THE Δt TURN-ON PROCEDURE*

by

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ABSTRACT

The Δt procedure is used for determining the rf phase and amplitude set points in modules 5 through 12 of LAMPF. The theoretical background as well as the experimental results will be described.

I. INTRODUCTION

The Δt turn-on procedure[1] is the method by which suitable rf amplitude and phase set points are determined for the first 8 modules (modules 5 - 12) of the LAMPF side-coupled linac. The name is derived from the relative time-of-flight measurements that are required. A method such as this must be used because direct field measurements are not sufficiently accurate to determine the rf amplitudes and phases within the required tolerances.

The objective of any turn-on scheme is to keep the beam within the acceptance bucket, the region in longitudinal phase space in which particles will be properly accelerated. Not only should the beam be kept within the acceptance bucket, but it should be kept away from the edge of the bucket so that beam quality is not degraded.

The Δt procedure allows us to determine not only the rf amplitude, but also the phase and energy displacements (from their design values) of the centroid of the beam.

The success of the Δt procedure depends, to a large extent, on the energy structure of the beam being reproducible on a pulse-to-pulse basis, because the measurement involves taking data on 2 separate beam pulses. If strict reproducibility is not possible, then at least the variation must be such that it can be averaged out over several beam pulses.

The other underlying assumption is that the beam can be adequately represented by its centroid. That is, the beam size in longitudinal phase space must not be so large as to seriously perturb the measurements because of nonlinear particle motion about the centroid. Numerical simulation of

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"reasonable" sized beams indicate that this should not be a serious problem.

II. DESCRIPTION OF PROCEDURE

The Δt procedure is a module-by-module operation starting with module 5 and progressing to module 12. The procedure assumes that the rf in all modules upstream to the one being adjusted are "on," the rf in all modules downstream are "off," and the rf in the module being adjusted is alternately "off" and "on" as required. "On" and "off" are accomplished by commanding the rf pulse to occur at the same time a beam pulse occurs, or at a later time.

Figure 1 represents a portion of LAMPF in the vicinity of module N, the module being adjusted. The procedure is based on beam-induced signals from pickup loops at the ends of modules N - 1, N, and N + 1, corresponding to locations A, B, and C, respectively, on the figure.

Let t_{AB} and t_{AC} be the time-of-flight of the beam centroid from locations A to B, and A to C, respectively. The measurement of interest is the change in these quantities when module N is switched from off to on; that is,

$$t_B = t_{AB,off} - t_{AB,on} \quad ;$$

$$t_C = t_{AC,off} - t_{AC,on} \quad .$$

Since these quantities are measures of the change in timing of signals rather than the absolute timing of signals, they are independent of the length of the cables used to gather the signals, and independent of the propagation velocity of the signals in the cables. All that is required is that the transit time of the signals in the cables remain constant (to the accuracy required) for the duration of 2 beam pulses (one for module N off, the other module N on).

The "design" values (the times-of-flight for the so-called "design particle") of t_B and t_C are known quantities. The t_{AB}'s are on the order of 100 nsec; the t_{AC}'s are roughly twice that. The range on t_B and t_C is from 1 to 10 nsec. For module 5, t_B = 2.906 nsec; t_C = 8.869 nsec. The desired accuracy in the measurements of t_B and t_C is on the order of 0.01 nsec.

III. MEASUREMENT OF t_B AND t_C

Since the same technique is used to measure both t_B and t_C, it is adequate to describe only the measurement of t_B. Referring again to Fig. 1, particle bunches pass through the pickup loops at A and B at the rate of one bunch every 5 nsec. This rate is set by the 201.25-MHz frequency at which the first stage of LAMPF is operated. The beam, therefore, induces 201.25-MHz signals in the pickup loops at A and B which are detected and sent to opposite sides of two phase bridges. The path length of the signal from A can be adjusted using the phase shifter t_1.

With module N off, phase shifter t_1 is adjusted until the signal from A just cancels the signal from B, and bridge 1 is at a null. Phase shifter t_2 is then adjusted until bridge 2, which is in parallel with bridge 1, is also at a null. This gives a reference for the time difference measurement. The t_2 phase shifter is then moved a known amount, so that when module N is turned on, bridge 2 will be at a null if t_B corresponds to the design value. In the case of module 5, t_2 would change the path from B to compensate for the 2.906 nsec shorter time-of-flight from A to B when module 5 is accelerating. When module N is turned on, the output of bridge 2 is proportional to Δt_B, the amount that t_B differs from its design value.

