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LA-6919

Special Distribution

Issued: January 1978

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LAMPF 201.25-MHz Linac Field Distribution

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CONTRACT W-7405-ENG. 36

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by

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ABSTRACT

Retuning of the 201.25-MHz accelerator structure field distributions after the 1975 shutdown is described and final data are given for use in beam dynamics studies. Several improvements made in procedures included a different method for stopband closure check and a positive method for post-coupler clamping. We found that to obtain accurate results for the first tank we had to use a rigorous data reduction technique that included the removal of a "signature" due to the bead-pull string itself. Other special studies are reported, including the effects of vacuum, bead size, slug tuners, and a bead-pull method for measuring the cavity quality factor Q .

I. INTRODUCTION

Initial operation of the Los Alamos Scientific Laboratory's (LASL's) LAMPF 201.25-MHz linac during 1972-1974 resulted in the acceleration of more protons than the total accelerated by all earlier machines. To obtain higher intensities, the following problems associated with the low-energy part of the linac, which accelerates protons from 750 keV to 100 MeV, required attention during the 1975 shutdown: (1) difficulty in operating at high power because of excessive heating and subsequent burning of the bellows that form the joint between the drift tubes and the structure wall; (2) excessive oscillations in the transverse trajectories of the two beams, which resulted in beam halos and steering difficulty; and (3) discrepancies in the longitudinal performance, which raised doubts about our ability to set the longitudinal tuning. The linac's four tanks were completely dismantled, repaired, cleaned, and reassembled. It was then necessary to retune the electric field distributions.

Tank 1 is an uncompensated, zero-mode Alvarez structure intended to have a field distribution that increases linearly from input to output. Tilt is produced by strongly perturbing cells 1 and 31 by moving the half-drift tube on the end wall to widen or narrow the gap. The field adjustment procedure involves achieving the required tilt by setting the end cells to the proper position. Because we suspected that deviations from the expected longitudinal performance originated in Tank 1, an extensive mapping of field distributions under different conditions was planned.^{1,2}

Tanks 2, 3, and 4 are post-coupler-compensated³ Alvarez structures with uniform field distribution. The tuning procedure involves achieving the uniform field distribution and making this distribution insensitive to perturbations. This is done by adjusting the post couplers.

The measurement method relies on the resonant frequency of such a structure being a sensitive function of the volume enclosed by the metallic surfaces. A small perturbation in the volume, in the form of a

bead suspended on a string introduced along the axis of the structure where the beam is to pass, will change the resonant frequency. The change in frequency indicates the strength of the electric field at the bead position. By drawing the bead slowly through the tank, the field distribution is mapped precisely.

II. FIELD TUNING DEFINITIONS

There are three conditions for tuning the tanks. The first, the unperturbed condition, is when the tank's end cells are in their operating configuration. The second, the positive perturbation condition, is when the frequency of the downstream end cell is raised by ~ 20 kHz and the tank's original frequency is restored by lowering the frequency of the upstream end cell. The third, the negative perturbation condition, is when the frequency of the upstream end cell is raised by ~ 20 kHz and the tank's original frequency is restored by lowering the frequency of the downstream end cell. When the tank is successfully tuned, the ratio of the positively-to-negatively perturbed field distribution should vary by no more than 1%, and the unperturbed field distribution should be within 1% of the desired field distribution. (See Figs. 1-4.)

When the post couplers are too far away from the drift tube, the gap between the post coupler and drift tube is too large and the frequencies of the post modes are too high. For this condition the post-coupled structure is said to be *overcompensated*. This condition is signified when the plot of the cell-by-cell ratio (ratio plot) of the "+" perturbation to the "-" perturbation results in a positive slope. A *positive* adjustment is used to correct this condition, that is, to make this gap smaller. The *undercompensated* condition is the opposite of the overcompensated condition. For the properly compensated tank the perturbations have no significant effect on the fields, so the ratio plot has zero slope everywhere. For a structure with both over- and undercompensated posts, the ratio plot will contain both positive and negative slope segments.

The eccentric tab on the end of the posts allows the fields of all cells downstream of a post to be adjusted relative to those upstream of the post. The tabs hang toward the bottom of the tank. The tab

Fig. 1a.
Tank 1 peak field distribution.

Fig. 1b.
Deviations of Tank 1 field distribution from a smooth curve.

adjustment is made with a "steering wheel" that attaches externally to the post. The steering wheel is calibrated from $+90^\circ$ to -90° . A positive adjustment of the steering wheel turns the tab downstream so that fields downstream of the post are increased relative to those upstream of the post. An example of how the tab rotation adjustment is made is illustrated with the aid of Fig. 3b. Gaps 2-9 have approximately the same field, the field in gaps 10-12 increases, and the field in gaps 13 and 14 decreases. The post between gaps 9 and 10 would be given a -5° adjustment and the post between gaps 12 and 13 would be given a $+5^\circ$ adjustment. These adjustments would leave the field in gaps 2-14 very nearly equal.

To measure the field distribution on the axis of the accelerator structure, a standard "bead-pull"

Fig. 2a.
Tank 2 peak field distribution.

Fig. 2b.
Normalized average gap fields in Tank 2.

