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The Δt Tuneup Procedure for the LAMPF 805-MHz Linac

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ABSTRACT

An important part of tuning the LAMPF accelerator is the adjustment of the phases and amplitudes in the 805-MHz linac. The technique used is called the Δt procedure because of the time-of-flight measurements that are required. This report presents the theory behind the Δt procedure, a brief description of the hardware, and a description of the many computer programs that have been written to implement the procedure.

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I. INTRODUCTION

The Δt procedure is a technique for adjusting the rf phases and amplitudes throughout the 805-MHz linac. The procedure uses beam induced signals detected at 2 pickup loops downstream of the module being adjusted. The adjustments are based on the phase changes produced in these signals by turning the module off and on.

The Δt procedure was conceived in the late 1960's, and the original work is described in Ref. 1. At that time, it was concluded that the Δt procedure would be useful only in the lower energy portion of the 805-MHz linac. A precise momentum measurement technique was to have been used in most of the linac. Consequently, pickup loops were installed only after modules 5 through 13, enabling the Δt procedure to be used in modules 5 through 12. However, in practice, the momentum measurement technique was found to be highly unsatisfactory, and a new look was taken at the possibility of using the Δt apparatus to tune the entire 805-MHz linac. A feasible method was found in late 1973 and described in Ref. 2. Subsequently, pickup loops were installed after even-numbered modules through the rest of the linac, starting at module 14. Loops were also installed after tanks 2, 3, and 4 of the 201.25-MHz linac.

After the additional pickup loops were installed in 1974, the Δt procedure was successfully used to tune the entire 805-MHz linac, using a set of computer programs which were written to implement the procedure. Since that time, both the Δt hardware and the software have been improved. The Δt procedure was automated in early 1976 and has since been used to tune the entire 805-MHz linac in a small fraction of the time that was previously required. The computer automation of the procedure also provides a consistency in the tuning.

The purpose of this report is to describe in detail the Δt procedure. For completeness, a fairly lengthy discussion is given on the theory behind the procedure, followed by a brief description of the Δt hardware as seen from a user's viewpoint. The bulk of the report is a description of the many computer programs that have been written to implement the procedure, including storage maps for the various disk data files.

II. Δt THEORY

The Δt procedure is a module-by-module operation. 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" or "on" as required. "On" and "off" are accomplished by commanding the rf pulse to occur at the same time a beam pulse occurs, or after the beam pulse has occurred.

Let t_{AB} be the time of flight of the beam centroid through the module being adjusted, where the module extends from location A to location B. In the earlier portion of the side-coupled linac, A and B correspond to the locations of the pickup loops. Where they exist, pickup loops are located 12.5 cm downstream of the end of the last cell in the module. A quantity of interest is the difference in the values obtained for t_{AB} when the module is turned from off to on; namely,

$$t_B = t_{AB,off} - t_{AB,on} . \tag{1}$$

When the module 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

$$t_{AB,off} = D_{AB}/v_A \ . \qquad (2)$$

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

$$t_{AB,off} = \frac{D_{AB}}{v_A+\Delta v_A} \approx \frac{D_{AB}}{v_A}\left(1 - \frac{\Delta v_A}{v_A}\right) \ . \qquad (3)$$

When the module 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

$$t_{AB,on} = t_d + (\Delta\phi_B - \Delta\phi_A)/\omega, \qquad (4)$$

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 quantity $\Delta\phi_A/\omega$ is simply a measure of how much later the particle left location A than did the design particle, and the quantity $\Delta\phi_B/\omega$ is simply a measure of how much later the particle arrives at B than does the design particle. The complicated acceleration process in the module makes no difference.

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

$$\Delta t_B = - D_{AB}\frac{\Delta v_A}{v_A^2} - (\Delta\phi_B - \Delta\phi_A)/\omega \ . \qquad (5)$$

Using the identities

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

$$v = \beta c \ ;$$

$$W = E_r(\gamma-1) \ ;$$

and $$\eta^2 = (\beta\gamma)^2 = \gamma^2-1 \ , \qquad (6)$$

where W is the kinetic energy, E_r is the rest energy of the particle, c is the velocity of light, and β and γ are the usual relativistic parameters, Δt_B can be written as

$$\Delta t_B = - \frac{D_{AB}}{E_r c\eta_A{}^3}\,\Delta W_A - (\Delta\phi_B - \Delta\phi_A)/\omega \ . \qquad (7)$$

If the first pickup loop following the module is at location B (as it is in modules 5 through 14), then the above equation is one of the two that are required. If the first pickup loop is farther downstream by one module, as it is in the odd numbered modules after module 13, then an additional term is required. To be general, let the first loop be a distance D_1 downstream of location B, where D_1 may or may not be zero. Because of common usage, however, the deviation from the difference in the design values of the arrival times at the first pickup loop will still be denoted by Δt_B, whether or not the pickup loop is at location B. The A and B subscripts on the phase and energy displacements will still denote these displacements at the entrance and exit of the module, respectively.

The general expression for Δt_B is, then,

$$\Delta t_B = - \frac{D_{AB}}{E_r c\eta_A{}^3}\,\Delta W_A - \frac{(\Delta\phi_B - \Delta\phi_A)}{\omega} - \frac{D_1}{E_r c}\left(\frac{\Delta W_A}{\eta_A{}^3} - \frac{\Delta W_B}{\eta_B{}^3}\right). \qquad (8)$$

The second pickup loop is located at a point designated by C. In modules 5 through 13, the second loop is one module downstream of the first loop; beyond module 14, the second loop is *two* modules downstream of the first loop. Let the distance from B (the end of the module being adjusted) to C be D_2. The distance between the two loops is then D_2-D_1, and

$$\Delta t_C = \Delta t_B - \frac{(D_2-D_1)}{E_r c}\left(\frac{\Delta W_A}{\eta_A{}^3} - \frac{\Delta W_B}{\eta_B{}^3}\right). \qquad (9)$$

We now have two equations relating Δt_B and Δt_C to the phase and energy displacements at the entrance and exit of the module. In addition, the output phase and energy displacements, $\Delta\phi_B$ and ΔW_B, are related in a known (calculable) way to the input phase and energy displacements, $\Delta\phi_A$ and ΔW_A, assuming that the accelerating field amplitude is known. Clearly, if the input displacements are zero, then the output displacements must also be zero. A particle with zero input displacements is the design particle and obviously exits from the module with zero displacements from itself. For

*This statement assumes that the lengths of the tanks and the drifts between tanks within the module are known to a sufficient accuracy. It was discovered that the actual tank and drift lengths differed significantly from their design values. All lengths were then measured, and the measured values were used in determining a "compromise" design.

small displacements, $\Delta\phi_B$ and ΔW_B are linearly related to $\Delta\phi_A$ and ΔW_A:

$$\begin{pmatrix} \Delta\phi_B \\ \Delta W_B \end{pmatrix} = M \begin{pmatrix} \Delta\phi_A \\ \Delta W_A \end{pmatrix} , \tag{10}$$

where M is the transformation matrix through the module.

The elements of M are the partial derivatives of the output displacements with respect to the input displacements, and are calculated by the same beam dynamics computer program that is used to determine the design particle and to calculate the design times of flight. These elements depend, also in a calculable way, on the accelerating field amplitude.

Using the relationships between the output and input phase and energy displacements, Δt_B and Δt_C can be expressed as a linear combination of the input displacements alone. In matrix notation,

$$\begin{pmatrix} \Delta t_B \\ \Delta t_C \end{pmatrix} = T \begin{pmatrix} \Delta\phi_A \\ \Delta W_A \end{pmatrix} , \tag{11}$$

with the elements of the T matrix defined as follows:

$$t_{11} = \frac{1-m_{11}}{\omega} + \frac{D_1 m_{21}}{E_r c \eta_B^3} ; \tag{12}$$

$$t_{12} = -\frac{m_{12}}{\omega} - \frac{D_{AB}}{E_r c \eta_A^3} - \frac{D_1}{E_r c}\left(\frac{1}{\eta_A^3} - \frac{m_{22}}{\eta_B^3}\right); \tag{13}$$

$$t_{21} = \frac{1-m_{11}}{\omega} + \frac{D_2 m_{21}}{E_r c \eta_B^3} ; \tag{14}$$

$$t_{22} = -\frac{m_{12}}{\omega} - \frac{D_{AB}}{E_r c \eta_A^3} - \frac{D_2}{E_r c}\left(\frac{1}{\eta_A^3} - \frac{m_{22}}{\eta_B^3}\right) . \tag{15}$$

Since Δt_B and Δt_C are the quantities that are measured, it is useful to solve for $\Delta\phi_A$ and ΔW_A in terms of Δt_B and Δt_C. If we define the matrix A to be the inverse of the matrix T, then

$$\begin{pmatrix} \Delta\phi_A \\ \Delta W_A \end{pmatrix} = A \begin{pmatrix} \Delta t_B \\ \Delta t_C \end{pmatrix} . \tag{16}$$

The phase and energy displacements at the exit of the module can also be solved for in terms of Δt_B and Δt_C. Since

$$\begin{pmatrix} \Delta\phi_B \\ \Delta W_B \end{pmatrix} = M \begin{pmatrix} \Delta\phi_A \\ \Delta W_A \end{pmatrix} , \tag{17}$$

then

$$\begin{pmatrix} \Delta\phi_B \\ \Delta W_B \end{pmatrix} = B \begin{pmatrix} \Delta t_B \\ \Delta t_C \end{pmatrix} , \tag{18}$$

where

$$B = MA . \tag{19}$$

Measured values of Δt_B and Δt_C can then be translated into calculated values for $\Delta\phi_A$, ΔW_A, $\Delta\phi_B$, and ΔW_B using the above equations.

As was mentioned earlier, the elements of the M matrix, which relate $\Delta\phi_B$ and ΔW_B to $\Delta\phi_A$ and ΔW_A, depend on the accelerating field amplitude. Consequently, in order for the calculations of the phase and energy displacements to be valid, either

1) the amplitude must be set correctly; or
2) the amplitudes must be measured or estimated, so that the elements of the M matrix can be evaluated correctly.

In the early modules (5 through 12) of the side coupled linac, the M matrix depends strongly on amplitude. This dependence weakens as the module number increases.

In the early modules, there are at least two ways to estimate the rf amplitude by using the time-of-flight measurements. One way (the first way that was used in practice) is to calculate the slope of the curve that is generated on the Δt_B, Δt_C plane as the input phase is varied in the vicinity of the design phase. That slope is simply

$$S = \frac{\partial t_C/\partial\phi_A}{\partial t_B/\partial\phi_A} \tag{20}$$

$$= t_{21}/t_{11}$$

Since the rate of change of the M matrix elements with respect to the rf amplitude can be calculated numerically, one can also calculate the change in S as a function of amplitude. By measuring S and finding its deviation from design, one can then calculate the approximate deviation in the rf amplitude.

A second way (the one being used at this writing) is to measure the change in energy out of the module as the input phase is changed. This quantity is, in fact, the m_{21} element of the M matrix. The energy change is calculated from the measured changes in the arrival times at the pickup loops when the module is on. The energy change could also be obtained by measuring changes in t_B and t_C, but there is no need to turn the module alternately off and on for this measurement. If t_1 and t_2 are the arrival times of the beam at loop 1 and loop 2, respectively, when the module is on, and D is the distance between the loops, then the energy change from some initial value is

$$\Delta W = - E_r c \eta_B{}^3 (\Delta t_2 - \Delta t_1)/D. \quad (21)$$

It should be emphasized that this is a measurement of the change in energy, not an absolute energy measurement. If the "clocks" represented by t_1 and t_2 could be synchronized with sufficient accuracy, then an absolute energy measurement could be made.

It may be appropriate at this point to see what can be accomplished with the tools that have been developed thus far. In Table I, for each of the modules in the side-coupled linac, calculated or measured values are given for a number of quantities defined earlier: The elements of the M matrix and their derivatives with respect to the rf amplitude; the distances D_{AB}, D_1, and D_2; the slope S and its derivative S', with respect to the amplitude; the design values for t_B and t_C; the design values for the input and output energies and their corresponding values of η.

The units of these quantities are:

m_{11} - unitless (deg/deg or radian/radian);
m_{21} - MeV/radian;
m_{12} - radian/MeV;
m_{22} - unitless (MeV/MeV);
m'_{ij} - the change in m_{ij} per unit (100%) change in the rf amplitude;
D_{AB} - cm;
D_1 - cm;
D_2 - cm;
S - unitless;
S' - the change in S per unit change in the rf amplitude;
t_B and t_C - nanoseconds (these times are modulo τ, but kept between $-\tau/2$ and $+\tau/2$, where τ is the period of the signal induced by the beam (1/.20125) ns);
W_A and W_B - MeV;
η_A and η_B - unitless.

The elements of the T and the U matrices are given in Table II, where T is as previously defined, and U is the matrix relating Δt_B and Δt_C to $\Delta\phi_B$ and ΔW_B. The units of these quantities are:

t_{11}, t_{21}, u_{11}, u_{21} - picoseconds/degree;
t_{12}, t_{22}, u_{12}, u_{22} - picoseconds/% energy displacement.

The elements of the inverses of the above matrices are given in Table III, in units of degrees per picosecond and % energy displacement per picosecond. From these values one can obtain the relationship between the uncertainties in the calculated displacements ($\Delta\phi_A$, ΔW_A, $\Delta\phi_B$, ΔW_B) and the uncertainties of the measured times (Δt_B, Δt_C). Let δt_B and δt_C be the uncertainty in the measurements of Δt_B and Δt_C, respectively. Then the uncertainty in the calculation of $\Delta\phi_A$ will be

$$\delta\phi_A = a_{11}\delta t_B + a_{12}\delta t_C \quad . \quad (22)$$

If the uncertainty in the measured values is random with an average of zero, then so is the uncertainty in $\Delta\phi_A$. A useful quantity is the root mean square of the uncertainty in $\Delta\phi_A$, which is the square root of the average (expected) value of $(\delta_A)^2$:

$$\sqrt{\langle(\delta\phi_A)^2\rangle} = \sqrt{a_{11}^2\langle(\delta t_B)^2\rangle + 2a_{11}a_{12}\langle\delta t_B \delta t_C\rangle + a_{12}^2\langle(\delta t_C)^2\rangle} \quad (23)$$

Assuming that the errors in the measurements are independent with averages of zero, then the middle term on the right vanishes. Also, assuming that the uncertainties in the two measurements are the same (one can be measured just as well as the other), then

TABLE I

Δt PARAMETERS

MJD	M11	M21	M12	M22	MP11	MP21	MP12	MP22	DAB
	D1	D2	S	SP	TB	TC	WA	WB	ETAA	ETAB
5	-.5968	-1.2674	.4761	-.6616	5.210	-13.780	2.402	10.069	1484.7
	.0	1509.5	-.67	-23.60	-2.004	-1.021	100.0	113.0	.4738	.5053
6	-.8381	-1.0859	.2354	-.8806	3.190	-16.939	3.470	5.668	1509.5
	.0	1577.4	-.09	-18.93	2.439	-2.312	113.0	126.0	.5053	.5354
7	-.9435	-.7429	.2462	-.8627	2.286	-16.675	2.569	4.172	1577.4
	.0	1566.5	.40	-14.08	2.196	1.742	126.0	139.5	.5354	.5653
8	-1.0315	-.6371	.1592	-.8687	1.559	-15.743	1.999	2.290	1566.5
	.0	1626.8	.56	-11.12	1.882	.998	139.5	153.3	.5653	.5945
9	-1.0265	.1341	.0799	-.9810	.254	-16.783	2.476	.659	1626.8
	.0	1600.8	1.08	-9.78	1.801	.520	153.3	167.9	.5945	.6245
10	-.9843	.3962	-.0624	-.9867	-1.269	-15.401	2.309	-.697	1600.8
	.0	1650.9	1.21	-8.43	1.489	-.290	167.9	182.1	.6245	.6525
11	-1.0128	.9114	-.0546	-.9353	-1.509	-13.799	1.943	-1.142	1650.9
	.0	1697.6	1.44	-6.97	1.367	-.642	182.1	196.6	.6525	.6804
12	-.8784	1.2655	-.0707	-1.0335	-2.202	-13.668	1.902	-1.293	1697.6
	.0	1523.6	1.52	-6.22	1.297	-1.270	196.6	211.4	.6804	.7081
13	-.4885	2.4363	-.2598	-.7461	-4.363	-4.198	2.014	-5.676	1523.6
	.0	1515.3	2.12	-5.21	1.057	-1.719	211.4	226.7	.7081	.7360
14	-.5401	2.7618	-.2008	-.8226	-3.665	-5.245	1.388	-3.501	1515.3
	.0	3053.9	3.25	-9.63	.895	-.296	226.7	241.2	.7360	.7617
15	-.3932	3.1741	-.2502	-.5192	-4.380	.432	1.401	-5.314	1526.5
	1557.4	4761.9	2.16	-1.52	-2.254	1.536	241.2	256.7	.7617	.7887
16	-.5102	3.3206	-.1936	-.6979	-3.455	-3.632	1.020	-3.319	1557.4
	.0	3234.5	3.35	-7.94	.777	-.899	256.7	271.6	.7887	.8140
17	-.4770	3.6671	-.1952	-.5056	-3.515	-1.594	.929	-3.545	1587.9
	1616.6	4632.4	2.10	-1.38	2.291	.418	271.6	286.9	.8140	.8396
18	-.3479	3.9760	-.2033	-.5478	-3.778	.675	.895	-3.936	1616.6
	.0	3215.8	3.63	-6.93	.710	-1.351	286.9	302.6	.8396	.8655
19	-.2369	4.2731	-.2189	-.3065	-3.902	5.898	.793	-4.447	1595.6
	1520.2	4927.6	2.20	-.91	1.990	-.236	302.6	318.5	.8655	.8912
20	-.2213	4.5596	-.1993	-.3806	-3.573	4.463	.570	-3.788	1620.2
	.0	3287.4	3.69	-5.64	.591	-1.892	318.5	334.2	.8912	.9161
21	-.1714	4.8349	-.1970	-.2711	-3.581	6.836	.615	-3.922	1645.2
	1642.2	4939.7	2.19	-.80	1.738	-.871	334.2	350.3	.9161	.9414
22	-.1765	5.2934	-.1787	-.2995	-3.283	6.487	.517	-3.419	1642.2
	.0	3297.5	3.96	-4.63	.513	-2.306	350.3	366.2	.9414	.9659
23	-.1748	5.6418	-.1679	-.2957	-3.107	6.563	.455	-3.163	1664.9
	1632.6	4956.2	2.21	-.73	1.401	-1.508	366.2	382.1	.9659	.9901
24	-.0162	5.6255	-.1709	-.1668	-3.108	10.053	.403	-3.275	1632.6
	.0	3523.5	4.28	-4.36	.436	2.280	382.1	397.8	.9901	1.0137
25	.0835	5.6790	-.1760	-.0139	-3.218	14.100	.389	-3.631	1652.8
	1670.8	5055.7	2.27	-.49	1.337	-1.784	397.8	414.3	1.0137	1.0383

