the transverse space densely but with all the particles at the same phase and energy. We then made many runs using the same transverse population and energy, but at many phases. We found that we could simulate the transverse influence by making a pencil beam with a 2-mm offset in one transverse coordinate and keeping the others at zero (Fig. 10). (This was also approximately the rms position of the particles in the experimental beams.) That is, the transmission cutoffs were nearly the same for the displaced pencil beam as for a beam with a randomly filled four-dimensional transverse phase space.

2. Geometric Effects. We measured the longitudinal positions of all the drift tubes, as well

Fig. 10.
Typical amplitude scans computed using a beam with a randomly populated transverse phase space and using an offset pencil beam.

as their lengths. This gave the errors in gap lengths, cell lengths, and gap center-to-center distances. The expression for the energy gain per cell shows how the first two quantities enter into the calculation.

$$\frac{dW}{dn} = E_0 L T \cos(\phi_s + \Delta\phi) .$$

The quantity $E_0 L$ is

$$E_0 L = \int_0^L E_z(r=0, z) dz .$$

The right-hand side is obtained from bead-pull data. Then the length errors are included in the calculation straightforwardly.

The second quantity affected is the transit time factor, T . The defining equation for T is

$$E_0 L T = \int_0^L E_z(r=0, z) \cos \frac{2\pi z}{L} dz .$$

An approximate form for T is

$$T(g, L) \approx \frac{\sin(\pi g/L)}{\pi g/L} \frac{I_0\left(\frac{2\pi r}{L}\right)}{I_0\left(\frac{2\pi a}{L}\right)} ,$$

where a is the bore hole radius. This approximation determines T poorly, but determines ΔT well. Using MESSYMESH for the first cell of Tank 1 with $\Delta g/g = 0.22$ and $\Delta L/L = 0.05$, we find that

$$\Delta T = -0.0111 .$$

Then by forming

$$\Delta T_{\text{PARM}} = \frac{T(g+\Delta g, L+\Delta L) - T(g, L)}{T(g, L)} T_{\text{PARM}} ,$$

we find that

$$\Delta T_{\text{PARM}} = -0.0109 ,$$

where we have kept the first three terms in the expansion for $I_0(2\pi a/L)$. This is the method used for approximating ΔT in PARMILA.

3. Other Possibilities. At one point, we conjectured that the model and experimental data might

disagree because movement of the rf curtains at the ends of the tank at high power gave a different field distribution from that at the bead-pull power level for the same nominal setting of the heads. Therefore, we installed a device to detect rf curtain movement while the tank was brought from zero to full power. No movement was detected.

Reference 8 indicates that the presence of the bead apparently tilts the electric field distribution during measurement. If not accounted for, this systematic tilt in the field distribution would give rise to beam dynamics effects similar to an injection energy error.

We made bead-pull measurements using 0.25-, 0.375-, and 0.5-cm beads. After extensive analysis,⁷ we concluded that any bead size effects were below measurement accuracy.

Also, two rf slug tuners used for resonance control in Tank 1 cause a large end-to-end tilt, depending on their positions. For instance, if the upstream tuner is completely withdrawn and the downstream one is completely inserted, the field distribution is tilted 4% relative to that when both are at their mid-positions. The tuners were at three-fourths of their mid-positions when the high-power experiment was run, but they were at their mid-positions when the fields were measured (bead pull). Hence, there could be a 0.5% effect on the field distribution. This effect may seem small, but it should be compared to the 2% change from tilt 1 to tilt 2.

So, both the bead-size and tuner effects could be significant. However, our measurements were not accurate enough to justify including these effects. It should be possible in future to improve the measurements systematically and thus resolve these difficulties. For our analysis, we choose to follow the injection energy error hypothesis only.

Straggling effects in the copper absorbers used in the experiments are also accounted for in the PARMILA calculations. The design thicknesses for the absorbers are 36, 65, and 95 MeV for Tanks 2-4, respectively; the corresponding design output energies are 41.32, 72.72, and 100.0 MeV.

D. Results

The amplitude scans calculated using both the model and the experimental data are shown in Fig. 11. These plots assume a C-W energy offset of 5.8

Fig. 11.
Experimental amplitude scans and those calculated from the model over a range of injection energies.

Fig. 11. (cont)

keV which gives the minimum sum of squared errors. Figure 12 shows the cutoffs versus energy for six experimental tilts and nine bead-pull tilts. The first experimental tilt and the first bead-pull tilt match with both heads at mechanical limits. The results match the head calibration as they should (see the last paragraph of Sec. II.B.4). Two sets of data are shown for experimental tilt 1. They were taken two weeks apart and show the reproducibility to be within 1%.

Figure 11 shows that a varying energy offset would fit the experimental data better, using less offset at lower injection energy and more at higher injection energy. However, the constant energy offset fits the data well in the region of primary interest around 750 keV and we will use it for two reasons. First, the machine is operated at a constant injection energy; our approach shows the effect of a possible error in measuring the injector voltage. Second, as stated above, we have not proved that the measured

voltage is wrong, but have only shown that the hypothesis of this error can produce much better agreement between measured and calculated results. If we assumed a generally steeper tilt at full power, the fit would be even better, but at this time we do not know how such an effect could be produced, nor can we measure the field distribution at full power.

Hence, we feel that our model satisfactorily represents the real linac. In the next section, we discuss using this model to investigate a specific question about longitudinal beam dynamics.

The details of the way particles are accelerated in a tilted field tank as a function of the tank gradient are fairly complicated. Appendix E contains a theoretical development that explains the capture process in a two-part model, depending on whether the gradient is above or below a threshold gradient. The model verifies the qualitative shape of the cutoff dependence on injection energy and tilt

shown in Fig. 12. The way the acceptance area reduces as cutoff is reached also is discussed.

III. MODEL APPLICATION

A. The Compromise Design

The axial electric field distribution as measured by bead pulls varies greatly from the design distribution. Figure 13 shows bead-pull tilt 2 and the design fields. The large fluctuations in the first few cells drive a large longitudinal oscillation. (The mechanism used to produce the tilted field; i.e., changing the gap length of only the first and last cells, produces these fluctuations. See App. F for a discussion of a method to prevent this.) In fact, the beam gets a 25° kick in the first cell, as shown in Fig. 14. This large kick travels through the nonlinear region of phase space which would presumably generate large tails on the beam and cause a large emittance growth. Our goal is to determine, for the existing linac, an input phase and energy and a field tilt that will optimize the longitudinal phase oscillation, tail generation, and emittance growth. We also want to have a small ΔE at the end of Tank 1. Then properly phasing Tank 2 will minimize the subsequent oscillation.

B. Compromise Design Procedure

1. Single-Particle Calculations. We explored the injection energy and phase space using a single particle to find the tilt and injection conditions giving a small overall phase and energy oscillation in Tank 1 and small ΔE at the end of Tank 1. Tilt 2 gave the best performance. Injection at 758 keV and -51° into Tilt 2 gave the smallest peak oscillations between cells 2 and 31, as shown in Fig. 14.b. The -25° offset in injection phase from the design synchronous phase of -26° is easy to understand, as that is the amount the phase is kicked in the first cell. The 8-keV offset gets the beam through the large field fluctuations in the first few cells with approximately the right energy to be near the synchronous energy throughout the rest of the tank. Another kick occurs in the last few cells, however, and as seen in Fig. 15, it is difficult to do much about the output energy offset near these operating

conditions. Because the energy width of the acceptance grows as a function of particle velocity (Figs. 16 and 17), the resulting oscillation in Tank 2 is not severe. Lowering the injection energy or the Tank 1 rf field level will reduce the Tank 1 output energy offset. The latter course is also favorable, as shown below, for reducing the output emittance.

2. Acceptance. Figure 16 shows the acceptance of Tank 1 for field Tilt 2, and the design acceptance. Particles were accelerated through Tank 1 and not accelerated through Tank 2, where they are exposed to the quadrupole fields set to the same values used when Tank 2 is accelerating. Striking the drift tube bores is the only loss mechanism; particles that reached the end of Tank 2 are shown. The 25° offset is clear. Fig. 17 shows the acceptance of Tanks 2, 3, and 4 if one were using the phase scan apparatus to detect it. In other words, particles that had enough energy to reach the collector at the end of the tank are shown. (Not all would accelerate further—particularly some in the tail region). All particles for these runs were injected at $x = +0.2$ cm, with other transverse coordinates equal to zero.

Next, one must make multiparticle bunched beam simulations to refine the choice of operating parameters.

3. Multiparticle Ellipse Calculations. An upright longitudinal ellipse $\pm 25^\circ$ wide by ± 10 keV high, randomly filled from a uniform distribution, was injected at various combinations of mean phase and energy. The beam was given no transverse emittance and was injected axially. This size was chosen because the original bunching criterion was to put as much current as possible into $\pm 25^\circ$ phase spread. This approach is useful because the distribution is initially compact and one can determine, subjectively or by fitting ellipses to the distribution as it progresses through the machine, how well the beam is holding together and whether tails are forming. Injection conditions near 758 keV and -51° as found for the single particle gave the most cohesive beam, Fig. 15 (right). It was not clear that this would be the case due to the proximity of the left side of the bunch to the edge of the acceptance. Fig. 18 shows how the emittance varies as a function of axial position for a typical case and how well the beam is matched. Fig. 19 shows the actual particle distribution as it progresses through Tank 1.

Fig. 12.

Experimental and theoretical amplitude scan cutoffs as functions of injection energy for the entire range of field distributions. The top curve was expected to match exactly; the remaining experimental curves have the proper shape, and fall at the expected intervals between the theoretical curves as interpolated from the tank head calibration.

Fig. 13.

The design axial field distribution and the actual field distribution at Tilt 2.

Finally, to check the optimum operating conditions, we made calculations using a bunched beam.

4. Multiparticle Bunched Beam Calculations.

The input beam for these calculations was a monoenergetic, dc beam with no transverse emittance which traversed two bunchers and arrived at the linac entrance with the longitudinal phase space shown in Fig. 20. Space charge was not included.

As noted previously, some particles that are no longer being accelerated will be transported through Tank 2. These particles are present in experimental measurements and must be considered; however, they are soon to be lost, so they should not confuse the issue of optimum tuning for the accelerated beam. To this end, we wrote an output routine for PARMILA which follows all of the particles through Tank 2 and determines which are captured and which are transmitted but not accelerated. The particles are then rerun, and at each cell the emittance of the captured particles and the total emittance are calculated.

The results of this calculation again show that injection near $(\Delta E, \Delta \phi) = (8 \text{ keV}, -25^\circ)$ and field tilt 2 give the best operating point.

Finding that tilt 2 is the best condition is satisfying in an important way. This tilt is the one that most closely matches the design tilt for the central part of the tank (Fig. 13). One would expect the geometrical features of the structure to dominate in spite of the strongly perturbed end cells, and this proves true.

Some of the outlying particles could be eliminated by lowering the Tank 1 ASP and thus shrinking the acceptance. When the amplitude is lowered, the synchronous phase changes, and the input conditions must be shifted accordingly. The results are shown in Table I. An amplitude of 96% of design gives the smallest emittance with only slight transmission loss and it has the fewest particles outside the accepted core; lowering the amplitude further puts the particles too far into the nonlinear regions and tails form.

The above calculations were made using an axial beam that had no transverse emittance and was transported only through bunchers and drifts. To check these results, we made calculations using off-axis beams transported through the full transport system, bunchers, drifts, quadrupoles, and bends. We saw no significant changes from the previous results.

5. Optimum Operating Conditions for Tank 1.

Using all the above considerations, we arrive at the following optimum conditions for Tank 1.

Injection energy: 758 keV

Injection phase: -48.5°

Amplitude: 96%

Field distribution: Tilt 2

The injection phase is not influenced strongly by slight changes in injection energy. To keep the same nominal 750.0-kV Cockcroft-Walton setting, which we have hypothesized is really 755.8 kV, we will generate the *operational phase scans at*

Injection energy: 755.8 keV (750.0 kV nominal)

Injection phase: -48.5°

Tank 1 amplitude: 96%

Field distribution: Tilt 2

6. Determination of rf Phase and Amplitude.

In using the phase scan method to set the rf phase and amplitude of the bunchers and Alvarez tanks, we vary the phase of a particular element and observe the current on a copper absorber and collector system. We set the phase and amplitude to produce phase scans that match the PARMILA results. The experiment is outlined in App. G.

The PARMILA and experimental results both are shown in Fig. 21. Note that the shape agrees well, the width agrees, and the ratio of maximum to minimum transmission agrees.

Fig. 14.

a. Phase and energy trajectories of a particle injected at the 750-keV and -26° design conditions, at each cell of Tanks 1 and 2. The Tank 1 field distribution is that of Tilt 2, chosen as the best. Particle is rephased at the entrance to Tank 2.

b. Trajectories for injection energy and phase of 758 keV and -51° .

Fig. 15.

(Left) Offset from design energy at the end of Tank 1 as a function of absolute injection phase at constant injection energy of 755.8 keV, and as a function of injection energy with the injection phase fixed at -51° . The graph also shows that with an injection energy of 755.8 keV and injection phase of -51° , lowering the Tank 1 field to 94% can reduce the Tank 1 output energy offset to zero.

(Right) RMS longitudinal phase space area, at the end of Tank 1 as functions of injection energy and phase as above.

Fig. 16.

The design acceptance that would result from a linear field distribution, and the actual acceptance of Tank 1 for the measured field distribution of Tilt 2.

Fig. 17.
Longitudinal phase-space acceptance at the entrances to Tanks 2, 3, and 4.

C. Conclusions and Recommendations

An existing accelerator can be modeled using practical beam-dynamics computational tools, and, to that extent, the model can be of use in understanding observed behavior and finding optimum combinations of the controllable variables.

The model described above was derived and used in an engineering sense, with physical dimensions, fields, and so on, measured as accurately as possible and used directly. The hypothesis of a possible error in the C-W high voltage as read from the voltage divider was necessary to achieve a good fit. In other respects, the modeling is straightforward. The

model is sensitive to measurement errors. However, the insistence upon a global fit to the data and its achievement indicate that systematic errors have probably been minimized and that the remaining random errors do not dilute the usefulness of the results. Figure 22 gives a feeling for the effects of errors.⁹

It shows an amplitude scan for a design linac, the effect of measured multipole components and quadrupole misalignments (the former not included in the model described above), and the error bars resulting from further 2-mil random misalignments and 2% errors in the quadrupole fields.

Fig. 18.

Typical longitudinal emittance profiles (not at optimum conditions) through the first two linac tanks, showing the outermost 100 particles.

This figure also shows how the results are confounded when the nonaccelerating Tank 2 must be traversed and an absorber is used to collect all remaining particles. The lower curve is the amplitude scan of particles with energy ≥ 4.4 MeV at the end of Tank 1; this curve is unchanged when the same error terms are applied. Using such an absorber with a collector behind it, as we do at 40, 70, 100, and 120 MeV, would make the measurement less prone to error and would simplify the model. Putting the 4.4-MeV absorber and collector directly after Tank 1 would help even more. Such an absorber can probably be made of carbon with due consideration to possible degradation by the beam. Also note that at 100% of design field, the curves coalesce. This fact was used in generating the phase scans in App. G to save computer time.

The other information we gathered has not been analyzed in detail. It is consistent with our present understanding of the dynamics in this part of the machine, and is available if further investigations are suggested.

Details of the final PARMILA model are given in App. H.