Fig. 2c.
Ratio of positively-to-negatively perturbed
field distribution in Tank 2.

technique is used to detect changes in resonant frequency as a metallic bead is moved along the axis. The measurement is made at discrete intervals and stored in a computer. The bead perturbs the resonant frequency when it is in an electric field region,

and the frequency shift is related to the electric field intensity. The field integral is defined as

$$\text{field integral} = \sum_{i=1}^N \sqrt{(\Delta F_i)^{1/2}},$$

where (ΔF_i) is the frequency shift resulting from the bead recorded for the i^{th} data interrupt. The total number of data interrupts across the cell is N . The average value of the field across a cell is

$$E_0 = \frac{\sum_{i=1}^N \sqrt{(\Delta F_i)^{1/2}}}{N}.$$

For Tank 1, because the desired field distribution is tilted rather than flat, a renormalized field is obtained by dividing the actual measured field integral by the product of the actual cell length and the design value of the field integral. The result is then in terms of the deviation from the design field.

III. FINAL FIELD DISTRIBUTIONS

A. Peak and Average Field Distributions

Final tuning results⁴ are shown in Figs. 1-4. Tank 1 has a tilted field produced by setting the gap length of cells 1 and 31. Figure 1a shows the peak field data with the cell 1 gap set at 1.694 cm and the cell 31 gap set at 4.041 cm. Figure 1b shows the deviations of the cell field integrals from a third-order polynomial fit to the integral field data. These deviations are termed the "microstructure" of the field distribution, that is, the nonsmoothly varying changes. Note the significant deviations at the beginning of the tank. The field deviations from a linear tilt cannot be tuned out by existing tuners. Questions about the beam dynamics in Tank 1 led us to leave the fields as shown, pending further analysis.² The cell 1 and cell 31 gap settings correspond to "Tilt 1" in Ref. 2. Table I lists the final data for nine sets of gap settings (Tilts 1-9). We obtained these data by using the data reduction techniques described in Sec. IV.B.

Tanks 2-4 are adjusted for a flat field, that is, a constant value of E_0 for all cells. Figures 2-4 show

Fig. 3a.
Tank 3 peak field distribution.

Fig. 3c.
Ratio of positively-to-negatively perturbed field distribution in Tank 3.

Fig. 3b.
Normalized average gap fields in Tank 3.

Fig. 3d.
Pretuning ratio of positively-to-negatively perturbed field distribution in Tank 3.

the final peak field distribution and normalized average gap field distribution after tuning. Table II lists the average fields for use in beam dynamics calculations.

B. End Cell Perturbation Sensitivity

The final sensitivity to end cell perturbations of ~ 20 kHz is shown in Figs. 2c, 3c, and 4c for Tanks 2, 3, and 4, respectively. The effect of the end cell perturbations on the field of a nonstabilized tank is shown in Fig. 3d, a ratio plot of the + to - perturbations in the initial condition of Tank 3 after reassembly.

C. Final Drift-Tube and Post-Coupler Measurements

Table III gives the measured cell lengths for the nine different tilts produced in Tank 1 by adjusting the lengths of cells 1 and 31. Cells 2-30 were always the same. After final adjustments to Tanks 2-4 were made, the gaps between the post couplers and the drift tubes were measured. An outside dimension that is related directly to the gap and the tab rotation of the post coupler were also measured. These data are given in Table IV and plotted in Figs. 5, 6, and 7 for Tanks 2, 3, and 4, respectively.

Fig. 4a.
Tank 4 peak field distribution.

Fig. 4b.
Normalized average gap fields in Tank 4.

Fig. 4c.
Ratio of positively-to-negatively perturbed field distribution in Tank 4.

IV. FIELD TUNING METHODS

A. Equipment Setup

The mechanical equipment setup is shown in Fig. 8. We initially used a bead made from household aluminum foil. Later we used a machined bead that was easily attached to the string. The string was supported by four pulleys mounted on shafts with ball bearing supports. The rate at which the bead was pulled varied from 1.4 cm/s for Tank 1 to ~9.4 cm/s for Tanks 3 and 4. Speed changes were made by using different-sized drive pulleys. A directional switch was provided, and microswitches actuated by a nylon bolt attached to the string automatically stopped the bead after it had traversed the tank. In Tanks 2-4 a Kel-F support was used to support and align the string in one or two places in the tank.

During the investigations several rf configurations were used. (A typical setup is shown in Fig. 9.) Reducers and a 50- Ω termination were applied to the rf drive loop at the tank. Drive and signal loops used were ~2 to 4 cm² in area. Self-oscillation was achieved by adjusting the trombones for resonance peak operation. Sometimes injection locking was used. Mode spectra were also taken on each tank. The reference frequency source was adjusted to give an unperturbed beat frequency of ~3.3 kHz from the mixer.

The computer data interface shown in Fig. 10a was composed of two main components—a frequency multiplier and a period counter. The frequency multiplier (Fig. 10b), a frequency-to-voltage converter joined to a voltage-to-frequency converter by an amplifier and filter network, provided both offset and frequency scaling. The "multiplication" factor on the change in beat frequency was ~10 and the filter had switchable time constants. We chose the time constant by observing the detailed bead-pull data for a given bead speed, increasing the filtering until there was distortion or asymmetry from the capacitance charging effects in the cell field distribution, and then decreasing the filtering.