IV. RELATING Δt_B AND Δt_C TO $\Delta\phi$ AND ΔW

When module N is off, a particle moving with the "design" velocity, v_A, will travel the distance, D_{AB}, from location A to location B in the time interval

$$t_{AB,off} = D_{AB}/v_A \quad .$$

A particle whose velocity differs slightly from the design value by Δv_A will require a slightly different length of time;

$$t_{AB,off} = D_{AB}/(v_A + \Delta v_A) \approx \frac{D_{AB}}{v_A}\left(1 - \frac{\Delta v_A}{v_A}\right) \quad .$$

When module N is turned on, the design particle takes a known amount of time, t_d, to travel from A to B. The time required for any other particle is

$$t_{AB,on} = t_d + (\Delta\phi_B - \Delta\phi_A)/\omega \quad ,$$

where $\Delta\phi_A$ and $\Delta\phi_B$ are phase displacements from design values at A and B, respectively, and ω is the angular frequency of the rf.

The difference in t_B from its design value, to first order, is

$$\Delta t_B = -D_{AB} \frac{\Delta v_A}{v_A^2} - (\Delta\phi_B - \Delta\phi_A)/\omega \quad .$$

Similarly, it is easy to show that

$$\Delta t_C = \Delta t_B - D_{BC}\left(\frac{\Delta v_A}{v_A^2} - \frac{\Delta v_B}{v_B^2}\right) \quad ,$$

where D_{BC} is the distance from B to C, and v_B is the design velocity at B (module N on). By using the identity,

$$\frac{\Delta v}{v} = \frac{1}{\gamma(\gamma + 1)} \frac{\Delta W}{W} \; ,$$

where W is the kinetic energy, both Δt_B and Δt_C can be expressed as a linear combination of longitudinal phase space coordinates, $\Delta\phi_A$, ΔW_A, $\Delta\phi_B$, and ΔW_B. Also, $\Delta\phi_B$ and ΔW_B are linearly related to $\Delta\phi_A$ and ΔW_A, and the coefficients relating them depend on the amplitude of the rf field. Consequently, Δt_B and Δt_C can be expressed as a linear combination of $\Delta\phi_A$ and ΔW_A:

$$\Delta t_B = b_\phi \Delta\phi_A + b_W \Delta W_A \quad ;$$

$$\Delta t_C = c_\phi \Delta\phi_A + c_W \Delta W_A \quad ;$$

and the coefficients depend on the rf amplitude.

Figure 2 shows how Δt_B and Δt_C depend on $\Delta\phi_A$, ΔW_A, and on E_o, the amplitude of the accelerating field for module 5. Five sets of curves are shown, where each set corresponds to a given initial energy. For the top set, the initial energy is 0.1% low; for the bottom set, it is 0.1% high. Each curve was numerically generated by sweeping the initial phase, ϕ_A, through 10° while holding the amplitude constant. To obtain the 5 separate curves in a set, the amplitude was stepped from 5% low to 5% high in 5 steps.

The variation in the slopes of these constant amplitude curves suggests that the proper accelerating field amplitude can be found by scanning the phase and plotting the measured values of Δt_B and Δt_C. The resultant curve indicates whether the amplitude is high or low. The slope of the curve is simply

$$S_\phi \equiv \frac{\partial t_C}{\partial\phi_A} \bigg/ \frac{\partial t_B}{\partial\phi_A} = c_\phi / b_\phi \quad .$$

In module 5, these curves rotate about their point of intersection at the rate of 7° for each 1% change in amplitude. The rate is 9.4°/% at module 6 and decreases to 1.3°/% at module 12.

It is interesting to note that, at a given initial energy, these curves have a common point of intersection. This point of intersection occurs when $\Delta\phi_B = \Delta\phi_A$ and $\Delta W_B = -\Delta W_A$. The slope, S_i, of the line passing through these points of intersection is simply $\Delta t_C/\Delta t_B$ evaluated at the above conditions. During a measurement, if the intersection point does not lie on the line passing through the origin with slope S_i, this indicates either a systematic error in the measurement or else there are tank-to-tank amplitude and/or phase errors within the module.[2] (Modules 5 through 12 each contain 4 tanks.)

The first step in finding the set points for a module, therefore, is to generate a constant amplitude curve and determine the amplitude from the slope of the curve. The coefficients relating Δt_B and Δt_C to $\Delta\phi_A$ and ΔW_A can then be evaluated, after which the phase and energy displacements can be determined.

V. EXPERIMENTAL RESULTS

The Δt procedure is implemented with the SEL 840-MP controls computer, which is used to take, display, and analyze the data as well as to change the set points and turn the module on and off. Figure 3 shows an example of 2 constant amplitude curves generated by sweeping the phase of module 5. The amplitude set point (ASP), phase set point (PSP) and the measured values of Δt_B and Δt_C are printed at the right of the graph. Each point is the average result of several measurements, and the lengths of the arms on the plotted crosses indicate the standard deviation of the measurements. After data is taken at several different phases, a straight line is fitted to the data, and the slope of this line is used to estimate the rf amplitude. The slopes of the lines in Fig. 3 indicate that an ASP of 1340 is about 5% higher than design, while an ASP of 1280 appears to be close to design. The energy of the beam entering module 5, as determined by this procedure, is 0.08% higher than design.

