10-20-77
148

LA-6959-MS

Informal Report

Lh. 1505

UC-28

Issued: September 1977

MASTER

Wire-Scanner Recentering Experiment Error Estimates

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UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7408-ENG. 36

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This work was supported by the US Energy Research and Development Administration, Division of Physical Research.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Printed Copy ~~\$4.00~~ Microfiche \$3.00

4.00
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WIRE-SCANNER RECENTERING EXPERIMENT ERROR ESTIMATES

by

George R. Swain

ABSTRACT

In the wire-scanner recentering experiment, the effective center of a wire scanner is determined by turning the previous quadrupole magnet on and off. The beam is steered into the quadrupole such that it drifts to the same point somewhere on a second wire scanner downstream, for the quadrupole both on and off. With this steering, the beam is assumed to be centered at the quadrupole and first wire scanner. Approximate formulas and more exact numerical calculations show that for any incoming position at the quadrupole (not just the center), there is a corresponding incoming angle such that the beams for the quadrupole on and off will drift to the same point. Errors in the recentering experiment of 9-13 February 1977 due to the beams not converging to exactly the same point and due to the convergence point being off axis are estimated to be 0.8 mm or less. Errors from quadrupole angular misalignments are estimated to be 0.5 mm or less.

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I. INTRODUCTION

The wire-scanner recentering experiment was performed on the LAMPF 805-MHz linac with the object of improving the calibration of the wire-scanner instrumentation. The wire scanners measure the position and profile of the beam in the horizontal and vertical planes by determining the amount of beam current collected on a pair of wires, one horizontal and one vertical, as they are moved diagonally through the beam. A program at the control computer accumulates and displays these data and calculates the centroids and effective widths of the beam for the two planes. The recentering experiment was designed to improve the accuracy of the centroids read out.

The procedure used in the experiment was to find the effective center of the quadrupole doublet focusing magnet immediately upstream of each wire scanner to be recalibrated. The procedure was to steer the beam upstream from this quadrupole such that the position read at the detector wire scanner did not change as the quadrupole was turned on and off. (See Fig. 1.) For

this condition, the beam was assumed to be at the quadrupole center and at the center of the wire scanner to be calibrated. The constants for the calibration wire scanner were then adjusted to make it read zero in both planes for this condition.

The indicated centroid was taken as the position readout in each case, regardless of the shape of the beam profile. Some of the profiles were extremely broad or had more than one peak. (See Fig. 2.) The detector wire scanner was at the next module down from the wire scanner to be calibrated. The position at the detector wire scanner was assumed to be the same if the difference in centroid for the quadrupole on and off was 0.02 cm or less. The beam was steered such that most of the profile appeared on the detector wire scan, but not necessarily near the center. The wire scanners were calibrated in order beginning at Module 48 and working back to Module 5.

The purpose of this report is to examine the errors resulting from the assumption that the beams were very near the quadrupole and calibration wire scanner centers when the beams agreed to 0.02 cm or less at some position at the detector wire scanner. It will be shown that the error depends upon both the position at the detector wire scanner and upon the difference in position at the detector wire scanner for the quadrupole on and off. In addition, quadrupole angular misalignments may introduce errors. This paper will not attempt to interpret the varying beam profiles or their effect on the error for this experiment.

In Part II, approximate formulas for the expected error are derived using thin-lens approximations for the quadrupole elements. The effect of the earth's magnetic field is considered. In Part III, the results of calculations using a more exact quadrupole model are reported, and estimates of the errors are made for the wire-scanner recentering experiment data of 9-13 February 1977. Conclusions are summarized in Part IV.

II. APPROXIMATE FORMULAS FOR BEAM TRAJECTORIES AND RESULTING ERROR

The quadrupoles in the 805-MHz linac are wired such that for the horizontal plane the first element is focusing and the second element is defocusing. For the vertical plane, the first element is defocusing and the second is focusing. (See Fig. 3.) The earth's magnetic field is present all along the accelerator. Its magnitude is about 0.5 gauss. It is directed down and to the north at about 30 degrees from the vertical. We ignore the fact that the magnetic declination is about 13° East and that the beam direction is a few degrees north of due east.

The trajectories for the recentering experiment for the horizontal plane are shown in Fig. 4. When the quadrupole is off, the beam drifts to the detector wire scanner with a slight curvature to the north due to the vertical component of the earth's magnetic field. (The trajectory for a positive beam is shifted slightly north of where it would have been in the absence of the earth's field.) When the quadrupole is on, the trajectory at the quadrupole entrance must be slightly diverging (as shown) in order that the beam arrive at the detector wire scanner at the same point. The first element bends the beam so that it is diverging less than it was. When it arrives at the second quadrupole element, it is slightly farther from the axis than at the first element, and hence is bent at a slightly sharper angle. Hence the trajectory past the second element converges toward the trajectory for the quadrupole off.

The corresponding trajectories for the vertical plane are shown in Fig. 5. When the quadrupole is off, there is again a slight curvature due to the earth's

Fig. 1.

Diagram of a portion of the 805-MHz linac showing the equipment used in the wire-scanner recentering experiment for one module. The beam was steered using steering magnets upstream of quadrupole doublet QD1.

Fig. 2.

Display for accelerator operators of wire scanners 15WS1 and 16WS1 with quadrupole doublet 15QD1 off. In some cases such as this, the beam profiles were very broad or had more than one peak.

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Fig. 3.

Sketch indicating directions of bends in beam in passing through a quadrupole doublet.

Fig. 4.

Sketch of beam trajectories in the horizontal plane for the wire-scanner recentering experiment.

Fig. 5.

Sketch of beam trajectories in the vertical plane for the wire-scanner recentering experiment.

Fig. 6.

Approximate and actual beam trajectories when considering the effect of the earth's magnetic field.

magnetic field. (For a positive beam moving eastward, the northward horizontal component of the earth's field deflects the trajectory slightly upward.) When the quadrupole is on, the trajectory at the quadrupole entrance must be slightly converging in order that the beam arrive at the same point on the detector wire scanner as the beam with the quadrupole off. When the quadrupole is on, the first element bends the beam to be slightly diverging. Thus the beam arrives at the second element slightly farther from the axis than it was at the first element. The bend at the second element is thus slightly greater than at the first element, which leaves the beam converging. Downstream of the quadrupole, the beam crosses the axis and arrives at the detector wire scanner off axis in the other direction from where it was entering the quadrupole.