TABLE I
TANK 1 AVERAGE CELL FIELDS FOR NINE FIELD TILTS
(Units = MeV/m)

Cell No.	Tilt 1	Tilt 2	Tilt 3	Tilt 4	Tilt 5	Tilt 6	Tilt 7	Tilt 8	Tilt 9
1	1.7231	1.7144	1.7657	1.8044	1.8209	1.8923	1.8881	1.9322	1.9513
2	1.5817	1.5994	1.6201	1.7191	1.7599	1.7992	1.8497	1.8760	1.9585
3	1.5030	1.4945	1.5794	1.6140	1.6706	1.7076	1.7348	1.7808	1.8410
4	1.6005	1.6455	1.6783	1.7090	1.7527	1.8078	1.8460	1.8818	1.9263
5	1.6344	1.7500	1.7093	1.7341	1.8045	1.8657	1.8726	1.8917	1.9583
6	1.6330	1.7074	1.7095	1.7486	1.7891	1.8960	1.8716	1.9078	1.9553
7	1.6268	1.6639	1.7022	1.7504	1.7933	1.8321	1.8336	1.8651	1.9464
8	1.6667	1.7200	1.7521	1.7851	1.7937	1.8883	1.9073	1.9264	1.9585
9	1.7093	1.7288	1.7622	1.7808	1.8513	1.8889	1.9273	1.9052	1.9899
10	1.6784	1.7042	1.7474	1.7936	1.8110	1.8633	1.8809	1.9133	1.9599
11	1.6841	1.7185	1.7463	1.7935	1.8022	1.9108	1.8714	1.8974	1.9370
12	1.7351	1.7480	1.7715	1.8184	1.8291	1.9325	1.9101	1.9371	1.9670
13	1.7194	1.7459	1.7774	1.8467	1.8130	1.9458	1.8865	1.8949	1.9318
14	1.7472	1.8257	1.8013	1.8627	1.8757	1.9183	1.9248	1.9389	1.9766
15	1.7970	1.8246	1.8393	1.8836	1.8978	1.9142	1.9169	1.9740	1.9949
16	1.7995	1.8255	1.8384	1.8916	1.9136	1.9089	1.9263	1.9498	1.9784
17	1.8589	1.8688	1.8980	1.9256	1.9467	1.9923	1.9706	2.0024	2.0372
18	1.8397	1.8511	1.8698	1.8895	1.8928	1.9298	1.9265	1.9589	1.9708
19	1.8811	1.8964	1.9123	1.9530	1.9267	1.9803	1.9661	1.9855	1.9923
20	1.8883	1.8863	1.9010	1.9356	1.9105	2.0243	1.9751	2.0052	2.0390
21	1.9442	1.9793	1.9721	2.0080	2.0091	2.0470	2.0288	2.0403	2.0398
22	1.9663	1.9817	1.9715	2.0222	2.0225	2.0468	2.0245	2.0544	2.0619
23	2.0166	2.0194	2.0098	2.0758	2.0518	2.0857	2.0473	2.0799	2.0567
24	2.0215	2.0415	2.0143	2.0795	2.0089	2.0859	2.0490	2.0861	2.0833
25	2.0489	2.0581	2.0636	2.0750	2.0624	2.0932	2.0584	2.0698	2.0792
26	2.1167	2.1167	2.1167	2.1167	2.1167	2.1167	2.1167	2.1167	2.1167
27	2.1183	2.0883	2.0592	2.0991	2.1705	2.1344	2.0771	2.0921	2.1058
28	2.1275	2.1105	2.0901	2.1392	2.1115	2.1447	2.0823	2.1176	2.1189
29	2.1661	2.1668	2.1397	2.1493	2.1186	2.1388	2.1188	2.1248	2.1261
30	2.2219	2.1914	2.1718	2.2082	2.1546	2.1755	2.1376	2.1589	2.1613
31	2.1782	2.1034	2.1533	2.1751	2.1750	2.2019	2.1341	2.1311	2.1464

A period counter counted the number of 5-MHz crystal oscillations that occurred during 64 periods of the beat frequency. The period was determined by the number of interrupts that occurred at an ~70-Hz rate, derived from the 5-MHz clock. Alternatively, the interrupt could be generated using an external oscillator. The computer converted the period data into frequency.

B. Data Display and Reduction

The on-line NOVA computer displays, on a storage scope, peak and average fields from a bead pull, averages the results of several runs, gives the ratio of different runs and plots the results, and prints the results on a teletype or punched paper

tape (PPT). The entire bead pull could also be put on the PPT (in sections for the longer tanks). The PPT could be read to the LAMPF Central Control Room (CCR) computer and to the LASL Central Computer Facility (CCF).^{*} The CCR computer, which allows quick access and interactive manipulation, led us to discover the string effects (described below) by plotting the point-by-point bead-pull data. These effects were subsequently removed. The worth of direct access to a powerful computer system was proven many times during the tuning. We were able to verify that the raw data had been captured and to analyze and answer the many questions that arose.

^{*}Because NOVA programs and transfer procedures from PPT to other computers were cumbersome and undocumented, they are being replaced with a new system.