MOD	M11	M21	M12	M22	MP11	MP21	MP12	MP22	DAB
D1	D2	S	SP	TB	TC	WA	WB	ETAA	ETAB
26	.0697	6.0652	-.1650	-.0251	-3.016	13.539	.341	-3.313	1670.8
.0	3394.9	4.32	-3.35	.400	2.108	414.3	430.7	1.0363	1.0624
27	.0993	6.3430	-.1577	-.0124	-2.925	14.292	.310	-3.192	1688.8
1706.1	5111.5	2.25	-.46	1.186	-2.174	430.7	447.2	1.0624	1.0864
28	.1239	6.5711	-.1517	.0147	-2.831	15.022	.281	-3.081	1706.1
.0	3405.4	4.36	-3.17	.362	1.877	447.2	463.7	1.0864	1.1103
29	.1092	6.9352	-.1435	.0361	-2.674	14.969	.250	-2.871	1723.0
1682.4	5091.0	2.25	-.40	1.037	2.452	463.7	480.2	1.1103	1.1339
30	.2753	6.7653	-.1424	.1294	-2.630	18.652	.222	-2.920	1682.4
.0	3408.6	4.69	-3.22	.313	1.638	480.2	496.7	1.1339	1.1571
31	.2942	6.7227	-.1393	.2125	-2.547	19.835	.204	-2.872	1697.3
1711.3	5115.6	2.27	-.30	.939	2.209	496.7	513.4	1.1571	1.1806
32	.3120	7.0129	-.1328	.2166	-2.460	20.335	.186	-2.753	1711.3
.0	3404.3	4.58	-2.42	.286	1.484	513.4	530.2	1.1806	1.2040
33	.3076	7.3226	-.1256	.2584	-2.350	20.482	.161	-2.546	1696.1
1708.2	5104.0	2.27	-.27	.836	1.962	530.2	546.9	1.2040	1.2271
34	.3998	7.1145	-.1235	.2995	-2.369	23.128	.154	-2.621	1700.2
.0	3395.8	4.70	-2.58	.268	1.362	546.9	564.2	1.2271	1.2507
35	.4094	7.1055	-.1200	.3573	-2.282	23.818	.143	-2.539	1721.4
1674.4	5055.3	2.28	-.24	.773	1.815	564.2	581.6	1.2507	1.2744
36	.4444	7.3326	-.1124	.3937	-2.061	23.786	.116	-2.272	1674.4
.0	3380.9	4.68	-1.71	.225	1.169	581.6	598.3	1.2744	1.2969
37	.4501	7.6302	-.1075	.3970	-1.984	23.974	.106	-2.174	1685.4
1695.5	5116.9	2.31	-.21	.662	1.567	598.3	615.0	1.2969	1.3193
38	.4539	7.9906	-.1028	.3916	-1.907	23.985	.097	-2.072	1695.5
.0	3421.4	4.73	-1.83	.204	1.056	615.0	631.5	1.3193	1.3413
39	.4954	7.8973	-.1001	.4205	-1.876	25.262	.091	-2.054	1705.6
1715.8	5175.2	2.32	-.24	.613	1.449	631.5	648.3	1.3413	1.3636
40	.5125	7.7579	-.0973	.4761	-1.825	26.322	.085	-2.316	1715.8
.0	3459.4	4.72	-1.30	.192	1.002	648.3	665.4	1.3636	1.3862
41	.5057	8.3027	-.0927	.4543	-1.745	25.880	.077	-1.903	1725.0
1734.4	5229.6	2.31	-.19	.563	1.329	665.4	682.3	1.3862	1.4082
42	.5267	8.4189	-.0896	.4642	-1.698	26.444	.072	-1.851	1734.4
.0	3495.2	4.82	-1.70	.176	.911	682.3	699.2	1.4082	1.4303
43	.5327	8.4624	-.0667	.4949	-1.641	26.904	.066	-1.792	1743.2
1752.0	5156.8	2.27	-.15	.522	1.210	699.2	716.2	1.4303	1.4523
44	.5679	8.4020	-.0642	.5133	-1.611	28.013	.063	-1.769	1752.0
.0	3404.6	4.71	-1.46	.165	.831	716.2	733.4	1.4523	1.4746
45	.6029	8.2395	-.0796	.5692	-1.460	28.087	.052	-1.612	1698.7
1706.1	5139.6	2.32	-.12	.456	1.077	733.4	750.1	1.4746	1.4960
46	.5960	8.7606	-.0763	.5555	-1.404	27.778	.048	-1.535	1706.1
.0	3433.5	4.84	-1.16	.139	.724	750.1	766.5	1.4960	1.5170
47	.6116	8.7671	-.0740	.5707	-1.367	28.295	.045	-1.497	1713.1
1720.4	3330.8	1.62	-.06	.418	.683	766.5	783.0	1.5170	1.5380
48	.6372	8.5661	-.0722	.5984	-1.339	29.246	.043	-1.478	1720.4
.0	1610.4	2.80	-.50	.132	.391	783.0	799.8	1.5380	1.5593

TABLE II

ELEMENTS OF THE T AND U MATRICES

MOD	T11	T12	T21	T22	U11	U12	U21	U22
5	5.5	-594.3	-3.7	-1369.8	-16.7	228.6	-27.9	1039.3
6	6.3	-522.5	-.6	-1377.1	-14.4	383.0	-22.7	1305.3
7	6.7	-521.8	2.7	-1314.3	-11.2	414.4	-15.9	1323.7
8	7.0	-474.1	3.9	-1254.5	-9.9	440.4	-13.5	1369.9
9	7.0	-446.1	7.5	-1212.7	-6.2	449.7	-5.6	1310.7
10	6.8	-371.7	8.3	-1126.4	-5.2	443.0	-3.6	1261.3
11	6.9	-365.0	10.0	-1086.8	-3.3	443.1	.1	1253.6
12	6.5	-349.2	9.9	-997.2	-2.8	386.4	1.0	1029.1
13	5.1	-213.9	10.9	-747.8	.5	286.0	6.9	760.8
14	5.3	-216.3	17.3	-1302.5	.2	272.1	13.5	1229.0
15	11.1	-620.3	23.9	-1532.9	8.5	667.7	22.8	1524.4
16	5.2	-191.5	17.5	-1165.9	.7	260.6	14.2	1156.2
17	11.3	-523.1	23.8	-1505.9	8.1	678.6	21.8	1523.0
18	4.7	-163.2	16.9	-994.4	1.4	224.1	14.8	961.3
19	10.2	-478.1	22.5	-1176.8	8.7	513.6	22.1	1158.4
20	4.2	-133.7	16.4	-844.0	1.8	192.1	15.0	822.3
21	9.9	-441.2	21.8	-1076.1	8.5	473.1	21.3	1057.1
22	4.1	-121.4	16.1	-750.2	2.0	174.8	15.0	742.0
23	9.9	-419.6	21.9	-1031.6	8.3	442.4	21.3	995.2
24	3.5	-99.4	15.0	-645.5	2.0	136.9	14.4	598.9
25	8.4	-315.7	19.1	-782.5	7.8	324.8	19.3	731.2
26	3.2	-84.7	13.9	-541.9	2.1	124.7	13.5	525.7
27	8.3	-301.7	18.8	-741.5	7.7	306.3	18.6	683.6
28	3.0	-77.4	13.2	-493.7	2.0	112.1	12.9	467.9
29	8.0	-271.7	18.1	-668.3	7.4	287.0	18.1	639.7
30	2.5	-61.8	11.7	-412.4	1.8	93.8	11.7	358.5
31	6.8	-212.7	15.4	-523.0	6.5	213.1	15.6	472.6
32	2.4	-55.0	10.9	-355.5	1.8	78.1	10.8	324.0
33	6.6	-191.0	14.9	-468.3	6.3	198.9	15.2	439.8
34	2.1	-46.2	9.7	-302.4	1.7	63.7	9.8	264.3
35	5.6	-155.3	12.8	-385.9	5.4	158.3	13.1	349.6
36	1.9	-38.0	9.0	-249.6	1.6	56.5	9.0	231.7
37	5.4	-140.1	12.4	-347.9	5.3	139.6	12.7	310.9
38	1.9	-36.4	8.9	-240.8	1.6	53.1	9.0	219.5
39	5.1	-129.4	11.7	-322.5	5.0	122.4	12.0	273.0
40	1.7	-31.3	7.9	-203.2	1.5	46.0	8.0	187.6
41	4.9	-116.5	11.4	-294.5	4.8	116.3	11.6	258.9
42	1.6	-29.8	7.9	-198.9	1.4	42.6	7.9	175.5
43	4.6	-106.7	10.5	-259.3	4.6	106.3	10.7	231.3
44	1.5	-26.4	7.0	-170.6	1.3	37.5	7.1	149.6
45	4.0	-85.6	9.2	-212.8	3.9	63.2	9.4	184.3
46	1.4	-22.7	8.7	-150.5	1.2	32.9	6.8	134.3
47	3.9	-82.3	6.3	-139.2	3.9	78.7	6.4	123.3
48	1.3	-19.9	3.5	-72.3	1.1	28.5	3.5	69.0

$$\sqrt{\left\langle(\delta\phi_A)^2\right\rangle} = \sqrt{a_{11}^2 + a_{12}^2}\,\sqrt{\left\langle(\delta t)^2\right\rangle} \quad . \qquad (24)$$

From the above expression, and from similar expressions for the uncertainties in ΔW_A, $\Delta\phi_B$, and ΔW_B, one can estimate the accuracy one can expect for these quantities for a given accuracy in the Δt measurement. The specification on the Δt hardware is that the time differences must be measured to within one degree at 201.25 MHz, which corresponds to 13.8 picoseconds. The resultant uncertainties in the input and output phase and energy displacements are shown in Fig. 1, in which the plot symbols A and B denote input and output values, respectively.

The size of the entire longitudinal acceptance bucket of the side-coupled linac is on the order of ±30 degrees by ±1% energy displacement. Consequently, the displacement of the beam centroid should be kept within a few degrees (perhaps 5) and 0.1 or 0.2 percent in energy. A quick glance at Fig. 1 will show why the Δt pickup loops were initially put only in the lower portion of the side-coupled linac; the uncertainties in the calculated displacements

TABLE III

ELEMENTS OF THE A AND B MATRICES

MOD	A11	A12	A21	A22	B11	B12	B21	B22
5	.141	-.061	-.0004	-.0006	-.094	.021	-.0025	.0015
6	.152	-.058	-.0001	-.0007	-.129	.038	-.0022	.0014
7	.178	-.071	.0004	-.0009	-.161	.050	-.0019	.0014
8	.181	-.068	.0006	-.0010	-.180	.058	-.0018	.0013
9	.237	-.087	.0015	-.0014	-.233	.080	-.0010	.0011
10	.244	-.080	.0018	-.0015	-.251	.088	-.0007	.0010
11	.279	-.094	.0026	-.0018	-.297	.105	.0000	.0008
12	.330	-.115	.0033	-.0021	-.316	.119	.0003	.0009
13	.494	-.141	.0072	-.0034	-.468	.176	.0043	-.0003
14	.409	-.068	.0054	-.0017	-.362	.080	.0040	-.0001
15	.726	-.294	.0113	-.0052	-.677	.297	.0101	-.0038
16	.426	-.070	.0064	-.0019	-.399	.090	.0049	-.0002
17	.664	-.275	.0105	-.0050	-.635	.283	.0091	-.0034
18	.532	-.087	.0090	-.0025	-.487	.114	.0075	-.0007
19	.932	-.379	.0179	-.0081	-.871	.386	.0166	-.0065
20	.618	-.098	.0120	-.0031	-.573	.134	.0105	-.0012
21	.977	-.400	.0198	-.0090	-.913	.409	.0184	-.0073
22	.686	-.111	.0147	-.0037	-.648	.153	.0131	-.0017
23	.978	-.398	.0208	-.0094	-.903	.402	.0193	-.0076
24	.836	-.129	.0195	-.0045	-.744	.173	.0179	-.0025
25	1.405	-.567	.0343	-.0151	-1.258	.559	.0331	-.0134
26	.959	-.150	.0245	-.0057	-.894	.212	.0230	-.0035
27	1.435	-.584	.0364	-.0161	-1.273	.570	.0351	-.0143
28	1.042	-.163	.0278	-.0064	-.951	.228	.0262	-.0041
29	1.469	-.597	.0398	-.0177	-1.357	.609	.0364	-.0157
30	1.349	-.202	.0384	-.0082	-1.133	.265	.0369	-.0058
31	1.958	-.796	.0577	-.0254	-1.710	.771	.0566	-.0234
32	1.442	-.223	.0441	-.0096	-1.272	.307	.0425	-.0072
33	2.017	-.823	.0644	-.0284	-1.836	.830	.0633	-.0263
34	1.715	-.262	.0552	-.0117	-1.451	.350	.0538	-.0092
35	2.400	-.972	.0796	-.0349	-2.107	.954	.0788	-.0328
36	1.815	-.276	.0652	-.0139	-1.636	.399	.0638	-.0112
37	2.635	-1.061	.0943	-.0408	-2.288	1.027	.0935	-.0388
38	1.868	-.283	.0691	-.0146	-1.656	.401	.0676	-.0118
39	2.910	-1.168	.1060	-.0456	-2.397	1.074	.1053	-.0435
40	2.167	-.333	.0846	-.0179	-1.948	.477	.0834	-.0151
41	2.989	-1.203	.1152	-.0498	-2.561	1.151	.1146	-.0476
42	2.203	-.330	.0872	-.0181	-1.895	.460	.0858	-.0151
43	3.213	-1.323	.1298	-.0573	-2.796	1.285	.1291	-.0550
44	2.474	-.383	.1019	-.0216	-2.116	.530	.1006	-.0185
45	3.869	-1.560	.1676	-.0723	-3.273	1.477	.1674	-.0701
46	2.659	-.402	.1191	-.0246	-2.320	.568	.1178	-.0214
47	5.768	-3.412	.2624	-.1624	-5.000	3.191	.2596	-.1575
48	3.472	-.954	.1684	-.0601	-3.244	1.339	.1636	-.0530

soon become overwhelming. (Values lying outside of the graph areas are plotted at the boundary.)

How, then, can the Δt measurements be used successfully to tune the higher modules, where the uncertainties are so large? First of all, it is instructive to explore why the uncertainties grow as large as they do.

In a single module tuneup procedure, the incoming energy displacement, ΔW_A, is not a quantity that can be adjusted; only $\Delta\phi_A$ can be adjusted. (The rf amplitude can also be adjusted, but, for small adjustments, the phase and amplitude knobs are somewhat interchangeable; they both accomplish the same end as far as the beam centroid is concerned. However, the amplitudes of the modules should be constant (or smoothly varying) along the linac so that the longitudinal acceptance of each module will be well matched to that of its neighboring modules.) Consequently, as $\Delta\phi_A$ is varied for tuning the module, a line, defined by ΔW_A = constant, is generated on the $(\Delta t_B, \Delta t_C)$ plane:

$$a_{21}\Delta t_B + a_{22}\Delta t_C = \text{constant.} \quad (25)$$

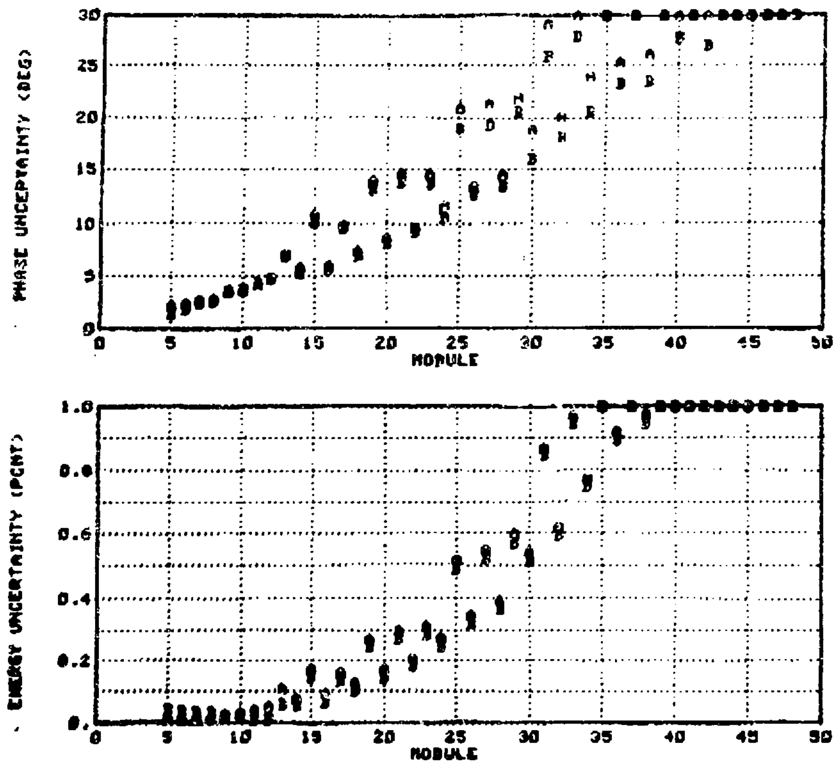

Fig. 1. Uncertainties in the input (A) and output (B) phase and energy displacements, assuming a 13.8-picosecond (1 degree at 201.25 MHz) uncertainty in the measurements of Δt_B and Δt_C.

As the phase is adjusted, the measured point moves along the line defined above until it intersects another line which defines the condition desired, for example, $\Delta\phi_A = 0$:

$$a_{11}\Delta t_B + a_{12}\Delta t_C = 0. \tag{26}$$

The problem arises because, as the module number is increased, the lines defined by $\Delta\phi_A = 0$, and ΔW_A = constant, become more nearly parallel. Consequently, small measurement errors will have a drastic effect on the point at which these 2 lines intersect.

Any practical turn-on procedure should be stable: That is, in the absence of measurement errors, the procedure should produce an output energy displacement that is less than the input energy displacement. The condition specified by $\Delta\phi_A = 0$ is always stable. The most stable condition (when it is achievable) is defined by $\Delta W_B = 0$. Unfortunately, over most of the linac, the line defined by $\Delta W_B = 0$ is even more nearly parallel to the line defined by ΔW_A = constant than is the $\Delta\phi_A = 0$ line, and measurement errors dominate the results.

It was recognized early in the game that the condition defined by $\Delta t_B = 0$ was also stable, but that uncertainties in the measurements made this condition unusable in the higher energy portion of the linac. It was also known that the condition defined by $\Delta t_C = 0$ was near the edge of stability, and was discarded for that reason. (At that time, the measurement loops were considered to be at the end of each module.) A further examination of the Δt procedure in late 1973, showed that the condition $\Delta t_C = 0$ should produce satisfactory results over most of the linac, especially when the C loop is located 2 or 3 modules downstream of the module being adjusted. In fact, the results found at that time can be summarized as follows: As the pickup loop is moved farther downstream, the condition defined by $\Delta t = 0$ at that loop more nearly approaches the stability limit, and simultaneously, the effects of

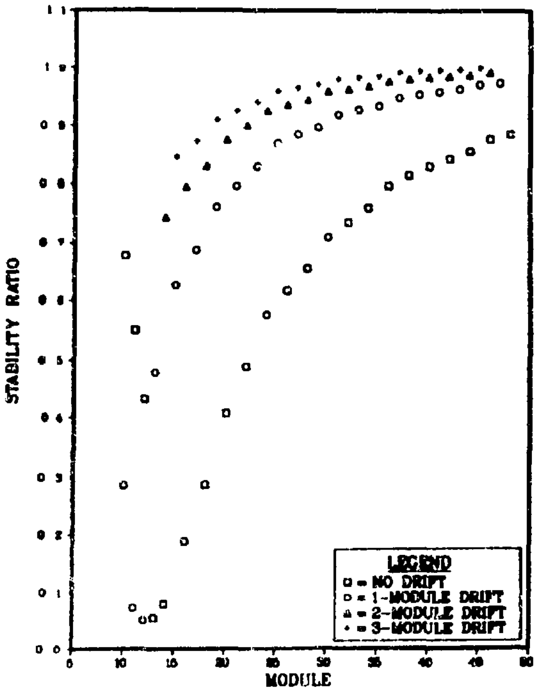

Fig. 2. Absolute value of the percentage energy displacement ratio obtained by adjusting the phase until $\Delta t = 0$. Stability limit is at 1.