The above discussion has indicated that beams may enter a quadrupole off axis in either the horizontal or vertical planes, yet arrive at the detector wire scanner at the same point for the quadrupole on and off. We will now derive approximate formulas for the errors which such trajectories might introduce in the recentering experiment. For this purpose, we use thin-lens approximations for the quadrupole elements. The effect of the earth's field may also be approximated by a single sharp bend since the angular deflection is small. The bend is assumed to be midway along the drift distance involved, as shown in Fig. 6. If the angle of the sharp bend is chosen to equal the angle subtended at the center of curvature for the actual trajectory, the ends of the approximate trajectory come out tangent to the actual trajectory.

Let the angles of parts of the trajectory be designated as in Fig. 7. Let the distances be designated as in Fig. 8. For the trajectory for the quadrupole off, we have

$$x_2 = x_1 + \alpha_1 D_1 \quad (1)$$

$$x_3 = x_2 + \alpha_2 D_1 \quad (2)$$

$$\alpha_2 - \alpha_1 = \theta_1 \quad (3)$$

The bend due to the earth's field, θ_1 , is given by

$$\theta_1 = 2D_1 B/M,$$

in which B is the component of the earth's field perpendicular to the plane being studied, and the magnetic rigidity of the beam, M , is

$$M = mv/q = \beta \gamma m_0 c/q, \quad (4)$$

with

$$\beta = v/c$$

and

$$\gamma = (1 - \beta^2)^{-1/2},$$

where m , m_0 , v , and q are the total mass, rest mass, velocity, and charge of the particles in the beam, respectively, and c is the velocity of light. For protons, $m_0 c/q$ is 3.1297 tesla-m (3.1297×10^6 gauss-cm).

For the trajectory with the quadrupole on, we have

$$x_4 = x_1 + \alpha_3 D_2 \quad (5)$$

$$x_5 = x_4 + \alpha_4 (D_1 - D_2) \quad (6)$$

$$x_3 = x_5 + \alpha_5 D_1 \quad (7)$$

$$\alpha_3 - \alpha_1 = \theta_2 \quad (8)$$

$$\alpha_4 - \alpha_3 = \theta_3 \quad (9)$$

$$\alpha_5 - \alpha_4 = \theta_1 \quad (10)$$

The bends at the quadrupole elements are

$$\theta_2 = -g_1 x_1 = -G_1 L x_1 / M \quad (11)$$

and

$$\theta_3 = g_2 x_4 = G_2 L x_4 / M, \quad (12)$$

where G_1 and G_2 are the gradients of the first and second quadrupole elements, L is the effective length of an element, and M is the magnetic rigidity given in Eq. (4).

From Eqs. (1) through (3), we find the detector position in terms of the position and angle entering the quadrupole is

$$x_3 = x_1 + 2D_1\alpha_1 + \theta_1 D_1 \quad (13)$$

for the quadrupole off. From Eqs. (5) through (12), we find

$$x_3 = (\alpha_1 - g_1 x_1 + g_2 x_1 - g_1 g_2 D_2 x_1 + g_2 D_2 \alpha_1) D_3 + (1 - g_1 D_2) x_1 + D_2 \alpha_1 + \theta_1 D_1 \quad (14)$$

for the quadrupole on. Equating the two expressions for x_3 from Eqs. (13) and (14), we find the correct incoming angle entering the quadrupole in terms of the distance off axis there is

$$\alpha_1 = \frac{g_1 D_2 - (g_2 - g_1 - g_1 g_2 D_2) D_3}{g_2 D_2 D_3} x_1 \quad (15)$$

Normally the quadrupole elements are the same except for the sign of the fields. For $g_1 = g_2 = g$, Eq. (15) simplifies to

$$\alpha_1 = (g + 1/D_3) x_1 \quad (16)$$

From Eqs. (13) and (16) we find the relation between x_1 , the distance the beam is off axis entering the quadrupole, and x_3 , the distance the beam is off axis at the detector wire scanner, is

$$x_1 = \frac{x_3 - \theta_1 D_1}{1 + (D_2 + D_3)(g + 1/D_3)} \quad (17)$$

For the gradually diverging (or converging) trajectories encountered in the 805-MHz linac, the distance of the beam off the axis at the calibration wire scanner is close to x_1 . Thus Eq. (17) may be considered to be an approximate formula for the error at the calibration wire scanner in terms of the beam position at the detector wire scanner.

If a more precise transverse position at the calibration wire scanner is desired, we may use

$$x_6 = x_4 + (D_4 - D_2)\alpha_4, \quad (18)$$

together with Eqs. (5), (8), (9), and (16) to find

$$x_6 = [1 + D_4/D_3 + g(1 + D_2/D_3)(D_4 - D_2)]x_1. \quad (19)$$

Equation (19) gives us x_6 , the distance the beam is off axis at the calibration wire scanner, in terms of x_1 , the distance off axis entering the quadrupole. Equations (19) and (17) taken together may be used to relate the transverse position at the calibration wire scanner to the transverse position at the detector wire scanner.

The form of Eqs. (13), (14), and (17) suggests a way of dealing with the effect of the earth's magnetic field. The effect appears in these three equations as a term $\theta_1 D_1$. The quantity $\theta_1 D_1$ represents an offset in transverse beam position at the detector wire scanner. Because the angular deflection of the beam due to the earth's field is small, the same offset $\theta_1 D_1$ will be introduced in any plausible trajectory reaching the detector wire scanner. Thus we may consider the detector wire scanner as having an effective center which is offset by $\theta_1 D_1$ from its physical center. If we steer a beam into the quadrupole at the entrance to the module with zero transverse position and zero angle, it will appear at the effective center of the detector wire scanner. Ideally, a wire scanner recentering experiment should aim to place the beam at the effective center of each detector wire scanner. Table I gives the horizontal and vertical coordinates of the effective centers in terms of the physical centers for the wire scanners following the modules indicated. We use the conventions that south is positive in the horizontal plane and up is positive in the vertical plane.* Figure 9 shows that these offsets are largest near the beginning of the linac, and decrease as the beam becomes stiffer with increasing energy. The offsets shown in Table I and Fig. 9 were calculated assuming a magnetic field of 0.5 gauss at 30 degrees from the vertical.