TABLE II
NORMALIZED AVERAGE FIELDS

Tank 2				Tank 3		Tank 4
Cell No.	Field	Cell No.	Field	Cell No.	Field	Field
1	0.9820	34	0.9879	1	0.9954	0.9984
2	0.9856	35	0.9919	2	1.0033	0.9971
3	0.9900	36	0.9950	3	1.0019	0.9998
4	0.9974	37	0.9914	4	1.0003	0.9983
5	0.9996	38	0.9916	5	1.0011	1.0003
6	1.0034	39	1.0013	6	1.0018	1.0002
7	0.9919	40	1.0128	7	1.0016	1.0005
8	1.0155	41	1.0063	8	1.0019	1.0012
9	1.0010	42	1.0057	9	1.0013	1.0023
10	0.9983	43	0.9902	10	1.0022	1.0006
11	0.9920	44	0.9991	11	1.0031	0.9963
12	0.9975	45	0.9915	12	1.0047	0.9986
13	0.9949	46	0.9921	13	1.0013	1.0011
14	1.0021	47	0.9951	14	0.9983	1.0018
15	0.9983	48	0.9913	15	0.9998	1.0006
16	1.0122	49	0.9900	16	1.0015	1.0047
17	1.0096	50	0.9889	17	1.0005	1.0018
18	1.0080	51	0.9939	18	0.9988	1.9999
19	1.0006	52	0.9969	19	0.9985	1.0013
20	1.0067	53	0.9887	20	1.0005	1.0039
21	1.0096	54	0.9950	21	1.0017	1.0037
22	1.0196	55	0.9987	22	1.0033	1.0026
23	1.0059	56	0.9943	23	1.0023	1.0039
24	1.0026	57	0.9912	24	1.0025	1.0022
25	1.0034	58	0.9976	25	0.9990	0.9966
26	1.0213	59	0.9971	26	1.0000	0.9959
27	1.0305	60	1.0000	27	1.0001	0.9946
28	1.0174	61	0.9988	28	0.9999	0.9936
29	1.0184	62	0.9962	29	1.0000	0.9912
30	1.0090	63	0.9910	30	0.9973	1.0050
31	0.9940	64	0.9993	31	0.9974	
32	0.9950	65	1.0100	32	1.0000	
33	1.0042	66	1.0075	33	0.9992	
				34	0.9945	
				35	0.9979	
				36	0.9976	
				37	0.9974	
				38	0.9898	

C. Measurement Noise

The uncertainty introduced by the equipment and environmental noise is shown in Fig. 11, a ratio plot of the average of two upstream pulls to the average of two downstream pulls for Tank 3. This ratio plot was used for each tank to ensure the quality of the data. Noise caused by mechanical vibrations, which changed the tank dimensions, was the least severe in Tank 4 and worsened in the up-

stream tanks. Tanks 1 and 2 had severe noise. It was necessary to have the accelerator tunnel air perfectly still and pay careful attention to the tuning and optimum filtering of the electronics to control the noise.

We believe that most of the noise in Tanks 1 and 2 is caused by mechanical vibrations of the drift tubes, each of which is a pendulum with a very high quality factor. During operation, these vibrations cause the beam to oscillate significantly in the

TABLE III

TANK I MEASURED CELL LENGTHS

(Units = cm)

Cell No.	Tilt 1	Tilt	Cell No.	Length
1	6.46928	2	1	6.46928
2	6.35348		31	15.50600
3	6.48162			
4	6.82110	3	1	6.39562
5	7.11772		31	15.50600
6	7.36005			
7	7.56440	4	1	6.43626
8	7.91873		31	15.53700
9	8.20841			
10	8.47759	5	1	6.32958
11	8.76965		31	15.55200
12	9.11858			
13	9.37472	6	1	6.40324
14	9.65969		31	15.60800
15	10.01814			
16	10.26191	7	1	6.27116
17	10.71876		31	15.60800
18	10.92006			
19	11.33698	8	1	6.22544
20	11.55904		31	15.66600
21	11.98847			
22	12.37173	9	1	6.27370
23	12.66845		31	15.66600
24	13.07568			
25	13.40028			
26	13.78342			
27	14.15525			
28	14.48783			
29	14.89048			
30	15.31240			
31	15.47300			

horizontal plane,⁵ characterized by a basic frequency of ~15 Hz, which is about the average of the mechanical resonant frequencies of the Tank 1 and 2 drift tubes. The amplitude of the oscillation varies considerably with time.

D. Tank 1 Tilt Tuning

The only adjustments made to Tank 1 are the upstream and downstream head positions. These adjustments change the gap of cells 1 and 31 and affect the tank tilt. Because the gap-to-gap fields are not adjustable, measurements of the actual field distribution were needed for use in beam dynamics calculations in which the optimum tuning of external parameters is explored.

The upstream gap was measured directly with the gap-measuring tool shown in Fig. 12. The downstream gap was measured indirectly by placing a dial indicator in the intertank spacer. The dial indicator measured the movement of an arbitrary radial position of the downstream rf surface. This indicator was then calibrated from inside the tank by measuring the downstream gap as a function of indicator reading.