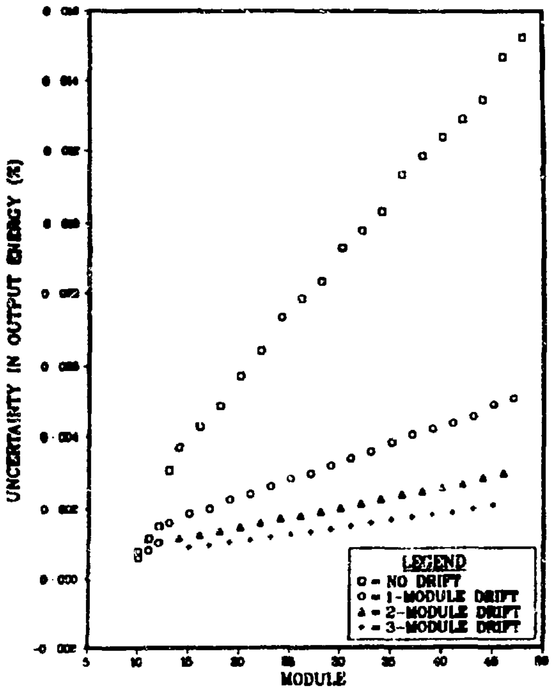

Fig. 3. Change in output percentage energy displacement per picosecond error in measurement of Δt.

measurement errors are reduced. These results (taken from reference 2) are shown in Figs. 2 and 3, for the $\Delta t = 0$ condition being required at 0,1,2, or 3 modules downstream of the module being adjusted.

The above discussion pertained to the use of only one measurement (one pickup loop). It is possible that a condition defined by

$$\Delta t_C = s_1 \Delta t_B , \tag{27}$$

which requires the measurement of both Δt_B and Δt_C, might be more stable and also produce fewer errors. Since large errors can be produced when the intersection of two nearly parallel lines is sought, it seems intuitively that the least error would be produced when we are seeking the point of intersection of two perpendicular lines.

As the phase of a module is adjusted, a line is generated on the $(\Delta t_B, \Delta t_C)$ plane with slope s_2, where $s_2 = -a_{21}/a_{22}$. If there are no measurement errors and if $\Delta W_A = 0$, then this line will pass through the origin and intersect there the line defined by $\Delta t_C = s_1 \Delta t_B$. Now assume that the measurements are in error by δt_B and δt_C, so that instead of passing through the origin, the measured line passes through the point $(\delta t_B, \delta t_C)$. The phase will then be shifted until this measured line intersects the $\Delta t_C = s_1 \Delta t_B$ line. The intersection occurs at:

$$\Delta t_B = (\delta t_C - s_2 \delta t_B)/(s_1 - s_2); \tag{28}$$

$$\Delta t_C = s_1(\delta t_C - s_2 \delta t_B)/(s_1 - s_2) . \tag{29}$$

The distance that the point has moved away from the proper (no errors) solution is then

$$\frac{\delta t_C - s_2 \delta t_B}{s_1 - s_2} - \delta t_B \tag{30}$$

in the Δt_B direction, and

$$\frac{s_1(\delta t_C - s_2 \delta t_B)}{s_1 - s_2} - \delta t_C \tag{31}$$

in the Δt_C direction. The resultant error in the output energy is

$$\delta W_B = \frac{(b_{21}+s_2b_{22})}{s_1-s_2}(\delta t_C - s_1\delta t_B) \ . \qquad (32)$$

The expected value for the square of the output energy is then

$$\left\langle(\delta W_B)^2\right\rangle = (b_{21}+s_2b_{22})^2 f(s_1,s_2) \left\langle(\delta t)^2\right\rangle \ , \qquad (33)$$

where

$$f(s_1,s_2) = (1+s_1^2)/(s_1-s_2)^2 \ , \qquad (34)$$

and it is assumed that the measurement errors are independent ($\left\langle\delta t_B\delta t_C\right\rangle = 0$) and equally uncertain ($\left\langle(\delta t_B)^2\right\rangle = \left\langle(\delta t_C)^2\right\rangle = \left\langle(\delta t)^2\right\rangle$).

When the expression for $\left\langle(\delta W_B)^2\right\rangle$ is minimized with respect to s_1, one finds that the solution is

$$s_1 = -\frac{1}{s_2} \ , \qquad (35)$$

as anticipated.

The line passing through the origin and perpendicular to the lines defined by ΔW_A = constant, is defined by

$$a_{22}\Delta t_B - a_{21}\Delta t_C = 0 \ . \qquad (36)$$

It can be shown that this condition is stable: that is,

$$\left| \frac{\Delta W_B/W_B}{\Delta W_A/W_A} \right| < 1 \ . \qquad (37)$$

If equation (36) is satisfied, one can solve for $\Delta\phi_A$ in terms of ΔW_A using equation (11). Using the result and Eq. (10), one can then solve for ΔW_B in terms of ΔW_A. The ratio of $\Delta W_B/W_B$ to $\Delta W_A/W_A$ can then be calculated. The resultant ratios for each module are shown in Fig. 4, along with the expected deviations of $\Delta W_B/W_B$, assuming 13.8-picosecond uncertainties in the Δt measurements.

A tuneup procedure as described above has a high probability of success in modules 13 through 48, assuming that the measurement errors are random. Numerical simulations have verified this statement, and the results are given in Ref. 2. If the errors in the time measurements are not random (there are systematic errors in the measurements), then this procedure will not work. (See Ref. 2.

The above procedure is used in setting the phase of each module, but says nothing about how to set the amplitude. One could again measure the slope of the output energy vs input phase curve, (m_{21}), but this quantity is very insensitive to amplitude, in spite of the large values given in Table I for the quantities m'_{21}. Remember that one must divide these table values by 100 in order to get the effect of 1% amplitude errors on m_{21}, and the values of m_{21} are themselves large.

A much more reliable way to set the amplitude in a module is to base it on a more distinctive feature of the energy vs phase curve; namely, the peak of the curve. A numerically simulated energy vs phase curve for module 30 is shown in Fig. 5. By measuring the energy change (using 2 pickup loops) as a function of phase one can compare the peak energy gain to the previously calculated values and determine whether the amplitude is too high or too low. If an amplitude change is required, then one must reset the phase via Δt and recheck the amplitude in an iterative procedure.

Possible Sources of Error

The design values for t_B and t_C, as well as the other quantities in Table I, are obtained from a computer model of the linac. If the computer model does not resemble closely enough the actual accelerator, then serious errors could occur. For example, the length errors in the accelerating tanks and in the drift spaces between tanks significantly affected the "design" values for the accelerator. In fact, the length errors were discovered because of some inconsistencies in the Δt results. The measured lengths have been used to generate a revised set of "design" values, but there is of course a limit on the accuracy of the measured lengths.

The computer calculations also assume that there is no rf phase shift between tanks in a module, and that the rf amplitude is the same in each tank in a module. (See reference 3 for a discussion on the effects of tank-to-tank amplitude and phase errors on the Δt procedure.) Tank-to-tank amplitude or phase errors larger than 1% or 1 degree, respectively, could adversely affect the Δt results, especially in the lower modules.

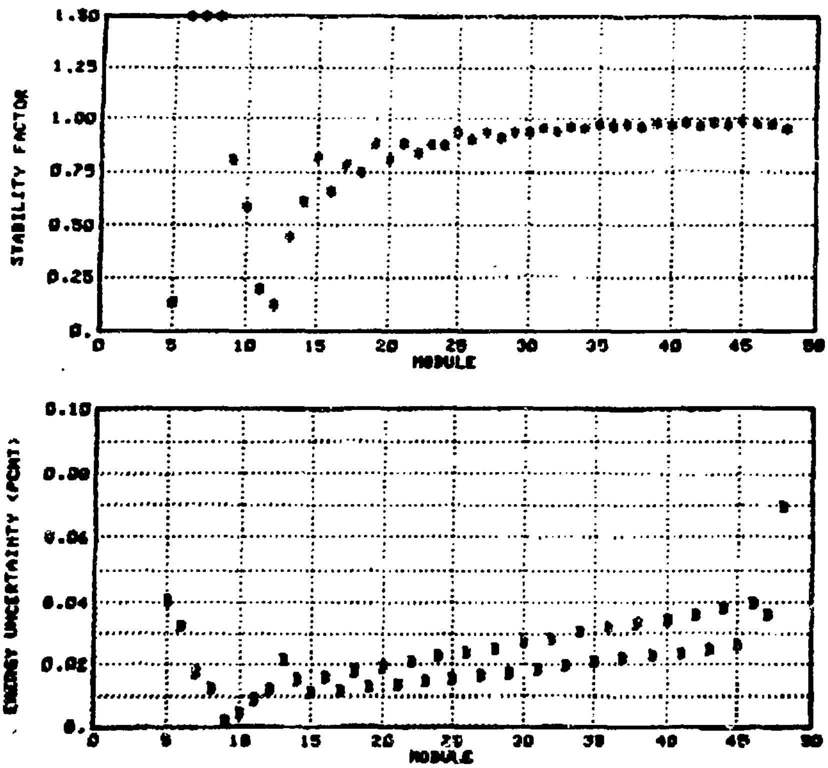

Fig. 4. The stability factor, $\left|\frac{\Delta W_B/W_B}{\Delta W_A/W_A}\right|$, obtained when the module's phase is adjusted until the line generated by the Δt measurements intersects its perpendicular, and the resultant uncertainty in the output energy assuming a 13.8-picosecond uncertainty in the measurements of Δt_B and Δt_C.

The accelerating field is also known to have some variation within each tank. This effect has not been taken into account when calculating design values, although numerical simulations have shown that the effect on particle dynamics is small as long as the average field in each tank is correct.

The design values were obtained by calculating the dynamics of a single "design particle." In reality, the beam consists of many particles having a finite spread in transverse as well as in longitudinal phase space. Some simulations of the Δt procedure have been made using a longitudinal bunch, and the main effect seems to be that, as the size of the beam gets larger, one tends to underestimate the amplitude. That is, one would tend to make the amplitude higher than 100% for the larger beams.

Positional errors in the location of the pick-up loops would affect the design values of t_B and t_C. Divide the distance D_{AB} into three segments: D_1, the distance from A to the beginning of the first cell in the module; D_2, the distance from the beginning of the first cell to the end of the last cell in the module; and D_3, the distance from the end of the last cell to the point B. The first segment, D_1, has no effect on the design values of t_B and t_C, since the time of flight over D_1 is the same when the module is on and off. Errors in D_2 are difficult to assess. One does not know how the errors combine when the module is turned off and on. For a beam simply drifting through module 5, a .050-inch error in D_2 would result in a 10-picosecond error in $t_{AB,off}$. Errors in D_2 would have less effect as the module number is increased. The effect of an error in D_3 can be calculated by

$$\delta t_B = \delta D_3\left(\frac{1}{v_A} - \frac{1}{v_B}\right) .$$

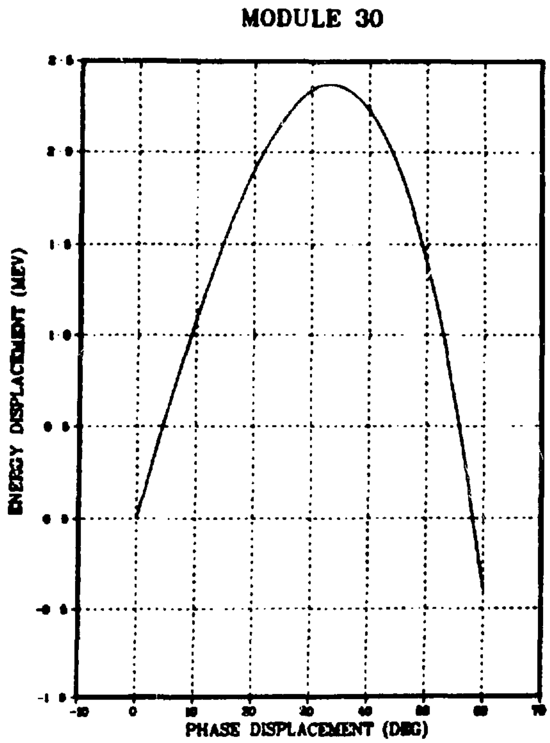

Fig. 5. *Energy versus phase curve calculated at module 30 for the design rf amplitude.*

At module 5, where this effect is largest, a 1-cm error in D_3 would produce a 4-picosecond error in t_B. This same error would apply for the position of the second loop (1 cm = 4 ps).

III. THE Δt HARDWARE

The Δt hardware is described in detail in reference 4. The main features, as seen from a user's viewpoint, will be briefly described below.

Operate Mode

In Fig. 6 is shown a simplified schematic diagram of the hardware configuration when the system is in the "operate" mode and capable of measuring Δt at module N. The two independent systems of electronics are connected to the appropriate pickup loops via a series of matrix switches. The beam-induced signal from the pickup loop is fed into one side of a phase bridge, and a 201.25-MHz reference signal is fed into the opposite side of the phase bridge. A control circuit drives an electronic phase shifter and maintains a null across the phase bridge during each beam gate. The output from the electronic phase shifter can be read by the computer and translated into degrees via a calibration table in the computer.

If the beam-induced signal is too noisy or too weak, then the control loop will come "unlocked" and not be able to maintain a null across the phase bridge. This situation will give rise to a large error signal, which can also be read by the computer. Previous calibrations of the error signals have shown that 100 counts in the analog data system corresponds to about one degree (at 201.25 MHz) error, which is the tolerance set for the Δt measurement.

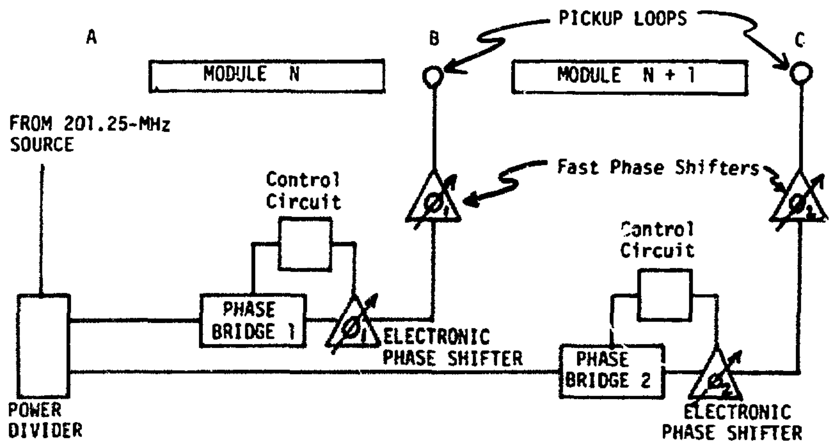

Fig. 6. Simplified schematic of the Δt hardware configuration when the system is in the "operate" mode.

In series with each electronic phase shifter is a fast phase shifter that is controllable from the computer (or manually). The fast phase shifter is used to supply the proper phase shift so that the output from the electronic phase shifter can be well centered in the calibration table. For example, assume that the design value for the time of flight of the beam from A to B when the module is off is 1.38 ns longer than when the module is on. This corresponds to approximately 100 degrees at 201.25 MHz. In this case, with the module turned off, the fast phase shifter would be adjusted until the output from the electronic phase shifter was displaced by +50 degrees from the center of the calibration table. When the module is turned on, if it is adjusted properly, the electronic phase shifter output should be displaced by approximately -50 degrees from the center of the calibration table. Both the electronic phase shifter and the fast phase shifter have ranges of approximately 400 degrees.

Calibrate Mode

When calibrating the electronic phase shifters, the system is configured as shown in Fig. 7. A precision line stretcher, or trombone, is used to change the phase of the reference signal that is sent to one side of the phase bridge. The control circuit causes the electronic phase shifter to supply the same phase change so that the phase bridge stays nulled. Starting at one limit, the trombone is driven through 400 degrees in steps of 5 degrees. At each step, the output from the electronic phase shifter is recorded in a calibration table.

It is highly desirable to generate a calibration curve that is monotonic. To accomplish this, one must be sure that the electronic phase shifter output is near one end of its operating range when the trombone is at its starting limit. At present, the hardware has been adjusted to attain this goal. Until recently, the fast phase shifters were also in the circuit when the system was being calibrated, and they were used for finding the proper starting values for the electronic phase shifters. To prevent the control circuit from "flipping over" after 360 degrees, a steering circuit is employed, with the steering based on the position of the trombone.

Computer Communication Channels

Through the computer, one is able to receive the data from the Δt hardware, and to send commands to some of the hardware. The output from the electronic phase shifters, the error signals, and the signal levels, all come to the computer on the same data channel, but from different modules, so that all six of these signals can be measured simultaneously. Most of the other signals are sent and

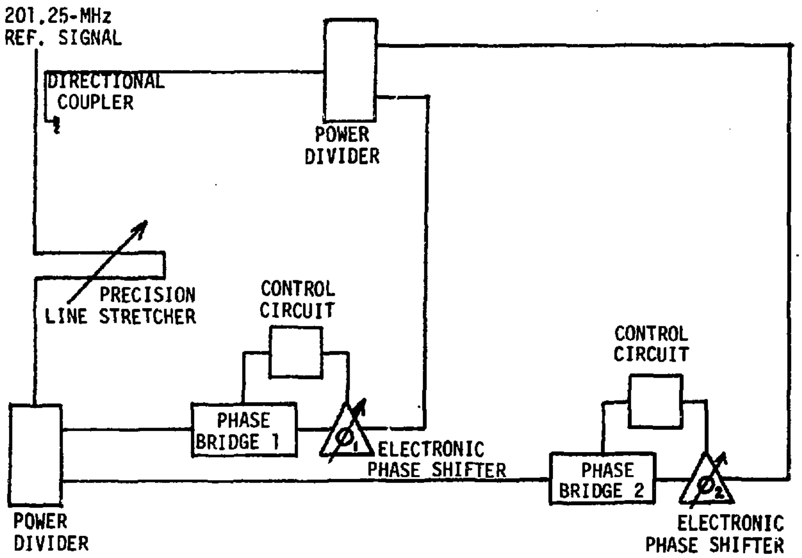

Fig. 7. Simplified schematic of the Δt hardware configuration when the system is in the calibrate mode.

TABLE IV

DATA CHANNELS FOR Δt HARDWARE

Operator designator	module	Channel	description
09PH3L1	9	B01-06,L01-06	operate/calibrate mode
06PH1E1	6	D27	electronic phase shifter output, system #1
07PH2E1	7	D27	electronic phase shifter output, system #2
09PH3E1	9	D27	error signal, system #1
10PH4E1	10	D27	error signal, system #2
05PH1E1	5	D27	signal level, system #1
08PH1E1	8	D27	signal level, system #2
09PH2D1	9	P15, D49	reference trombone
09PH3D1	9	D50	fast phase shifter, system #1
09PH4D1	9	D51	fast phase shifter, system #2
09PH6B	9	B03	digital power supply, system #1
09PH7B	9	B04	digital power supply, system #2

received through module 9, where the rack containing the Δt hardware is located. The only exceptions are the matrix switches, which receive commands through the video system at the sector in which they are located. The command and data channels are given in Table IV.