Now that the simulation model agrees well with the observed longitudinal behavior, it can be used to develop tuning criteria for high peak current beams where space charge will influence the beam dynamics. We suspect that the bunching criteria used here may not be the optimum for minimum particle loss along the machine. It would also be operationally desirable to tune the beam at the peak current to be used, requiring the model to be used to generate phase scans as in Appendix G with space charge included. The technique demonstrated by Fig. 4 is a powerful way to observe how tuning affects the longitudinal phase profile, especially at the entrance to the 805-MHz linac using the 120-MeV phase scan. Varying the amplitudes of Tanks 2-4, with corresponding adjustment of the phases, can "rotate" the profile at 100 MeV and allow it to be viewed from all angles so the longitudinal emittance can be estimated.

ACKNOWLEDGMENTS

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Fig. 19.

Progression of a beam injected as a randomly filled right ellipse $\pm 25^\circ$ wide and ± 10 keV high, centered at 758 keV and -25° .

Fig. 20.
Longitudinal phase-space population at the entrance to Tank 1 for a bunched beam centered at $\Delta E = 8 \text{ keV}$ and $\Delta d = -25^\circ$.

TABLE I
BEAM QUALITY AT 40 MeV AS A
FUNCTION OF TANK 1 RF AMPLITUDE

<u>Per Cent of Tank Design Field</u>	<u>Emittance at 40 MeV (MeV-Deg)</u>	<u>No. Particles Accelerated (500 Injected)</u>	<u>No. Particles Transmitted (500 Injected)</u>
100.	6.5	429.	433.
97.	5.3	426.	432.
96.	3.9	424.	430.
95.	10.1	390.	404.
94.	9.3	339.	350.

a.

b.

Fig. 21.

a. Operational Tank 1 phase scan calculated using the optimized PARMILA model.

b. Experimental Tank 1 phase scan at optimized settings.

Fig. 22.
Effects of errors and energy discrimination on a typical amplitude scan for design linac; injection energy 780 keV.

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APPENDIX A

EXPERIMENTAL APPROACH AND PROCEDURE

We try to achieve self-consistent understanding of the drift tube linac longitudinal behavior by

- Increased understanding of field distributions from bead-pull data, which requires data analysis before application
- Experiments to obtain empirical data on Tank 1, and subsequent analysis. The proposed experiments have essentially been done before, so the procedures are straightforward
- Past experience with the side-coupled linac structure length problem, with which the present problem has many similarities.

I. OBJECTIVE

We want to determine tuning procedures for the drift tube linac variables: injection energy, Tank 1 head and slug tuner positions, and buncher and tank rf phases and amplitudes. These variables are required for minimizing

- Longitudinal oscillations in the drift tube linac
- Total longitudinal emittance, particularly at 100 MeV
- Sensitivity to tuning or other parameter variations.

II. STRATEGY

A. We propose to develop a realistic, consistent, longitudinal dynamics model of the drift tube linac, including the

- Longitudinal coordinate position of all components
- Actual drift tube lengths and gap lengths
- Actual field distributions (bead-pull data)
- Space-charge considerations.

B. We will check the model validity by

- Using it to design machine experiments
- Performing these and other experiments to obtain empirical data
- Achieving consistency between model and experimental results. (This may involve modifications to the model or machine.)

C. The model will be used to determine the optimum tuning procedure across the entire drift tube linac as necessary. Step C is the crux of this strategy. Even without the optimization step, the tuneup parameters (phase scans) are determined using a PARMILA model. The optimization step, similar to the length problem solution, permits the desired minimization.

III. GOALS FOR TANK 1 MODEL

A. Analyze bead-pull data on

- Field tilt as a function of head position
- Effect of slug tuners
- Actual field distribution (end-cell effect, tilt, microstructure).

B. Verify PARMILA model tilt predictions under actual operating conditions

IV. EXPERIMENTS

The results are used

- To map actual longitudinal emittance or acceptance contours
- To find changes in acceptance or emittance characteristics
- For comparison with PARMILA model predictions.

A. Emittance Measurements

At different (≥ 5) Tank 1 tilts, we measured Tank 1 cutoff characteristics at four different Tank 2 amplitudes. The approach, suggested by the

PARMILA model, involves attempting to measure the size of the energy oscillation in Tank 2. When Tank 1 is near cutoff, a small bunch is delivered to Tank 2. As Tank 1 is brought to cutoff, the Tank 2 phase is searched to prevent uncertainty in the phase dimension.

We also measured the Tank 1 emittance phase width.

The 100-MeV emittance was not measured. It would have involved setting up Tanks 1-4, according to a prescription that pins the Tank 1 amplitude at the control probe, and treats Tanks 2-4 as a unit. At each tilt, and 750-keV injection energy, Δt at Module 5 would have been measured to get beam centroid data versus tilt. The 100-MeV emittance would have been measured using the bucket rotator to get emittance area data versus tilt.

The last two emittance experiments have only marginal utility. There are few characteristic features and several extra variables. The second experiment would be more useful than the last.

B. Acceptance Measurements

At different (≥ 5) Tank 1 tilts and nine different injection energies, we measured Tank 1 amplitude with T2 OFF and T2 ON (100%).

We then measured Tank 1 Phase at seven different Tank 1 amplitudes, using a minimum phase-width bunch.

C. Other Measurements were the

- Tank 1 rf probes
- Total rf power delivered to Tank 1
- Beam current transformers
- Transverse data: harp profiles; EM3, 7, and 11; and 805 wire scanner profiles.

The variation in energy gain measured at the Δt loops after Tank 2 and Tank 3 was also studied; but no resolvable relationships were found.

V. Procedure

A. Preliminary Steps

1. Set bias phase scan absorber at +50 V, collector at -50 V.

2. Calibrate Tank 1 amplitude set point vs delivered power, and phase shifters.

3. At 750-keV injection energy, bunchers off, Tank 2 off, and 2 mA, 100- μ s beam, set Tank 1 amplitude to yield ratio capture 28%. (02CM/TDCM03).

This assumes that no beam is lost on the aperture at the EM-3 collector. The amplitude thus found will be the nominal 100% ASP for all subsequent

runs. The amplitude controller keeps the field constant at its probe. Therefore changes in tilt will rotate the field about this point at a given amplitude set point.

$$\text{"100%" ASP} = \underline{1672}.$$

4. Find settings for the amplitudes of bunchers B1 and B2 so that the left edge of the Tank 1 phase scan is the steepest. This defines a "minimum phase width" bunch

$$\text{B1 ASP} = \underline{0}, \text{B2 ASP} = \underline{600}.$$

5. Find transport setup conditions for each energy (720, 730, 740, 745, 750, 755, 760, 770, and 780 keV). Record parameters and dump emittance data to tape.

6. Standard current conditions:

18 mA H^+ out of column

1.5 mA accepted in linac with main buncher B2 on; reduction accomplished with EM-2 jaws.

B. Procedures At Each Tilt

1. Measure all five Tank 1 probe outputs using oscilloscope with slideback plug-in.

2. Record forward power 01JV1D1, reflected power 01JV1D2, and cavity fields 01JV1D5 and 01ML1E1.

3. Scan Tank 1 amplitude with T2 delayed and in time.

a. Delay both bunchers and Tanks 2-4 and insert 40-MeV absorber.

b. Scan Tank 1 amplitude (absorber current vs T1 ASP) to >100% amplitude and photograph the plot, with all parameters standard and 750-kV C-W voltage.

c. Change X and Y axes on the 3320 CCI lines to 50 counts full-scale and repeat step b.

d. Put Tank 2 in time with T2 ASP at 100% and repeat steps b and c for collector current vs T1 ASP. In step c, move the module 2 phase shifter ± 200 counts near the Tank 1 cutoff point to make sure all protons are seen.

4. Tank 1 amplitude scans

a. Scan Tank 1 amplitude vs 40-MeV collector current with Tank 2 in time, $\phi = 398$, and at T2 ASP $\approx 100\% = 1061$. Use this plot to determine Tank 1 cutoff for use in the next step.

b. With Tank 1 slightly above cutoff and Tank 2 at ASP = 100% = 1061, scan the Tank 2 phase using 3320. Y = collector current, X = Tank 2 phase (2D4). Set Tank 2 phase for maximum current on the collector.

c. Lower Tank 1 ASP until collector current just equals zero. This ASP is the absolute cutoff. Repeat scan of Tank 2 phase.

d. Repeat steps a-c for Tank 2 ASP at 95% (see Table II), 92%, and slightly above cutoff. Find cutoff by Tank 2 amplitude scan with Tank 1 ASP at 100%, and set Tank 2 ASP seven counts higher. Label appropriately.

5. Tank 1 phase scans

a. Put buncher 2 in time, set to 600 counts (step 1.d), and delay Tank 2.

b. At each injection energy, phase scan Tank 1 at amplitudes of 100, 95, 92, and 90% and just above cutoff.

6. Make Tank 2 phase scans at 740, 745, 750 and 755 keV.

a. With bunchers delayed, T1 and T2 set to 100% values listed in Table II, and C-W at 750 kV, phase scan Tank 2.

b. Repeat to show left edge on expanded scale in phase plane. Set design phase where left edge is at half-maximum and scan 60° in 30 steps. Call "Phase Spread" button to analyze.

c. Repeat steps a and b for C-W at 740, 745, and 755 kV.

C. Changing Tilt

While running at high power, observe the reflected power signal. In small steps, move the

downstream head toward the desired setting and return the reflected power to the minimum by moving the upstream head. Do not overshoot. Move the downstream head in the OUT direction only and the upstream head in the IN direction only.

APPENDIX B

QUADRUPOLE AND DRIFT TUBE MEASUREMENTS

by E. D. Bush, Jr.

I. TANK 3 AND 4 DRIFT TUBE QUADRUPOLE MAGNET DATA COLLECTED IN SEPTEMBER 1974

This exercise was to determine whether there were any faulty drift tube quadrupole magnets, verify the magnet polarity, check the bore tube location with respect to the magnetic centerline, and check the location of the half-drift tube bore tubes relative to the reference diameter on the Tank 3 downstream and Tank 4 upstream heads.

We made a special fixture that held a Hall chip at a fixed radius from the bore tube center and a fixed distance from the upstream end of each drift tube. The fixture was machined to have a slip fit in the bore tubes with a diametral clearance ranging from zero to approximately 0.004 in. in the drift tubes and about 0.008 in. in the half-drift tubes. The probe was positioned on each pole axis by using an external bubble level on the corresponding horizontal reference surface, and the diametral clearance was taken out by drifting the fixture in the direction of the pole being measured. This method proved satisfactory and was used for all measurements, although we had provided O-ring grooves as a back-up centering technique.

The Hall chip mounted in the fixture obviated use of conventional calibrating magnets. For reference, we compared a small permanent reference magnet against a standard calibrated Hall probe. This reference magnet was compared periodically during the measurements for a rough calibration. Accurate

calibration was not required as our prime objective was to compare the fields of opposite poles; however, the Hall probe data were normalized using the known operating current, verified using the digital-volt-meter (DVM) in the 201-MHz control area, and are plotted with the design gradients and present operating gradients in Table B-I.

Opposite poles in a quadrupole magnet have the same field polarity, and our purpose was to compare the fields of opposite poles. This is fortunate because Hall chips typically have a different calibration for each field polarity. The major errors in the system were $\sim 0.2\%/h$ drift and probe positioning. We used a DVM for readout, estimated the fourth digit, and read all four poles of each magnet, usually within less than a minute. We made at least two readings on each magnet, one set upon entering the tank and the other when leaving it. The readings were compared, and more measurements were taken on those magnets that didn't compare reasonably well with prior readings. The readings were averaged, and coordinates were rotated 45° and converted to X and Y displacements in inches. Table B-I shows the relative position of the bore tube centerline with respect to the magnetic centerline. The field readings were taken at one axial station within the magnet, not necessarily on the drift tube axial (Z) centerline. The maximum fixture length was established by the minimum gap length in the upstream end of Tank 3. While the drift tube was being fabricated, rotating coils longer than the quadrupole length were used to

TABLE B-I

BORE TUBE AND LOCATION RELATIVE TO MAGNETIC CENTERLINE

(+ x bore tube centerline south of magnetic centerline
+ y bore tube centerline above magnetic centerline)

Tank 3			Tank 4		
Cell	X	Y	Cell	X	Y
99	-0.0010	-0.0022	INITIAL	+0.0006	+0.0014
101	+0.0001	-0.0026	137	+0.0001	+0.0024
103	-0.0006	-0.0018	139	-0.0004	-0.0024
105	-0.0012	-0.0021	141	-0.0004	+0.0000
107	-0.0008	-0.0018	143	+0.0003	-0.0009
109	-0.0007	-0.0004	145	+0.0011	-0.0029
111	+0.0006	-0.0017	147	+0.0003	-0.0017
113	+0.0007	+0.0011	149	-0.0009	-0.0009
115	+0.0004	-0.0001	151	-0.0004	-0.0002
117	-0.0038	+0.0001	153	+0.0000	-0.0018
119	-0.0018	+0.0006	155	+0.0002	+0.0014
121	-0.0011	-0.0011	157	-0.0019	+0.0005
123	+0.0002	-0.0011	159	+0.0005	-0.0013
125	+0.0001	-0.0021	161	-0.0005	-0.0041
127	-0.0001	-0.0008	163	+0.0026	-0.0018
129	+0.0002	-0.0030			
131	+0.0002	-0.0013			
133	-0.0012	+0.0012			
135	-0.0001	-0.0006			

determine the magnet harmonic content. The sub-harmonic indicated the bore tube centering error.

The data reveal another interesting thing that apparently occurred during fabrication. Of the 32 drift tube assemblies, 24 indicate that the bore tube centerlines are below the magnetic centerlines. This can be attributed to the fact that all of the final furnace brazing heats were made with the drift tubes vertical and supported at their bottoms. The Young's modulus of copper decreases considerably with increased temperature, thus shifting the lower two poles against the bottom of the bore tube. The horizontal position errors were divided equally between the north and south bore tube locations.

To measure the concentricity of the bore tubes of the half-drift tube relative to the reference diameter on the heads, we made a special tool consisting of a brass mandrel with a slip fit in the bore to support an arm that held a dial indicator. Four readings

were taken on each of eight equally spaced stations. The concentricity of the bore tube centerline also was compared with the reference diameter on the quadrupole housing. The data for the Tank 3 upstream and Tank 4 downstream heads are shown in Figs. B-1 and B-2.

While reducing the data, I noticed a slight error between the design quadrupole gradients (β') and the gradients at which the machine is now operated. This small error was introduced when the gradients were converted to magnet current. The β' versus I for Tank 1 Initial and Model I are not linear at the higher current levels as the iron approaches saturation. Models II-V are linear enough so that a constant can be applied to determine the required current. Table B-II shows the design gradient and the present operating gradient. These errors are small and probably of the same order as the accuracy of the instrumentation we used to measure

Fig. B-1.

Reference diameter and half-drift-tube quadrupole bore tube concentricity measurements for Tank 3 downstream head, looking upstream. Dimensions in inches.

Fig. B-2.

Reference diameter and half-drift-tube quadrupole bore tube concentricity measurements for Tank 4 upstream head, looking downstream. Dimensions in inches.

gradients; however, they may be worth considering in beam analysis studies. (Ed. Note—They were.)

II. TANKS 1 AND 2 DRIFT QUADRUPOLE MAGNET MEASUREMENTS OF JULY 1975

These measurements (Tables B-III and B-IV) were a continuation of the Tank 3 and 4 measure-

ments made in September 1974 to locate possibly faulty magnets and determine the position of the drift tube bore with respect to the magnetic centerline.