We may then describe transverse positions at the detector wire scanner as distances from the effective center. Such effective distances will be designated with an overbar. Thus Eq. (17) becomes

$$\bar{x}_1 = \frac{\bar{x}_3}{1 + (D_2 + D_3)(g + 1/D_3)} \quad (20)$$

Henceforth in this report, when we use the term effective position, we mean positions with respect to the effective centers listed in Table I.

*This convention is consistent with the standard LAMPF coordinate system.

Fig. 7.

Angle nomenclature. Each α is the angle between the portion of the trajectory shown and a line parallel to the linac axis.

Fig. 8.

Position nomenclature. (Not to scale - D_1 and D_3 are actually large compared with D_2 and D_4 .)

Fig. 9.

Variation of offsets introduced by the earth's magnetic field with position along the 805-MHz linac. (These data are also given in Table I.)

TABLE I

OFFSETS DUE TO EARTH'S FIELD

Module Number	Position (cm) Det. W.S.	
	Cal.W.S.	V Plane
6	-.335	.194
7	-.337	.195
8	-.320	.185
9	-.327	.189
10	-.303	.175
11	-.309	.178
12	-.312	.180
13	-.244	.141
14	-.226	.130
15	-.225	.130
16	-.226	.131
17	-.228	.131
18	-.229	.132
19	-.216	.125
20	-.217	.125
21	-.218	.126
22	-.211	.122
23	-.212	.122
24	-.199	.115
25	-.199	.115
26	-.199	.115
27	-.199	.115
28	-.198	.114
29	-.198	.114
30	-.185	.107
31	-.184	.107
32	-.178	.103
33	-.174	.101
34	-.173	.100
35	-.173	.100
36	-.161	.093
37	-.160	.092
38	-.159	.092
39	-.159	.091
40	-.158	.091
41	-.157	.091
42	-.156	.090
43	-.155	.090
44	-.154	.089
45	-.143	.083
46	-.143	.082
47	-.142	.082

As a numerical example, we consider 09WS01, the wire scanner in front of Module 9. For the quadrupole immediately upstream of this wire scanner,

$$G = 2.5171 \text{ kilogauss/cm}$$

$$L = 10. \text{ cm}$$

$$\beta_Y = .5945$$

$$g = GL/M = 0.01353/\text{cm for the horizontal plane,}$$

$$D_2 = 20. \text{ cm}$$

$$D_3 \approx 1600. \text{ cm .}$$

If we retain only the most significant terms in Eq. (20), we have the following rough estimate:

$$x_1 \approx \bar{x}_3/(D_3 g) = \bar{x}_3/21 . \quad (21)$$

Thus the error at the calibration wire scanner is approximately 1/21 times the effective position at the detector wire scanner. This is considerably larger than we would expect if we considered only the lever arms to the various positions involved.

For the vertical plane, the rough estimate corresponding to Eq. (21) becomes

$$y_1 \approx -\bar{y}_3/21 ,$$

since the sign of g is reversed.

III. CALCULATED ERRORS FOR THE RECENTERING EXPERIMENT

Trajectories were calculated for the recentering experiment using thick-lens representations for the quadrupole elements. The calculations employed the same quadrupole and drift subroutines that are used in the SIMALAC beam dynamics code for the 805-MHz linac.* An iterative procedure was used. For a given position entering the quadrupole, a corresponding angle was estimated using Eq. (15) of Part II. If the trajectories did not converge to the same point at the detector wire scanner for the quadrupole on and off, the angle entering the quadrupole was adjusted and the calculation run again. Details on the algorithms used for these calculations are given in Appendix A.

In the experiment, the beams for the quadrupole on and off were not always steered to exactly the same point, but to points up to 0.02 cm apart. The algorithm for calculating trajectories was written so that we may require the beams to arrive at the detector wire scanner a specified distance apart, for the quadrupole on and off. Using this feature, we find that the required angle α_1 entering the quadrupole may be quite sensitive to the difference in the beam positions at the detector wire scanner. Therefore, the position at the calibration wire scanner may be quite sensitive to the difference in beam

*The SIMALAC code was developed by Kenneth R. Crandall over the period 1969-1976.

positions at the detector wire scanner. Figure 10 illustrates this point. The curves show the ratio of beam distances off axis, calibration wire scanner to detector wire scanner, as a function of the beam distance off axis entering the quadrupole. The curve for a detector wire scanner difference of +0.02 cm (quadrupole off to quadrupole on) is considerably different from the curves for a difference of 0.00 cm or -0.02 cm.

If the beams arrive at exactly the same point on the detector wire scanner (middle curve of Fig. 10), the ratio is constant, and hence the beam position at the calibration wire scanner is simply proportional to the effective beam position at the detector wire scanner. This result is consistent with Eqs. (19) and (20) as derived from the thin-lens theory.

Trajectories were calculated assuming the wire scanner at the start of a module was the one to be calibrated and the wire scanner following the module was the detector. This was done for modules 6 through 47. The ratios of beam position at the calibration wire scanner to effective beam position at the detector wire scanner found from these calculations are shown in Fig. 11 for the horizontal plane and in Fig. 12 for the vertical plane. The ratios are plotted for three values of quadrupole off-on difference at the detector wire scanner. The ratio of calibration to detector positions is strictly independent of the initial distance off axis only if the difference at the detector is zero. (This can be seen in Fig. 10.) The curves for which the difference at the detector is nonzero in Figs. 11 and 12 are plotted from data for beam trajectories which were 0.1 cm off axis entering the quadrupole.

We see from Figs. 11 and 12 that the effect of a nonzero quadrupole off-on difference in beam position at the detector wire scanner is small at the beginning of the linac and increases as we proceed downstream along the machine.