The signal levels, mentioned above, are used to indicate whether or not the beam-induced signals are sufficiently strong. If not, this may mean that either the beam intensity is too low, or perhaps one or more of the rf amplifiers in the system has failed. The signal levels are not actively used by any of the Δt programs, except for one program which simply reads and displays the six signals referred to above.

As was mentioned earlier, a series of matrix switches are used for connecting the two systems of electronics to the proper pickup loops. To simplify the switches, each Δt system of electronics is capable of being connected to only half of the pickup loops. System #1 can be connected to every other loop starting with the loop following module 2, and system #2 can be connected to every other loop starting with the loop following module 3. The commands to the matrix switches are sent over the video system, which is a convenient way of sending switching information. The matrix switches and their associated decoders are located in modules 9, 20, 32, and 44. A list of the matrix switch commands is given in Table V.

After a command is received by a matrix switch, the command is echoed in bits 7, 8, 9, and 10 of binary channel 9 in modules 10, 20, 32, and 44, with bit 7 being the low order bit of the command. (The data is the reverse of the command.) After issuing a command, the data from the binary channel may be checked to see if the command was received.

IV. Δt SOFTWARE

Most of the Δt programs may be accessed via the pushbutton card shown in Fig. 8. Some additional programs can be accessed only by demand at the keyboard. A list of the Δt programs and their purposes are given below. A detailed description of each program will follow, and the contents of the disk files used by the Δt programs will be given.

Program #	Purpose
3330	Calibrate Δt electronic phase shifters.
3332	Smooth the calibration curves, compare them with the previous curves, and store

TABLE V

MATRIX SWITCH COMMANDS

Δt at module	system #1 loop after module	system #2 loop after module	matrix switch commands to module 9	20	32	44
2	2	3	1	3	3	1
3	4	3	2	3	3	1
4	4	5	3	3	3	1
5	6	5	4	3	3	1
6	6	7	5	3	3	1
7	8	7	6	3	3	1
8	8	9	7	3	3	1
9	10	9	8	3	3	1
10	10	11	9	3	3	1
11	12	11	10	3	3	1
12	12	13	11	3	3	1
13	14	13	12	4	3	1
14	14	16	0	5	3	1
15,16	18	16	0	6	3	1
17,18	18	20	0	7	3	1
19,20	22	20	0	8	3	1
21,22	22	24	0	9	3	1
23,24	26	24	0	10	4	1
25,26	26	28	0	11	5	1
27,28	30	28	0	11	6	1
29,30	30	32	0	11	7	1
31,32	34	32	0	11	8	1
33,34	34	36	0	11	9	1
35,36	38	36	0	11	10	2
37,38	38	40	0	11	11	3
39,40	42	40	0	11	11	4
41,42	42	44	0	11	11	5
43,44	46	44	0	11	11	6
45,46	46	48	0	11	11	7
47,48	48+	48	0	11	11	8
test			0	11	11	11

Program #	Purpose
	the curves on disk so that they can be used by other Δt programs.
3340	Control program for several Δt programs. It initializes conditions for doing Δt at a given module.
3331	Issue matrix switch commands and check for completion.
3333	Set fast phase shifters for centering electronic phase shifter outputs.
3338	Draw Δt_B, Δt_C graph background on storage scope.
3339	Draw energy and phase displacement background graph on storage scope.
3334	Measure Δt_B and Δt_C.
3337	Print and plot Δt_B and Δt_C.

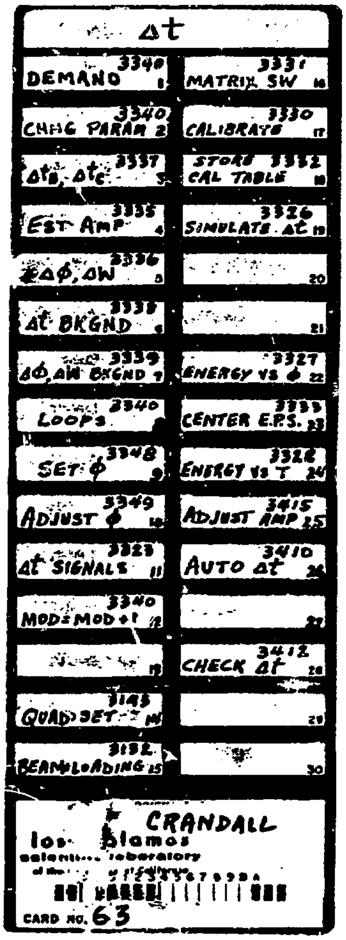

Fig. 8. Insertable push button card for the Δt programs.

Program #	Purpose
3336	Calculate and plot energy and phase displacements.
3335	Estimate rf amplitude from slope of variable phase curve on Δt_B, Δt_C plane.
3341	Print certain Δt parameters on CCI.
3348	Set phase shifter in any 805-MHz module based on the phase of the previous module and on a stored phase shift between these modules.
3349	Automatically adjust phase in one module, based on Δt.
3415	Automatically adjust amplitude in one module.
3416	Check amplitude set point and cavity field data against values previously stored on disk.
3410	Front end for automatic adjustment of amplitude and/or phase via Δt throughout the 805 MHz linac.
3411	Driver for automatic amplitude and/or phase adjustment.
3412	Front end for automatic Δt check.
3413	Driver for automatic Δt check.
3414	Measure energy change via drifting beam between 2 Δt loops.
3347	Store module-to-module phase shifts on disk.
3323	Monitor the six Δt signals from channel D27 and write them on the CCI.
3318	Write on the storage scope the results of the last Δt measurements made on each module.
3327	Plot the change in energy of the beam leaving a module as a function of its input phase.
3328	Plot the change in beam energy out of a module versus either real time or any specified data channel.
3329	Timed updater for 3328.
3326	Plot Δt_B and Δt_C versus any data channel. This program has been used for checking the Δt hardware using simulated signals in place of beam-induced signals.
3344	Front end program for monitoring, at specified time intervals, the Δt electronic phase shifter outputs as the matrix switches step through a specifiable series of pickup loops. The purpose is to observe phase shifts in the beam.
3345	Timed data taker for program 3344.
3381	Restarts 3345 after computer crash and restart.
3380	Plot Δt signal levels.

Program 3330: Calibrate Δt Electronic Phase Shifters
Access: /DE3330 or push button #17, card #63
Description:

When first called, this program tries to put the Δt hardware in calibrate mode. If it does not succeed, a message will be written on the character scope:

*3330 CALIBRATE ELECTRONIC PHASE SHIFTER
LOCAL OPER-CAL SWITCH IN WRONG POSITION

Check the local switch at the Δt rack at module 9. It must be in the "operate" position for the computer to have control.

After putting the Δt system in the calibrate mode, the following message appears on the character scope:

```
*3330 CALIBRATE ELECTRONIC PHASE SHIFTER
          DIR POT REV AVG NDEG   T  BG  CYC
           -1   0   1   4  400 300   1    0
```

The definitions of these parameters are:

- DIR = 1; move trombone in positive direction,
  = -1; move trombone in negative direction.
- POT = 0; base calibration on motor pulses,
  = 1; base calibration on trombone pot.
- REV = 0; store values in calibrating table in the same order in which they are generated,
  = 1; store values in calibration table in reverse order.
- AVG number of times data is taken at each trombone position and averaged.
- NDEG number of degrees to calibrate.
- T sample time.
- BG beam gate flag (H^+ beam gate is required)
- CYC = 1, take data on positive half of cycle,
  = -1, take data on negative half of cycle.
  = 0, don't care.

The values of the parameters are the values that were last used and are probably correct, with the possible exception of T, which should be at least 80 microseconds after beam gate.

After making any changes (or none) in the parameters, hit the END key with the cursor anywhere in the 3 lines except under the *. The reference trombone is then driven to one limit, and the message

DRIVING REFERENCE TROMBONE TO LIMIT

appears on the character scope. The data from the trombone position pot will be written to the right of the above message.

After a limit has been reached, the calibration curves are generated by moving the trombone through the desired range in 80 steps, recording the output from the electronic phase shifters at each step. The calibration curves are plotted on a storage scope, and the message

GENERATE CALIBRATION CURVE

appears on the character scope.

When the calibration has been completed, the parameters and calibration tables are written on disk, the reference trombone is centered, and the system is put back in the operate mode. After this, the character scope message showing the parameters appears. Normally, the program would then be dropped by placing the cursor under the * and hitting END. Program 3332 must be used next to smooth the tables and to store the tables into the proper disk storage for usage by the Δt programs.

The program may be stopped at any point in the procedure by placing the cursor under the * and waiting, since the cursor position is checked periodically. To restart, move the cursor away from the * and hit END.

General Information:

The Δt hardware has undergone quite an evolution since it was first installed. Consequently, it was found quite early that a flexible calibration program would be advantageous. Some of the control parameters are on the disk and unseen by the user. These parameters may be read and modified, if desired, by program 3240.

The calibration may be based either on the number of pulses sent to the reference trombone, or on the position potentiometer of the trombone. If the value of the parameter, POT, is zero, then the calibration depends on the number of pulses sent; otherwise it depends on pot position. The critical values are the number of pulses per degree (81.5) and the number of counts per degree (4.022) from the pot. (These values are imbedded in the code, and if something is changed that affects these values, then these values must be changed in the code.) If the stepping motor does not skip pulses, then the calibration curves based on pulses are smoother and more exact than would be the curves based on readings from the pot.

Another important consideration is the direction to move the trombone when generating a calibration curve. The programs that use the calibration tables assume that the tables are in order of increasing time of arrival of the beam at the pickup loop. That is, the N+1 st table entry corresponds to a later arrival time than does the Nth entry. Consequently, one must know on which side of the phase bridge the trombone is located. At this writing, the trombone is located on the opposite side of the bridge to the beam-induced signal. Consequently, the calibration tables could be generated by driving the trombone with positive pulses, which shortens the trombone. Alternatively, the tables could be generated by sending negative pulses, which lengthens the trombone, and then storing the values in the table in the reverse order. This latter way is actually the way the parameters are set at this writing (DIR = -1, REV = 1), because the hardware was adjusted so that the electronic phase shifter outputs were near their limits when the trombone was on its clockwise (shortened) limit.

Until recently, the fast phase shifters were in the circuit also when the system was in the calibrate mode. They could be (and were) used to automatically set the starting values of the electronic phase shifters to specified values. This feature is controlled by 3 numbers read from disk file 3134 starting at word 395: IAUTO, IEPS(1), and IEPS(2). If IAUTO = 1, then, after the trombone is sent to its starting limit, the fast phase shifters are used to set the electronic phase shifter outputs to the values specified by IEPS(1) and IEPS(2).

During the generation of the calibrate tables, at each trombone step the error signals are read in addition to the electronic phase shifter outputs. If an error signal exceeds (in absolute value) the value of the parameter, LOCK (obtained from disk file 3138, word 23), then the associated phase control system is assumed to be out of lock and the electronic phase shifter output is set to full scale (± 2048 counts, depending on the sign of the output). The value used for LOCK is nominally 100 counts. For each step at which the error signal is less than LOCK, the error signals are accumulated to attain an average value, which is then used as the "zero offset" value for the error signal. The zero offset values for the 2 systems are stored on disk file 3138, words 24 and 25. During an actual Δt measurement, these zero offsets are subtracted from the error signals before comparing the error signals to LOCK.

After the calibration tables have been generated, the entries are stored on disk file 3134 starting at word 410 (160 entries). The parameters specified on the character scope are stored in words 402-409 of disk file 3134. The millisecond clock is read, and the 2 words are stored in words 29 and 30 of disk file 3138. This time is written on the Δt graphs so that the user will know how long it has been since the last calibration.

An example of the calibration curves produced by the program is shown in Fig. 9.

Program 3332: Smooth, Compare, and Store Δt Calibration Tables.

Access: /DE3332 or push button #18, card 63

Description:

The purpose of this program is to do one or more of the following:

1) Plot the calibration curve for either system #1 or system #2 on the storage scope.

2) Smooth and plot the calibration curve for either system.

3) Compare the latest calibration with the previously stored calibration and plot the differences.

4) Reverse the order of the calibration table of either system, if necessary.

5) Store the calibration table on disk for usage by the Δt programs.

When first called, this program writes the following message on the character scope:

*3332 SYSTEM 1, STORE REVRS COMPAR SMOTH

The normal procedure is to place the cursor under the pseudo-word SMOTH, and hit END. The calibration curve for system #1 will then be smoothed and plotted on the storage scope (see Fig. 10). Next, place the cursor under COMPAR and hit END. The smoothed curve will then be compared with the previously stored (and smoothed) calibration table for system #1, and the differences will be plotted on the storage scope (see Fig. 11). The vertical displacement of this comparison curve has no significance; only the slope and curvature have meaning. These indicate how much the Δt electronics have drifted since the previous calibration. After comparing, the current smoothed calibration table for system #1 is stored on disk by hitting END with the cursor under STORE. Then change the "1" to a "2" and repeat the above procedure for system #2. After any END hit, the * is turned red to indicate that the program received the interrupt.

When finished with the program, drop it by placing the cursor under the * and hitting END.

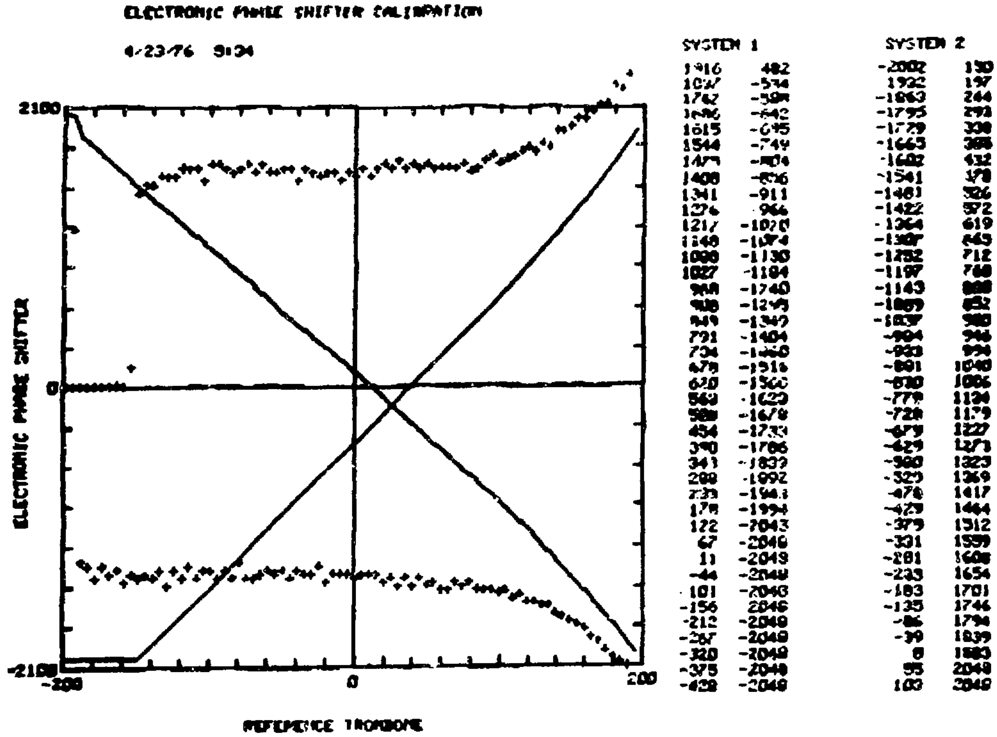

Fig. 9. Sample output from Δt calibration program 3330.

General Information:

The calibration program, 3330, stores its calibration tables on disk file 3134, with system #1 beginning at word 410, and system #2 beginning at 490, each table consisting of 80 words. When program 3332 is asked to smooth the table for either system, the smoothed values are written on these same words on the disk file. The same is true of the command to reverse; the table will be rewritten over itself in the reverse order. (If one accidentally hits the END key when the cursor is under REVRS, hitting the END key again with the cursor under REVRS will get the table back to its original state.)

When the END key is hit with the cursor under STORE, the table values are stored on disk file 3134 in the locations from which they will be read by the other Δt programs. The table for system #1 will be stored starting at word 88; the system #2 table will be stored starting at word 168.

When the cursor is placed between columns 2 and 13 and the END key is hit, the calibration curve for the specified system is plotted on the storage scope.

Program 3340; Δt General Control Program

Access: /DE3340, or push button #1, card 63.

Description:

This program has a variety of functions, depending on which push button is pushed.

P.B.#1, or /DE: Four lines are reserved on the character scope and a storage scope is selected. The message

*3340 DELTA-T TURN-ON PROCEDURE

is written on the character scope. The Δt hardware is put in the operate mode, unless the local operate/calibrate switch is in the wrong position (it must be in "operate"), in which case the message

OPER-CAL SWITCH IN WRONG POSITION

is written on the character scope.

P.B.#2: This entry allows the user to change any or all of the several parameters, including the module number; the data sampling time; the number of times to take data and average when measuring Δt; the number of pulses per step to send to the module's phase shifter when the amplitude is being estimated from the slope of the Δt_C vs. Δt_B line; the number

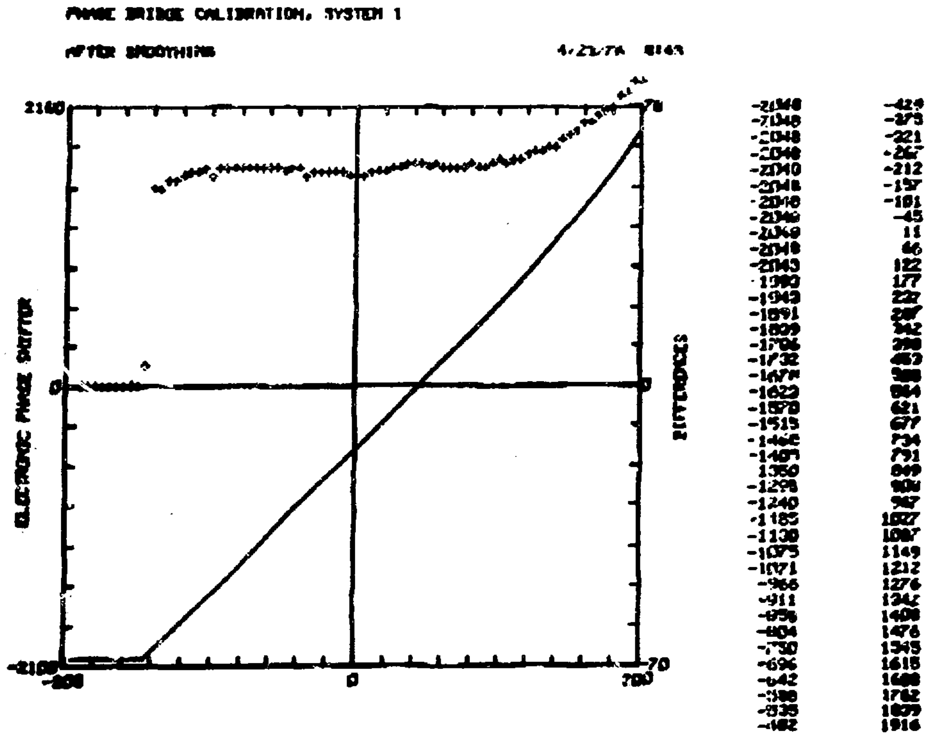

Fig. 10. Sample output of smoothed calibration curve from program 3332.

of steps to take in the case just mentioned; and the number of times to generate this line for the purpose of taking the average of the slopes. After changing any, all, or none of these parameters, hit the END key with the cursor anywhere within these lines.