Similar measurements, instrumentation, and techniques were used in Tanks 1 and 2, but they were modified from prior measurements because of the space limitations imposed by the short gaps and small bores. A Hall probe fixture similar to that

TABLE B-II
QUADRUPOLE CURRENTS AND GRADIENTS

<u>Tank</u>	<u>Model</u>	<u>Cell</u>	<u>Current (A)</u>	<u>Design β'(G/cm)</u>	<u>Operating β'(G/cm)</u>
1	initial	initial	382	4500	4520
1	I	1	686	7664	7700
1	I	2	668	7534	7570
1	I	3	651	7412	7450
1	I	4	636	7298	7320
1	I	5	613	7128	7150
1	I	6	622	7193	7220
1	II	7-14	430-398	Operating β' ~ 0.2% lower than design β' .	
1	III	15-30	316-251	Operating β' ~ 1.6% lower than design β' .	
2	IV	31-59	459-346	Operating β' ~ 2.2% higher than design β' .	
2,3,4	V	60-163	426-107	Operating β' ~ 2.5% higher than design β' .	

These values were found using different interpolations in the BI curves from the ones we finally used.

used in Tanks 3 and 4 was used in the downstream end of Tank 2 where the gaps were relatively large and the bores were 30 mm in diameter. In Tank 1 and the upstream end of Tank 2, the short gaps and small bores (Tank 1, 15 mm; Tank 2, 20 mm) obviated use of the bubble level for probe orientation. The probes were mounted on extension rods that prevented drifting the probe radially in the direction of the pole being measured to eliminate the probe-to-bore clearance error. The larger errors in Tanks 1 and 2 reflect the positioning and clearance errors.

Drift tube fabrication techniques were identical for Tanks 2, 3, and 4, and the tubes were fabricated essentially at the same time, with the same staff and facilities. The Tank 1 drift tubes differ in that the bores were machined after furnace brazing and, therefore, are at least as accurate as the bore tubes ground before brazing (Tanks 2, 3 and 4).

We were asked to measure the Tank 1 drift tube lengths. Measurements were taken on the left and right sides of each drift tube, and the average length was compared with the theoretical dimension. Table B-V shows the drift tube length error.

III. 201-MHz DRIFT TUBE LINAC QUADRUPOLE MAGNET CHARACTERISTICS AND POWER SUPPLY CALIBRATIONS

A. Model INITIAL Iron Length = 1.722 cm
Eff. Length = 2.621 cm

Tank 1, Power Supply 1-0, Cell INITIAL

<u>Current(A)</u>	<u>Gradient(G/cm)</u>
300	3517
400	4716
460	5373
500	5643
600	6244
700	6680
800	7008

Shunt: 100 mV = 1000 A.

B. Model I

Iron Length = 2.616 cm
Eff. Length = 3.379 cm

Tank 1, Power Supply 1-1, Cell 1-6

<u>Current(A)</u>	<u>Gradient(G/cm)</u>
300	3596
400	4881
500	6037
600	7034
700	7769
800	8294
900	8635
1000	8924
1100	9134

<u>Current(A)</u>	<u>Gradient(G/cm)</u>
250	3071
310	3858
350	4331
450	5512
550	6745
650	7953
750	8766

Shunt: 100 mV = 800 A.

E. Model IV

Iron Length = 7.876 cm
Eff. Length = 9.086 cm

Tanks 1 and 2, Power Supply 2-1,2-2, Cell 31-59

<u>Current(A)</u>	<u>Gradient(G/cm)</u>
250	1312
350	1916
450	2467
550	3045
650	3622
750	4173

Shunt: 100mV = 800 A.

C. Model II

Iron Length = 3.777 cm
Eff. Length = 4.624 cm

Tank 1, Power Supply 1-2, Cell 7-14

<u>Current(A)</u>	<u>Gradient(G/cm)</u>
250	3097
350	4436
450	5748
475	5984
550	6982
650	8005
750	8661

F. Model V

Iron Length = 16.286 cm
Eff. Length = 17.52 cm

Tanks 2-4 Power Supply 2-3, 2-4, 2-5, 2-6, 3-1, 4-1,
Cell 60-163

<u>Current(A)</u>	<u>Gradient(G/cm)</u>
250	630.
350	892.
408	1024.
450	1155.
550	1417.
650	1680.

Shunt: 100 mV = 800 A.

D. Model III

Iron Length = 5.482 cm
Eff. Length = 6.223 cm

Tank 1, Power Supply 1-3, Cell 15-30

Shunt: Power Supply 3-1: 100 mV = 400 A. All
others: 100 mV = 800 A.

TABLE B-III

**BORE TUBE CENTERLINE LOCATION RELATIVE
TO MAGNETIC CENTERLINE**

(+ X bore tube centerline south of magnetic centerline
+ Y bore tube centerline above magnetic centerline)

Tank 1			Tank 2					
Cell	X(in.)	Y(in.)	Cell	X(in.)	Y(in.)	Cell	X(in.)	Y(in.)
INIT	+0.0001	-0.0001	INIT	+0.0002	+0.0041			
1	+0.0012	-0.0006	32	-0.0008	+0.0009	64	+0.0006	-0.0011
2	-0.0015	-0.0006	33	-0.0012	-0.0002	65	-0.0008	-0.0020
3	-0.0005	-0.0016	34	+0.0001	-0.0006	66	-0.0005	+0.0001
4	-0.0002	-0.0037	35	-0.0008	-0.0002	67	+0.0004	-0.0010
5	-0.0005	-0.0018	36	-0.0009	-0.0003	68	-0.0002	-0.0008
6	-0.0018	-0.0009	37	-0.0014	-0.0011	69	+0.0012	+0.0003
7	+0.0021	+0.0009	38	-0.0001	-0.0018	70	+0.0002	+0.0006
8	+0.0006	-0.0043	39	-0.0005	.0000	71	-0.0001	+0.0004
9	+0.0010	-0.0029	40	-0.0008	-0.0008	72	+0.0003	+0.0003
10	-0.0003	-0.0020	41	-0.0010	+0.0005	73	-0.0003	+0.0001
11	-0.0006	+0.0006	42	-0.0009	-0.0014	74	-0.0003	-0.0001
12	~0	-0.0025	43	-0.0004	-0.0007	75	-0.0002	-0.0002
13	-0.0035	+0.0017	44	-0.0001	+0.0001	76	+0.0006	-0.0002
14	+0.0031	-0.0023	45	-0.0005	+0.0004	77	+0.0008	+0.0004
15	-0.0020	-0.0010	46	-0.0009	-0.0011	78	-0.0002	-0.0004
16	-0.0034	-0.0046	47	-0.0011	-0.0018	79	-0.0016	-0.0015
17	+0.0035	-0.0045	48	-0.0003	-0.0001	80	-0.0008	-0.0011
18	-0.0028	-0.0026	49	-0.0005	-0.0009	81	-0.0004	-0.0008
19	-0.0044	+0.0018	50	+0.0009	-0.0020	82	-0.0006	-0.0003
20	+0.0001	-0.0016	51	-0.0008	-0.0012	83	-0.0001	-0.0016
21	+0.0007	-0.0024	52	-0.0016	-0.0025	84	-0.0004	-0.0040
22	-0.0027	-0.0081	53	+0.0004	-0.0032	85	+0.0013	-0.0004
23	+0.0018	-0.0045	54	+0.0008	+0.0008	86	+0.0003	-0.0033
24	+0.0008	-0.0005	55	-0.0023	-0.0023	87	-0.0011	-0.0018
25	-0.0003	-0.0012	56	-0.0001	+0.0007	88	+0.0001	-0.0010
26	+0.0013	-0.0031	57	+0.0006	+0.0006	89	-0.0020	-0.0001
27	+0.0025	-0.0039	58	-0.0014	-0.0010	90	+0.0020	+0.0022
28	-0.0019	+0.0040	59	-0.0016	-0.0012	91	+0.0044	-0.0012
29	+0.0018	-0.0037	60	+0.0006	-0.0016	92	-0.0012	+0.0018
30	-0.0005	-0.0029	61	+0.0002	-0.0015	93	-0.0012	-0.0016
31	+0.0020	+0.0016	62	-0.0008	-0.0008	94	-0.0022	-0.0012
			63	-0.0004	-0.0008	95	-0.0005	+0.0028
						96	-0.0001	-0.0001
						97	0.0000	+0.0008

TABLE B-IV**DRIFT TUBE BORE TO MAGNET CENTER ERROR**

<u>Error (in.)</u>	<u>T1</u>	<u>T2</u>	<u>T3</u>	<u>T4</u>
Average Horiz. X	0.0015	0.0010	0.0008	0.0007
Average Vert. Y	0.0025	0.0015	0.0014	0.0016
Max. Horiz. X	0.0044	0.0044	0.0038	0.0026
Max. Vert. Y	0.0081	0.0041	0.0030	0.0041

TABLE B-V**TANK 1 DRIFT TUBE LENGTH
MEASUREMENTS**

(Minus sign indicates length less than
theoretical dimension.)

<u>Cell</u>	<u>DT Length Error (in.)</u>	<u>Cell</u>	<u>DT Length Error (in.)</u>
INIT	-	16	-0.002
1	+0.001	17	-0.002
2	-0.005	18	-0.002
3	+0.005	19	-0.002
4	+0.001	20	-0.002
5	+0.001	21	-0.001
6	-0.001	22	.000
7	-0.004	23	+0.001
8	-0.003	24	+0.001
9	-0.002	25	-0.001
10	-0.001	26	-0.001
11	.000	27	.000
12	-0.002	28	-0.001
13	.000	29	-0.003
14	-0.001	30	-0.001
15	-0.001	31	+0.008

APPENDIX C

TANK 1 HEAD CALIBRATION

I. CALIBRATION DATA

A. Downstream Head - (Intertank Spacer)

1. With the original return springs:

Cell 31 Gap	Relative Position Read with Dial Indicator	Position Potentiometer Panel Meter Reading
1.591	0 (In limit)	0.87
1.602	0.004 in.	0.80
1.615	0.014	0.73
1.623	0.020	0.69
1.638	0.030	0.63
1.648	0.035	0.60
1.661	0.042 (End of linearity)	0.55
1.661	0.042 (Out limit)	0.46

2. With stiffer return springs:

0(In limit)	0.86
0.005 in.	0.80
0.019	0.70
0.034	0.60
0.043	0.54
0.047(End of linearity)	0.50
(Out limit)	0.43

Adding heavier springs would not change the in-limit gap, but it would give more travel at the out end. The curves should be basically the same except near the out end.

3. Position potentiometer readings (using DVM) versus frequency shift show a hysteresis effect, Fig. C-1. Assuming that the frequency shift is the same when the gap is the same, these data show the hysteresis in a gap vs position potentiometer graph as well.

4. The downstream head calibration is shown in Fig. C-2.

B. Upstream Head

1 Measurements of the first gap show the following.

Cell 1	Limit
0.667 in. (Micrometer)	OUT
0.675 in. (Tool)	
0.500 in. (Micrometer)	IN
0.504 in. (Tool)	

2. Other data show frequency shift versus upstream head position potentiometer reading, including hysteresis effect, Fig. C-1.

II. BEAD-PULL FIELD TILT RUNS

The procedure was to move alternate heads, one at a time, first introducing a known frequency shift with one head, then removing it with the other. The downstream head was moved from its IN limit toward the OUT limit, and its position was read using a dial indicator attached to the spider. The upstream head was moved from its OUT limit toward the IN limit, and the actual gap was measured using a special tool. These data are listed in Table C-I and plotted in Fig. C-3.

III. TANK 1 TILT INVESTIGATION, Exp. No. 14, 11-75.

A. Again the heads were moved to give equal frequency increments. This time, both heads were moved at each step to keep the resonant frequency constant. Movements were made while rf power was on. Settings for the downstream head were made using Fig. C-3 data. The upstream settings were as needed to restore the frequency. The settings are listed in Table C-II.

A comparison of the frequency shifts between experimental points as plotted on Figs. C-1 and C-3 is listed in Table C-III, and indicates good agreement among the methods used to derive the calibration curves.

Fig. C-1.
Tank 1 frequency shift vs head position calibration.

Fig. C-2.
Cell 31 gap calibration.

Fig. C-3.
Gap position vs resonant frequency shift.

TABLE C-I

GAP POSITION VS RESONANT FREQUENCY SHIFT

Bead Pull Tilt Run No.	Cell 1 GAP (in.)	Downstream Head Relative Position (in.)	Freq. Shift (kHz)	Cell 31 GAP (in.)
1	0.667	0	0	1.591
2	0.667	8	27.59	1.604
3	0.638	8	27.45	1.604
4	0.645	15	27.28	1.615
5	0.612	19	27.42	1.622
6	0.614	32	27.34	1.643
7	0.589	32	27.36	1.643
8	0.590	42	19.87	1.660
9	0.571	42	19.86	1.660

TABLE C-II

HEAD SETTINGS AND GAPS FOR TANK 1 TILT INVESTIGATION

<u>Power Tilt Run No.</u>	<u>Upstream Head Pos.Pot Reading</u>	<u>Downstream Head Pos.Pot Reading</u>	<u>Cell 1 Gap (in.)</u>	<u>Cell 31 Gap (in.)</u>
A	0.113	8.50	0.664	1.593
(B)	(1.236)	(7.93)	(0.645)	(1.602)
C	2.12	7.50	0.629	1.610
D	3.26	6.95	0.611	1.622
E	4.03	6.42	0.597	1.636
F	4.87	5.86	0.580	1.652
E'	4.01	6.39	0.592	1.640
D'	3.18	6.92	0.605	1.628
C'	2.20	7.46	0.621	1.615
B'	1.33	7.92	0.639	1.605
A'	0.108	8.47	0.659	1.594
B	1.236	7.93	0.645	1.602

TABLE C-III

**COMPARISON OF FREQUENCY SHIFTS BETWEEN
EXPERIMENTAL POINTS ON FIGS. C-1 AND C-3**

<u>Between</u>	<u>Δf, Fig. C-3</u>	<u>Δf, Fig. C-1</u>
A-B	19.5	17.
B-C	17.	15.
C-D	19.	18.
D-E	15.	17.
E-F	18.	17.5
F-E'	13.	13.
E'-D'	13.5	14.5
D'-C'	16.5	17.5
C'-B'	19.	16.
B'-A'	22.	23.5

APPENDIX D

DATA INTERPOLATION: CUBIC SPLINE WITH SPECIAL END POINT CONDITIONS

A cubic spline is a function for fitting data which can be formulated so that it interpolates the data; i.e.,

$$S(X_i) = y_i; \quad i = 1, 2, \dots, n$$

(cf. least squares cubic splines). The construction of a cubic spline is straightforward. On the interval (X_i, X_{i+1}) , let

$$\begin{aligned} h_i &= X_{i+1} - X_i \\ W &= (X - X_i)/h_i \\ \bar{W} &= 1 - W. \end{aligned}$$

Now write

$$S(X) = Wy_{i+1} + \bar{W}y_i + h_i^2 \left[(W^3 - W)\sigma_{i+1} + (\bar{W}^3 - \bar{W})\sigma_i \right], \quad (1)$$

where σ_i and σ_{i+1} are constants to be determined. Note that because $W(X_i) = 0$ and $W(X_{i+1}) = 1$, $S(X_i) = y_i$.