The results shown in Figs. 11 and 12 were used to estimate the errors in the wire-scanner recentering experiment of 9-13 February 1977. The errors considered were from neglecting the effect of the beams being off axis at detector wire scanner and from the effect of the beams not converging to exactly the same transverse position at the detector wire scanner. The error was estimated using the formula

$$\text{Error} = \bar{x}_{dn} \left\{ R(-.02) + \frac{(x_{df} - x_{dn}) - (-.02)}{(.02) - (-.02)} [R(.02) - R(-.02)] \right\},$$

where x_{dn} = meas. transverse position at det.w.s., quad. on

$\bar{x}_{dn}$ = effective transverse position at det. w.s., quad. on

x_{df} = meas. transverse position at det. w.s., quad. off

$R(d)$ = ratio of cal. to det. w.s. positions calculated for the det.
w.s. difference, $d = x_{df} - x_{dn}$

The quantity $R(d)$ is also dependent upon the module under consideration. (See Figs. 11 and 12.) Further details are given in Appendix B and Appendix C.

The experimental data¹ and the corresponding estimated errors are given in Tables II and III. (The experimental data are the position centroids at the calibration wire scanners before the results were used to update the calibration constants for these, and the position centroids at the detector wire scanners after the previous results were used to update the calibration

Fig. 10.

Calculated ratios of beam position at the calibration wire scanner to effective beam position at the detector wire scanner as a function of the beam position entering the quadrupole for Module 48.

Fig. 11.

Calculated ratios of beam position at the calibration wire scanner to effective beam position at the detector wire scanner for the horizontal plane.

Fig. 12.

Calculated ratios of beam position at the calibration wire scanner to effective beam position at the detector wire scanner for the vertical plane.

TABLE II

DATA AND ESTIMATED ERRORS, HORIZONTAL PLANE

H.S. No.	Horizontal Position, cm					
	Det. W.S.			Cal. W.S.		Est. Error in Meas.
	Quad. Off	Quad. On	Q.On, Eff.	Quad. Off	Quad. On	
6-1	.09	.09	.43	.12	.11	.03
7-1	-.74	-.73	-.39	.25	.28	-.02
8-1	-.75	-.76	-.44	.09	.09	-.03
9-1	.53	.53	.86	.15	.13	.05
10-1	-.12	-.12	.18	.07	.06	.01
11-1	-1.00	-1.00	-.69	-.03	-.03	-.04
12-1	.66	.69	1.00	.18	.16	.06
12-1	.65	.67	.98	.19	.16	.06
13-1	.06	.04	.28	-.06	-.07	.02
14-1	.72	.70	.93	.32	.28	.08
15-1	-.92	-.93	-.71	-.15	-.12	-.05
16-1	.13	.15	.38	.13	.11	.03
17-1	.26	.26	.49	.11	.10	.04
18-1	.07	.08	.31	.04	.03	.02
19-1	-.62	-.62	-.40	0.00	.01	-.03
20-1	-.10	-.10	.12	.09	.08	.01
21-1	-.18	-.20	.02	.12	.13	.00
22-1	-.46	-.48	-.27	.03	.04	-.02
23-1	-.44	-.42	-.21	.04	.06	-.02
24-1	.04	.04	.24	.08	.07	.02
25-1	-.45	-.44	-.24	.06	.08	-.02
26-1	-.19	-.21	-.01	.09	.08	-.00
27-1	-.31	-.31	-.11	.10	.09	-.01
28-1	-.55	-.55	-.35	.03	.04	-.03
29-1	-.64	-.63	-.43	.12	.13	-.04
30-1	-.47	-.46	-.28	.10	.10	-.02
31-1	.03	.01	.19	.15	.14	.02
32-1	-.39	-.37	-.19	.20	.19	-.02
33-1	-.44	-.45	-.28	.21	.21	-.02
34-1	-.20	-.20	-.03	.21	.20	-.00
35-1	.05	.04	.21	.22	.19	.02
36-1	-.44	-.45	-.29	.10	.10	-.03
37-1	-.71	-.70	-.54	-.10	-.09	-.05
38-1	.06	.05	.21	.03	.02	.02
39-1	.13	.15	.31	.13	.13	.03
40-1	-.40	-.40	-.24	.04	.03	-.02
41-1	.02	.02	.18	.13	.12	.02
42-1	-.11	-.13	.03	.16	.17	.00
43-1	.22	.24	.40	.20	.19	.03
44-1	-.02	-.01	.14	-.01	-.02	.01
45-1	-.47	-.47	-.33	.09	.08	-.03
46-1	-.18	-.19	-.05	0.00	-0.00	-.01
47-1	.13	.14	.28	.14	.13	.03

TABLE III

DATA AND ESTIMATED ERRORS, VERTICAL PLANE

H.S. No.	Vertical Position, cm					
	Det. H.S.			Cal. H.S.		Est. Error in Meas.
	Quad. Off	Quad. On	Q.On, Eff.	Quad. Off	Quad. On	
6-1	-.29	-.28	-.47	.09	.09	.02
7-1	.15	.15	-.04	.16	.17	.00
8-1	.26	.26	.08	-.03	-.04	-.00
9-1	-.19	-.19	-.38	0.00	-.01	.02
10-1	.27	.28	.10	0.00	.01	-.00
11-1	.22		.24	0.00	0.00	-.01
12-1	-.67	-.68	-.86	.08	.08	.04
12-1	-.67	-.67	-.85	.08	.08	.04
13-1	.03	.02	-.12	0.00	0.00	.01
14-1	-.03	-.04	-.17	.02	.04	.01
15-1	-.03	-.01	-.14	-.02	-.02	.01
16-1	.49	.48	.35	.04	.04	-.03
17-1	.07	.08	-.05	0.00	.01	.00
18-1	-.12	-.13	-.26	-.46	-.47	.02
19-1	.42	.44	.31	.02	0.00	-.02
20-1	.55	.54	.41	-.03	-.04	-.03
21-1	.26	.28	.15	.03	.02	-.01
22-1	.03	.04	-.08	.04	.03	.01
23-1	-.07	-.06	-.18	.06	.07	.01
24-1	-.30	-.31	-.43	-.02	-.03	.03
25-1	-.25	-.24	-.35	.12	.13	.03
26-1	.89	.90	.79	-.03	-.04	-.06
27-1	-.24	-.24	-.35	.06	.07	.03
28-1	-.51	-.52	-.63	.07	.09	.05
29-1	.29	.30	.19	0.00	.01	-.01
30-1	.09	.08	-.03	-.03	-.03	
31-1	-.11	-.12	-.23	.04	.05	.02
32-1	.14	.13	.03	.06	.05	-.00
33-1	.33	.32	.22	.07	.07	-.02
34-1	-.14	-.15	-.25	.24	.24	.03
35-1	-.08	-.09	-.19	.02	.05	.02
36-1	.26	.27	.18	-.24	-.24	-.02
37-1	-.37	-.37	-.46	-.06	-.07	.05
38-1	.12	.13	.04	0.00	0.00	-.00
39-1	.39	.39	.30	.23	.24	-.03
40-1	.04	.02	-.07	.02	.04	.01
41-1	-.34	-.35	-.44	.15	.15	.06
42-1	-.36	-.35	-.44	.10	.11	.05
43-1	.32	.31	.22	.08	.07	-.03
44-1	-.13	-.15	-.24	-.12	-.14	.03
45-1	.01	.02	-.06	.09	.07	.01
46-1	.33	.33	.25	.07	.07	-.03
47-1	.30	.30	.22	.09	.10	-.03