If the module number has been changed, then the rf is delayed in the specified module and in all downstream modules, and all upstream 805-MHz modules are put "in time". Assuming that the first two downstream pickup loops are the ones to be used when doing Δt on this module, a set of Δt parameters are calculated and stored on disk file 3138.

The pickup loops are hooked to the Δt electronics by sending the appropriate commands to the matrix switches via program 3331, which also checks the data to see if the commands were accepted. Program 3331 sets a matrix switch flag, MS, to zero or nonzero depending on whether the matrix switch commands were all accepted or not, and writes MS on disk file 3138, word 26. This flag is checked by program 3340, and if it is not zero, then the message

MATRIX SWITCH DID NOT GET SET CORRECTLY

is written on the character scope, and program 3340 is finished. If MS=0, then program 3333 is called upon to adjust the electronic phase shifter output (via the fast phase shifters) so that the design values of Δt_B and Δt_C will be centered in the calibration tables.

P.B.#8: This entry allows the user to specify which pickup loops to use if, for some reason, the normal loops cannot be used. Because of the way the matrix switch works, however, consecutive loops must be specified. The possibility also exists of doing Δt on more than one module at a time. That is, 2 or 3 modules may be turned off and on as a unit, and Δt measured for this unit. This mode of operation is not recommended because of the uncertain phase shift between the modules, but the possibility does exist and may be exploited in the future.

When push button #8 is pressed, on the character scope the message

NUMBER OF MODULES = n

USE LOOPS AFTER MODULES m_1 AND m_2

will appear, where n should be a "1" unless the

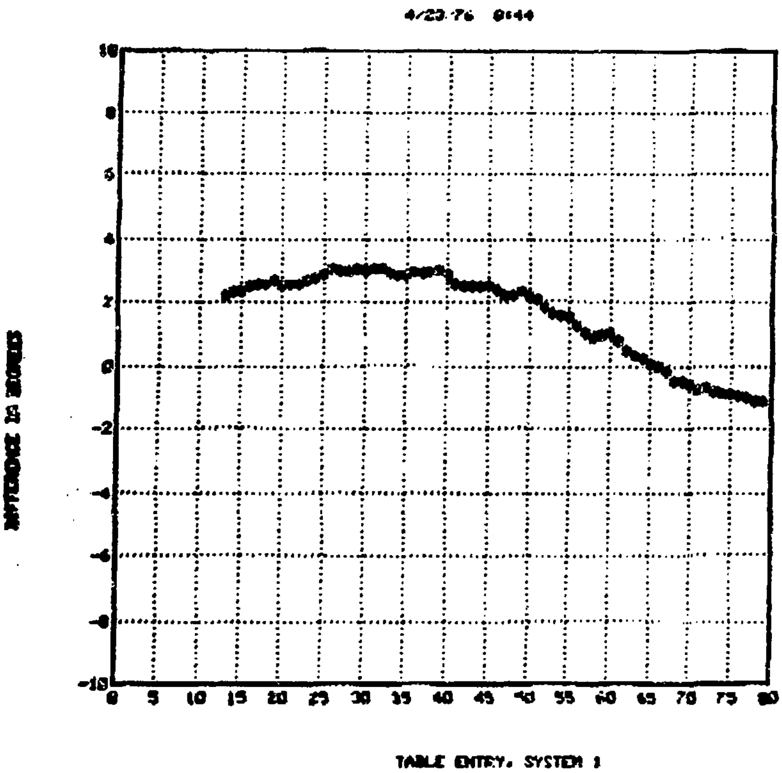

Fig. 11. Sample storage scope output generated by program 3332 when comparing the current calibration table with the previous calibration table.

user really wants to do Δt on 2 or 3 modules at a time, and m_1 and m_2 are module numbers of the normal loops for doing Δt at this module. Change any, all, or none of the parameters and hit END. New Δt parameters are then calculated and written on disk file 3138, the matrix switches are set, and the electronic phase shifter outputs are centered in the calibration tables.

P.B.#12: This entry is a convenient way of setting up to do Δt on the next consecutive module. It accomplishes the same thing as pressing button #2 and changing the module number by +1.

General Information:

Whenever program 3340 is called, it drops program 3334, which is the program that measures Δt. The reason for dropping 3334 is so that a fresh copy of the program will be loaded from the disk the next time that 3334 is demanded. When this happens, 3334 reads the calibration tables and other Δt parameters from disk. Since program 3340 may change some of these parameters, it must insure that 3334 reads the new values.

The Δt parameters that program 3340 collects or calculates and stores on disk file 3138 starting at location 215, are the 19 quantities given in Table I. The elements of the M matrix and their derivatives with respect to rf amplitude, D_{AB}, D_1, and D_2, the design values for t_B, W_A, and W_B, all are obtained from disk file 3129 for which a storage map is given at the end of this report. The remainder of the 19 parameters are calculated. If multiple-module Δt is specified, additional calculations are done so that these 19 parameters refer to the system of modules.

Program 3331: Issue Matrix Switch Commands
Access: /DE3331, or push button #16, card #63.
Description:

Through this program, the user may specify to which pickup loops the Δt electronics should be connected. If called by /DE or by the push button, the message

*3331 SET DELTA-T MATRIX SW FOR MOD m

appears on the character scope, where m is a module number. The initial value of m is read from disk file 3138, word 359, which is where program 3340 stores the module number. Changing m to the desired module and hitting the END key will cause the proper matrix switch commands to be issued so that the first two loops downstream of the specified module will be hooked to the Δt gear. After the commands have been sent, the associated data channels are checked to see if the commands were executed. If the data from all 4 matrix switches do not agree with the commands sent, then the commands are sent again. If, after 5 tries, there is not complete agreement between the commands sent and the data received, then a message will appear in the status lines of the character scope

PROBLEM SETTING DT MATRIX SWITCHES nnnn

where each n will be 0 or 1. The rightmost n refers to the matrix switch at module 9, and a 0 signifies agreement between command and data, and a 1 signifies disagreement at the module 9 matrix switch. The other n's, from right to left, represent the matrix switches at modules 20, 32, and 44, respectively. The number nnnn is also stored on disk file 3138, word 26, and is referred to elsewhere as MS, the matrix switch flag.

To drop program 3331, place the cursor under the * and hit END.

Program 3331 may also be demanded by another program, as it is by program 3340. In this case, the calling program sends 3 arguments: the number of arguments (3); the station number; and the module to which the Δt hardware is to be connected. No message will appear on the character scope, except for the possible error message in the status lines.

Program 3333: Adjust Fast Phase Shifters to Obtain Desired Electronic Phase Shifter Outputs.

Access: /DE3333, or push button #23, card #63

Description:

When this program is called, it reserves 3 lines on the character scope and reads some Δt parameters and calibration tables from disk. From the Δt parameters, the program calculates the approximate values that the electronic phase shifters should be set at when the module is off, so that the central portions of the calibration tables will be used when the module is properly adjusted. If program 3333 is demanded by another program and sent 4 arguments, it is assumed that the third and fourth arguments are the desired electronic phase shifter outputs for systems 1 and 2, respectively.

The message

#3333 SET FAST PHASE SHIFTERS FOR DELTA-T

MOD = m, E.P.S. SHOULD READ eps1 eps2

is written on the character scope, where m is the assumed module number, and eps1 and eps2 are the specified or calculated values at which to set the electronic phase shifters. The matrix switch flag, MS, is checked and if found to be nonzero, then the message

WARNING -- MATRIX SWITCH FLAG = ms

is written in red on the third character scope line, and a 10-second delay is given. Regardless of the value of MS, the program turns the * red and exits, waiting for another interrupt. The purpose of the wait is to allow the user to specify the values of eps1 and eps2, if he desires.

Hitting the END key with the cursor anywhere under the first 2 lines causes the values of MOD, eps1, and eps2 to be read. If the cursor was under the *, then the program is dropped. Otherwise, the program tries to adjust the fast phase shifters, first system #1 and then system #2, until the electronic phase shifters attain their specified values. The progress of the program is shown on the third line of the character scope, on which is written

MOVING FAST SHIFTER n pot epsn errn

where n is 1 or 2 indicating the system, pot is the potentiometer data from the fast phase shifter, and epsn and errn are the electronic phase shifter output and the error signal, respectively. Each time that the fast phase shifter is adjusted by the program, the data on the third line are updated if the program succeeds in getting the electronic phase shifter set closely enough to their specified values, then the program drops itself.

Although the program is usually successful, there is a possibility that it will have trouble (for reasons that will be discussed later), and user intervention will be required. The user may stop the program at any time by placing the cursor under the * and waiting. When the * turns red, the program has stopped. The values of eps1 and eps2 on the second line may then be changed and the program restarted by hitting the END key. If the cursor is anywhere in the first 2 lines (except under the *), then the program tries to set both systems to their specified values. If the cursor is under the third line, then only the system specified by the fast phase shifter number on line three is adjusted.

General Information

In trying to obtain the desired electronic phase shifter output, several difficulties may be encountered. The circuit that controls the electronic phase shifter may go out of lock, or it may cause the electronic phase shifter to suddenly shift by 360° when the fast phase shifter is changed only slightly. This task is an example of one that is easy to do manually, but one for which it is difficult to write a foolproof program that is not too slow.

The fast phase shifter in each system is controlled by a digital power supply. The relationships between the power supply setting, the fast phase shifter output, and the electronic phase shifter output are stored in a short table on disk file 3134. This table contains the lower and upper limits of the fast phase shifters, and the corresponding digital power supply values and the electronic phase shifter outputs. The table values of the electronic phase shifters are only relative, and represent the amount that the electronic phase shifter output would change (if possible) when the corresponding fast phase shifter is moved from its lower limit to its upper limit.

Using this short calibration table as a guide, the fast phase shifter is adjusted (via the digital power supply) until the electronic phase shifter is within 100 counts of the specified value. If the error signal indicates that the control circuit is out of lock, then a systematic search is made by stepping the digital power supply through its range (specified by the table) in 30 equal steps. At each step, the electronic phase shifter and the error signal are checked for being within the required limits. If a satisfactory setting is not found after stepping through the entire range, then the * on the character scope is turned red and the program is stopped.

Program 3338: Draw Δt_B, Δt_C Graph Background on Storage Scope

Access: /DE3338, or push button #6, card #63

Description:

This program is used to draw the Δt_C versus Δt_B graph background on the storage scope assigned to program 3340. When called, this program writes on the character scope the message

DTMAX = .400, NI = 8

and waits for a keyboard interrupt. The user may now specify the range of the graph in nanoseconds, DTMAX, and the number of grid intervals, NI. The storage scope will be erased and the graph background drawn and scaled. The range of both Δt_B and Δt_C will be ±DTMAX.

In addition to the graph background, the module number, the date and time of day, and the time of the last Δt calibration are written on the scope. The heading for a set of measurements of amplitude set point, phase set point, Δt_B, and Δt_C is also written on the scope. A dashed line passing through the origin with a positive slope is also drawn on the graph background. Measurements that fall on this line represent the condition $\Delta W_B = - \Delta W_A$, which is one limit of the tuneup stability criteria. If several "variable phase curves are generated for different amplitudes, then these curves should intersect each other on this dashed line. If the module number is greater than 12, then an additional object line is drawn. This is the line that the

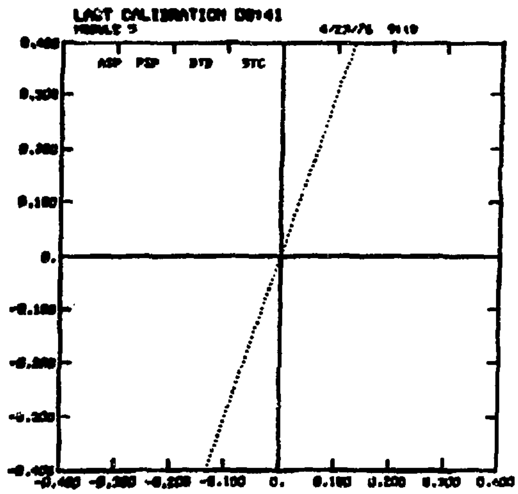

Fig. 12. Sample Δt graph background produced by program 3338

resultant Δt_B, Δt_C measurement should lie on when the modules phase is adjusted properly (according to the procedure discussed in the Δt Theory section of this report).

An example of the storage scope output from this program is shown in Fig. 12.

Program 3339: Draw Energy- and Phase-Displacement Background Graph on Storage Scope

Access: /DE3339, or push button #7, card #63

Description:

An example of the storage scope output from this program is shown in Fig. 13. (This output goes on the storage scope assigned to program 3340.) The range on the phase displacement scale is always ±20 degrees, and a comparable energy displacement range is chosen in percent. The date and time, as well as the time of the last Δt calibration, are also written on the scope. A heading is written for subsequent measurement of the amplitude set point, the cavity field (Channel D28), the estimated normalized rf amplitude (based on the value of the cavity field when the amplitude was last estimated), the phase set point, and the input and output phase and energy displacements (in degrees and percent, respectively). At module 5, two additional parameters are recorded: the 805-MHz reference phase set point, and the phase set point of tank 3. These 2 quantities are often adjusted to bring the phase and energy displacements to zero at module 5.

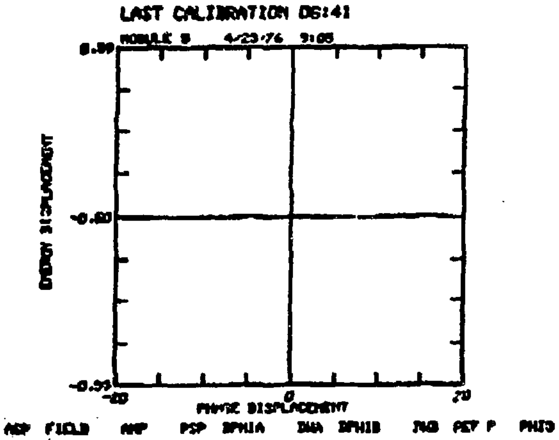

Fig. 13. Sample graph background produced by program 3339.

Program 3334: Measure Δt_B and Δt_C.

Access: Demanded by other programs and passed 5 arguments:

1. number of arguments sent (5);
2. program number of calling program;
3. module number;
4. number of times to repeat the measurements and average;
5. data sampling time.

Description:

This program is called upon by the other Δt programs to perform the actual Δt measurements. It uses the following procedure.

1. If this program is already in core when it is demanded, then go to step 2. Otherwise, read from disk the Δt calibration tables and other parameters, including: NDEG, the number of degrees spanned by the calibration tables; LOCK, the tolerance on the error signals; the zero offsets for the error signals; the design values for t_B and t_C; NMT, the number of modules to be treated as a unit; L1 and L2, the module numbers at which the pickup loops are used; and KK, the Δt system # that is connected to the first (upstream) loop. A mask is obtained from the channel tables concerning the binary word containing the timing bit for the module specified in the calling arguments.

2. If the module specified is between 5 and 48, inclusive, go to step 3. Otherwise, set an error flag to -1 and return it to the calling program.

3. Read the binary channel containing the timing bit for the specified module and construct (using the previously obtained mask) the bit patterns for delaying and undelaying the module. Delay the module; or, if NMT > 1, delay NMT modules starting with the specified module. (Caution: the mask was obtained for only the module specified in the calling arguments.) Convert the design values of t_B and t_C to degrees at 201.25 MHz.

4. With the module(s) delayed, read the data from the electronic phase shifters and from the corresponding error signals. If a fast protect occurred during the pulse at which the data was taken, or if any of the 4 signals had an associated parity error, then the data are retaken. If either error signal exceeds the tolerance specified by LOCK (after subsraction of the zero offsets) for 3

consecutive tries, then an error flag is set and returned to the calling program. Otherwise, continue.

5. Put the module(s) in time and repeat the same measurements described in step 4. Delay the module(s).

6. Convert the differences in the module delayed - module undelayed measurements to degrees using the calibration table. If any measurement falls outside the range of the calibration table, set an error flag and return it to the calling program. Otherwise, make sure the differences are between -180 and +180 degrees, subtract the design values, and convert back to nanoseconds. Repeat the procedure from step 4 until it has been done the number of times specified in the calling arguments.

7. Calculate the average values and the standard deviations of the measurements of Δt_B and Δt_C. If the measurement was done only once, set the standard deviations to zero. Read the time clock (locations 2 and 3 in core), the amplitude set point, and the phase set point of the module, and write these values along with the measured Δt_B and Δt_C on disk file 3319 starting at location 6 (m-5), where m is the module number.

8. Return the results to the calling program.

Program 3337: Write and Plot Δt_B and Δt_C

Access: /DE3337, push button #3 on card #63, or demanded by another program.

Description:

This program calls upon program 3334 to measure Δt_B and Δt_C. The error flag returned by 3334 is checked, and if it is zero, then the quantities Δt_B, Δt_C, and their standard deviations, are written on the character scope in the lines reserved by program 3340. If the Δt background graph has been drawn on a storage scope, then the measurement is also plotted on the storage scope with crossed horizontal and vertical lines. The lengths of the line segments represent the magnitude of the standard deviations of the measurements. The module amplitude and phase set points, and the measured values of Δt_B and Δt_C are also written on the storage scope.

An example of the storage scope results is shown in Fig. 14.

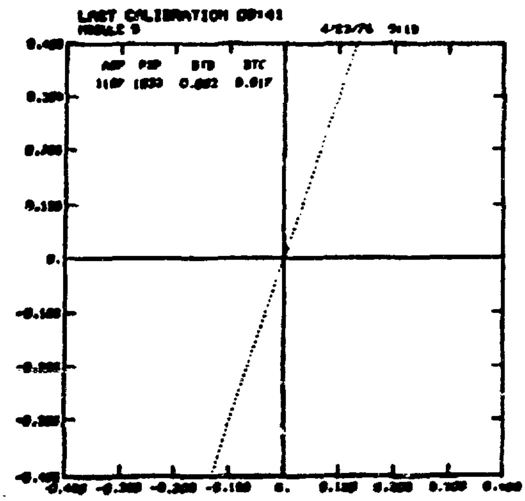

Fig. 14. Sample storage scope output from program 3337.

If the error flag returned by program 3334 is not zero, then an error message is written on the character scope and program 3334 is dropped. The error message will either say:

DATA OUT OF CAL TABLE RANGE, SYSTEM n

1,OFF	1,ON	2,OFF	2,ON
xxx	xxx	xxx	xxx

where n is the Δt system # (1 or 2), and the xxx's represent electronic phase shifter outputs for the 2 systems when the modules are off and on; or

SYSTEM n OUT OF LOCK, MODULE OFF (ON),

where n specifies the system whose error signal exceeded the tolerance set by parameter LOCK when the module was turned off or on, as specified.

If program 3337 was demanded by another program and passed 3 arguments, then the error flag and the measured values of Δt_B and Δt_C are returned to the calling program.

Program 3336: Calculate and Plot Energy- and Phase-Displacements

Access: /DE3336, push button #5 on card #63, or demanded by another program

Description:

This program is normally used in only modules 5 through 12.

If the module number specified on disk file 3138 is not between 5 and 48 inclusive, then the message

PROG 3336 DATA ERROR. MOD = m

is written on the character scope lines reserved by program 3340, where m is the module number.