Now by differentiating $S(X)$ three times, we get

$$S'(X) = (y_{i+1} - y_i)/h_i + h_i \left[(3W^2 - 1)\sigma_{i+1} - (3\bar{W}^2 - 1)\sigma_i \right]$$

and

$$S''(X) = 6W\sigma_{i+1} + 6\bar{W}\sigma_i,$$

and

$$S'''(X) = 6(\sigma_{i+1} - \sigma_i)/h_i = \text{constant}.$$

Note that $S''(X)$ is a linear function that interpolates the values $6\sigma_i$ and $6\sigma_{i+1}$. Hence,

$$\sigma_i = S''(X_i)/6. \quad (2)$$

Evaluating $S'(X)$ at the end points of the subinterval gives

$$S'_+(X_i) = \Delta_i - h_i(\sigma_{i+1} + 2\sigma_i)$$

$$S'_-(X_{i+1}) = \Delta_i + h_i(2\sigma_{i+1} + \sigma_i),$$

since

$$W(X_i) = \bar{W}(X_{i+1}) = 0$$

and

$$W(X_{i+1}) = \bar{W}(X_i) = 1,$$

where

$$\Delta_i = (y_{i+1} - y_i)/h_i.$$

To obtain continuity in $S'(X)$, impose the conditions

$$S'_-(X_i) = S'_+(X_i), \quad i = 2, \dots, n-1$$

at the interior knots. This gives

$$\Delta_{i-1} + h_{i-1}(2\sigma_i + \sigma_{i-1}) = \Delta_i - h_i(\sigma_{i+1} + 2\sigma_i),$$

and, hence,

$$h_{i-1}\sigma_{i-1} + 2(h_{i-1} + h_i)\sigma_i + h_i\sigma_{i+1} = \Delta_i - \Delta_{i-1}$$

for

$$i = 2, \dots, n-1.$$

This procedure gives $n-2$ equations for n unknowns, so two more equations are necessary. If one chooses these to be $\sigma_1 = 0$ and $\sigma_n = 0$, the result is the natural cubic spline.¹ My choice is to estimate the second derivatives at the end points by using a four-point Lagrangian interpolation. The form of $y(X)$ is given by

$$y(x) = \sum_{i=0}^n l_i(x) y_i,$$

where $l_i(x)$

$$= \frac{(x-x_0)(x-x_1)\cdots(x-x_{i-1})(x-x_{i+1})\cdots(x-x_n)}{(x_1-x_0)(x_1-x_1)\cdots(x_1-x_{i-1})(x_1-x_{i+1})\cdots(x_1-x_n)}.$$

These $l_i(x)$ are such that

$$l_i(x_j) = 0 \quad j = 1, 2, \dots, i-1, i+1, \dots, n$$

and

$$l_i(x_i) = 1,$$

so that

$$y(x_i) = y_i$$

and, hence, this is an interpolating polynomial.

From this function, we get for the second derivative

$$y''(x_1) = 2 \left[\frac{x_1-x_2+x_1-x_3}{(x_1-x_2)(x_1-x_3)(x_4-x_1)} y_4 + \frac{x_1-x_2+x_1-x_4}{(x_3-x_1)(x_3-x_2)(x_3-x_4)} y_3 + \frac{x_1-x_3+x_1-x_4}{(x_2-x_1)(x_2-x_3)(x_2-x_4)} y_2 + \frac{x_1-x_2+x_1-x_3+x_1-x_4}{(x_1-x_2)(x_1-x_3)(x_1-x_4)} y_1 \right]$$

and, *mutatis mutandis*, $y''(x_n)$. Hence, from Eq. (2), we get

$$\sigma_1 = y''(x_1)/6$$

and

$$\sigma_n = y''(x_n)/6.$$

Now this system of equations has the tridiagonal form

$$\begin{pmatrix} 1 & 0 & 0 \\ h_1 & 2(h_1+h_2) & h_2 \\ & h_2 & 2(h_2+h_3) & h_3 \\ & - & - & - \\ & - & - & - \\ & - & - & - \\ & & h_{n-2} & 2(h_{n-2}+h_{n-1}) & h_{n-1} \\ & & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \vdots \\ \sigma_{n-1} \\ \sigma_n \end{pmatrix} = \begin{pmatrix} \sigma_1 \\ \Delta_2 - \Delta_1 \\ \Delta_3 - \Delta_2 \\ \vdots \\ \Delta_{n-1} - \Delta_{n-2} \\ \sigma_n \end{pmatrix}$$

Applying Gaussian elimination reduces this to the upper triangular form

$$\begin{pmatrix} \alpha_1 & 0 & & & & \\ & \alpha_2 & h_2 & & & \\ & & \alpha_3 & h_3 & & \\ & & & \ddots & & \\ & & & & \ddots & \\ & & & & & \alpha_{n-1} & h_{n-1} \\ & & & & & & \alpha_n \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \vdots \\ \sigma_{n-1} \\ \sigma_n \end{pmatrix} = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \vdots \\ \beta_{n-1} \\ \beta_n \end{pmatrix}$$

where

$$\alpha_1 = \alpha_n = 1, \alpha_2 = 2(h_1 + h_2)$$

and

$$\alpha_i = 2(h_{i-1} + h_i) - \frac{h_{i-1}^2}{\alpha_{i-1}};$$

$$i = 3, 4, \dots, n-1.$$

The inhomogeneous terms are given by

$$\beta_1 = \sigma_1, \beta_n = \sigma_n$$

and

$$\beta_i = (\Delta_i - \Delta_{i-1}) - \frac{h_{i-1}\beta_{i-1}}{\alpha_{i-1}}.$$

Finally, the elements of the unknown vector σ are found by back-substitution to be

$$\sigma_i = \frac{\beta_i - h_i \sigma_{i+1}}{\alpha_i}; i = n-1, n-2, \dots, 2.$$

Now one can either store the σ_i and use Eq. (1) for arbitrary values of x or write the equation in the form

$$s(x) = y_1 + b_1(x-x_1) + c_1(x-x_1)^2 + d_1(x-x_1)^3.$$

Because

$$s'(x_1) = b_1,$$

we have

$$b_1 = (y_{i+1} - y_i)/h_i - h_i(\sigma_{i+1} + \sigma_i).$$

Similarly

$$s''(x_1) = 2c_1,$$

so

$$c_1 = 3\sigma_i.$$

Finally

$$s'''(x_1) = 6d_1,$$

so

$$d_1 = (\sigma_{i+1} - \sigma_i)/h_i.$$

REFERENCE

1. G. E. Forsythe, M. A. Malcolm, and C. B. Moler, "Computer Methods for Mathematical Computations," Computer Science Department report, Stanford University (1972).

APPENDIX E

DEPENDENCE OF TANK GRADIENT ON INJECTION ENERGY AND TANK TILT

by R. L. Gluckstern

I. INTRODUCTION

The dependence of the tank gradient on the incoming beam energy and tank tilt provides a sensitive method for exploring the dynamic consequences of gap-to-gap field fluctuations in the first tank. This appendix shows a crude derivation of the relationship among the parameters, and serves as a means of understanding the relevant mechanisms.

In general, we will assume that particles which traverse the entire first tank are captured in the longitudinal bucket. This is not completely true, as the criterion used to signify traversal is the *transverse* confinement. Nevertheless it is a reasonable first approximation.

In all measurements and computations to date, the tank field is tilted so that the lowest gradients are at injection. For this reason, the injection parameters are likely to govern capture. It appears that there are two more or less independent phenomena that govern.

II. CALCULATION OF MODEL

A. Tank Gradient Above the Threshold Gradient

1. In this region, there will be a phase stable region at injection. The lowest energy particles that can be captured are those at the bottom of the acceptance. We can show readily from the (approximate) energy invariant,

$$\frac{\beta^3}{2} \left(\frac{d\phi}{dz} \right)^2 + \frac{2\pi e E T}{M c^2 \lambda} \left(\frac{\phi \phi_s}{2} - \frac{\phi^2}{6} \right) = \text{const},$$

that

$$\begin{aligned} W_{\min} - W_s &\approx - \sqrt{\frac{2}{3\pi} M c^2 e E T \lambda \beta^3} |\phi_s|^{3/2} \\ &\approx - \sqrt{\frac{4}{3\pi} W_s \frac{\Delta W_s}{\Delta n}} |\phi_s|^{3/2}. \end{aligned}$$

Because $\cos \phi_s \approx 1 - \phi_s^2/2 = E_s/E$, with E being the gradient at the *injection* end of the tank, we can write near threshold

$$\phi_s \approx \sqrt{2(x-1)} \quad \text{where} \quad x = \frac{E}{E_c}.$$

to give

$$W_{\min} - W_s = \frac{2^{7/4}}{\sqrt{3\pi}} \sqrt{W_s \frac{\Delta W_s}{\Delta n}} (x-1)^{3/4}$$

or

$$x = 1 + \frac{(W_s - W_{\min})^{4/3}}{W_s^{2/3} \left(\frac{\Delta W_s}{\Delta n} \right)^{2/3}} \frac{(3\pi)^{2/3}}{2^{7/3}}.$$

For $W_s = 750$ keV, $W_{\min} = 720$ keV, $\Delta W_s/\Delta n = 63$ keV, one finds $x = 1.063$, which is reasonably close to the measured values (1.03-1.055).

2. Dependence on tilt. If the gradient increases along the tank, the phase stable region will grow and particles that at first seem longitudinally unstable will be captured. Thus the curve in Fig. E-1 will be shifted both to the left and downward because particles with lower energy can be captured, and capture can take place with lower initial gradient. The analytic treatment of these effects is more complicated, and not worth pursuing here.

B. Tank Gradient below the Threshold Gradient

If there is a positive tilt, it is even possible to capture particles without an initial phase stable region. The injection energy at which this capture takes place can be estimated crudely by assuming that particles travel at the crest ($\phi=0$) until the bucket is established, at which time they will be captured if they have the correct synchronous energy

Fig. E-1.

Tank gradient cutoff behavior above the threshold gradient.

corresponding to that longitudinal position. This energy can be estimated to be

$$W_{min} - W_s = \frac{\Delta W_s / \Delta n}{2q} (1 - x)^2 ,$$

where q is the fractional increase in field level in the first cell. The result is shown in Fig. E-2.

The experimental data shown in Fig. E-3 and Fig. 12 in the body of the report seem to be a composite of the data in Figs. E-1 and E-2. There may even be some evidence of a kink at $W_s = 750$ keV.

C. Acceptance as a Function of Tank 1 Amplitude

Figure E-4 shows how the Tank 1 acceptance shrinks as a function of rf amplitude. Note that it does not close at the synchronous phase and energy. Rather, the closure point slides up and to the right.

Fig. E-2.

Cutoff behavior for tank gradient below the threshold gradient.

Also, the rf amplitude at which closure occurs is lower than one would get from

$$dW/dz = E_0 L T \cos \phi_s = \text{constant} ,$$

which is just a manifestation of the previous statement.

III. CONCLUSION

It is important to normalize the gradients to the injection end of the tank in comparing the result for different tilts.

The general features of the dependence of x on W_{min} are reproduced by the model. We have not included careful calculations of the effect of increasing bucket size. Moreover, in the actual tank, the field levels in the first few cells fluctuate significantly, so one might expect some departure from the numerical calculations.

Fig. E-3.

Experimental and theoretical amplitude scan cutoffs as functions of injection energy for the entire range of field distributions. The top curve was expected to match exactly; the remaining experimental curves have the proper shape and fall at the expected intervals between the theoretical curves as interpolated from the tank head calibration.

Fig. E-4.
Acceptance of Tank 1 as a function of rf amplitude.

APPENDIX F

METHOD FOR SMOOTHING FIELD DISTRIBUTIONS

The first tank of the 201-MHz linac has a field distribution that varies linearly with axial position along the tank (a tilted field). This distribution is produced by moving the first and last drift tubes so as to increase the first gap and decrease the last gap while preserving frequency. The measured distribution is shown in Fig. F-1. From a beam dynamics

point of view, it is desirable to smooth this distribution. The goal of this work is to find a way to do this.

The approach is to produce the desired tilt by perturbing several cells at each end of the tank. This spreads the perturbation and thus smooths the wrinkles produced by the previous method. To study this method, we used a multicell cavity code that allows perturbations in the gap lengths or cell lengths. The method is to generate a perturbation matrix $\partial E/\partial g$ by changing each gap by a fixed percentage and determining the resultant change in all the gap fields. One then has the system of equations

$$\frac{\partial E}{\partial g} \Delta g = \Delta E$$

Then, for a given ΔE , one writes

$$\Delta g = \left(\frac{\partial E}{\partial g} \right)^{-1} \Delta E$$

which then gives the gap perturbations necessary to produce a given field distribution.

Fig. F-1.
Measured and design field distributions in Tank 1.

Fig. F-2.

Cell geometry for perturbation study.

This method is good for a tank with a small number of cells, but it is impractical for a large number of cells. Hence, we do calculations for an eight-cell case in this manner and try to arrive at an algorithm that can be extended to the many-cell case (N greater than 8).

It is also impractical to vary drift tube lengths as well as gap lengths, as this requires rebuilding drift tubes. Hence, a better solution is to generate our perturbation matrix by changing the gaps only while keeping the drift tube lengths constant. The geometry we perturb is shown in Fig. F-2. The flat-field geometry is given in Table F-I, and the initial field distribution is shown in Fig. F-3. This distribution is very close to flat. Table F-II shows the geometry given a perturbation in the first and last cells, and Fig. F-4 shows the resulting, nonlinear field distribution. Table F-III gives the geometry, and Fig. F-5 shows the field distribution that results from the perturbation matrix method.

The perturbation matrix was calculated using 10% gap perturbations. The resulting Δg does not preserve frequency. To preserve frequency, each gap perturbation is changed according to

$$(\Delta g)_n = (\Delta g)_0 - \Delta L/N,$$

where N is the number of cells and ΔL is the overall length change. The goal was to go from the flat field distribution to one with a $\pm 5\%$ end-to-end linear tilt. Note that the resulting field distribution is linear but it has only a $\pm 4\%$ tilt.

The data from this case show that

$$\frac{\Delta g}{g} L = (.435 \ .214 \ .107 \ .023 \ -.051 \ -.125 \ -.212 \ -.403)$$

This is very close to

$$\frac{\Delta g}{g} L = (1 \ \frac{1}{2} \ \frac{1}{4} \ \frac{1}{8} \ -\frac{1}{8} \ -\frac{1}{4} \ -\frac{1}{2} \ -1); \Delta = 0.435.$$

TABLE F-I
FLAT FIELD GEOMETRY

Cell No.	Total Length (cm)	Gap Length (cm)
1	3.00477	1.34075
2	9.23380	1.38591
3	15.69689	1.43806
4	22.40242	1.49321
5	29.35611	1.55017
6	36.56226	1.60791
7	44.02400	1.66499
8	51.74096	1.71593

Fig. F-3.

Initial field distribution in unperturbed tank.

TABLE F-II
FIRST AND LAST GAPS PERTURBED

Cell No.	Total Length(cm)	Gap Length(cm)
1	3.42515	2.1815
2	10.05735	1.3515
3	16.49270	1.4170
4	23.18350	1.4848
5	30.13530	1.5548
6	37.35335	1.6271
7	44.84300	1.7016
8	52.24995	1.0583

Fig. F-4.
Perturbed field distribution, given perturbations in the first and last gaps.

Fig. F-5.
Perturbed field distribution resulting from the perturbation matrix method.