constants for these.) The largest estimated error is seen to be 0.8 mm in the horizontal plane and 0.6 mm in the vertical plane.

The errors given in Tables II and III do not include the effects of quadrupole alignment errors. For a module 16 meters long, we may think of a hypothetical error of half a milliradian in yaw or pitch of the quadrupole as corresponding to 8-mm deflection in horizontal or vertical position at the detector wire scanner. This would introduce roughly 0.8 mm of error at the calibration wire scanner. (See Figs. 11 and 12 for more exact ratios of calibrate to detector wire scan positions.) The errors in quadrupole yaw and pitch are generally considerably less than half a milliradian. The largest measured yaw angle was 0.4 milliradian and the pitch angles were believed to be less than ± 0.25 milliradian in the last survey.² The contributions to calibration error from quadrupole misalignment are thus likely to be 0.5 mm or less, and it is reasonable at present to ignore them.

IV. CONCLUSIONS

In the wire-scanner recentering experiment, we use trajectories drifting through a module with the preceding quadrupole magnet on and off. The beam trajectories may have a significant transverse displacement at the calibration wire scanner immediately downstream of the quadrupole if the beams do not converge to exactly the same point at the detector wire scanner downstream, or if the incoming trajectory is not parallel to the quadrupole axis. The incoming trajectory will not be parallel to the quadrupole axis if either the quadrupole has an alignment error in yaw or pitch, or the beams reach the detector wire scanner off axis from its effective center. The effective center of the detector is displaced from its physical center in order to take into account the earth's magnetic field.

Errors in the recentering experiment of 9-13 February 1977 due to the beams not converging to the same point and the convergence point being off axis are estimated to be 0.8 mm or less in the horizontal plane and 0.6 mm or less in the vertical plane. Errors from quadrupole angular misalignments are estimated to be 0.5 mm or less.

If it is necessary to repeat the wire-scanner recentering experiment at some future date, the procedure should call for more precise positioning of the beams on the detector wire scanner. For both the quadrupole on and quadrupole off, the steering should aim to put the beams close to the effective detector wire scanner centers listed in Table I, and the beams should land very close to the same point on the detector wire scanners. In order to achieve a precision of 0.05 cm at the calibration wire scanners, it is recommended that the beam positions at the detector wire scanners be within 0.5 cm of the effective centers listed in Table I, and that the difference in positions at the detector wire scanner for the quadrupole on and off be 0.02 cm or less. If it becomes feasible to make a more accurate survey of quadrupole yaw and pitch misalignments, it is recommended that the wire-scanner recentering experiment take these angles into account.

In order to achieve an accuracy greater than that obtained in the wire-scanner recentering experiment of 9-13 February 1977, it may also be necessary to understand the cause of multiple peaks in the transverse beam profiles. In order to improve the accuracy, it may be necessary to eliminate multiple peaks or know how to take them into account.

REFERENCES

1. Andrew A. Browman, "Wire Scanner Recentering Experiment," Los Alamos Scientific Laboratory, unpublished data, February 1977.
2. D. J. Liska, "Final Alignment Data for 805-MHz Linac," Los Alamos Scientific Laboratory internal document (Jan. 3, 1974).

APPENDIX A

The following computer listing shows a portion of the SIMALAC beam dynamics code for the 805-MHz Linac. The modifications and additions used for analyzing the wire scanner recentering experiment are shown.

```

SUBROUTINE CHASE(AMP,DPHI)
C   CHASES PARTICLES THROUGH MODULE MOD (FROM TANK NT1 TO NT2,
C   INCLUSIVE). AMP AND DPHI ARE THE AMPLITUDE AND PHASE KNOB
C   SETTINGS, RESPECTIVELY.
COMMON/ERRS/AT,EOTF(105),DA,DAT(45),DPH,DPHIT(45),DEL,
1 DELTB(45),DELTC(45),DPOP,DJOW(45),MULT
COMMON/JITTER/ATJ,DAJ,DPHTJ,DELJ,DPOPJ
COMMON/ACOM/ID,AE(20),ARG(20),COMMENT(6)
COMMON/COM1/EOT,NC(105),CL(105),DBT(105),ERP(105),NS,HP(105),IRQ
COMMON/CONST/CLIGHT,RADIAN,PI,TWOPI,EOM,EP,FREQ,WAVEL,BRHO
COMMON/COM3/NT1,NT2,NTT(45),NMOD,M1,M2,IP,NT,MOD,RBORE(44)
COMMON/COORD/NP,W(500),PHI(500),ITC,XY(4,500),LOST(500)
COMMON/CHARGE/Q,ZMORM,RMESH,NR,NZ,ERS(300),EVS(300),NSCSPT
DIMENSION PH(500)
EQUIVALENCE PH(1),PHI(1)
DATA ISTANK/1/,ISQUAD/2/,ZENTR/1./,ZEXIT/1./
EOTR=EOT*AMP
...
120 CONTINUE
C   CHASE PARTICLES FROM TANK NT1 THROUGH TANK NT2
DO 855 N=NT1,NT2
...
C   -finds trajectory through tank N
...
200 CONTINUE
C   TRANSFORM COORDINATES THROUGH DISTANCE BETWEEN TANKS
IF(DBT(N).LE.0.)GO TO 855
GAM=ERP(N+1)/ER
BETAD=SQRT(GAM*(2.+GAM))/(1.+GAM)
NX=2.*DBT(N)/(BETAD*WAVEL)+.5
FNX=NX
C   Relativistic parameter gamma=(total mass)/(rest mass)
C   GAM=(K.E.)/(rest mass) gamma=GAM+1.
...
260 DRF=.5*(DBT(N)-30.)
...