E. Field Flattening Procedure for Post-Coupled Tanks

1. Central Cell Tuning. The tuning problem can be divided into two parts—tuning of the tank's central cells and tuning of the last few cells at each end of a tank.

The posts in Tanks 2-4 were very nearly restored to the positions that were measured before their removal. The end cells were then perturbed + and - to obtain the data for a ratio plot, and appropriate adjustments were made to the gaps between the post coupler and drift tube as outlined in Sec. II. Tab rotation adjustments were then made. This order was selected because tab rotation adjustments affect the post-coupler and drift-tube capacitance, which, in turn, affects the coupling. Iteration is thus required until the desired tank stability and field flatness are obtained.

Two perturbation methods used for checking stopband closure are discussed in Sec. V.B.1. For the final check and adjustment of Tanks 2-4 we placed metallic cylinders on the bottom of the tank at one of the ends to raise the frequency and inserted

a cylinder through the half-drift-tube bore at the opposite end to restore the unperturbed frequency. Adjustment of the central cells of the post-coupled tanks using these procedures was straightforward.

2. End Cell Tuning. End cell tuning of the post-coupled tanks did not follow the tuning pattern and is therefore still not understood. Because the position and rotation of the post couplers near the ends of the tank could be changed without affecting the field distribution or the perturbation ratio plots, we concluded that these criteria do not lead to a unique

solution. Part of the difficulty undoubtedly is due to the end cells being highly perturbed during the tilt sensitivity measurement.

Late in the tuning work, we noticed a discontinuity in the gaps between the post coupler and drift tube in Tank 2 between the 53rd and 54th post couplers (cell 85). Examination of the structural drawings revealed a radial weld in the tank wall at this location. We found that this gap discontinuity (seen in Fig. 5) also occurred in the original tuning when those data were plotted. Locations of the other

TABLE IV
FINAL GAP AND ROTATION SETTINGS OF POST COUPLERS

Tank 2							
Coupler No.	Rotation (deg)	Gap (cm)	Ext Gap (cm)	Coupler No.	Rotation (deg)	Gap (cm)	Ext Gap (cm)
1	-26.0	4.938	0.955	34	-2.0	6.175	1.552
2	26.0	4.727	0.699	35	15.0	5.829	1.445
3	-17.0	5.071	1.186	36	8.0	6.114	0.912
4	-3.0	5.281	1.501	37	-14.0	5.890	0.978
5	1.0	5.215	1.478	38	-27.0	5.946	1.059
6	-30.0	5.317	1.621	39	-12.0	6.035	1.153
7	14.0	5.272	1.544	40	-2.0	6.144	0.886
8	0.0	5.394	1.659	41	-10.0	6.093	1.161
9	1.0	5.430	1.646	42	11.5	6.276	1.113
10	-27.0	5.702	1.709	43	34.0	6.167	1.115
11	-10.0	5.581	1.730	44	-4.5	6.227	1.107
12	-23.0	5.399	1.732	45	1.0	6.269	1.199
13	4.5	5.229	1.760	46	-9.0	6.304	1.133
14	-29.0	5.594	1.727	47	-4.0	6.388	1.364
15	17.5	5.875	1.768	48	-9.0	6.414	1.214
16	-20.0	5.585	1.814	49	13.0	6.289	1.308
17	9.0	5.662	1.826	50	-2.0	6.408	1.234
18	19.0	5.597	1.252	51	0.0	6.353	1.351
19	-1.0	5.585	1.298	52	-12.0	6.379	1.184
20	-8.0	5.813	1.295	53	-30.0	6.388	1.532
21	3.0	5.549	1.240	54	13.0	6.198	1.306
22	-4.0	5.795	1.278	55	14.0	6.241	1.321
23	9.0	5.423	1.331	56	-22.0	6.363	1.346
24	10.0	5.679	1.280	57	8.0	6.344	1.278
25	-20.0	5.635	1.242	58	-3.0	6.429	1.494
26	12.0	5.685	1.351	59	-15.0	6.533	0.912
27	8.0	5.637	1.275	60	19.0	6.444	0.960
28	2.0	5.807	1.448	61	2.0	6.496	0.866
29	2.5	5.786	1.349	62	7.0	6.381	1.156
30	-7.0	5.856	1.311	63	-8.0	6.375	0.678
31	-12.0	5.912	1.443	64	-27.0	6.271	0.973
32	6.0	6.003	1.382	65	4.0	6.558	1.140
33	-18.0	5.908	1.435				

TABLE IV (cont)