TABLE F-III

ALL GAPS PERTURBED:
MATRIX INVERSION METHOD

Cell No.	Total Length (cm)	Gap Length (cm)
1	3.07232	1.47584
2	9.40321	1.45454
3	15.91971	1.47627
4	22.65125	1.50701
5	29.60706	1.54061
6	36.79079	1.57264
7	44.20049	1.59617
8	51.81242	1.57468

TABLE F-IV

ALL GAPS PERTURBED: ALGORITHM

Cell No.	Total Length (cm)	Gap Length (cm)
1	3.15002	1.63124
2	9.59330	1.52392
3	16.16124	1.50977
4	22.91775	1.52344
5	29.87360	1.52426
6	37.03322	1.54078
7	44.19831	1.53520
8	51.72274	1.46067

If this algorithm works, it can be extended easily to many cells.

To test this prescription, we will try to change the field tilt from 4 to 10% and from 0 to 10%. The results are shown in tables F-IV and F-V and Fig. F-6. The resulting field distribution in both cases is linear, but it has only $\pm 8\%$ tilt in the former case (Fig. F-6, Curve B) and $\pm 7\%$ tilt in the latter (Fig.

F-6, Curve A). This is a measure of the linearity, and it indicates limits on the extrapolation. In particular, a 2% step will be handled very well whereas a 5% step will not be.

These results thus show that our algorithm is useful, although not exact, and that it can be used to predict how drift tubes should be moved to produce a smooth tilted field distribution.

TABLE F-V

ALL GAPS PERTURBED: ALGORITHM

Cell No.	Total Length (cm)	Gap Length (cm)
1	3.13212	1.59544
2	9.54564	1.50021
3	16.09362	1.49354
4	22.84058	1.52057
5	29.79463	1.52534
6	36.96110	1.55520
7	44.34502	1.56203
8	51.91241	1.51977

Fig. F-6.

Test cases for the perturbation matrix method of testing linearity and limits on the extrapolation.

APPENDIX G

PHASE SCAN NOTES AND PROCEDURES

I. INTRODUCTION

The phase scan procedure is used to set the rf phases and amplitudes of the two buncher cavities and four Alvarez cavities that make up the 100-MeV linac. Using the mathematical model of the linac, the PARMILA code generates plots of beam transmission versus rf phase of the element being set as a function of the amplitude (power) of that element. On the actual linac, the amplitude of an element is varied until a phase scan is produced which agrees with that generated by PARMILA. To minimize subjectivity, the full-width-at-half-maximum (FWHM) and for some cases a peak-to-valley-ratio (PVR) are calculated from the scan for comparison with target values from PARMILA. The rf phase of the element is then varied to give a distance to center from the left edge (DCLE) of the actual scan which agrees with the computer-generated one. The following sections detail the procedure for generating phase scans by use of PARMILA and of the machine.

II. COMPUTER-GENERATED PHASE SCANS

A. The Procedures

1. **General.** The PARMILA code is used to generate theoretical phase scans. The code is written to transform a multiparticle beam through a linac and an initial transport system.

A typical data file used for a phase scan computation is shown in Appendix H. That file shows the prebuncher (B1) as the initial transport element. For the scans that require B1 to be turned off, the data cards for the transport region are changed so that the main buncher (B2) is the first element.

Buncher design amplitudes of 4 kV for B1 and 10 kV for B2 put a large fraction of the beam* within $\pm 25^\circ$ of ϕ_s .^{1,2}

*Other bunching criteria would be possible. The buncher amplitudes used here are for zero space-charge; higher values are needed for higher beam currents.

The transport system was designed with drift distances between the bunchers and from B2 to the linac entrance so that a 750-keV beam that gets no ΔE in either buncher will arrive at the linac entrance at -26° with respect to the rf wave. For an off-energy beam, the bunchers must be phase-shifted to compensate. An additional phase shift in both bunchers must be made to satisfy the compromise design of beam entrance at -51° . The sample data file shows the correct buncher cards for design amplitude, injection energy of 755.8 keV, and -51° in phase.

2. H⁺ Phase Scan of Tank 1. Tank 1 is scanned at 104, 102, 100, 98, and 96% of design amplitude under two sets of conditions: with B1 turned off and B2 set at design amplitude, and with both bunchers on and set at design amplitudes. (The data file in Appendix H is set up for the second condition.) The results of these scans are shown in Figs. G-1 and G-2.

Tank 1 is scanned next at design amplitude with B1 turned off and B2 set for 9, 10, and 11 kV. The results are shown in Fig. G-3.

Finally, Tank 1 is scanned with T1 and B2 set at design amplitudes and B1 set for 4, 5, and 6 kV. The results are shown in Fig. G-4.

All of the above scans are done using the output subroutine given in Table G-I.

Input subroutine INPUT1 is used with the INPUT card as shown in the sample data file.

The data file must have output requested at the beginning and end of Tank 1. START 0 and STOP 31 are the appropriate formats for those cards. The ELIMIT 1 card should be included.

Buncher parameters are set on the appropriate TRANS1 cards, and care is taken to set the phases so as to satisfy the energy and phase offsets as discussed earlier.

Fig. G-1.

Phase scans of Tank 1. Prebuncher off, main buncher at design conditions of 10 kV and -100° for a 755.8-keV beam entering the tank at -51° . Scans at amplitudes of 104, 102, 100, 98, and 96% of the design amplitude are labeled 1-5, respectively.

Fig. G-2.

Tank 1 phase scans with prebuncher at design conditions of 4 kV and 226° and main buncher at design conditions of 10 kV and -100°, which deliver the beam to tank at -51°. Scans at 104, 102, 100, 98 and 96% design amplitude are labeled 1-5, respectively.

The OPTCON card is most important. It has 12 entries.

	1	2	3	4	5	6	7	8	9	10.	11	12
OPTCON	1	5	200	0	1.04	0	1	200	0	-10.2	0.162	0.624

The parameters are as follows.

1. Dummy variable no longer used. Leave it at 1.
2. Step size in degrees.
3. Negative of starting phase offset for scan.
4. Dummy variable. Keeps track of phase.
5. Amplitude of tank to be scanned.
6. Variable that allows for energy shift.
7. Number of tank to be scanned.
8. Final phase offset for scan.
9. Phase shift of beam at entrance to Tank 1. Always zero.
- 10-12. Phase shifts at entrance of Tanks 2, 3, and 4, respectively.

The phase offsets in 10-12 correct the reference frame as discussed in Sec. 4; they are not used for Tank 1 scans.

To change the amplitude of Tank 1, a new OPTCON card is added after each BEGIN card with parameter 5 changed as desired. It is also necessary to include new START, INPUT, and OUTPUT cards as shown.

As the plotting symbol for phase scans is the RUN number, a new RUN card also should be added.

For the scans where buncher amplitudes are changed, the OPTCON card need not be repeated, but RUN, START, and OUTPUT cards must be.

Fig. G-3.

Tank 1 phase scans with tank at design amplitude and prebuncher off, for main buncher settings of 9, 10, and 11 kV.

The buncher card being changed is always the first TRANS1 card in the file, and it is, of course, modified as needed. It is necessary to repeat the last TRANS1 card as well, or the code would assume that the new run was to be made with a transport consisting of only one element.

3. H⁺ Phase Scan of Prebuncher. The output subroutine in Table G-II is used to scan B1. The plotting subroutines are not included because they are the same as those in Table G-I. In the data file, B2 and Tank 1 are set at design and the amplitude of B1 is set at 3, 4, and 5 kV. The results are shown in Fig. G-5.

No OPTCON card is necessary, since the phase of the pre-buncher is set by the TRANS1 card, and the program decrements the phase until 400° have been scanned. In all other respects, the data file is the same as for Tank 1 scans in which B1 amplitudes are varied.

To inject a particle at the entrance of Tank 1 at the desired phase of -51°, B1 must be set at -226°

(or +134°) for an energy of 755.8 keV. Hence, an initial phase of 300° for B1 is convenient. It must be remembered that the design particle is at 134°, and the DCLE must be measured to this point.

4. Phase Scans of Tanks 2, 3, and 4. Phase scans of Tanks 2, 3, and 4 (Figs. G-6 through G-8) are done in separate runs using a data file with only one BEGIN card followed by an END card, and using the same output subroutine as for a Tank 1 scan. The ELIMIT card should be deleted, since the energy discrimination depends upon the absorber thicknesses^{3,4} and is calculated by the output subroutine.

It is important to note that the subroutine produces phase scans by changing the phases of particles at the input of the element to be scanned. The results are plotted in terms of this relative phase shift, *not* in the rf reference frame of PARMILA where $-\phi_0$ is normally plotted as zero. This is important when errors and measured quantities are included, because the beam appearing at an element

TABLE G-I

PARMILA OUTPUT SUBROUTINE USED TO GENERATE TANK PHASE SCANS

```

SUBROUTINE OUTPUT
C-----THIS SUBROUTINE IS NAMED OUT12. IT IS USED FOR PHASE SCANS.
C-----THE COMMON BLOCK WAS UPDATED TO CONFORM TO THE REST OF THE
C-----PARMILA ROUTINES ON 12/9/76. THIS SUBROUTINE WAS ONCE
C-----CALLED OUTPT10, BUT WAS CHANGED TO AVOID CONFUSION WITH OUT10.
COMMON NCELL,NPOINT,NT,NTWK,NSTART,NSTOP,NLAST,NCTOTL,IRUN,NN,PI
1  TWCP1,RADIAN,BRHOF,EREST,FREQ,WAVEL,TZERO,PZERO,BTAZRO,CELL(30,30
20),TANK(30,6),CORD(1,500),COR(6,500),COFT(5,36),OPTCON(30),SCE(10)
3  TITLE(8),VV(100),ERRL(10),ERROR,IBEAM,ELIMIT,NTR1,NTR2,TRANS1(10,
480),TRANS2(10,40)
C OPTCON(1)=TANK AMP (SHOULD ALWAYS BE 1)
C OPTCON(2)=STEP SIZE IN DEGREES
C OPTCON(3)=NEGATIVE OF THE STARTING PHASE
C OPTCON(4)=KEEPS TRACK OF PHASE
C OPTCON(5)=PERCENT CHANGE IN TANK AMP
C OPTCON(6)=ALLOWS ENERGY SHIFT
C OPTCON(7)=NUMBER OF TANK TO BE SCANNED
C OPTCON(8)=FINAL PHASE
C-----PROGRAM MODIFIED ON 770216 TO SHIFT PHASES AT ENTRANCES OF TANKS
C-----AMOUNT OF SHIFT IN PHASE IS FOUND ON OPTCON CARD
C-----OPTCON(9)= PHASE SHIFT ENTRANCE OF TANK 1 (USUALLY 0)
C-----OPTCON(10)=PHASE SHIFT ENTRANCE OF TANK 2
C-----OPTCON(11)= PHASE SHIFT ENTRANCE OF TANK 3
C-----OPTCON(12)=PHASE SHIFT ENTRANCE OF TANK 4
C
  DIMENSION NLT(4),NSAT(4)
  DATA(NLT(1),I=1,4)/0,31,97,135/, (NSAT(1),I=1,4)/1,32,98,136/
  DATA FLAG/0/
  DIMENSION P(2,3),ER(2,3),SIGMA(20),CUNORM(20),SIG(3),PP(3)
  DATA (P(I),I=1,6)/.2112,.2304,.5961,.6462,1.1607,1.2533/
  DATA (ER(I),I=1,6)/35.08,36.88,63.49,66.49,92.71,97.04/
  DATA (SIG(I),I=1,3)/.0032,.0084,.0154/
  DATA (PP(I),I=1,3)/.2208,.6211,1.207/
  DATA (SIGMA(I),I=1,20)/0.,.3,.6,.8,1.0,1.1,1.2,1.3,1.4,1.5,1.6,1.7
  * 1.8,1.9,2.0,2.2,2.4,2.6,2.8,3.3/
  DATA (CUNORM(I),I=1,20)/0.,.118,.226,.288,.341,.364,.385,.403,.419
  * .433,.445,.455,.464,.471,.477,.486,.492,.495,.497,.499/
  I=OPTCON(7)
  TANK(27,NT)=0.
  IF(NCELL.GT.NLT(I)) GO TO 20
  PHSFT=OPTCON(NT+8)*RADIAN
  DO 1 J=1,NPOINT
1  CORD(5,J)=CORD(5,J) - PHSFT
  IF(NT.NE.I) RETURN
  ERROR = 1.0
  ERRL(1)=1.0
  ERRL(3)=1.0
C  COUNT GOOD PARTICLES AND REORDER CORD
  NB=NPOINT+1
  DO 50 NGOOD=1,NPOINT
  IF (NGOOD.GE.NB) GO TO 60
  IF (CORD(7,NGOOD).EQ.0.) GO TO 50
11 NB=NB+1
  IF (CORD(7,NB).EQ.0.) GO TO 300
  IF (NB.GT.NGOOD) GO TO 11
C  SWAP BAD PARTICLE FOR GOOD ONE
300 DO 44 N=1,7
  T=CORD(N,NGOOD)
  CORD(N,NGOOD)=CORD(N,NB)
44 CORD(N,NB)=T
50 CONTINUE
60 NPOINT1=NPOINT
  NPOINT=NGOOD-1
  DO 10 NP=1,NPOINT
  DO 5 J=1,4
5  COR(J,NP)=CORL(J,NP)
  COR(5,NP)=CORD(5,NP)-OPTCON(3)*RADIAN
  CORD(5,NP)=COR(5,NP)
  CCR(6,NP)=CORD(6,NP)-OPTCON(6)
  CORL(6,NP)=COR(6,NP)
10 CONTINUE
  ISAVE=IRUN
  IF(ISAVE.EQ.1) CALL ADV(1)
  IF(ISAVE.GT.1) GO TO 4
  CALL DLCH(144,50,80,TITLE,1)
  CALL DGA(150,950,100,900,-OPTCON(3),OPTCON(8),100.,0.)