If the module number is from 5 to 48, then the amplitude set point and cavity field (channel 028) for the module are read and program 3334 is demanded. If the error flag returned by program 3334 is zero, then the input and output energy and phase displacements are calculated. The first step in the calculation is to estimate the present value of the rf amplitude. This estimate is based on the relationship of the present value of the cavity field to the value of the cavity field when the amplitude was last estimated or adjusted by program 3335 or program 3414. The coefficients relating the output displacements to the input displacements can then be calculated from the estimated amplitude and the design values of the coefficients and their derivatives with respect to the amplitude. The displacements themselves are then calculated, plotted on the storage scope, written on the character scope using the lines reserved by program 3340, and saved on disk file 3138.

The displacements are also written on the storage scope, along with the amplitude and phase set points, the cavity field, the estimated normalized amplitude, and the time of day. At module 5, the values of the 805-MHz reference phase and the phase set point of tank 3 are also written on the storage scope, since these quantities are often adjusted when doing Δt on module 5. An example of the storage scope results is shown in Fig. 15.

If the error flag returned by program 3334 is not zero, then an error message is written on the character scope stating that either the data were out of the range of the calibration table, or that one of the systems was out of lock, just as is done when program 3337 detects an error flag.

If program 3336 was demanded by another program and passed 3 arguments, then the error flag and the calculated values of $\Delta\phi_A$ and ΔW_A are returned to the calling program.

Program 3335: Estimate Amplitude from Slope of Variable Phase Curve

Access: Push button #4, card #63

Description:

The purpose of this program is to estimate the rf amplitude of a module by generating a curve on the Δt_B - Δt_C plant as the phase of the module is changed. The slope of this curve, near the design phase, is related in a known way to the amplitude. The slope is a sensitive function of the amplitude in the first few 805-MHz modules, but soon becomes insensitive. However, it is possible to treat 2 or 3 modules as a unit, and the slope again becomes more sensitive to amplitude (at least in theory).

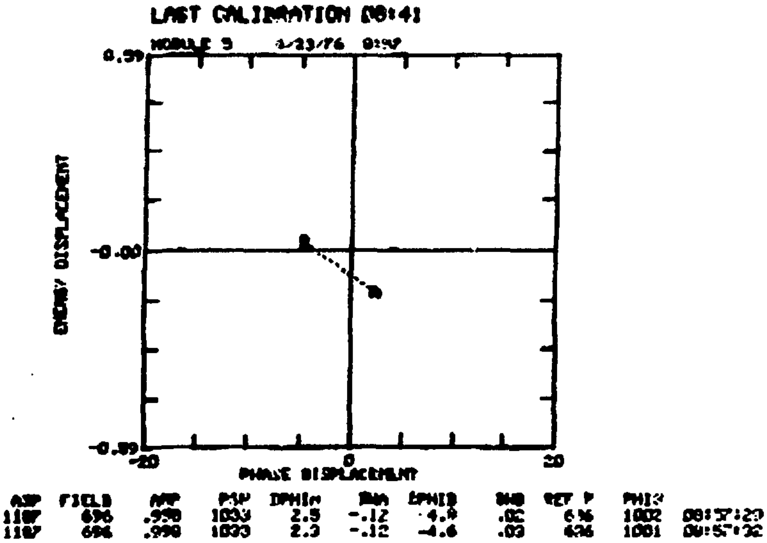

Fig. 15. Sample storage scope output from program 3336.

This program has been made somewhat obsolete by the use of another program (3414) which automatically checks and adjusts the amplitude in all of the 805-MHz modules. Program 3335 is also a little complicated to use properly, in that the user must be sure that he starts generating the curve at a reasonable phase set point.

When this program is first called, program 3334 is dropped and some parameters are read from disk file 3138. If the number of steps (as specified in program 3340 under push button #2) is less than 2, then an error message is written on the character scope lines owned by program 3340:

DATA ERROR. NS L.T. 2. CHECK DISK FILE 3138, LOC 364

If the module number is not a legitimate 805-MHz module, then the error message

DATA ERROR. MODULE. CHECK FILE 3138 LOC 359

is written on the character scope.

If the above data errors did not occur, then the program prepares to generate the number of curves previously specified (push button #2). (If the number of curves is less than 1, then 1 curve is generated but a slope is not calculated nor is the amplitude estimated.) Program 3334 is called on to measure Δt_B and Δt_C at the initial phase set point, and then the phase shifter is sent IDP pulses per step for the specified number of steps. At each phase shifter step, Δt is measured and the error flag, Δt_B, Δt_C, σ_B, and σ_C are written on the character scope, where σ_B and σ_C are the rms values of the Δt_B and Δt_C measurements, respectively. If, at any time in the procedure, the error flag is nonzero, then the module phase shifter is returned to its initial value and the program is terminated.

As the measurements are made, points are plotted on the storage scope. After the specified number of phase steps, a straight line is fit to the data points and its slope is calculated. The straight line is also drawn on the storage scope. The phase shifter is returned to its starting point.

The amplitude is calculated from the slope, using the values of the design slope and its derivative with respect to amplitude.

After the specified number of curves have been generated, the average value of the estimated amplitude and its standard deviation are calculated. The value of the amplitude displacement, ΔA, is written on disk file 3138 at locations 253-254. If the module is one of the first eight 805-MHz modules (the only modules at which this method is valid for a single module), then the estimated amplitude, its standard deviation, the module amplitude set point, and the cavity field (from channel D28) are written on the character scope and on disk file 3138. If the specified module is 13 or greater, then the estimated amplitude, the number of modules treated as a unit, and the starting module number are written on the character scope.

Program 3341: Write the Δt Parameters (Initialized by Program 3340) on the Character Scope.
Access: /DE3341
Description:

This program allows the user to look at the values assigned by program 3340 to the 19 parameters specified in Table I. One would use this program if there was reason to believe that something had gone wrong, like a disk file having been clobbered.

Program 3348: Set Phase of any 805-MHz Module
Access: /DE3348, push button #9 on card #63, or demanded by another program
Description:

If demanded by another program, this program assumes that the third argument is the module number. Otherwise, the module number is read from disk file 3138, word 359. The phase shift between the specified module and the module preceding it is read from disk file 3129. (The phase shifts between modules are written on disk file 3129 by program 3347, which should be demanded after the completion of a tuneup.)

The phase set point of the preceding module is read and converted into degrees via the calibration table in the channel tables. The new phase of the specified module is then calculated from the phase of the preceding module and the specified phase shift. (If module 5 is specified, module 5 is treated as the preceding module, and the 805-MHz reference phase is treated as the specified module and is adjusted.) The message

*SET PHASE OF MOD m TO p DEG

is written on the character scope, where m is the specified module number, and p is the calculated phase. The user may change either m or p, and hit END with the cursor anywhere under the line except under the *. The program then attempts to shift the phase to the specified value.

As the phase is being shifted, the updated value of the phase is written to the right of the character scope message. The program may be stopped at any time by placing the cursor under the *. When the * turns red, the program has stopped.

Program 3349: Adjust Phase in 805-MHz Module
Access: /DE3349, push button #10 on card #63, or
demanded by another program
Description:

When this program is demanded by another program, it must be passed at least 2 arguments, the second argument being the station number. Some Δt parameters, including the module number, are read from disk file 3138. The message

*3349 ADJUST PHASE IN MODULE m

is written on the character scope, where m is the module number read from disk. The user may change the module number and hit END.

After receiving a keyboard interrupt, the program reads the module number from the character scope. If the cursor was under the *, or if the module number is not between 5 and 48 inclusive, then the program is dropped. Otherwise, the following procedure is used.

1. The phase adjust flag is set to 1 and stored on disk file 3138, word 361. This indicates that program 3349 is in the process of adjusting the phase. Set a counter to zero.

2. If the specified module number is greater than 12, then go to step 7. If the specified module number is 5, then set the data channel numbers so that the 805-MHz reference phase is adjusted instead of the phase of module 5.

3. Call on program 3336 to calculate and plot $\Delta\phi_A$ and ΔW_A. If $|\Delta\phi_A| \leq 1°$, go to step 6. If the returned error flag is not zero, or if $|\Delta\phi_A| > 30°$, then go to the phase scan procedure. Otherwise, continue.

4. Check the position of the cursor. If it is under the *, stop the program.

5. Move the phase of the module the amount indicated by $\Delta\phi_A$ and increase the counter by 1. Go to step 3.

6. If the specified module number is not 5, then go to step 10. If it is module 5, and if $|\Delta W_A| < .02\%$, then go to step 10. Otherwise, calculate the phase shift required at tank 3 in order to make $\Delta W_A = 0$, and shift tank 3's phase by this amount. Go to step 3.

7. At this point, the specified module is between 13 and 48 inclusive. Calculate the equation of the line to intersect.

8. Call on program 3337 to measure and plot Δt_B and Δt_C. If the returned error flag is not zero, or if $|\Delta t_C| > 0.8$ nanoseconds, then go to the phase scan procedure.

9. If the measured point is within .005 nanoseconds of intersecting the calculated line, or the required phase change is less than 0.5 degrees, then go to step 10. Otherwise, check the cursor. If it is under the *, stop the program. If not, change the module's phase the calculated amount, add 1 to the counter, and go to step 8.

10. At this point, the measurements have indicated that the phase of the module has been set satisfactorily. However, if the counter is zero, indicating that the initial conditions satisfied the convergence criteria, then the phase is deliberately moved by approximately -5° and the procedure is restarted at step 2. This action prevents the phase from being left on the "wrong" side of the rf wave.

11. If the counter is greater than zero, then the phase adjust flag is set to zero, indicating completion, and stored on disk file 3138, word 361.

The purpose of the phase scan procedure, referred to in some of the above steps, is to search for a phase at which the Δt results are in the right ballpark while the module is in phase and amplitude control. This phase scan procedure will only be tried once. On the second transfer to this procedure, the message

CAN NOT FIND SUITABLE PHASE. CHECK RF

is written on the character scope and the program is stopped. On the first time through, the phase scan procedure is as follows:

1. Check the H^- current monitor (channel 20) at the module. If the absolute value of the data is less than or equal to 100 counts, then the assumption is made that either the beam is off, or

that the intensity is too low for the Δt procedure. In this case, the message

IS THE BEAM OFF

is written on the character scope, and the program is stopped. Otherwise, continue.

2. Move the phase set point to 100 counts and set J = 0.

3. The message

SCANNING PHASE. PSP = p

is written on the character scope, where p is the data from the phase set point.

4. Check for phase and amplitude control with the module turned on. If a servo is indicated, write the word "SERVO" on the character scope to the right of the phase set point, set J = 0, and go to step 8.

5. If a servo is not indicated, then call on program 3337 to measure and plot Δt_B and Δt_C. If the returned error flag is not zero, or if either Δt_B or Δt_C is greater than 0.8 nanoseconds in absolute value, then set J = 0 and go to step 8. Otherwise, continue.

6. If J = 0, indicating that this is the first good point, then save the value of Δt_B, set J = 1, and go to step 8.

7. If J $\neq$ 0, see if Δt_B has changed in the right direction at the last phase step. If so, the search is complete. If not, save the value of Δt_B.

8. Increment the phase set point by 100 counts. If the phase set point is less than 1900 counts, go to step 3. Otherwise, write the error message

CAN NOT FIND SUITABLE PHASE. CHECK RF

on the character scope and stop the program.

Program 3415: Adjust Amplitude in any 805-MHz Module
Access: /DE3415, push button #25 on card #63, or
demanded by another program
Description:

When this program is called, it reads some parameters from disk file 3138, and gets from the channel tables the calibration table for the module's phase shifter. The message

*3415 ADJUST AMPLITUDE IN MODULE m

is written on the character scope.

Two different procedures are used for adjusting the amplitude, depending on whether the specified module is between 5 and 12 or between 13 and 48. In modules 5-12, the adjustment is based on the slope of the output energy versus input phase curve. This slope must be evaluated at the design input phase, which in turn depends on the amplitude. Consequently, an iterative procedure of setting the phase, checking and adjusting the amplitude, and resetting the phase is required until both amplitude and phase are within tolerance. In modules 13-48, the adjustment is based on the height (above design value) of the peak of the output energy versus input phase curve. This is also an iterative procedure of adjusting the phase and then adjusting the amplitude.

The detailed procedure used in modules 5-12 is as follows:

1. The graph background for the output energy versus input phase curve is drawn on the storage scope, including a line showing the slope for the correct amplitude.

2. The module is delayed and the cursor position is checked. If the cursor is under the *, the procedure is stopped and the * is turned red. The adjust flag is set to 2 and stored on disk file 3138, word 361. Otherwise, continue.

3. Program 3336 is called on to calculate and plot the energy and phase displacements. If $|\Delta\phi_A| \leq 1°$, go to step 4. Otherwise, program 3349 is called on to adjust the phase. If program 3349 is successful, go to step 4; if not, the message

PROBLEM IN ADJUSTING THE PHASE

is written on the character scope and the procedure is stopped.

4. The phase set point is measured and the module is turned on. Using program 3414, the change in the output energy is measured as the phase is changed ±5°. If a problem is encountered in moving the phase shifter, then an error message

PHASE SET POINT NOT MOVING PROPERLY

is written on the character scope, and the procedure is stopped.

5. The amplitude is calculated and is written on the character scope and the storage scope, along with the amplitude set point and the cavity field. These three quantities are also written on disk file 3138. If the calculated amplitude is more than 10% away from design, the message

AMPLITUDE IS MORE THAN 10 PERCENT OFF

is written on the character scope and the procedure is stopped. Otherwise, the amplitude set point is adjusted. If a problem is encountered in moving the amplitude set point, the message

AMPLITUDE SET POINT NOT MOVING PROPERLY

is written on the character scope and the procedure is terminated.

6. If the calculated amplitude (before the set point was adjusted) was more than 1% away from design, then go to step 2. If the amplitude was within 1% of design, the amplitude set point and the cavity field are saved on disk file 3138, and the adjustment is complete.

In modules 13-48, the following procedure is used:

1. The design values of ΔW_{max} and phase displacement at which the maximum energy gain occurs are read from disk file 3129. (See Table VI.) The initial value of the phase set point is read and the graph background for the energy versus phase curve is drawn on the storage scope.

2. The module is delayed. If the cursor is under the *, the procedure is terminated.

3. Program 3349 is called on to adjust the phase of the module.

4. The module is turned on and the present phase set point is recorded. If this is not the first time through the iteration, go to step 5. If it is the first time through, the Δt fast phase shifter positions are saved and program 3333 is called on to adjust the fast phase shifters until the electronic phase shifter outputs are nearly zero with the module on. Record the new fast phase shifter positions, and go to step 6.

5. The fast phase shifters are set to their module-on values, obtained on the first time through step 4.

6. The values of the amplitude set point and the cavity field are read. The phase is set near to where the energy peak should occur, and then the phase is scanned in approximately 2° steps until the energy peak is found. The amplitude is changed by 2% and the corresponding energy change is measured to give $\partial W_{max}/\partial A$, where A is the normalized amplitude. However, when the amplitude is changed, the "synchronous" (or "design") phase also changes, so the total derivative of W_{max} with respect to normalized amplitude is

$$\frac{dW_{max}}{dA} = \frac{\partial W_{max}}{\partial A} + \frac{\partial W_{max}}{\partial \phi_s}\,\frac{\partial \phi_s}{\partial A} \quad ,$$

TABLE VI

Energy Displacement (from Design) at Maximum Energy Output, and the Corresponding Phase Displacement

Module	ΔW_{max} (MeV)	$\Delta\phi$ (deg)
5	1.12	44.8
6	1.19	48.9
7	1.29	52.1
8	1.54	59.6
10	1.57	51.2
11	1.88	52.6
12	1.99	47.7
13	1.30	33.9
14	1.90	41.3
15	1.45	33.3
16	2.25	43.5
17	2.24	42.1
18	2.10	38.3
19	1.78	33.8
20	2.19	38.1
21	2.11	36.1
22	2.34	39.5
23	2.86	41.8
24	2.57	38.1
25	2.06	32.5
26	2.36	35.4
27	2.48	35.5
28	2.57	35.8
29	2.88	37.8
30	2.37	33.2
31	2.26	32.5
32	2.40	33.1
33	2.59	34.4
34	2.22	30.8
35	2.17	30.5
36	2.33	31.8
37	2.51	32.8
38	2.73	34.2
39	2.57	32.8
40	2.39	31.2
41	2.77	33.8
42	2.79	33.5
43	2.80	33.7
44	2.66	32.5
45	2.56	32.1
46	2.91	34.2
47	2.89	34.1
48	2.67	32.2

where ϕ_S is the synchronous phase. At the design value of $\phi_S = -30°$, the synchronous phase changes by approximately -1° for a +1% change in amplitude, which makes $\partial\phi_S/\partial A = -100$. Also,

$$\frac{\partial W_{max}}{\partial \phi_S} = -\frac{\partial W_B}{\partial \phi_A} \quad ,$$

where the term on the right is evaluated at the design phase. The amplitude displacement is calculated by

$$\Delta A = \frac{\Delta W_{max}}{\partial W_{max}/\partial A} \quad .$$

7. The estimated amplitude, the amplitude set point, and the cavity field are written on the storage scope and on the character scope. The amplitude set point and the phase set point are returned to their initial values at the beginning of this iteration. The Δt fast phase shifters are set to their original module-off values.

8. If the estimated amplitude is more than 10% away from design, then the procedure is terminated. If not, then the amplitude is adjusted to the design value, based on the calculated ΔA. If $|\Delta A| > 2\%$, then go to step 2. If $|\Delta A| \leq 2\%$, then the adjusted amplitude set point and cavity field are stored on disk file 3138 and the procedure is terminated.

Program 3416: Check the Present Values of the Amplitude Set Point and the Cavity Field against Disk Values

Access: /DE3416, or demanded by another program

Description:

The purpose of this program is to alert the operator to a discrepancy in either the amplitude set point or the cavity field of an 805-MHz module. Each time that the amplitude of a module is adjusted by program 3415, the final values of the amplitude set point and the cavity field are stored on disk file 3138. When program 3416 is called, the present values are compared to these stored values. If either, or both, differ by more than 1%, a message is written on the character scope:

DISCREPANCY IN ASP AND/OR FIELD, MOD = m
ASP = asp (aspd), FLD = cf (cfd) GO

where asp and cf are the present values of the amplitude set point and the cavity field, respectively, and aspd and cfd are their stored disk values. The quantities that differ by more than 1% are written in red.

The program then waits for a keyboard interrupt. If the cursor is under the word GO when the END key is hit, then a flag is set to zero and stored on disk file 3138 at word 361. This informs the calling program to proceed. If the cursor is not under the word GO when the END key is hit, then a -1 is stored on disk. The programs that automatically adjust the phase and amplitude will then be terminated.

Program 3410: Front End for Automatic Δt Tuneup Procedure

Access: /DE3410, or push button #26, card #63.

Description:

When this program is called, the message

*3410 AUTOMATIC DELTA-T. START STOP
ADJUST AMP/PH PHASE IN MODS m_1 THRU m_2

is written on the character scope. Initially, the word "PHASE" is written in yellow, indicating that the selected option is that of adjusting only the phases of the modules. To select the option of adjusting both amplitude and phase, place the cursor under the letters "AMP/PH" and hit the END key. The option selected will be written in yellow. Hitting the END key with the cursor under PHASE will select the "adjust phase only" option.

The user should insert the desired values of m_1 and m_2, the first and last modules to be automatically adjusted, and hit END with the cursor anywhere under the second line. The values of m_1 and m_2 are then read and stored on disk file 3138, words 27 and 28.