Coupler No.	Tank 3			Tank 4		
	Rotation (deg)	Gap (cm)	Ext Gap (cm)	Rotation (deg)	Gap (cm)	Ext Gap (cm)
1	10.0	5.3315	0.9449	0.50	6.2509	1.2827
2	44.0	5.2807	1.0338	13.50	6.2281	1.2573
3	28.0	5.3975	0.9271	37.50	6.3094	0.7468
4	5.0	5.4102	1.0541	5.00	6.3221	1.0516
5	10.5	5.4559	0.9474	21.00	6.3170	0.6769
6	8.0	5.6388	1.3767	12.00	6.2967	1.1049
7	-3.0	5.5347	1.0719	2.50	6.3983	0.8598
8	11.0	5.6439	1.4224	25.00	6.4313	1.0389
9	-12.0	5.6490	1.2167	30.00	6.4922	0.8560
10	4.0	5.5016	1.3030	25.50	6.5634	1.1595
11	6.0	5.7099	1.2979	20.75	6.5710	0.8661
12	10.0	5.5651	1.2116	15.50	6.6319	1.1430
13	17.0	5.8369	1.4376	-21.00	6.6624	1.0414
14	-21.0	5.8242	1.4783	6.50	6.4795	1.0795
15	19.0	5.8445	1.3487	24.50	6.5329	1.0592
16	0.0	5.8903	1.5011	20.00	6.4897	0.6604
17	14.0	5.8496	1.2802	-6.00	6.5380	0.6401
18	-39.0	5.9360	1.5748	-15.00	6.7056	0.7468
19	13.0	5.9284	1.4859	15.75	6.7716	0.7112
20	-5.0	5.9233	1.6408	24.00	6.7640	0.7036
21	13.0	5.8191	1.3589	-19.50	6.7412	0.6706
22	16.0	5.8979	1.3513	20.00	6.7005	0.7747
23	-4.0	6.0122	1.5062	-24.00	6.6116	0.7772
24	3.0	5.9817	0.8915	46.00	6.7945	0.8636
25	8.0	6.0630	0.9246	24.00	6.8021	0.7112
26	5.0	6.1239	1.1024	15.00	6.8453	0.7087
27	1.0	6.0554	0.9271	-38.00	6.8986	0.7760
28	-1.0	5.9334	0.9525	-29.50	6.9977	1.2014
29	-24.0	6.0731	1.0287	17.00	7.0739	1.0630
30	-6.0	6.1747	1.1760			
31	10.0	6.3678	1.0109			
32	-21.0	6.3322	1.3564			
33	1.0	6.2662	0.9296			
34	15.0	6.3271	1.5215			
35	-28.0	6.3348	0.9525			
36	-4.0	6.4592	1.3335			
37	16.0	6.5557	1.3437			

radial seams* are given in Table V. The radial joints are indicated on Figs. 5-7; there seem to be further correlations, possibly masked somewhat by the random rotations of the tabs. In each tank, the gap between the post coupler and drift tube increases along the tank, and the tab rotation tends to decrease.

We believe that the characteristics of Figs. 5-7 could be developed further into a more complete, although heuristic, tuning procedure. The adjustments would then be more specific and the end cells would be adjusted close to the smooth lines.

*There are also radial seams at each end of each tank. The longitudinal weld seam in each tank is 15° above horizontal on the north side.

3. Reproducibility Check. After a tank had been stabilized and the field flattened, the bead-pull apparatus was completely removed. Several days later the apparatus was reinstalled and a final bead-pull measurement was made. The result had to agree within $\pm 1\%$ with the previous result when compared using the ratio plot.

V. SPECIAL STUDIES

Special studies done during the course of the tuning are discussed below in terms of those associated with Tank 1 and those generally applicable only to the post-coupled tanks.

Fig. 5.

Final gap and tab rotation settings of Tank 2 post couplers. A, B, and C denote positions of radial welds in the tank wall (cells 23, 40, and 54, respectively). D denotes the position at which the drift-tube bore increases.

A. Tank 1 Studies

1. Vacuum Effect. The bead pulls done at LAMPF typically are done at atmospheric pressure. One report on bead-pull studies⁶ has indicated a vacuum effect. To verify that we were not sensitive to this effect at LAMPF, vacuum flanges and feedthroughs were fabricated. One flange was attached to the upstream end of Tank 1 and the other, to the first slug tuner port of Tank 2. The string passed through Tank 1, then through a teflon guide that fit into and was concentric with the bore of a Tank 2 drift tube just upstream of the first Tank 2 tuner port, and then out the tuner port. Tanks 1 and 2 form a single vacuum chamber that was evacuated to ~ 1 mm of mercury using the Tank 2 roughing pumps. During these studies the tanks were pumped down and then shut off. The pressure rose very slowly because of the leaks in the string supports.

For this study we took bead pulls at atmospheric pressure and at ~ 1 mm of mercury and compared

Fig. 6.

Final gap and tab rotation settings of Tank 3 post couplers. A, B, and C denote positions of radial welds in the tank wall (cells 10, 20, and 29, respectively).

the results. We found that the resonant frequency changed by ~ 250 kHz, as expected. However, we observed no other effect on the field distributions above the uncertainty of the data.

2. Bead Size Effect. The relation between frequency perturbation and axial field used for these measurements is derived from the characteristics of a small perturbation in a single cell cavity. Especially in the first cells of the LAMPF linac, a practical bead* fills a significant fraction of the active field region,** so it might be necessary to use higher order terms to include the effect of the electric field gradient.⁷

A second effect^{7,8} results in multicell cavities when a perturbation is made in a single cell. Because of the coupling between cells, the adjacent cells will also be perturbed. In an uncompensated structure such as Tank 1, the overall effect looks like a tilt in the field distribution.

*One that gives a Δf (or $\Delta\phi$) large enough for good resolution.

**Cell 1 of Tank 1 has a gap of 1.5 cm, and the bore diameter is 1.5 cm. We used beads up to 0.5 cm in diameter.

Fig. 7.