Although experimental data such as this is not too difficult to obtain at the present time, getting it for the first time was quite a struggle. Based on direct power measurements, module 5 was set at what was thought to be the design rf amplitude. By scanning the phase, a phase interval was found in which beam loading could be detected. When the Δt procedure was tried, the data just did not make sense. The source of the problem was not known; whether it was in the software, in the hardware, in the Δt theory, or in the accelerating tanks themselves. Finally, after the power into module 5 was raised by 25 or 30%, the sought for Δt patterns appeared. The values for the design power had been based on measurements of shunt impedance and Q. The reason for the discrepancy between these measurements and the Δt measurements is unresolved at this writing.

REFERENCES

1. K. R. Crandall, D. A. Swenson, "Side-Coupled Linac Turn-on Problem," Los Alamos Scientific Laboratory, Internal Report, February 9, 1970.

2. K. R. Crandall, "Effects of Tank-to-Tank Amplitude and Phase Errors on Particle Dynamics in the Side-Coupled Linac," Los Alamos Scientific Laboratory, Internal Report, December 9, 1970.

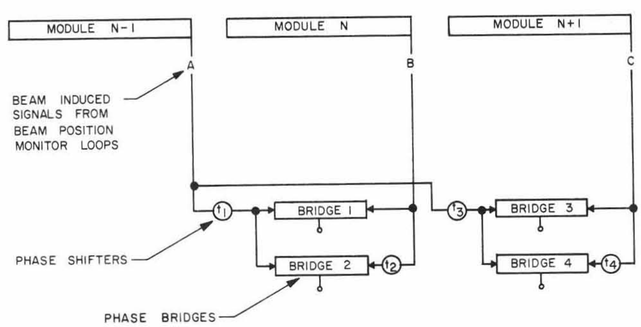

Fig. 1. Turn-on problem for module "N" of side-coupled linac.

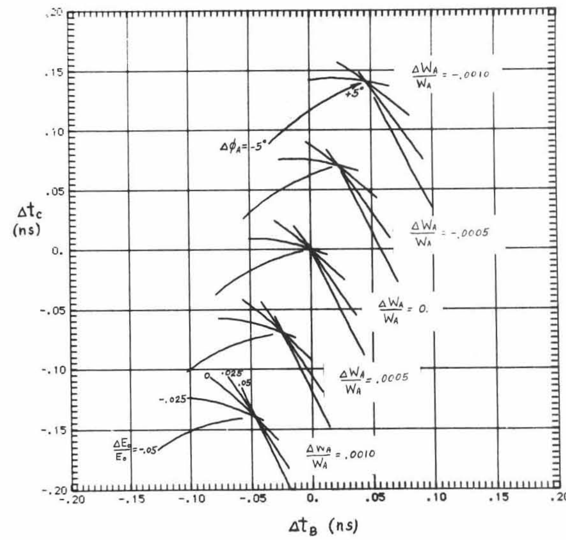

Fig. 2. Constant amplitude curves for module 5.

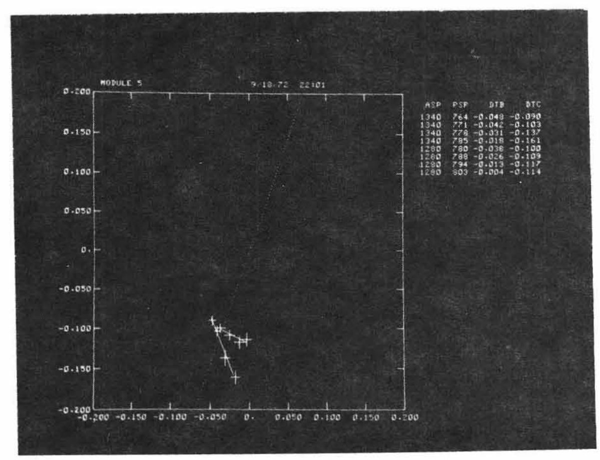

Fig. 3. Constant amplitude curves (Δt_C vs. Δt_B) generated experimentally at module 5.

DISCUSSION

Gregory A. Loew, SLAC: Are the numbers you have on the board based on what you assume the energy was at one point or another, and calculated using time of flight?

Crandall: Yes, that is correct.

Loew: That assumes that you know the lengths of the sections and the positions of your detectors very accurately.

Crandall: Not so accurately because they both use the same path length. A 1-cm error in the path length would only make a 0.005-nsec error in the measurement.

Loew: Could you explain a little better what you did when you varied the amplitude? Do you mean that you change the amplitude of the klystron from zero to maximum and look at the change in energy or the change in phase?

Crandall: No, we had the amplitude set at what we thought was approximately correct. Then we vary the phase to generate a constant-amplitude, variable-phase curve. Then we change the amplitude if it doesn't look right, for example, raise it a few percent and generate another curve. The curves in Fig. 2. give a good idea of what the amplitude is if we are within 5% to start.

Loew: Is this the amplitude of the rf signal from the klystron added to the signal of the beam induced?

Crandall: No, just the set point of the rf cavity field amplitude, which is independent of beam in the cavity.