```

```

DO 300 M=1,NP
IF(LOST(M).LE.MOD)GO TO 300
GAM=W(M)/ER
BG=SQRT(GAM*(2.+GAM))
BETA=BG/(1.+GAM)
XN=2.*DBT(N)/(BETA*WAVEL)
300 PH(M)=PH(M)+3.14159265*(XN-FNX)
CALL DRIFT(DRF)

C
C The following section finds the trajectory
C through a quadrupole doublet. The quad is
C assumed to be midway between tanks.
H=HP(N)
IF(IRQ.LT.0)H=-H
CALL CCS(ZENTR,N,ISQUAD)
CALL QUAD(H,10.,MULT)
CALL DRIFT(10.)
CALL QUAD(-H,10.,MULT)
CALL CCS(ZEXIT,N,ISQUAD)
CALL DRIFT(DRF)

C
C The section from here through statement 790
C was inserted in the CHASE subroutine in order
C to analyze the wire-scanner re-centering
C experiment.
IF(N.NE.NT2) GO TO 790 $ CALL MOVEXY(1,9)
EFA=PI*ARG(13)/180. $ IF(IRQ.LT.0)EFA=EFA+PI
EFV=-ARG(12)*COS(EFA) $ EFH=-ARG(12)*SIN(EFA)
C ARG(13)=inclination of earth field from vertical
C in deg. ARG(12)=magnitude of earth field, gauss
M=ABS(ARG(10))+.5 $ D2=20.
C ARG(10)=1. for horizontal plane, =3. for vertical
C plane. D2,D3,D4,D5 = various distances, cm
IF(M.EQ.1)IHV=1HH $ IF(M.EQ.3)IHV=1HV
G1=H*10./(3129.7*BG) $ G2=G1*(1.+ARG(11))
IF(M.EQ.3)G1=-G1 $ IF(M.EQ.3)G2=-G2
D3=FLOAT(NC(N+1))*(CL(N+1)+CL(N+2))+.5*DBT(N)+
2 DBT(N+1)+DBT(N+2)-20.+10.-D2
D4=0.5*DBT(N)+15.-20. $ D5=D4-30.
IF(N.LT.29) D3=D3+DBT(N+3)+DBT(N+4)+
2 FLOAT(NC(N+1))*(CL(N+3)+CL(N+4))
EFCF=0.5*(D2+D3+5.)*2/(3129700.*BG)

C
C RATIO=ratio of angle to position entering
C quad (from thin lens theory)-
RATIO=(G1*D2-(G2-G1-G1*G2*D2)*D3)/(G2*D2*D3)

C
WRITE(4,707) M1,N,H,BG,D2,D3,G1,G2,RATIO,IHV
707 FORMAT(' M=*,I2,I4,' H=*,F8.4,F7.4,' D=*,F5.1,F7.1,
2 * G=*,2F8.5,' RATIO=*,F7.5,1X,A1)

C
C Find trajectories starting at -.2,-.1,.0,
C .1, and .2 cm off axis entering quad-
DO 750 JJ=1,5 $ XY(M,1)=JJ-3 $ XY(M,1)=.1*XY(M,1)
XY(M+1,1)=XY(M,1)*RATIO
CALL MOVEXY(1,2)

C
C The following loop tries 50 times to make
C the trajectories differ by ARG(14) at the
C detector wire scanner for the quad on and
C off.
DO 720 JJJ=1,50 $ CALL MOVEXY(2,1)

```

```

C
C Find trajectory for quad off-
CALL DRIFT(D2+D3+5.) $ CALL MOVEXY(1,3)
C
C Include earth field in above-
XY(1,7)=XY(1,3)+EFV*EFCF $ XY(3,7)=XY(3,3)-EFH*EFCF
C
C Now go back and find trajectory through
C quad, quad on. Ignore earth field.
CALL MOVEXY(2,1)
CALL QUAD(H,10.,0.) $ CALL DRIFT(10.)
CALL QUAD(-H*(1.+ARG(11)),10.,0.) $ CALL MOVEXY(1,6)
C
C Continue trajectory to det. w.s. position:
CALL DRIFT(D3-5.)
C
C Try new initial angle next time through
C loop based on how trajectories agree-
XY(M+1,2)=XY(M+1,2)-00.1*(XY(M,1)-XY(M,3)+ARG(14))*RATIO
IF(ARG(10).GT.0.) WRITE(4,733) XY(M,1),XY(M+1,2),XY(M,3)
720 CONTINUE $ CALL MOVEXY(1,22)
C
C Find trajectory at cal. w.s., quad off-
CALL MOVEXY(2,1) $ CALL DRIFT(D4) $ CALL MOVEXY(1,4)
C
C Find trajectory at cal. w.s., quad on-
CALL MOVEXY(6,1) $ CALL DRIFT(D5) $ CALL MOVEXY(1,5)
C
C Find ratio of transverse displacement at
C cal. w.s. to displacement at det. w.s.,
C quad on, earth field ignored-
CALL MOVEXY(22,1) $ RXY=XY(M,5)/(XY(M,1)+.00000001)
C
C Find difference in pos. at det. w.s.-
730 XY(M,8)=XY(M,3)-XY(M,1)
WRITE(4,733) XY(M,2),XY(M+1,2),XY(M,4),XY(M,5),XY(M,6),XY(M,1),
2 XY(M,3),XY(M,8),XY(M,7),RXY
733 FORMAT(F8.4,F10.6,F8.4,F6.3)
750 CONTINUE $ CALL MOVEXY(9,1)
790 CONTINUE
...
DP=DPHI+DPJ
DO 950 M=1,NP
950 PHI (M)=PH(M)*RADIANS+DP
IF(ITC.NE.0)GO TO 970
960 RETURN
970 LOC=2*NP*(NMOD+1)+4*NP*MOD
CALL ECWR(XY,LOC,4*NP,IE)
GO TO 960
END
C
SUBROUTINE MOVEXY(J,K)
C This routine moves the block of
C information in XY(N,J) to XY(N,K).
COMMON/COORD/NP,W(500),PHI(500),ITC,XY(4,500),LOST(500)
DO 4 L=1,4 $ XY(L,K)=XY(L,J)
4 CONTINUE $ RETURN
END