Final gap and tab rotation settings of Tank 4 post couplers. A, B, and C denote positions of radial welds in the tank wall (cells 7, 15, and 22, respectively).

Fig. 8.

Basic bead transport setup for the bead-pull measurement.

A third factor in determining whether a bead-size effect is present is the necessity for careful removal of noise and base line effects. Figure 13 shows the ratio of the Tank 1 Tilt 1 field distribution to the design field distribution, measured with machined

Fig. 9.

The rf circuit used for the bead-pull measurement.

(1) Amplifier, Avantek Inc., Model PS-18, SN-53. (2-4) Isolator, Microwave Associates Inc., Model 7K986. (5) Mixer. (6) Trombone. (7) Frequency-power meter. (8) Reference signal source.

beads of 0.254-, 0.381-, and 0.508-cm diam. Although there seems to be no significant bead-size effect, the use of simple linear or parabolic cell-by-cell base line fitting techniques indicated there was an effect. When the string signature base line was removed from the data before the cell-by-cell base line fitting was applied, the result shown in Fig. 13 was obtained.

Further work, as suggested in Ref. 7, is needed to understand the bead-size effect in detail. In a given experiment, several sizes should be used to verify the existence or nonexistence of a bead-size effect.

3. String Signature. Perturbation of the tank resonant frequency caused by the string was 330 Hz in Tank 1, 340 Hz in Tank 2, and 260 Hz in Tank 4. Pulling the string through the tank without a bead on it produced a very reproducible and sufficiently large signature, particularly in Tank 1, that had to be removed. String signature is the characteristic

Fig. 10a.
Computer data interface.

Fig. 10b.
Frequency multiplier.

Fig. 11.
Uncertainty in Tank 3 data caused by equipment and environmental noise.

Fig. 12.
Drift-tube gap-measuring tool.

TABLE V
LOCATIONS OF RADIAL SEAMS

Tank	Cell No.	Post Couplers
2	54	22-23
	71	39-40
	85	53-54
3	108	10-11
	113	20-21
	127	29-30
4	143	7-8
	151	15-16
	158	22-23

Fig. 13.
Ratio of Tank 1 Tilt 1 field distribution to design field distribution. Ratios 1, 2, and 3 are for machined beads of 0.254-, 0.381-, and 0.508-cm diam, respectively.

Fig. 14.

Example of string signature in Tank 1.

frequency change caused by string irregularities. It is a function of the string's position in the tank. Figure 14 shows a typical example. With the bead on the string, the cell fields dominate, but when the bead is in the drift tubes, the signature shows. By keying on strong features of the signature, for example at about 6850 on the abscissa of Fig. 14, the signature could be lined up with a normal run and subtracted out. Programs were written to accomplish this interactively and also automatically using a least squares fit.

4. Peak-to-Integral Field Ratio. The problems discussed above regarding measurement noise led us to consider using only the peak field in a cell to set the field distribution. At the peak, the perturbation is largest and least sensitive to noise. A fit to points near the peak would identify the maximum very accurately. In contrast, evaluating the field integral is difficult; string signature and noise require decisions to be made about data reduction that can be misleading. Efforts to compare the ratio of peak-to-integral fields from the experimental results to LALA and MESSYMESH calculational results* were not successful. Investigation of the LALA calculations revealed convergence problems that showed the code was incapable of <1% error. The code SUPERFISH,^{9,10} has revolutionized field dis-

tribution calculations in cylindrically symmetrical structures. It is being modified to improve the accuracy of its axial field calculations. With reliable calculational results, the question can be reopened. We must, however, be aware of the greater sensitivity of the peak field, compared to the integral field across the gap, to an off-axis bead. This must be checked on each particular structure. In Tank 3 of the LAMPF linac, this effect was negligible.

5. Slug Tuner Effects. Tank 1 resonance is controlled by two slug tuners, one near cell 11 and the other near cell 25. Figure 15a shows the ratios of the average field distributions with the tuners at the four combinations of extreme positions to the field distribution with the tuners at midposition. Figures 15b and 15c, which repeat separately the cases where the tuners move in opposite directions, show a definite change in the overall tilt of the field distribution. For similar movements of the tuners (Figs. 15d and 15e), the overall tilt does not change. The field changes caused by opposing movements could affect the beam dynamics; note that the tuner penetrations should be kept nearly equal.*

Tank head movement vs tuner effect was also studied. The initial condition was with the upstream head at its out-limit, the downstream head at its in-limit, the upstream tuner at midrange, and the downstream tuner at its out-limit. The second condition was with the upstream head moved in to lower the tank's resonant frequency by ~40 kHz. The final condition moved the downstream tuner to restore the initial resonant frequency. Figure 16 shows the cell-by-cell field ratio of the second and initial conditions as ratio 1 and the final and initial conditions as ratio 2.

B. Post-Coupled Tank Studies

1. Reproducibility and Stopband Closure Checks. The reproducibility check for the initial adjustment of Tank 4 showed an s-shaped structure that exceeded the $\pm 1\%$ tolerance. When the ratio plot for this check on Tank 3 showed a definite slope and >1% deviation we knew there were inherent problems in the procedure.