```

TABLE G-I (cont)

```

CALL FRAME(150,950,100,900)
CALL SCALE(10,1,0,0)
INPO=(OPTCON(8)+OPTCON(3))/5.
CALL PIP(INPO,10,10)
INSO=INPO/10.
CALL SCALE(4,0,1,INSO,0)
4 CONTINUE
OPTCON(4)=-OPTCON(3)
TANK(20,NT)=OPTCON(5)
NSTART=NSAT(1)
RETURN
20 CONTINUE
IF(IFLAG.EQ.0) PRINT 101,TITLE
IFLAG=1
IF(I.EQ.1) GO TO 21
C STRAGGLING IN ABSORBERS. USED FOR TANKS 2,3,AND 4.
PCAPT=0.
IND=NT-1
DO 22 NP=1,NPOINT
IF(CORD(6,NP).LT.ER(1,IND)) GO TO 22
IF(CORD(6,NP).GT.ER(2,IND)) GO TO 16
PINT=(CORD(6,NP)-ER(1,IND))*(P(2,IND)-P(1,IND))/(ER(2,IND)-
2 ER(1,IND))+P(1,IND)
DELP=(PINT-PP(IND))/SIG(IND)
IF(DELP.NE.0.) GO TO 18
PCAPT=PCAPT+.5
GO TO 22
18 CONTINUE
DO 23 I=1,20
IF(ABS(DELP).GE.SIGMA(I)) K=I
IF(ABS(DELP).LT.SIGMA(I)) GO TO 25
23 CONTINUE
25 CONTINUE
RINT=(ABS(DELP)-SIGMA(K))*(CUNORM(K+1)-CUNORM(K))/(SIGMA(K+1)-
2 SIGMA(K))+CUNORM(K)
SG=1.
IF(DELP.LT.0.) SG=-1
PCAPT=PCAPT+.5+SG*RINT
GO TO 22
16 CONTINUE
PCAPT=PCAPT+1.
22 CONTINUE
PCAPT=100.*PCAPT/NPOINT1
21 CONTINUE
IF(I.GT.1) GO TO 31
NCAPT=0
DO 30 NP=1,NPOINT
IF(CORD(7,NP).NE.0.) GO TO 30
NCAPT=NCAPT+1
30 CONTINUE
PCAPT=FLOAT(NCAPT)/FLOAT(NPOINT1)*100.
31 CONTINUE
PRINT 100,OPTCON(5),OPTCON(4),PCAPT
IX=150+800*OPTCON(3)+OPTCON(4)/(OPTCON(8)+OPTCON(3))
IY=-8.*PCAPT+900
CALL PLT(IX,IY,ISAVE)
DO 40 NP=1,NPOINT
COR(5,NP)=COR(5,NP)+OPTCON(2)*RADIAN
40 CONTINUE
OPTCON(4)=OPTCON(4)+OPTCON(2)
IRUN=-1
IF(OPTCON(4).GT.OPTCON(8)) IRUN=ISAVE
RETURN
100 FORMAT(10X,F7.4,5X,F6.1,5X,F7.2)
101 FORMAT(8A10//,
19X,*AMPLITUDE*,4X,*PHASE*,6X,*PCAPT*)
END
SUBROUTINE DGA(IXL,IXR,IYT,IYB,XL,XR,YT,YB)
COMMON/GGGGGG/IXY(4),XY(4)
IXY(1)=IXL
IXY(2)=IXR
IXY(3)=IYT
IXY(4)=IYB
XY(1)=XL
XY(2)=XR
XY(3)=YT
XY(4)=YB
IF(IXY(1).LT.IXY(2))GO TO 1
IXY(1)=IXY(2)
IXY(2)=IXL

```

TABLE G-1 (cont)

```

1 IF(IXY(3).LT.IXY(4))GO TO 2
  IXY(3)=IXY(4)
  IXY(4)=IXY(3)
2 DO 3 I=1,4
3 CALL TCR(IXY(I))
  RETURN
  END
SUBROUTINE CONV(A,K,NC,BCD)
  CONVERT A FLOATING POINT NUMBER TO BCD
  A = FLOATING POINT NUMBER
  K = FORMAT CODE
  NC = NUMBER OF BCD CHARACTERS
  BCD = LOCATION OF FIRST WORD IN WHICH TO PUT CHARACTERS
  DIMENSION BCD(2),TEN(9)
  DATA TEN/1.,10.,100.,1000.,10000.,100000.,1000000.,10000000.,
1 100000000./
  IF(A.NE.0.)GO TO 10
  BCD(1)=2H0.
  NC=2
  IF(K.EQ.0)NC=1
  GO TO 90
10 J=IABS(K)
  IF(J.GT.9)GO TO 60
  B=ABS(A)*TEN(J+1)+.5
  IF(B.LT.TEN(9))GO TO 20
  J=14
  GO TO 60
20 DO 30 I=1,9
  L=I-1
  IF(B.LT.TEN(I))GO TO 40
30 CONTINUE
40 IF(L.LT.J)L=J
  IF(L.EQ.0)L=1
  IF(J.NE.0)L=L+1
  IF(A.LT.0.)L=L+1
  ENCODE(6,50,FMT)L,J
50 FORMAT(2H(F,I1,1H.,I1,1H))
  GO TO 80
60 IF(J.GT.16)J=16
  J=J-10
  L=J+6
  IF(A.LT.0.)L=L+1
  ENCODE(7,70,FMT)L,J
70 FORMAT(2H(E,I2,1H.,I1,1H))
80 ENCODE(L,FMT,BCD)A
  NC=L
90 RETURN
  END
SUBROUTINE SCALE(SIDE,SIZE,HORV,NI,K)
  WRITE A NUMERICAL SCALE ALONG ONE SIDE OF A GRAPH
  SIDE = 1,2,3, OR 4 FOR LEFT, RIGHT, TOP, AND BOTTOM
  SIZE = 0 FOR NORMAL 4020 SIZE CHARACTERS
  = 1,2,3,4 FOR 4 POSSIBLE WLCV SIZES
  HORV = 1 OR 2 FOR HORIZONTAL OR VERTICAL
  NI = NUMBER OF LINEAR INTERVALS
  K = FORMAT CODE
  COMMON/CGGCGG/IXY(4),XY(4)
  DIMENSION BCD(2)
  INTEGER SIDE,SIZE,HORV
  IOP=SIDE
  IS=SIZE
  IF(IS.GT.4)IS=0
  IH=HORV
  IF(IH.NE.2)IH=1
  I=1
  IF(IOP.LT.3)I=3
  M=IABS(NI)
  IF(M.GT.50.OR.M.LT.1)GO TO 130
  XM=M
  X1=IXY(I)
  X2=IXY(I+1)
  XI=(X2-X1)/XM
  DX=(XY(I+1)-XY(I))/XM
  M=M+1
  DO 120 J=1,M
  F=J-1
  A=XY(I)+F*DX
  CALL CONV(A,K,NC,BCD)
  IZ=X1+F*XI+.5
  IF(IS.NE.0)GO TO 40

```

TABLE G-I (cont)

```

C      STANDARD 4020 CHARACTER SIZE, ONLY WRITTEN HORIZONTALLY
      IF(IOP-2)20,10,30
10     IX=IXY(2)+8
      GO TO 25
20     IX=IXY(1)-8*NC
25     CALL TSP(IX,IZ,NC,BCD)
      GO TO 120
30     IX=IZ-4*(NC-1)
      IZ=IXY(4)+16
      IF(IOP.EQ.3)IZ=IXY(3)-16
      GO TO 25
40     IF(IH.EQ.2)GO TO 80
C      LARGE CHARACTERS, HORIZONTALLY
      IF(IOP-2)60,50,70
50     IX=IXY(2)+8
      GO TO 65
60     IX=IXY(1)-6*(IS+1)*NC-8
65     IY=IZ-4*(IS+1)
66     CALL WLCH(IX,IY,NC,BCD,IS)
      GO TO 120
70     IX=IZ-3*(IS+1)*NC
      IY=IXY(4)+4*(IS+1)
      IF(IOP.EQ.3)IY=IXY(3)-11*(IS+1)
      GO TO 66
C      LARGE CHARACTERS, VERTICALLY
80     IF(IOP-3)110,90,100
90     IY=IXY(3)-8
      GO TO 105
100    IY=IXY(4)+6*(IS+1)*NC+8
105    IX=IZ-4*(IS+1)
106    CALL WLCV(IX,IY,NC,BCD,IS)
      GO TO 120
110    IY=IZ+3*(IS+1)*NC
      IX=IXY(2)+4*(IS+1)
      IF(IOP.EQ.1)IX=IXY(1)-11*(IS+1)
      GO TO 106
120    CONTINUE
      CALL EMPTY
130    RETURN
      END
      SUBROUTINE PIP(NX,NY,L)
      COMMON/GGGGGG/IXY(4),XY(4)
      IF(NX.LE.0)GO TO 15
      X1=IXY(1)
      X2=IXY(2)
      XM=NX
      XI=(X2-X1)/XM
      M=NX+1
      DO 1 J=1,M
      F=J-1
      IX=X1+F*XI+.5
      CALL DRV(IX,IXY(3),IX,IXY(3)+L)
1     CALL DRV(IX,IXY(4),IX,IXY(4)-L)
15     IF(NY.LE.0)GO TO 3
      X1=IXY(3)
      X2=IXY(4)
      XM=NY
      XI=(X2-X1)/XM
      M=NY+1
      DO 2 J=1,M
      F=J-1
      IY=X1+F*XI+.5
      CALL DRV(IXY(1),IY,IXY(1)+L,IY)
2     CALL DRV(IXY(2),IY,IXY(2)-L,IY)
3     RETURN
      END

```

to be scanned will probably be on an oscillation and will not be centered at $-\phi_s$. Then, a shift to the usual reference frame will be necessary. Hence, before doing the phase scans, one must know the offsets at the end of each tank.

The OUTPUT subroutine in Table G-III calculates the phase centroid of particles at the end of Tank 1. Only those particles that will eventually survive through Tank 2 are used.

For Tanks 2, 3, and 4, the phase centroids of particles successfully accelerated through the previous elements are calculated using the OUTPUT subroutines in Table G-IV. There must be an ELIMIT 5 card in the data file to determine success. Note that the phase centroid at the end of Tank 1 must have been predetermined before this subroutine can be used.

Fig. G-4.

Tank 1 phase scans with tank and main buncher at design conditions, prebuncher at -226° and at 3-, 4-, and 5-kV amplitude, labeled 1-3, respectively.

After the phase offsets for each tank are known, they are entered as parameters on the OPTCON card. Parameter 7 must be equal to the tank being scanned.

The data file must be checked for several other things. The INPUT card remains as on the sample data file. Tank 2 must be turned on. The STOP card must be equal to the number of the last cell to be scanned, and output calls at the beginning of each tank where a phase shift is to be made must be present, as well as at the entrance and exit of the tank to be scanned.

5. Tuning Targets. The FWHM, DCLE, and PVR numbers are obtained from Figs. G-1 through G-8. Accuracy requirements are estimated from these results and from reproducibility experience on the actual linac. The numbers are worked into the machine-tuning procedure below.

III. PROCEDURE FOR GENERATING PHASE SCANS ON THE ALVAREZ LINAC

A. Hardware Conditions at Tank 2

The absorber and collector assembly at the end of Tank 2 should be connected as follows.

TABLE G-II

PARMILA OUTPUT SUBROUTINE USED TO GENERATE PREBUNCHER PHASE SCANS

```

SUBROUTINE OUTPUT
C-----THIS SUBROUTINE IS CALLED OUT13.
C-----THIS SUBROUTINE IS USED TO SCAN THE PREBUNCHER (B1).
C-----JAN,1978. BECAUSE OPERATIONAL PHASE SCANS ARE PIVOTED ABOUT TANK1
C-----THE PREBUNCHER PHASE SCAN MUST BE PLOTTED SO THAT AS THE PREBUNCHER
C-----PHASE(TRANS1(3,1)) IS INCREASED, A PARTICLE ARRIVES LATER AT BLZ.
C-----THEREFORE, THE INITIAL PHASE OF THE PREBUNCHER IS 300 DEG. AND IS
C-----DECREMENTED IN STEPS FOR A TOTAL SPAN OF 400 DEG. THE INITIAL PHASE
C-----IS SET BY THE TRANS1 CARD IN THE DATA FILE.
C-----OUTPUT IS CALLED AT THE BEGINNING AND END OF TANK1, AN ELIMIT OF 1
C-----IS NECESSARY.

```

```

COMMON NCELL,NPOINT,NT,NEWTK,NSTART,NSTOP,NLAST,NCTOTL,IRUN,NN,PI
1,TWOPI,RADIAN,BRHO,EREST,FREQ,WAVE,TZERO,PZERO,BTAZRO,CELL(30,30
20),TANK(30,0),CORD(7,500),COR(6,500),COPT(5,36),OPTCON(30),SCE(10
3,TITLE(8),VV(100),ERRL(10),ERROR,IBEAM,ELIMIT,NTR1,NTR2,TRANS1(10,
480),TRANS2(10,40)
DATA IFLAG/0/
IF(IFLAG.NE.0) GO TO 10
IFLAG = 1
PRINT 101,TITLE
PHBEG=TRANS1(3,1)
PHEND=PHBEG-400.
CALL ADV(1)
CALL DLCH(200,50,80,TITLE,1)
CALL DGA(150,950,100,900,PHBEG,PHEND,100.,0.)
CALL FRAME(150,950,100,900)
CALL SCALE(1,0,1,10,0)
INPO=(PHEND-PHBEG)/5.
CALL PIP(INPO,10,10)
INSO=INPO/4.
CALL SCALE(4,0,1,INSO,0)
10 IF(IRUN.GT.0) ISAVE=IRUN
IF(NCELL.EQ.0) RETURN
NCAPT=0
DO 30 NP=1,NPOINT
IF(CORD(7,NP).NE.0.) GO TO 30
NCAPT=NCAPT+1
30 CONTINUE
PCAPT=FLOAT(NCAPT)/FLOAT(NPOINT)*100.
PRINT 100,TRANS1(2,1),TRANS1(3,1),PCAPT
IX=150+800*(TRANS1(3,1)-PHBEG)/(PHEND-PHBEG)
IY=-8.*PCAPT+900
CALL PLT(IX,IY,ISAVE)
TRANS1(3,1)=TRANS1(3,1)-10.
IRUN=-1
IF(TRANS1(3,1).LT.PHEND) IRUN=ISAVE
100 FORMAT(14X,F7.4,3X,F7.2,2X,F7.4)
101 FORMAT(8A10//
115X,'AMP B1',5X,'PHASE',4X,'PCAPT')
RETURN
END

```

B. Beam Conditions

The beam conditions should be:

current	~1 mA
pulse length	100 μ s
rep rate	3.75 pulses/s

These limits should not be exceeded, to avoid damage to the apparatus. The EM-3's should be set to operating conditions. The sample time should be 10-20 μ s from the end of the beam pulse.

C. General Considerations

The programs for the phase scan experiment are all on the PHASE SCAN CARD. To set up starting conditions, insert this card and: push DEMAND; insert the 40-, 70-, and 95-MeV absorbers by use of the insert buttons; delay Tank 2 and the prebuncher; put the main buncher in time; select the H⁺ option; demand GENERAL SETUP; and set Tank 1 phase set-point (PSP) at 1000. (Always

Fig. G-5.

Prebuncher phase scans for prebuncher amplitudes of 3, 4, and 5 kV, with main buncher and Tank 1 at design conditions.

Fig. G-6.

Tank 2 phase scan.

PHASE SHIFT AT BEGINNING OF T2 & T3 TANK 1 & 2 ARE DESIGN TANK 3 SCAN

Fig. G-7.
Tank 3 phase scan.

PHASE SHIFT AT BEGINNING OF T2, T3, T4 TANK 1, 2, 3 ARE DESIGN TANK 4 SCAN

Fig. G-8.
Tank 4 phase scan.