```

The following is an excerpt of the output generated on the TAPE4 file by the above code. The blocks of unlabeled columns of figures, from left to right, are:

1. Transverse beam position entering the quadrupole (cm)
2. Angle entering the quadrupole (radian)
3. Beam position at cal. w.s., quad. off (cm)
4. Beam position at cal. w.s., quad. on (cm)
5. Beam position at quad. exit, quad. on (cm)
6. Beam position at det. w.s., quad. on (cm)
7. Beam position at det. w.s., quad. off (cm)
8. Diff. in beam positions at det. w.s., quad. off less quad. on (cm)
9. Offset at det. w.s. from 0.5 gauss earth field at 30° (cm)
10. Ratio of cal. to det. w.s. transverse positions

```

M= 5   4   H=  2.3151  .5052 D= 20.0 1539.6 G= .01464 .01464 RATIO= .01529 H
-.2000 -.002720 -.3340 -.2742 -.2208 -4.4763 -4.4563 .0200 -4.7914 .061
-.1000 -.001383 -.1681 -.1383 -.1111 -2.2843 -2.2643 .0200 -2.5995 .061
0.0000 -.000046 -.0023 -.0025 -.0014 -.0923 -.0723 .0200 -.4075 .027
.1000 .001291 .1636 .1333 .1083 2.0996 2.1196 .0200 1.7845 .063
.2000 .002628 .3294 .2691 .2180 4.2916 4.3116 .0200 3.9765 .063

M= 6   8   H=  2.3796 .5355 D= 20.0 1590.6 G= .01420 .01420 RATIO= .01483 H
-.2000 -.002636 -.3374 -.2796 -.2202 -4.4790 -4.4590 .0200 -4.7962 .062
-.1000 -.001341 -.1699 -.1412 -.1108 -2.2867 -2.2667 .0200 -2.6039 .062
0.0000 -.000046 -.0024 -.0027 -.0014 -.0944 -.0744 .0200 -.4117 .028
.1000 .001249 .1651 .1358 .1080 2.0978 2.1178 .0200 1.7806 .065
.2000 .002544 .3326 .2743 .2174 4.2901 4.3101 .0200 3.9729 .064

M= 7  12   H=  2.4470 .5653 D= 20.0 1591.5 G= .01383 .01383 RATIO= .01446 H
-.2000 -.002571 -.3162 -.2596 -.2198 -4.3763 -4.3563 .0200 -4.6761 .059
-.1000 -.001309 -.1591 -.1309 -.1106 -2.2363 -2.2163 .0200 -2.5361 .059
0.0000 -.000047 -.0021 -.0023 -.0014 -.0963 -.0763 .0200 -.3962 .024
.1000 .001215 .1549 .1263 .1078 2.0436 2.0636 .0200 1.7438 .062
.2000 .002477 .3119 .2549 .2170 4.1836 4.2036 .0200 3.8838 .061

```

APPENDIX B

File QQ1 combines the ratio information from six different SIMALAC runs. (There are ratios for quadrupole on-off position differences at the detector wire scanner of -0.02, 0, and 0.02 cm for horizontal and vertical planes.) File QQ1 was generated by program TGEN, which is a general abstracting program for combining parts of computer output files for plotting. (A second file created by TGEN was used as input to the DRAW program from the LASL program library to produce the ratio graphs given in the body of this report.) File QQ1 also contains the horizontal and vertical positions of the effective center at the detector wire scanner when the earth's field is considered. Program QWS (see Appendix C) used the data from file QQ1 to estimate the errors in the February 1977 recentering experiment. A listing of file QQ1 follows.

APPENDIX C

PROGRAM QWS AND DATA LISTINGS

The program QWS was used to calculate the estimated errors in the wire-scanner recentering experiment of 9-13 Feb. 1977 using tables of calibrate/detector w.s. position ratios. (See Appendix A for the code added to SIMALAC to calculate the ratios, and Appendix B for lists of the ratios obtained.) Following the program listing is a listing of the experimental data. The columns in the data listing, from left to right, are:

1. Calibrate wire scanner no. (05-2 means 05WS002, etc.)
2. Horizontal position at cal. w.s. with quadrupole off (cm)
3. Vertical position at cal. w.s. with quadrupole off (cm)
4. Horizontal position at det. w.s. with quadrupole off (cm)
5. Vertical position at det. w.s. with quadrupole off (cm)
6. Horizontal position at cal. w.s. with quadrupole on (cm)
7. Vertical position at cal. w.s. with quadrupole on (cm)
8. Horizontal position at det. w.s. with quadrupole on (cm)
9. Vertical position at det. w.s. with quadrupole on (cm)
10. Detector wire scanner no. (blank means next w.s. down from cal. w.s.)

SWAINGR, CM77000, TS.

ACCOUNT, 69385.

CHARGE, 8909, E209.

HEADING, G. R. SWAIN. -

GET(QQ1)

FUN(6)

REPLACE(TAPE7)

REPLACE(TAPE8)

REPLACE(TAPE9)

(ICARD WITH 7-8-9 PUNCH IN COL. 1)

PROGRAM QWS(QQ1, INPUT, TAPE9, TAPE3-QQ1, TAPE7, TAPE8, TAPE10-INPUT)

REAL NE, NEMIN

DIMENSION IHW(10), LABJ(6, 10), V(10, 50), NE(10), LABX(6), VJ(10),

2 VJL(10), IFMT(2), JFMT(2, 10), XY(16)

165 REWIND 3 \$ READ(3, 167) NDAT

READ(3, 166) V, NE \$ NDATL-NDAT \$ NFL-NF

166 FORMAT(10E12.5)

167 FORMAT(A1)

WRITE(9, 177) V \$ WRITE(9, 178)

177 FORMAT(10X, 10F6.3)

178 FORMAT(/, /)

211 READ(10, 222) NQC, NQCDN, XCF, YCF, XDF, YDF, XCN, YCN, XDN, YDN, NQD, NQDON

222 FORMAT(13, 12, 8F5.2, 13, 12)

IF(NQC.LT.5 .OR. NQC.GT.48) GO TO 900

DO 290 J=1, 16 \$ XY(J)=0.