To start the automatic procedure, place the cursor under START and hit END. This program then demands program 3411, which actually controls the automatic tuneup. The tuneup procedure may be stopped at any time by placing the cursor under STOP and hitting the END key. This causes programs 3340, 3349, 3411, 3414, and 3415 to be dropped.

If a problem is encountered during the tuneup procedure, then a message is written on the second line of this program's character scope lines. To get the original second line rewritten, hit END with the cursor anywhere in the 2 lines except under the *, which drops the program.

Program 3411: Driver for Automatic Δt Tuneup
Access: Demanded by program 3410
Description:

This program sequentially calls on other Δt programs to perform their specific tasks. It essentially "pushes the buttons" for the operator in the proper order, and checks for proper completion of the various programs. The tuneup procedure is continued through the specified modules, one by one, until all the specified modules have been tuned, or until a condition arises which requires operator action. Messages are written to the operator through the character scope lines reserved by program 3410.

Program 3411 must be passed 8 arguments:

1. the number of arguments (8);
2. the station number;
3, 4, and 5. not used;
6. m_1, the number of the first module to be tuned;
7. m_2, the number of the last module to be tuned;
8. a flag specifying whether to adjust only the phases (zero) or to adjust both amplitudes and phases (nonzero).

Program 3411 uses the following procedure:

1. The specified module numbers, m_1 and m_2, are checked for being in the proper range. If they are not in the proper range, then this program is terminated. Otherwise, the number $m_1 - 1$ is stored as the module number on disk file 3138, word 359. Program 3340 is dropped and then demanded as if by /DE.

2. Program 3340 is demanded and passed arguments that will be interpreted as if push button #12 had been used. This tells 3340 to set up for the next module.

3. The matrix switch flag, MS, is checked (disk file 3138, word 26). If MS = 0, go to step 5. Otherwise, up to 3 additional tries are made at setting the matrix switches using program 3331. If successful, go to step 4. If not successful, the message

MATRIX SWITCH PROBLEM. ABORTING AUTO DT

is written on the second character scope line belonging to program 3410, and program 3411 is terminated.

4. Program 3333 is called on to center the electronic phase shifter outputs.

5. The "job complete" flag, set by program 3333 is checked. If it is not zero, then the message

EPS CENTERING PROBLEM. ABORTING AUTO DT

is written on the character scope and program 3411 is terminated.

6. The graph background is drawn on the storage scope, using program 3339 for modules 5 through 12, and program 3338 for modules 13 through 48.

7. Program 3348 is called on to set the phase of the module based on the phase of the previous module and on the stored phase shift between the 2 modules.

8. Program 3416 is called on to check the present values of the amplitude set point and cavity field against their disk values. If they agree within 1%, or if the user accepts the values as being satisfactory, then go to step 9. Otherwise, the message

FIELD OR ASP PROBLEM. ABORTING AUTO DT.

is written on program 3410's character scope lines, and program 3411 is terminated.

9. If the "adjust flag" (the 8th argument passed to this program) is not zero, then program 3415 is called on to adjust the amplitude. If a problem was encountered in adjusting either the amplitude or the phase, then the appropriate message is written on the character scope and program 3411 is terminated.

10. Program 3349 is called on to adjust the phase. If a problem was encountered, then a message is written on the character scope and program 3411 is terminated. Otherwise, the procedure is repeated from step 2 until all specified modules have been adjusted, at which point the message

AUTO DELTA-T COMPLETED

is written on the character scope and program 3411 is terminated.

The storage scope output produced by this automatic tuneup procedure at two different modules is shown in Figs. 16 and 17.

Program 3412: Front End for Automatic Δt Check
Access: /DE3412, or push button #28, card #63.
Description:

When this program is called, the message

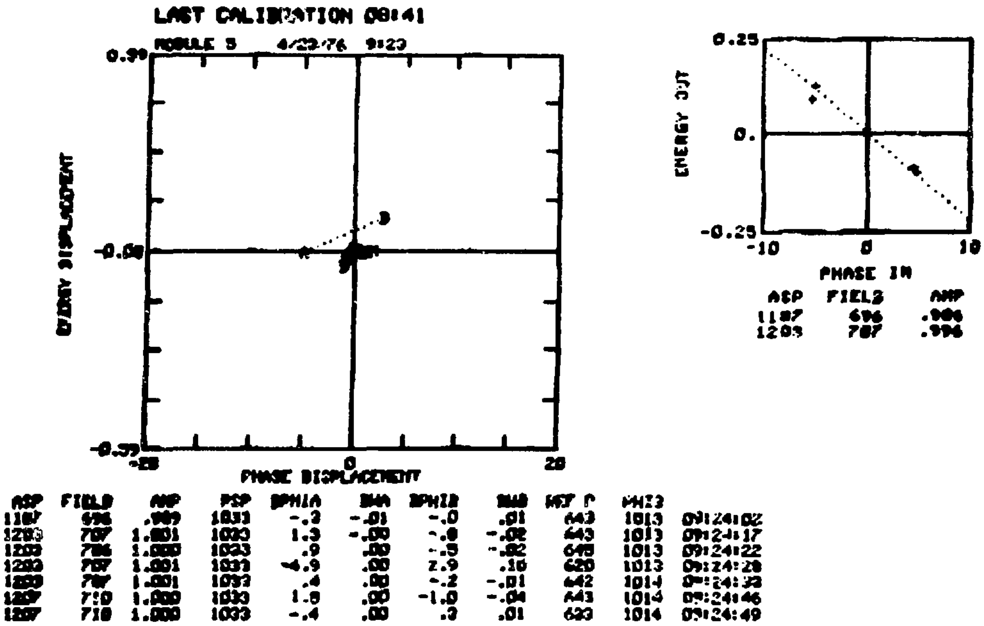

Fig. 16. Sample storage scope output produced by the automatic tuneup procedure at module 5.

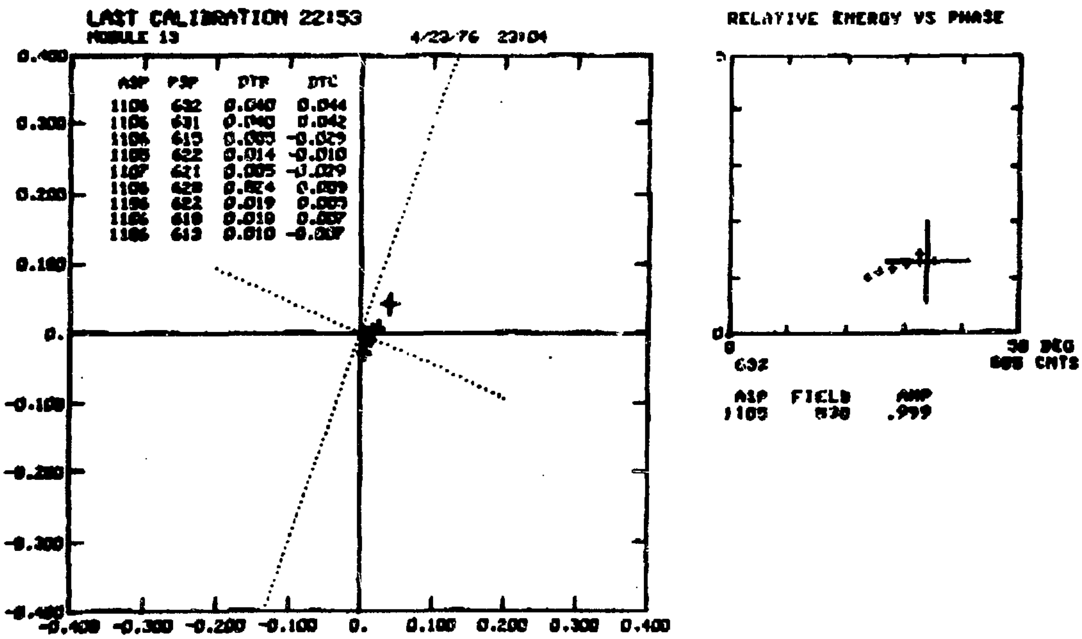

Fig. 17. Sample storage scope output produced by the automatic tuneup procedure at module 13.

*3412 AUTO CHECK DELTA-T START STOP

CHECK DELTA-T MODULES m_1 THRU m_2.

is written on the character scope. The user should specify the values of m_1 and m_2, the first and last modules to be automatically checked, and hit the END key. The module numbers m_1 and m_2 are then read and stored on disk file 3138, words 27 and 28.

To start the automatic checking procedure, place the cursor under START and hit the END key. This program then demands program 3413, which actually controls the automatic checking. The procedure may be stopped at any time by placing the cursor under STOP and hitting the END key. This drops programs 3340 and 3413.

If a problem is encountered during the checking procedure, then a message is written on the second line of this program's character scope lines. To get the original second line rewritten, hit END with the cursor anywhere in the 2 lines except under the *, which drops the program.

Program 3413: Driver for Automatic Δt Checking
Access: Demanded by program 3412.
Description:

This program sequentially calls on other Δt programs to perform their specific tasks. It essentially "pushes the buttons" for the operator in the proper order, and checks for proper completion of the various programs. The checking procedure is continued through the specified modules, one-by-one, until all the specified modules have been checked, or until a condition arises which requires operator action. Messages are written to the operator through the character scope lines reserved by program 3412.

Program 3413 is passed 7 arguments by 3412:

1. the number of arguments (7);
2. the station number;
3, 4, and 5. not used;
6. m_1, the first module to be checked;
7. m_2, the last module to be checked.

The following procedure is used by program 3413:

1. If the specified modules are not in the proper range, then program 3413 is terminated. Otherwise, m_1 - 1 is stored as the module number on disk file 3138, word 359. Program 3340 is dropped and then demanded as if by /DE.

2. Program 3340 is demanded and passed arguments that will be interpreted as if push button #12 had been used. This tells 3340 to set up for the next module.

3. The matrix switch flag, MS, is checked (disk file 3138, word 26). If MS = 0, go to step 5. Otherwise, up to 3 additional tries are made at setting the matrix switches using program 3331. If the attempt is successful, go to step 4. If not, the message

MATRIX SWITCH PROBLEM. ABORTING AUTO DT.

is written on the character scope, and program 3413 is terminated.

4. Program 3333 is called on to center the electronic phase shifter outputs.

5. The graph background is drawn on the storage scope, using program 3339 for modules 5 - 12, and program 3338 for modules 13-48.

6. Program 3416 is called on to check the present values of the amplitude set point and cavity field against their disk values. If they agree within 1%, or if the user accepts the values as being satisfactory, then go to step 7. Otherwise, the message

FIELD OR ASP PROBLEM. ABORTING AUTO DT.

is written on the character scope, and program 3413 is terminated.

7. Δt is checked and plotted on the storage scope 5 times. Program 3336 is used for modules 5-12, and program 3337 is used for modules 13-48. If Δt could not be measured for some reason, then the message

PROBLEM. ABORTING AUTO DELTA-T CHECK.

is written on the character scope and program 3413 is terminated. Otherwise, the procedure is repeated from step 2 until all specified modules have been checked, at which point the message

AUTO DELTA-T CHECK COMPLETED.

is written on the character scope and program 3413 is terminated.

Program 3414: Measure Changes in Energy of Beam Drifting between 2 Δt Pickup Loops
Access: Demanded by another program
Description:

The first time that this program is called, it must be sent 3 arguments:

1. the number of arguments (3);

2. the number of the calling program;

3. NT, the number of times to repeat the measurement.

Parameters are read from disk file 3138 specifying which pickup loops are used, the distance between these loops, the design energy of the beam, the data sampling time, and the tolerance on the Δt error signals. The calibration tables for the elctronic phase shifters are read from disk file 3134. The electronic phase shifter outputs are read NT times and averaged. This gives the reference times at which the beam arrives at each loop. On subsequent calls to this program, energy changes are calculated from the changes in the arrival times at each loop.

When this program completes its initialization procedure, it returns 2 arguments to the calling program:

1. the number of arguments (2):

2. an error flag having the value 0, 1, or -1, meaning there were no errors, the error signal exceeded tolerance, or the data were outside the range of the calibration table, respectively.

When this program is called and sent anything but 3 arguments, it reads the electronic phase shifter outputs NT times, averages the results, and calculates the energy change from the initial energy. It returns 4 arguments to the calling program:

1. the number of arguments (4);

2. the error flag (described above);

3. & 4. the energy change, in MeV (2 words are required for a floating-point number).

Program 3347: Store Module-to-Module Phase Shifts on Disk File 3129.

Access: /DE3347

Description:

This program reads the phase set points of all the 805-MHz modules, including the 805-MHz reference line, converts the data into degrees via the channel table calibrations, and calculates the phase shift between adjacent modules. These phase shifts are then written on disk file 3129, and also written on the storage scope. (See Fig. 18.)

Program 3347 should be run each time that the linac is re-tuned. The phase shifts stored on disk will be used in calculating the initial phase setting when the linac is next tuned. A comparison of the storage scope outputs will show how consistent or inconsistent the phase shifts are for different tuneups.

PHASE SHIFTS BETWEEN MODULES 23 APR 1976 09:18:22

4 -5	117.1	26-27	-123.1
5 -6	57.1	27-28	31.3
6 -7	-30.6	28-29	-97.9
7 -8	15.5	29-30	-109.8
8 -9	-31.4	30-31	5.0
9-10	119.2	31-32	72.2
10-11	-73.8	32-33	134.0
11-12	-175.1	33-34	-171.8
12-13	-1.9	34-35	-103.1
13-14	-100.2	35-36	108.8
14-15	-111.8	36-37	-7.7
15-16	67.8	37-38	97.3
16-17	43.4	38-39	110.2
17-18	-17.5	39-40	-172.8
18-19	161.8	40-41	-80.6
19-20	170.0	41-42	-174.9
20-21	-87.5	42-43	-69.1
21-22	118.0	43-44	64.9
22-23	61.4	44-45	51.0
23-24	-82.7	45-46	58.8
24-25	-141.7	46-47	51.0
25-26	74.8	47-48	-135.6

Fig. 18. Sample storage scope output produced by program 3347.

Program 3323: Monitor and Display the Δt Signals

Access: /DE3323, or push button #11, card #63

Description:

This program monitors the data from channel D27 in modules 5 through 10, which are the electronic phase shifter outputs, the error signals, and the signal levels for the 2 Δt systems of electronics. The sample time is read from disk file 3138, word 360. The data from these 6 devices are written on the character scope beneath the lines

*3323 MONITOR DELTA-T SIGNALS

EPS1 SL1 ERR1 EPS2 SL2 ERR2.

If a parity error is obtained on the data-take on any module, the corresponding data will be displayed as 9999.

If the cursor is placed under the *, the program will stop taking data. To restart the data taking, hit the END key when the cursor is anywhere within the 3-line display except under the *, which drops the program.

Program 3318: Display on the Storage Scope the Results of the Last Δt Measurements at each Module.

Access: /DE3318

SUMMARY OF DELTA-T SETTINGS

DATA			TIME	MOD	ASP	PSP	DTB	DTC	DPA	DWA	DPB	DWB
24	APR	1976	07:53:02	5	1200	1033	2	2	.1	-.00	-.2	-.00
23	APR	1976	20:11:39	6	1522	1129	-19	-48	-.1	.04	.7	-.03
23	APR	1976	20:12:11	7	1602	1050	31	131	-.1	-.10	-1.7	.08
23	APR	1976	20:12:37	8	1523	1133	-34	-93	-.0	.07	.9	-.06
23	APR	1976	20:13:43	9	1357	1161	34	94	-.1	-.06	-.6	.07
23	APR	1976	20:14:16	10	1277	192	-14	-43	.0	.04	-.3	-.04
23	APR	1976	22:17:34	11	1318	1228	30	84	.4	-.07	-.1	.07
24	APR	1976	05:24:19	12	1266	670	-15	-70	3.0	.10	-3.4	-.07
24	APR	1976	05:27:32	13	1103	601	10	-6				
24	APR	1976	05:28:50	14	1273	268	-6	10				
24	APR	1976	05:30:17	15	1306	1008	-5	-5				
24	APR	1976	05:31:36	16	1206	1242	-11	5				
24	APR	1976	05:33:11	17	1472	104	1	-4				
24	APR	1976	05:39:12	18	1562	1319	0	5				
24	APR	1976	05:47:27	19	1516	720	4	-11				
24	APR	1976	05:48:03	20	1518	1352	2	5				
24	APR	1976	05:48:26	21	1346	1099	0	-6				
24	APR	1976	05:49:56	22	1640	320	-4	0				
24	APR	1976	05:49:22	23	1274	619	5	0				
24	APR	1976	07:24:14	24	1363	416	-5	-1				
24	APR	1976	07:25:30	25	1243	1234	4	2				
24	APR	1976	07:32:27	26	1320	240	-3	-1				
24	APR	1976	07:34:07	27	1332	1240	6	4				
24	APR	1976	07:35:36	28	1225	1411	0	-3				
24	APR	1976	07:37:34	29	1201	1080	4	6				
24	APR	1976	07:39:22	30	1208	722	-11	3				
24	APR	1976	07:55:31	31	1272	984	8	-11				
24	APR	1976	07:57:01	32	1593	1230	1	0				
24	APR	1976	07:58:34	33	1500	494	-1	-4				
24	APR	1976	08:00:18	34	1213	1207	-4	1				
24	APR	1976	08:02:22	35	1693	918	7	3				
24	APR	1976	08:03:50	36	1442	1349	10	0				
24	APR	1976	08:32:46	37	1505	143	-3	0				
24	APR	1976	08:34:03	38	1382	556	-6	5				
24	APR	1976	08:42:00	39	1111	974	5	-1				
24	APR	1976	08:43:25	40	1292	465	4	0				
24	APR	1976	08:44:44	41	1380	170	0	-5				
24	APR	1976	08:45:34	42	1109	1012	-3	2				
24	APR	1976	08:47:35	43	1289	787	5	-6				
24	APR	1976	08:51:30	44	1412	1033	2	-2				
24	APR	1976	08:53:14	45	1408	114	0	-4				
24	APR	1976	08:54:28	46	1454	416	-2	0				
24	APR	1976	09:00:27	47	1706	980	0	3				
24	APR	1976	09:06:20	48	1173	677	0	2				

Fig. 19. Sample storage scope output produced by program 3318.

Description:

Each time that program 3334 makes a measurement of Δt_B and Δt_C, these values, along with the amplitude and phase set points and the millisecond clock (2 words), are saved on disk file 3319. Likewise, each time that program 3336 calculates the phase and energy displacements, it stores these quantities on disk file 3138.

Program 3318 simply reads this information from the disk and writes it on the storage scope. An example of the storage scope output is shown in Fig. 19.

Program 3327: Plot the Change in the Output Energy versus the Input Phase at any 805-MHz Module

Access: /DE3327, or push button #22, card #63

Description:

When first called, this program reads the Δt calibration tables from disk file 3134, and the module number, m, and data sampling time, t, from disk file 3138, words 359 and 360. The message

```
*3327 PLOT ENERGY VS PHASE FOR MODULE m
GRAPH BOUNDARIES + AND - 100. DEG 10.0 MEV
SAMPLING TIME = TO + t.     RE-CENTER EPS
```

is written on the character scope. The user may then change any (or none) of the parameters and hit the END key with the cursor anywhere within the 3 lines except under the * or under the words "RE-CENTER EPS." The storage scope is then erased and the graph background is drawn.