TABLE G-III

**PARMILA OUTPUT SUBROUTINE USED TO IDENTIFY ACCELERATED AND
NONACCELERATED PARTICLES AT THE END OF TANK 2, FOR REPHASING
OF THE CENTROID. (See comments)**

```

SUBROUTINE OUTPUT
C   OUTPUT SUBROUTINE NUMBER OUT11
C-----THIS SUBROUTINE IS USED TO TAG PARTICLES WHEN THEY REACH
C-----END OF TANK 2 ACCORDING TO WHETHER OR NOT THEY ARE GOOD.
C-----AT THE END OF TANK TWO, THE PARTICLES ARE ORDERED, AND
C-----THE RUN IS RESTARTED.  THE NGOOD PARTICLES ARE USED FOR CALC.
C-----OF ELLIPSE AREA AND PHASE AND ENERGY CENTROIDS OF PARTICLES
C-----AT END OF CELL 31.  THOSE VALUES ARE ALSO PRINTED FOR ALL
C-----PARTICLES.  AN ELIMIT 2 CARD MUST BE IN DATA FILE.  NOTE THAT
C-----IT IS CHANGED AT END OF FIRST PASS.
COMMON NCELL,NPOINT,NT,NEWTK,NSTART,NSTOP,NLAST,NCTOTL,IRUN,NN,PI
1,TWOPI,RADIAN,BRHOF,EREST,FREQ,WAVEL,TZERO,PZERO,BTAZRO,CELL(30,30
20),TANK(30,6),CORD(7,500),COR(6,500),COFT(5,36),OPTCON(30),SCE(10)
3,TITLE(8),VV(100),ERRL(10),ERROR,IBEAM,ELIMIT,NTR1,NTR2,TRANS1(10,
440),TRANS2(10,40)
DIMENSION X(500),Y(500),XX(500),YY(500)
DATA IFL/0/
IF (IRUN.LT.0) GO TO 90
IF (NCELL.LT.NSTOP) RETURN
C   COUNT GOOD PARTICLES AND REORDER COR
NB=NPOINT+1
DO 50 NGOOD=1,NPOINT
IF (NGOOD.GE.NB) GO TO 20
IF (CORD(7,NGOOD).EQ.0.) GO TO 50
10 NB=NB-1
IF (CORD(7,NB).EQ.0.) GO TO 30
IF (NB.GT.NGOOD) GO TO 10
20 NGOOD=NGOOD-1
GO TO 60
C   SWAP BAD PARTICLE FOR GOOD ONE
30 DO 40 N=1,6
T=COR(N,NGOOD)
COR(N,NGOOD)=COR(N,NB)
40 COR(N,NB)=T
50 CONTINUE
60 IRJNS=IRUN
IRJNS=-1
ELIMIT = 45.0
RETURN
90 CONTINUE
IF (IFL.EQ.0) PRINT 100 ,TITLE
100 FORMAT(8A10//
1      1X,'CELL NO OF AREA PBAR EBAR GOOD NO OF AREA
1      PBAR EBAR*/2X*NO PART. PHI-W ALL ALL PART
2.    PHI-W*)
IFL=1
C   REJECT LOST PARTICLES AND SORT
NG=0
IF(NT.GE.2.A.NEWTK.EQ. 1) CALL PHSHT(NGOOD)
PS=TANK(3,NT)
WS=TZERO
IF (NCELL.GT.0) WS=CELL(3,NCELL)
DO 70 NP=1,NPOINT
IF (CORD(7,NP).NE.0.0) GO TO 70
NG=NG+1
XX(NG)=(CORD(5,NP)-PS)/RADIAN
YY(NG)=CORD(6,NP)-WS

```

TABLE G-III (cont)

```

70 CONTINUE
C      FIT AN ELLIPSE TO A COLLECTION OF POINTS
      MX=1
      CALL ELIPS (NG,XX,YY,MX,A,B,XB,YB)
      G=(1.0+A**2)/B
C      CALCULATE AN AREA ASSOCIATED WITH EACH POINT
      DO 120 NP=1,NG
      X(NP)=XX(NP)-XB
      Y(NP)=YY(NP)-YB
      X(NP)=G*X(NP)**2+2.0*A*X(NP)*Y(NP)+B*Y(NP)**2
120 CONTINUE
C-----SORT AREAS,
      CALL SORT(NG,X)
      CALL ELIPS(NGOOD,XX,YY,MX,A,B,XXB,YYB)
C-----CALCULATE AN AREA ASSOCIATED WITH EACH GOOD PARTICLE
      G=(1.0+A**2)/B
      DO 122 NP=1,NGOOD
      XX(NP)=XX(NP)-XXB
      YY(NP)=YY(NP)-YYB
      XX(NP)=G*XX(NP)**2+2.0*A*XX(NP)*YY(NP)+B*YY(NP)**2
122 CONTINUE
      CALL SORT(NGOOD,XX)
      PRINT 125,NCELL,NG,X(NG),XB,YB,NGOOD,XX(NGOOD),XXB,YYB
125 FORMAT(1X,I3,4X,I3,1X,F8.2,2X,F6.2,1X,F6.3,3X,I3 ,7X, 1X,
1 F6.2,3X,F6.2,F8.3)
      IF(NCELL.EQ.NSTOP)IRUN=IRUNS
150 CONTINUE
      RETURN
      END

      SUBROUTINE PHSHT(NGOOD)
      COMMON NCELL,NPOINT,NT,NEWTK,NSTART,NSTOP,NTLAST,NCTOTL,IRUN,NN,PI
1,TWOPI,RADIAN,BRHOF,EREST,FREQ,WAVEL,TZERO,PZERO,BTAZRO,CELL(30,30
20),TANK(30,6),CORD(7,500),COR(6,500),COFT(5,36),OPTCON(30),SCE(10)
3,TITLE(8),VV(100),ERRL(10),ERROR,IBEAM,ELIMIT,NTR1,NTR2,TRANS1(10,
440),TRANS2(10,40)
C-----THIS SUBROUTINE ASSUMES AN ELLIPTICAL BUNCH OF PARTICLES, WHICH
C-----HAVE BEEN PUT INTO LINAC WITH SAME PHASE AND ENERGY. ALL PARTICLES
C-----ARE REPHASED AT ENTRANCE TO EACH TANK. PHASE OF CENTROID IS
C-----CALCULATED, THEN SHIFTED TO THIS.
      TPHS=0.

      DO 1 I=1,NGOOD
      TPHS=TPHS+CORD(5,I)
1 CONTINUE
      IF(NGOOD.EQ.0) RETURN
      AVPH=TPHS/NGOOD
      SHFT=AVPH-TANK(3,1)
      DO 10 I=1,NGOOD
10 CORD(5,I)=CORD(5,I)-SHFT
      RETURN
      END
      SUBROUTINE SORT(N,X)
C      REARRANGE N DATA WORDS IN ARRAY X IN ORDER OF INCREASING VALUE
      DIMENSION X(2)
      IF (N.LE.1) RETURN
      IF (X(2).GE.X(1)) GO TO 10
      R=X(2)
      X(2)=X(1)
      X(1)=R

```

TABLE G-III (cont)

```

      IF (N.LE.2) RETURN
10  DO 40 I=3,N
      L=I-1
      IF (X(I).GE.X(L)) GO TO 40
      R=X(I)
      X(I)=X(L)
      DO 20 J=2,L
      K=I-J
      IF (R.GE.X(K)) GO TO 30
      X(K+1)=X(K)
20  CONTINUE
      K=0
30  J=K+1
      X(J)=R
40  CONTINUE
      RETURN
      END
      SUBROUTINE ELIPS(NP,F,G,MX,ALPHA,BETA,XBAR,YBAR)
      C      FITS AN INERTIAL ELLIPSE TO A GROUP OF NP POINTS
      C      THE EQUATION FOR AN ELLIPSE IS
      C      
$$\text{GAMMA}^2 \text{X}^2 + 2 \cdot \text{ALPHA} \cdot \text{X} \cdot \text{Y} + \text{BETA} \cdot \text{Y}^2 = \text{EOPI}$$

      C      NP=NO. OF POINTS
      C      F AND G=COORDINATE ARRAYS
      C      MX=MEMORY SPACING BETWEEN ADJACENT COORDINATES IN ARRAYS
      C      RETURNS ALPHA,BETA,XBAR,YBAR
      DIMENSION X(500), Y(500), G(2), F(2)
      N=1
      DO 10 M=1,NP
      X(M)=F(N)
      Y(M)=G(N)
10  N=N+MX
      C      DETERMINE CENTROID OF PARTICLES
      XC=0.0
      YC=0.0
      DO 20 N=1,NP
      XC=XC+X(N)
20  YC=YC+Y(N)
      P=FLOAT(NP)
      XBAR=XC/P
      YBAR=YC/P
      C      DETERMINE ORIENTATION (A) OF ELLIPSE
      SUM1=0
      SUM2=0
      SUM3=0
      SUM4=0
      DO 30 N=1,NP
      X(N)=X(N)-XBAR
      Y(N)=Y(N)-YBAR
      SUM1=SUM1+X(N)*Y(N)
      SUM2=SUM2+X(N)**2+Y(N)**2
30  SUM3=SUM3+X(N)**2-Y(N)**2
      SUM4=-SUM3
      A=ATAN(2.0*SUM1/SUM3)/2.0
      C      DETERMINE ECCENTRICITY OF ELLIPSE
      YY=SUM2/2.0+SUM3*COS(2.0*A)/2.0+SUM1*SIN(2.0*A)
      XX=SUM2/2.0+SUM4*COS(2.0*A)/2.0-SUM1*SIN(2.0*A)
      B=SQRT(YY/XX)
      C      FIND ALPHA BETA AND GAMMA OF SKEW ELLIPSE
      GAMMA=COS(A)**2/B+SIN(A)**2*B
      ALPHA=SIN(A)*COS(A)*(1/B-B)
      BETA=SIN(A)**2/B+COS(A)**2*B
      RETURN
      END

```

change PSP's using the SETUP P subroutine, button 6.)

D. H⁺ Main Buncher and Tank 1 ASP Settings

To phase scan Tank 1, push the START button (No. 1). Choose TANK=1. Set the parameters as follows.

WIDTH	400	DW 10	IMAX 1
TIME	320	SCALE	MODE 1

SCALE should be set so that the maximum beam transmission in data system counts is approximately two-thirds of full-scale (with the 4-mA amplifier, there should be about 400 counts of beam). Set the main buncher (B2) ASP to 500 counts. Adjust the ASP of Tank 1 to set the FWHM at $109^\circ \pm 2^\circ$.

Then change the PSP of B2 to set the distance to the center from the left edge (DCLE) at $38^\circ \pm 2^\circ$. Finally, vary the amplitude of B2 to set the peak to valley ratio (PVR) to 4.6 ± 0.1 .

Iterate if necessary in the following order: Tank 1 ASP; B2 PSP; B2 ASP.

E. H⁺ Prebuncher Settings

Choose the option H⁺B. Put the prebuncher (B1) in time. Set its ASP to 800 counts. (This number is not critical, but it must be high enough to give a PVR greater than 2 so that a FWHM can be calculated.) Set TANK=-1. All the remaining parameters are unchanged. Adjust B1 ASP to set the PVR at 3.9 ± 0.05 and the FWHM at $251^\circ \pm 5^\circ$. Adjust B1 PSP to set the DCLE at $111^\circ \pm 2^\circ$.

F. Redundancy Check

Scan Tank 1 with both bunchers on. The results should be:

FWHM	$110^\circ \pm 2^\circ$
DCLE	$39^\circ \pm 2^\circ$
PVR	17 ± 1

If you do not get these numbers, vary the B1 ASP and PSP to achieve them.

G. Set Tank 1 to 98% of Design Amplitude*

Multiply Tank 1 ASP as determined from above by 0.98. Set Tank 1 ASP to this new value. Change the DESIGN PHASE of B1 and B2 by -1° using the SETUP P subroutine (button No. 6).

H. Set Tanks 2, 3, and 4

1. Scan Tank 2

Put Tank 2 in time. Choose TANK=2. Set the parameters to

WIDTH 200 DW = 5

Adjust the ASP and PSP to get

FWHM $85^\circ \pm 2^\circ$

DCLE $31^\circ \pm 2^\circ$

2. Scan Tank 3

Retract the 40-MeV absorber. Choose TANK=3. All scan parameters remain unchanged. Adjust the ASP and PSP to get

FWHM $87^\circ \pm 2^\circ$

DCLE $33^\circ \pm 2^\circ$

3. Scan Tank 4

Retract the 70-MeV absorber. Choose TANK=4. The program will demand that the main line bender be turned down. It will be necessary to turn off the transition region spill monitor. The scan parameters remain unchanged. Adjust the ASP and PSP to get

FWHM $99^\circ \pm 2^\circ$

DCLE $42^\circ \pm 2^\circ$

I. H⁻ Prebuncher Phase Scan

Choose the option H⁻ B. Put the prebuncher in time. Set its ASP to 800 counts. (Set the ASP high enough to get a PVR greater than 2.) Set TANK = -3. Set the DCLE at one-half of the FWHM.

*Experimental investigation of the most compact bunch indicated a minimum at 98% rather than at 95%.

TABLE G-IV

**PARMILA OUTPUT SUBROUTINE USED TO CALCULATE PHASE SHIFTS
AT THE ENDS OF TANKS 2, 3, AND 4.**

```

SUBROUTINE OUTPUT
C-----TEMP SUBROUTINE TO CALCULATE PHASE SHIFTS AT END OF T2,T3,T4. NOS
C-----WILL BE USED FOR PHASE SCANS AND CAN BE USED TO PRINT CENTROIDS AT ANY
C-----CELLS ON OUTPUT CARDS. SHIFTS ARE MADE ONLY AT BEGINNING OF TANKS.
C-----
COMMON NCELL,NPOINT,NT,NEWTK,NSTART,NSTOP,NLAST,NCTOTL,IRUN,NN,PI
1,TWOPI,RADIAN,BRHOF,EREST,FREQ,WAVEL,TZERO,PZERO,BTAZRO,CELL(30,30
20),TANK(30,6),CORD(7,500),COR(6,500),COFT(5,36),OPTCON(30),SCE(10)
3,TITLE(8),VV(100),ERRL(10),ERROR,IBEAM,ELIMIT,NTR1,NTR2,TRANS1(10,
440),TRANS2(10,40)
DATA IFL/0/

C-----THE FOLLOWING DATUM WAS DETERMINED FROM EARLIER RUN. IT IS
C-----THE CENTROID OF THE GOOD PARTICLES AT END OF T1. -10.20 DEG.
C-----IT HAS BEEN CHANGED TO RADIAN TO USE IN SHIFTING.
C-----FOR T1=1 RADIAN=-.1780. FOR T1=.98 RADIAN = -.1112
DATA ADPHI/-.1112/
IF(IFL.EQ.0) PRINT 10,TITLE
10 FORMAT(/8A10/'NCELL NGOOD PCAPT DPHASE DENG#')
IFL=1
IF(NCELL.EQ.31) GO TO 25
TPHI=0.
TENG=0.
NG=0
DO 5 I=1,NPOINT
IF(CORD(7,I).NE.0.0) GO TO 5
TPHI=TPHI +CORD(5,I)
TENG=TENG+CORD(6,I)
NG=NG+1
5 CONTINUE
IF(NG.EQ.0) RETURN
ADPHI=TPHI/NG-TANK(3,NT)
AENG=TENG/NG-CELL(3,NCELL)
PHSF=ADPHI/RADIAN
PCAPT=FLOAT(NG)/FLOAT(NPOINT)
PRINT 20,NCELL,NG,PCAPT,PHSF,AENG
20 FORMAT(I4,I8,F8.2,F10.4,F7.3)
IF(NEWTK.EQ.0) RETURN
25 DO 30 I=1,NPOINT
30 CORD(5,I)=CORD(5,I)-ADPHI
RETURN
END

```

Now set TANK=1 and do a phase scan. If the DCLE of the H⁻ phase scan is not equal to the DCLE of the H⁺ phase scan, change the C-W energy to make the H⁻ DCLE overlap that of H⁺. (One keV is equivalent to a 6° phase shift.) If the energy change is large (more than 2 keV), you will have to retune the H⁻ transport line.

After changing the energy, repeat the phase scans.