290 CONTINUE

DO 300 J=1, 50 \$ H=V(1, J)+.5 \$ IF(H.GE.NQC) J 301

300 CONTINUE

301 CONTINUE

XY(1)-XDF \$ XY(2)-XDN \$ XY(3)-XDF-XDN

XY(4)-YDF \$ XY(5)-YDN \$ XY(6)-YDF-YDN

```

XY( 7)-XCF $ XY( 8)-XCN $ XY( 9)-XCF-XCN
XY(12)-YCF $ XY(13)-YCN $ XY(14)-YCF-YCN
IF(NQCON.NE.-1) GO TO 311
XY(10)-XDN=V(2,J)
XY(11)-XDN=(V(4,J)+V(3,J)-V(4,J))*(XY(3)+.02)/.04)
XY(15)-YDN=V(6,J)
XY(16)-YDN=(V(8,J)+V(7,J)-V(8,J))*(XY(6)+.02)/.04)
WRITE(7,333) NQC,NQCON,XY(1),XY(2),XY(7),XY(8),XY(11)
IF( MOD(NQC-5,6).EQ.0 ) WRITE(7,167) NQAT
WRITE(8,333) NQC,NQCON,XY(4),XY(5),XY(12),XY(13),XY(16)
IF( MOD(NQC-5,6).EQ.0 ) WRITE(8,167) NQAT
311 WRITE(9,333) NQC,NQCON,XY
333 FORMAT(13,12,16F6.2)
GO TO 211
900 STOP
END
FUNCTION MOD(N,M) $ J=N/M $ MOD=N-(J*M) $ RETURN

```

```

END
ICARD WITH 7-8-9 PUNCH IN COL. 1)
05-2      -0.46 0.10      -0.45 0.11 05-4
05-3      -0.80 0.29      -0.84 0.28 06-1
05-4      0.03 0.03      0.02 0.03 06-2
06-1 0.12 0.09 0.09-0.29 0.11 0.09 0.09-0.28 07-1
06-2      -0.17-0.18      -0.16-0.18 07-1
06-3      -0.47 0.30      -0.45 0.29 07-2
06-4      -0.16 0.12      -0.14 0.10 07-2
07-1 0.25 0.16-0.74 0.15 0.28 0.17-0.73 0.15 08-1
07-2      -0.45 0.06      -0.45 0.05 08-1
07-3      -1.02-0.09      -1.03-0.12 08-1
07-4      -0.23 0.06      -0.23 0.06 09-1
08-1 0.09-0.03-0.75 0.26 0.09-0.04-0.76 0.26
09-1 0.15-0.00 0.53-0.19 0.13-0.01 0.53-0.19
10-1 0.07 0.00-0.12 0.27 0.06 0.01-0.12 0.28
11-1-0.03-0.00-1.00 0.41-0.03 0.00-1.00 0.42
12-1 0.18 0.08 0.66-0.67 0.16 0.08 0.69-0.68
12-1 0.19 0.08 0.65-0.67 0.16 0.08 0.67-0.67
13-1-0.06 0.00 0.06 0.03-0.07 0.00 0.04 0.02
14-1 0.32 0.02 0.72-0.03 0.28 0.04 0.70-0.04
15-1-0.15-0.02-0.92-0.03-0.12-0.02-0.93-0.01
16-1 0.13 0.04 0.13 0.49 0.11 0.04 0.15 0.48
17-1 0.11 0.00 0.26 0.07 0.10 0.01 0.26 0.08
18-1 0.04-0.46 0.07-0.12 0.03-0.47 0.08-0.13
19-1 0.00 0.02-0.62 0.42 0.01 0.00-0.62 0.44
20-1 0.09-0.03-0.10 0.55 0.08-0.04-0.10 0.54
21-1 0.12 0.03-0.18 0.26 0.13 0.02-0.20 0.28
22-1 0.03 0.04-0.46 0.03 0.04 0.03-0.48 0.04
23-1 0.04 0.06-0.44-0.07 0.06 0.07-0.42-0.06
24-1 0.08-0.02 0.04-0.30 0.07-0.03 0.04-0.31
25-1 0.06 0.12-0.45-0.25 0.08 0.13-0.44-0.24
26-1 0.09-0.03-0.19 0.89 0.08-0.04-0.21 0.90
27-1 0.10 0.06-0.31-0.24 0.09 0.07-0.31-0.24
28-1 0.03 0.07-0.55-0.51 0.04 0.09-0.55-0.52
29-1 0.12 0.00-0.64 0.29 0.13 0.01-0.63 0.30
30-1 0.10-0.03-0.47 0.09 0.10-0.03-0.46 0.08

```


31-1 0.15 0.04 0.03-0.11 0.14 0.05 0.01-0.12
32-1 0.20 0.06-0.39 0.14 0.19 0.05-0.37 0.13
33-1 0.21 0.07-0.44 0.33 0.21 0.07-0.45 0.32
34-1 0.21 0.24-0.20-0.14 0.20 0.24-0.20-0.15
35-1 0.22 0.02 0.05-0.09 0.19 0.05 0.04-0.09
36-1 0.10-0.24-0.44 0.26 0.10-0.24-0.45 0.27
37-1 0.10-0.06-0.71-0.37 0.09-0.07-0.70-0.37
38-1 0.03 0.00 0.06 0.12 0.02 0.00 0.05 0.13
39-1 0.13 0.23 0.13 0.39 0.13 0.24 0.15 0.39
40-1 0.04 0.02-0.40 0.04 0.03 0.04-0.40 0.02
41-1 0.13 0.15 0.02-0.34 0.12 0.15 0.02-0.35
42-1 0.16 0.10-0.11-0.36 0.17 0.11-0.13-0.35
43-1 0.20 0.08 0.22 0.32 0.19 0.07 0.24 0.31
44-1 0.01-0.12-0.02-0.13-0.02-0.14-0.01-0.15
45-1 0.09 0.09-0.47 0.01 0.08 0.07-0.47 0.02
46-1 0.00 0.07-0.18 0.33-0.00 0.07-0.19 0.33
47-1 0.14 0.09 0.13 0.30 0.13 0.10 0.14 0.30

(END-OF-JOB CARD, 6-7-8-9 FUNCH IN COL. 1)