Program 3340 is then called and passed 3 arguments: 3; station number; module number. Program 3340 then puts all the modules up to, and including, the specified module "in time" and delays the downstream modules, calculates the Δt parameters associated with the specified module and stores them on disk file 3138, and connects the standard pickup loops to the Δt electronics via program 3331. Program 3327 reads the necessary parameters from disk, including the design coordinates of the energy peak. Program 3333 is then called on to adjust the fast phase shifters until the electronic phase shifter outputs are centered in the calibration table. The

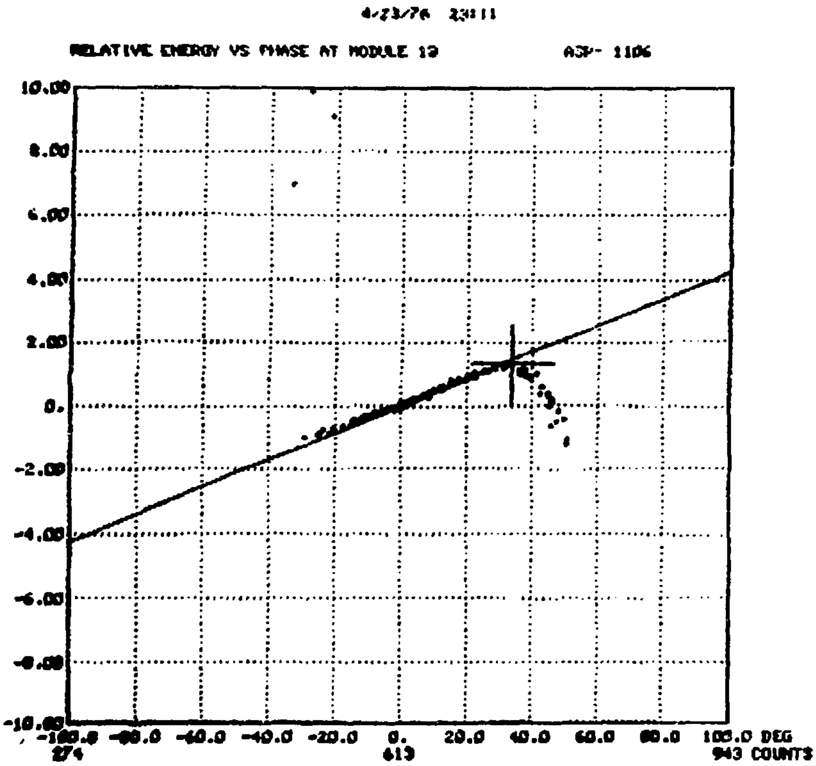

Fig. 20. Sample storage scope output produced by program 3327.

design slope of the energy versus phase curve is drawn through the origin, and the location at which the peak of the curve should occur is marked with a large cross. The "initial values" of the electronic phase shifters are read and saved.

The program then takes data from the electronic phase shifters, compares the data to the initial values, and calculates an energy change. The phase set point is read, and the energy change is plotted versus the phase. This program continues to take data and plot the results until it is stopped by placing the cursor under the *. This program does not itself change the phase of the module; it simply takes data. The user may change the phase using a tweek knob.

The user may restart the program by hitting the END key. If the cursor is under the *, then the program is dropped. If the cursor is under the words "RE-CENTER EPS", then program 3333 is called on to re-adjust the fast phase shifters until the outputs from the electronic phase shifters are again centered in the calibration table. Plotting is then continued at the point at which it was stopped. If the cursor is elsewhere within the 3 lines, then the procedure is restarted from the beginning. (Sample storage scope output is shown in Fig. 20.)

Program 3328; Plot Energy Change versus Time or versus any Arbitrary Channel.
Access: /DE 3328, or push button #24, card #63
Description:

The purpose of this program is to measure and plot the changes in the energy of a beam that is drifting between 2 Δt pickup loops.

When this program is first called, it reads an initial set of parameters from words 0 - 14 of disk file 3134 and writes them on the character scope in the following message:

*3328 MEASURE ENERGY CHANGE OUT OF MOD m
USING PICKUP LOOPS AFTER MODS m_1 AND m_2.
ESCALE= e, T= t, INT= i, STOP CONT
MOD CHAN TIME BMG CYC MIN MAX NI

m_x c_x t_x b c x_{min} x_{max} n_x

where the small letters represent the values of the 14 parameters. The energy scale of the graph will be between ±e, the data sampling time for the energy change is specified by t, and i specifies the time interval between sample times, in milliseconds. The information on the bottom line refers to the data channel to be plotted as the abscissa; the module number; the channel number; the sample time; the H^+ beam gate parameter (-1, 0, or +1); the cycle parameter (-1, 0, +1); the minimum and maximum values of the data range (the values assigned to the left and right boundaries of the graph); and the number of graph intervals along the abscissa. If the user wants to plot the energy change versus real time, then he sets m_x to a negative number. In this case, the only parameters on the last line that have any significance are x_{max} and n_x, where x_{max} will specify the right boundary of the time scale (in seconds), and n_x is still the number of intervals. The left boundary of the time scale will be zero.

After specifying the set of parameters, hit the END key with the cursor anywhere within the lines except under the *, or under the words STOP or CONT (continue). Program 3329 (which actually does the measurements and the plotting) is dropped, the graph background is drawn on the storage scope, and then program 3329 is called and passed the parameter set.

The measurements and plotting may be stopped at any time by the user by placing the cursor under STOP and hitting END. To continue the plotting (without erasing the scope and drawing a new graph), place the cursor under CONT and hit END. Hitting END with the cursor under the * will drop the program.

This program does not delay any modules or set any matrix switches. The user must set up the desired accelerator configuration and set the matrix switches prior to calling this program.

Program 3329: Plot the Energy Change for Program 3328

Access: Demanded by program 3328

Description:

This program is called by program 3328 and sent the parameter set specified by the user. The design output energy of the specified module, and the module lengths are read from disk file 3129. The Δt calibration tables are read from disk file 3134. The relationship between the energy change and the signals from the pickup loops is calculated, and the initial values of the electronic phase shifters are read.

Program 3329 then proceeds to take data from the electronic phase shifters and from the specified channel (or from the time clock), and to plot the resultant energy change (from its initial value) versus the specified quantity. After plotting each point, program 3329 delays itself the specified time interval before taking the next measurement.

Program 3326: Plot Δt_B and Δt_C Versus any Data Channel

Access: /DE3326

Description:

When this program is called, the message

*3326 PLOT DELTA-T VS PHASE SHIFTER 1,
MOD= m, TIME= t, NTIMES= n, SCALE= 10.0
MOVE SHIFTER FROM 150 TO 1700, NP= 31,
MC=9, ICC= 15, MD= 9, IDC= 49, ERASE

is written on the character scope. The user may then change any of the parameters and hit the END key. The present value is read from the specified data channel, IDC, at module MD. The data are then driven to the first specified value (150 in the above message) assuming that the commands are sent through channel ICC at module MC.

Program 3334 is called on to measure Δt_B and Δt_C at module m. (The user must have set the matrix switches properly.) The results obtained from program 3334 are written on the character scope, including the number of arguments received, the error flag, Δt_B, Δt_C, σ_B, σ_C, the electronic phase shifter outputs from systems 1 and 2 with the modules both off and on, and these 4 outputs converted into degrees (at 201.25 MHz). If the error flag is not zero, then the program is stopped.

If the cursor was under the word ERASE when the END key was hit, then the storage scope is erased and the graph background is drawn. The values of Δt_B and Δt_C are plotted against the specified data. The phase shifter is stepped through the specified range in NP steps, and Δt_B and Δt_C are measured, plotted, and written on the character scope at each step. A nonzero error flag received from program 3334 will stop the program. Otherwise, after the specified range has been covered, the phase shifter is returned to its initial value.

Program 3344: Monitor the Δt Electronic Phase Shifter Outputs at a Specifiable Series of Pickup Loops.

Access: /DE3344.

Description:

The purpose of this program is to detect phase shifts along the linac, if they occur, via the Δt pickup loops. At a specified time interval, for example every 10 minutes, the Δt electronics can be sequentially connected to series of pickup loops and the electronic phase shifter outputs recorded on a disk file. The outputs from the electronic phase shifters are also recorded with the systems placed in the calibrate mode, for the purpose of detecting drifts in the electronics. The real time clock is also sampled and stored.

At the user's request, the electronic phase shifter output at any pickup loop, or in the calibrate mode, may be plotted versus time. Ideally, the curve should be a straight horizontal line, which would indicate that the beam arrived at the pickup loop at a phase that was constant in time. In practice, the curves are not constant, usually interpreted to be caused by the drift in the Δt electronics. The user also has the option of subtracting the changes in the calibrate signal from the pickup loop signal before plotting.

When this program is called, the message

*3344 MONITOR DELTA-T LOOP SIGNALS

START CONTINUE STOP PRINT PLOT

is written on the character scope. The user specifies one of the options by placing the cursor under one of the words on the second line and hitting the END key. The various procedures are described below.

START The monitoring procedure is started. Five parameters are read from disk file 3346 and written on the character scope:

MOD1 = m_1, NLOOPS = n_ℓ, NAVERAGE= n_a

INTERVAL= i SEC, SAMPLE TIME= t.,

where m_1 is the first module number at which to start monitoring the signal from the pickup loop; n_ℓ is the total number of loops to monitor, n_a is the number of times to take data and obtain the average, i is the interval in seconds at which to take data, and t is the sample time in microseconds. The user may change any of these parameters and hit the END key. The parameters are then read and stored on disk file 3146 along with 3 other parameters: NS, MAXD, and IR. NS is the number of storage words required at each time interval, and is equal to the number of loops specified + 4 (2 words for the calibrate signals and 2 words for the time). MAXD is the maximum number of data takes that would fill the reserved disk file. IR is set to 1, indicating that monitoring is in progress. Program 3345 is then demanded on a timed basis.

STOP The monitoring process is stopped. Program 3345 is terminated and IR is set to 0 and stored on disk file 3346.

CONTINUE The monitoring process is restarted. Program 3345 is again restarted on a timed basis, and IR is set to 1.

PRINT The data collected so far are written on the line printer. The parameters m_1, n_ℓ, n_a, i, t, MAXD, and n are written at the top of the page, where n is the number of data sets taken thus far, and the other parameters are as defined above. The data are then printed, starting with the time, the signals from system 1 and system 2 in the calibrate mode, followed by the values from the n_ℓ loops.

PLOT The signal from any pickup loop or from the calibrate signal is plotted versus real time. The message

LOOP AFTER MODULE m, SCALE= s COUNTS

is written on the second line of program 3344's 2 character scope lines. The user specifies the desired loop (or a 0 or 1 to indicate the signal from system 1 or 2, respectively, in the calibrate mode), and the graph scale. (The vertical scale will be $d_1 \pm s$, where d_1 is the first data value for the specified loop.) If the cursor is under the second line when the END key is hit, then the data are plotted without modification; if the cursor is under the top line, then changes in the calibrate system are subtracted from the data before plotting.

Program 3344 is dropped by placing the cursor under the * and hitting the END key.

Program 3345: Monitor Data from Δt Loops

Access: Demanded on a timed basis

Description:

Each time that this program is run, it goes through the following procedure:

1. The number of data sets taken thus far is compared to the maximum number allowed. If the maximum number has been taken, then this program does nothing.

2. The H^- run permit bit is checked. If the bit is zero, then no data is taken.

3. The time is read (from memory locations 2 and 3). The Δt system is put in the calibrate mode and data taken from the electronic phase shifters. The system is then put back in the operate mode.

4. The matrix switches are used to connect the Δt systems to the specified pickup loops, and data are taken at each loop.

5. The number of data sets is incremented by 1 and stored on disk file 3346, and the time and electronic phase shifter data are stored on disk file 3346.

Program 3381: Restart Loop Monitoring after Computer Restart

Access: Automatically called by the computer system after a computer restart.

Description:

This program checks the run flag, IR, from word 9 of disk file 3346. If IR = 1, then it starts program 3345 running again on a timed basis.

Program 3380: Plot Δt Signal Levels

Access: /DE3380

Description:

When this program is called, the message

*3380 PLOT DELTA-T SIGNAL LEVELS

TIME= t, SCALE= y_{min} y_{max}

is written on the character scope. The user specifies the data sampling time, t, and the values to be assigned to the bottom and top boundaries of the graph. After the END key is hit, the graph background is drawn on the storage scope, and the Δt electronics is sequentially connected to the pickup loops via program 3331. At each pickup loop, the Δt signal levels are read (data channel 27 at modules 5 and 8) and plotted on the graph.

The program is dropped by placing the cursor under the * and hitting the END key.

STORAGE MAP FOR DISK FILE 3129

location	contents
0-97	Design values of W_A. (Also the design value of W_B, since the design input energy at any module is the same as the design output energy at the previous module.)
200-295	Phase shifts between modules, based on tuned-up settings and on phase shifter calibrations in the channel tables. (These values are stored here by program 3347.)
300-395	The phase shift, in degrees, from the design phase to the phase at which the output energy is a maximum.
400-495	The output energy displacement when the phase is set for maximum energy gain (ΔW_{max}).
500-597	D_{AB}, the module lengths. (One additional length is stored, the distance between the 2 loops downstream of module 48.)
600-695	Design values for t_B.
700-1403	Elements of M and M' matrices, where M is the matrix relating the output phase and energy displacements to the input phase and energy displacements, and M' is derivative of M with respect to the rf amplitude.
1450-1657	Measured values of 805-MHz tank lengths.
1658-1865	Measured values of drift lengths between tanks.

All values are floating-point numbers, which require 2 words of storage each.

STORAGE MAP FOR DISK FILE 3138

Location	Contents
0	IDVIS, the storage scope device # for prog 3340
1	NPG, the number of the program reserving devices (3340)
2	LI, line intensity for drawing vectors on storage scope
3	ICS, character size for storage scope characters
4	IHV, horizontal or vertical flag for storage scope characters
5-6	ICP, storage scope "current points"

7-8 MRG, storage scope margins

9-12 IXY, storage scope graph boundaries

13-20 XY, floating-point values assigned to graph boundaries

21 NSN, station at which prog 3340 is being run

22 NCCI, character scope device code assigned to prog 3340

23 LOCK, tolerance on Δt error signals

24 LZ1, zero offset for error signal, system #1

25 LZ2, zero offset for error signal, system #2

26 MS, matrix switch flag

27 M1, first module when doing automatic Δt

28 M2, last module when doing automatic Δt

29-30 time of last Δt calibration

31 "job complete" flag set by program 3333

50-137 amplitude set points and cavity fields (Channel D28) corresponding to 100% amplitude, as estimated by program 3411. ASP for module m is stored in location 50 + 2x (m-5), cavity field is stored in 51 + 2x (m-5)

215-222 M, 2 x 2 matrix relating output displacements to input displacements

223-230 M', derivative of M matrix with respect to rf amplitude

231-232 D_{AB}, module length

233-234 D_1, distance from end of module to first pickup loop

235-236 D_2, distance from end of module to second pickup loop

237-238 S, slope of Δt_C vs Δt_B line at design amplitude

239-240 derivative of S with respect to amplitude

241-242 design value of t_B

243-244 design value of t_C

245-246 W_A, design value of input energy

247-248 W_B, design value of output energy

249-250 η_A corresponding to input energy

251-252 η_B corresponding to output energy

253-254 $\Delta A/A$, estimated amplitude displacement (by program 3335)

279-294 estimated normalized amplitudes of modules 5 through 12 at the last running of program 3336

295-310 last calculated values of ΔW_A for modules 5 - 12

311-326 last calculated values of $\Delta\phi_A$ for modules 5 - 12

327-342 last calculated values of $\Delta\phi_B$ for modules 5 - 12

343-358 last calculated values of ΔW_B for modules 5 - 12

359 MOD, the module number

360 IST, the data sampling time

361 phase adjust and amplitude adjust flag (set by programs 3349 and 3415)

362 NTIMES, the number of times to repeat Δt

363 NMT, the number of modules to be treated as a unit

364 NS, the number of steps to take when constructing a variable phase curve with program 3335

365 NCA, the number of curves to be constructed by program 3335 to obtain average slope

366 IDP, the number of pulses per step sent to the module phase shifter by program 3335

367 L1, the module number just upstream of first pickup loop

368 L2, the module number just upstream of second pickup loop

369 K, system attached to first loop (1 or 2)

370-371 CX, conversion factor for horizontal scale of graph

372-373 CY, conversion factor for vertical scale of graph

374 NX, number of intervals in horizontal axis

375 NY, number of intervals in vertical axis

376 IXP, horizontal scope coordinate for data writes

377 IYP, vertical scope coordinate of last data write

378 IG, flag denoting which background is on storage scope

380-387 amplitude set points for modules 5-12 when program 3335 or program 3415 was last run on these modules

388-395 cavity field values (D28) for modules 5-12 when program 3335 or program 3415 was last run on these modules

396-411 normalized amplitudes of modules 5-12, as estimated by the last running of program 3335 or program 3415

412-427 standard deviation of estimated normalized amplitude, computed from slopes of NCA curves by program 3335

STORAGE MAP FOR DISK FILE 3134

The first 15 words are used by program 3328

Word	Contents
0	MOD, the module number at which to measure energy change
1,2	WMAX, maximum value for energy scale
3	IST, data sampling time
4	IDT, delay time (in milliseconds) between measurements
5	MODX, module number for abscissa
6	ICHAN, data channel for abscissa
7	IT, sample time for abscissa data
8	IBG, H^+ beam gate parameter for abscissa data
9	ICY, cycle parameter for abscissa data
10	MIN, minimum value of abscissa
11	MAX, maximum value of abscissa
12	NI, number of intervals along abscissa
13	L1, module number just upstream of first pickup loop
14	L2, module number just upstream of second pickup loop
88-167	calibration table for system #1
168-247	calibration table for system #2
250-261	IDPST(I,J,K), short calibration table for digital power supplies for the fast phase shifters. K refers to the system # (1 or 2). The J index is 1 or 2 referring to the minimum or maximum values of the digital power supplies and the fast phase shifters. The I index is 1, 2, or 3, referring to the power supply, the fast phase shifter, or the electronic phase shifter output.
395	IAUTO, flag tested by program 3330. If it is non-zero, then program 3330 adjusts the fast phase shifters until the starting values of the calibration tables are as specified by IEPS1 and IEPS2.
396	IEPS1
397	IEPS2
402	IDIR, specifies direction to move trombone when calibrating
403	IP, 0 means base calibration on motor pulses; 1 means base calibration on trombone pot.
404	IR, 1 means to reverse the calibration table; 0 means don't reverse the calibration table
405	IAV, number of times to take data and average
406	NDEG, number of degrees covered by calibration table
407	IST, data sampling time
408	IBG, H^+ beam gate parameter
409	ICY, cycle parameter
410-489	newly generated calibration table for system #1
490-569	newly generated calibration table for system #2

STORAGE MAP FOR DISK FILE 3319

Each time that program 3334 measures Δt_B and Δt_C, it also reads the millisecond clock and the amplitude- and phase-set points of the module, and writes these values on disk file 3319. Six storage words are required, since the time clock requires 2 words. The data are stored in the following order: time (2 words); amplitude set point; phase set point; Δt_B; and Δt_C. Both Δt_B and Δt_C are stored as integers in picoseconds. The first word location of these values on disk for module m is at 6(m-5).

REFERENCES

1. K. R. Crandall, D. A. Swenson, "Side-Coupled Linac Turn-On Problem," LASL Internal Report, February 9, 1970.

2. K. R. Crandall, "Δt Revisited," office memorandum dated January 3, 1974.

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

4. Duard Morris, "Turn-over of Δt Hardware to MP-11," office memorandum dated September 18, 1975.