REFERENCES

1. W. E. Jule, "Notes on Bunchers," Los Alamos Scientific Laboratory internal document (February 7, 1977).
2. K. R. Crandall, "MRA, A FORTRAN IV Code to Simulate Beam Bunching," Los Alamos Scientific Laboratory internal document (March 20, 1967).
3. J. K. Halbig, "Absorber Collector Thicknesses," Los Alamos Scientific Laboratory internal document (December 31, 1975).
4. J. K. Halbig, "Phase Scan Absorber Thicknesses," Los Alamos Scientific Laboratory internal document (May 12, 1975).

APPENDIX H

DATA FILE DEFINING FINAL PARMILA MODEL

The following data file contains the parameters that define the PARMILA model. The RUN card initiates the files. The cards labeled LINAC, TANK, and COFT contain the parameters necessary for generating a linac. The (CHANGE 3) cards redefine the lengths of generated quadrupoles to make groups of quadrupoles of equal lengths to facilitate their manufacture. The TRANS1 cards define the transport region. The cards beginning with START through the TITLE card define

parameters for a particular dynamics run. The (CHANGE 8) cards specify measured Tank 1 cell lengths. The (CHANGE 7) cards specify the measured axial electric field distribution. The (CHANGE 2) cards specify the measured quadrupole gradients. Each BEGIN card causes the execution of a new dynamics run. The case shown is set up to do phase scans for five different Tank 1 amplitudes.

```

RUN 1 0
LINAC 4 0.75 201.25 1
TANK 1 5.2 -26.0 0.01 1.6 2.11327E-3 15.903 -0.0 1.5 -15.0
-0.5 1 2 22.0 0.0 .75 0.0 0.0 0.0 0.0
COFT .022068 32.374 -503.60 3617.8 -10030.0
.15553 -3.0747 29.419 -93.986 0.0
.79504 -10.606 105.80 -346.39 0.0
.0061929 1.6827 -19.352 75.884 0.0
.16376 1.3816 -5.3093 18.576 0.0
36.702 1119.9 -12241.0 46638.0 0.0
TANK 2 4.0 -26.0 0.024 0.0 0.0 85.625 0.0 1.135 -16.4
-0.5 1 2 22.0 0.0 1.0 1.5 60.0 0.0 0
COFT .58530 5.1819 -28.767 50.052 0.0
.11279 -1.3489 7.4478 -12.742 0.0
.62030 -4.2025 21.652 -29.334 0.0
.050250 .0061908 -2.6879 1.8936 0.0
.015268 1.8376 -6.2859 14.172 0.0
58.660 205.19 -908.64 917.54 0.0
COFT .70195 2.2484 -9.0865 8.4913 0.0
.081713 -5.8747 2.4241 -2.2573 0.0
.63335 -3.654 16.849 -20.282 0.0
.067330 -2.9097 1.6300 -2.3659 0.0
.059334 .86445 4.8897 -1.1149 0.0
78.519 -64.841 211.86 -393.07 0.0 6
TANK 3 72.2 -26.0 0.024 0.0 0.0 110.952 0.0 0.8 -12.5 -0.5
3 1 22.0 0.0 1.5 0.0 0 0.0 0
COFT .56275 3.3888 -11.600 10.098 0.0
.13063 -1.0174 3.5377 -3.2105 0.0
.72640 -4.0159 15.543 -15.727 0.0
.071197 -2.8072 1.3445 -1.7019 0.0
.096621 4.1188 1.6934 -2.1615 0.0
2.2830 627.76 -2005.4 2011.1 0.0
TANK 4 99.5 -26.0 0.024 0.0 0.0 0.0 0.8 -12.5 -0.5 3 1
21.0 0.0 1.5 0.0 0.0 0.0
COFT -.36862 10.220 -28.089 23.173 0.0
.34632 -2.5861 7.2737 -6.1147 0.0
1.2591 -7.5109 22.699 -20.076 0.0
.076153 -2.3573 .99021 -1.1705 0.0
.34874 -1.4166 6.0476 -5.5705 0.0
-159.97 1780.4 -4662.2 3973.0 0.0
CHANGE 3 2.621 0 0 1
CHANGE 3 3.379 1 6
CHANGE 3 4.624 7 14
CHANGE 3 6.223 15 30
CHANGE 3 9.086 31 59 2
CHANGE 3 17.52 60 97
CHANGE 3 17.52 98 135 3
CHANGE 3 17.52 136 165 4
TRANS1 1 2 .004 -226 1 1 0 .5 .025 180 .04 PREBUNCHER FILE UPDATED JULY7-77.
TRANS1 2 1 22.29 4 3.49 DRIFT
TRANS1 3 3 123.5 14.63 3.49 TDQL01 Q1
TRANS1 4 4 14.65 3 3.49
TRANS1 5 3 -89.9 26.06 3.49 TDQL01 Q2
TRANS1 6 4 14.65 3 3.49
TRANS1 7 3 50.9 14.63 3.49 TDQL01 Q3
TRANS1 8 1 110.16 22 3.49 EM TWO
TRANS1 9 1 23.11 5 3.49
TRANS1 10 3 93.4 14.63 3.49 TDQL02 Q1
TRANS1 11 1 12.88 2 3.49
TRANS1 12 3 -177.8 14.63 3.49 TDQL02 Q2
TRANS1 13 1 20.42 4 3.49
TRANS1 14 3 173.4 14.63 3.49 TDQL02 Q3
TRANS1 15 1 12.88 2 3.49

```

```

TRANS1 16 3 -85.1 14.63 3.49          TDQL02 Q4
TRANS1 17 1 37.42 7 3.49
TRANS1 18 4 -30 -65.2 0 -15          TDBM02
TRANS1 19 1 31.06 6 3.49
TRANS1 20 4 30 50.0 15              TDBM03
TRANS1 21 1 54.0 5 3.49
TRANS1 22 6 .95
TRANS1 23 1 15.24 6 3.49
TRANS1 24 2 .010 -100 1 0 .5 .025 50 .04 BIGBUNCHER
TRANS1 25 1 32.7 6 3.49            EM THREE
TRANS1 26 1 7.7 2 2.22
TRANS1 27 9 -3 0
TRANS1 28 3 -247.3 10.86 2.22      TDQL03 Q1
TRANS1 29 1 6.7 1 2.22
TRANS1 30 9 -3 0
TRANS1 31 3 445.1 10.86 2.22      TDQL03 Q2
TRANS1 32 1 19.36 4 2.22
TRANS1 33 9 -2 0
TRANS1 34 3 -603.8 10.86 2.22      TDQL04 Q1
TRANS1 35 1 6.7 1 2.22
TRANS1 36 9 -2 0
TRANS1 37 3 549.0 10.86 2.22      TDQL04 Q2
TRANS1 38 1 12.30 3 2.22
TRANS1 39 6 .5 0 0 0 0
TRANS1 40 1 14.03 2 2.22 0 0
TRANS1 41 1 9.0 1 .75 0 0 .5 .025 50 .04
APERTURE--AT END OF BB HOLDING EM3 COLL.
DRIFT-SPACE IN FRONT OF COL.
BLZ RADIUS OF BUSH COLLIM.
START 0
STOP 31
INPUT 6 180 0 1 0 0 1 0 180 0 0 0 0 0 0 .0058
OUTPUT 3 1 0 0 0 0 1
OUTPUT 1 1 0 0 0 0 31
OPTCON 1 10 200 0 1.04 0 1 200 0 0 0 0
ELIMIT 1.
ERROR 1 0 1 0
TITLE
SCAN TANK1. B1=.004,-226. B2=.010,-100. 755.8 KEV. T1=1.04,1.02,1.0,-.98,.96
CHANGE 8 1 6.4693 2 6.3535 3 6.4816 4 6.5211 5 7.1177
CHANGE 8 6 7.3601 7 7.5644 8 7.9187 9 8.2084 10 8.4776
CHANGE 8 11 8.7697 12 9.1186 13 9.3747 14 9.6597 15 10.0181
CHANGE 8 16 10.2619 17 10.7138 18 10.9271 19 11.3370 20 11.5580
CHANGE 8 21 11.9885 22 12.3717 23 12.6685 24 13.0757 25 13.4003
CHANGE 8 26 13.7834 27 14.1553 28 14.4878 29 14.8905 30 15.3124
CHANGE 8 31 15.506
CHANGE 7 1 1.7398 2 1.6231 3 1.5166 4 1.6698 5 1.7759
CHANGE 7 6 1.7326 7 1.8885 8 1.7455 9 1.7543 10 1.7294
CHANGE 7 11 1.7439 12 1.7738 13 1.7717 14 1.8527 15 1.8516
CHANGE 7 16 1.8525 17 1.8964 18 1.8784 19 1.9214 20 1.9142
CHANGE 7 21 2.0085 22 2.0110 23 2.0492 24 2.0717 25 2.0885
CHANGE 7 26 2.1479 27 2.1192 28 2.1417 29 2.1988 30 2.2238
CHANGE 7 31 2.1345
CHANGE 7 32 0.9820 33 0.9856 34 0.9900 35 0.9974 36 0.9996
CHANGE 7 37 1.0034 38 0.9919 39 1.0155 40 1.0010 41 0.9983
CHANGE 7 42 0.9920 43 0.9975 44 0.9949 45 1.0021 46 0.9983
CHANGE 7 47 1.0122 48 1.0046 49 1.0080 50 1.0006 51 1.0067
CHANGE 7 52 1.0096 53 1.0196 54 1.0059 55 1.0026 56 1.0034
CHANGE 7 57 1.0213 58 1.0305 59 1.0174 60 1.0184 61 1.0090
CHANGE 7 62 0.9940 63 0.9950 64 1.0042 65 0.9879 66 0.9919
CHANGE 7 67 0.9950 68 0.9914 69 0.9916 70 1.0013 71 1.0128
CHANGE 7 72 1.0063 73 1.0057 74 0.9902 75 0.9991 76 0.9915
CHANGE 7 77 0.9921 78 0.9951 79 0.9913 80 0.9900 81 0.9889
CHANGE 7 82 0.9939 83 0.9968 84 0.9887 85 0.9950 86 0.9987
CHANGE 7 87 0.9943 88 0.9912 89 0.9976 90 0.9971 91 1.0000
CHANGE 7 92 0.9986 93 0.9962 94 0.9910 95 0.9993 96 1.0100
CHANGE 7 97 1.0075 98 0.9954 99 1.0033 100 1.0019 101 1.0003
CHANGE 7 102 1.0011 103 1.0018 104 1.0016 105 1.0019 106 1.0013
CHANGE 7 107 1.0022 108 1.0031 109 1.0047 110 1.0013 111 0.9983
CHANGE 7 112 0.9998 113 1.0015 114 1.0005 115 0.9988 116 0.9985
CHANGE 7 117 1.0005 118 1.0017 119 1.0033 120 1.0023 121 1.0025
CHANGE 7 122 0.9990 123 1.0000 124 1.0001 125 0.9999 126 1.0000
CHANGE 7 127 0.9973 128 0.9974 129 1.0000 130 0.9992 131 0.9945
CHANGE 7 132 0.9979 133 0.9976 134 0.9974 135 0.9898 136 0.9984
CHANGE 7 137 0.9971 138 0.9998 139 0.9983 140 1.0003 141 1.0002
CHANGE 7 142 1.0005 143 1.0012 144 1.0023 145 1.0006 146 0.9963
CHANGE 7 147 0.9986 148 1.0011 149 1.0018 150 1.0006 151 1.0047
CHANGE 7 152 1.0018 153 0.9999 154 1.0013 155 1.0039 156 1.0037
CHANGE 7 157 1.0026 158 1.0039 159 1.0022 160 0.9966 161 0.9959
CHANGE 7 162 0.9946 163 0.9936 164 0.9912 165 1.0050
CHANGE 2 1 7686.62 2 -7562.04 3 7438.59 4 -7298.19 5 7102.73
CHANGE 2 6 -7210.47 7 5389.53 8 -5452.91 9 5335.11 10 -5244.23
CHANGE 2 11 5159.65 12 -5090.56 13 5003.09 14 -5035.74 15 3862.32
CHANGE 2 16 -3906.89 17 3832.56 18 -3776.69 19 3731.91 20 -3628.43
CHANGE 2 21 3645.91 22 -3605.94 23 3574.68 24 -3529.62 25 3509.58
CHANGE 2 26 -3466.95 27 3448.13 28 -3412.97 29 3358.92 30 -3070.22
CHANGE 2 31 2111.51 32 2520.72 33 -2337.51 34 2302.29 35 -2261.32
CHANGE 2 36 2226.14 37 -2182.91 38 2162.17 39 -2130.50 40 2107.48
CHANGE 2 41 -2076.43 42 2063.21 43 -2035.05 44 2019.55 45 -1997.16
CHANGE 2 46 1977.66 47 -1957.02 48 1941.54 49 -1923.79 50 1904.89
CHANGE 2 51 -1886.58 52 1875.15 53 -1842.00 54 1847.71 55 -1816.87
CHANGE 2 56 1824.30 57 -1816.87 58 1790.63 59 -1866.86 60 1070.67
CHANGE 2 61 -1089.03 62 1065.95 63 -1060.18 64 1051.79 65 -1046.02
CHANGE 2 66 1040.25 67 -1030.29 68 1026.36 69 -1018.24 70 1010.12
CHANGE 2 71 -1004.62 72 998.33 73 -991.00 74 984.72 75 -979.48
CHANGE 2 76 972.94 77 -967.18 78 963.26 79 -957.76 80 952.79
CHANGE 2 81 -948.35 82 942.86 83 -938.15 84 931.62 85 -930.57
CHANGE 2 86 924.56 87 -921.42 88 917.24 89 -914.11 90 910.45
CHANGE 2 91 -906.53 92 903.14 93 -898.44 94 892.17 95 -892.69

```

```

CHANGE 2 96 777.81 97 -762.74
CHANGE 2 -1 -4502.54 -2 -2445.62
CHANGE 2 99 -767.93 101 632.2 103 -628.33 105 626.78 107 -622.65 109 619.04
111 -618.5 113 613.62 115 -611.04 117 609.24 119 -605.63 121 602.79
123 -601.5 125 599.95 127 -600.21 129 596.09 131 -595.57 133 570.34
135 -574.71 137 -560.31 139 540.77 141 -540.26 143 539.23 145 -538.46
CHANGE 2 147 537.69 149 -536.66 151 535.89 153 -535.12 155 534.61 157 -534.09
159 533.58 161 -534.09 163 274.17 165 0.0
-3 703.59 -4 544.63
BEGIN
RUN 2 0
START 0
INPUT 6 180 0 1 0 0 1 0 180 0 0 0 0 0 0 .0058
OPTCON 1 10 200 0 1.02 0 1 200 0 0 0 0
OUTPUT 3 1 0 0 0 0 1
BEGIN
RUN 3 0
START 0
INPUT 6 180 0 1 0 0 1 0 180 0 0 0 0 0 0 .0058
OUTPUT 3 1 0 0 0 0 1
OPTCON 1 10 200 0 1.00 0 1 200 0 0 0 0
BEGIN
RUN 4 0
START 0
INPUT 6 180 0 1 0 0 1 0 180 0 0 0 0 0 0 .0058
OPTCON 1 10 200 0 0.98 0 1 200 0 0 0 0
OUTPUT 3 1 0 0 0 0 1
BEGIN
RUN 5 0
START 0
INPUT 6 180 0 1 0 0 1 0 180 0 0 0 0 0 0 .0058
OPTCON 1 10 200 0 .96 0 1 200 0 0 0 0
OUTPUT 3 1 0 0 0 0 1
BEGIN
END

```