*LALA and MESSYMESH, which calculated rf field distributions in cylindrically symmetrical rf cavities, have been replaced by SUPERFISH.

*In other linacs (CERN and KEK) the tilted field distribution is obtained by adjusting a number of slug tuners in the tank wall. This produces a smoother tilt without the severe deviations in the end cells seen in Fig. 1.

Fig. 15.

Tank 1 head-position and slug-tuner interaction.

(a) Four combinations of two tuners at extreme positions (1 is out-limit and 0 is in-limit).

(b) Repeat of ratio 4, Fig. 15a: tuner 1 out, tuner 2 in.

(c) Repeat of ratio 2, Fig. 15a: tuner 1 in, tuner 2 out.

(d) Repeat of ratio 1, Fig. 15a: tuner 1 out, tuner 2 out.

(e) Repeat of ratio 3, Fig. 15a: tuner 1 in, tuner 2 in.

One problem was the end-cell perturbation method. The $\pm$ perturbation ratio ensures that the stopband of the post-coupler-compensated

structure is closed. The original method used the standard tank head and adjustable half-drift tubes. The adjustable half-drift tube was not attached to

Fig. 16.

Tank 1 tuner vs head movement effect.

Fig. 17.

Ratio of field distribution with adjustable drift tubes to distribution with operational hardware for (a) Tank 3 and (b) Tank 4.

the rf web at the end of the tank as are the operating half-drift tubes, so the end cell wall geometry remained unchanged although the gap changed. We abandoned this perturbation method when we found that the reproducibility check after the operating hardware was installed gave a different

field distribution. Figures 17a and 17b show the ratio of field distribution with adjustable drift tubes to distribution with operational hardware for Tanks 3 and 4, respectively.

In the method finally used, we first placed metal cylinders in the magnetic field on the bottom of the tank at one of the ends to raise the frequency, then inserted a metal cylinder through the half-drift-tube bore at the opposite end to restore the unperturbed frequency by perturbing the electric field in the gap. Placement of the cylinders in the magnetic field was found to be critical to the tank's stable oscillation. It was also difficult to obtain the desired frequency perturbation; the size of the perturbation was not only a function of the size of the cylinders laid on the bottom of the tank but also of their placement. The electric field perturbation in the gap was also severe. These observations and the behavior of the structure during end cell tuning raised questions about the tuning procedure, as mentioned above. However, a distinct advantage of this method is that the tank, except for the perturbation, is in its final configuration. This second method was used for the final check and adjustment of Tanks 2-4, and the reproducibility check, which is now identical to the original tuning setup except later in time, was successful.

A better method should be found. Movements of the slug tuners might provide adequate perturbations.

2. Post-Coupler Clamping. Another problem with reproducibility was post-coupler clamping. The post-coupler mounts allowed the inner tip of the post to move by as much as 1 cm. We solved this problem by clamping two circular cross-section "C" wedges between the post coupler and the tank. The resultant effect is seen in the ratio plot of the fields in Tanks 3 and 4 before and after the post couplers were clamped (Figs. 18a and 18b, respectively).

3. Drive Point Independence. In the weakly coupled side-coupled structure used in the LAMPF 805-MHz linac, the drive and pickup points used in the bead-pull measurement could affect the result.¹¹ The results of a check on Tank 2 are shown in Fig. 19, which gives the ratio of seven runs made driving the tank at one end while picking up signal at the other end, to seven runs made with the drive point

Fig. 18.

Ratio of field distribution before post-coupler clamping to after post-coupler clamping for (a) Tank 3 and (b) Tank 4.

Fig. 19.

Effect of bead-pull measurement drive and pickup points on the field distribution in post-coupled tanks.

at the center. These results indicate that there is no significant effect for the post-coupled tanks.

4. Vacuum Port Effects. Another check was made to measure the effect of the size of the vacuum

Fig. 20.

Effect of the size of rf endplate vacuum spider holes on the field distribution in post-coupled tanks.

spider holes in the rf end plates. Figure 20 shows the ratio of the average of 12 runs in the original configuration to 10 runs in a configuration where the area of the holes was reduced from 325.81 cm² (50.5 in.²) to 80.39 cm² (9.36 in.²). These data were taken on Tank 4.

A comparison of Figs. 20 and 17b shows a similar pattern except at the ends. One can conclude that the decrease in the size of the spider holes caused a perturbation similar to that from the adjustable half-drift tubes. The tank can be stabilized in either case, but the fields must be different in the end cells.

C. Phase Bead Pulls

The bead-pull method may be used to obtain a measurement of cavity quality factor Q . The ratio of the cavity shunt impedance R to Q is¹²

$$\frac{R}{Q} = \frac{\left(\int_0^l E dz \right)^2}{2\omega U},$$

where E is the electric field, z is the distance along the axis, l is the length of the cavity, ω is the oscillation radian frequency, U is the total energy stored in the cavity, and it is assumed that there is only electric field on the axis.

The electric field can be measured from the frequency perturbation caused by introducing a small

metallic sphere on the axis. This is the basis of the bead-pull technique. The perturbation is

$$\frac{\omega_0^2 - \omega^2}{\omega_0^2} = \frac{3\epsilon E}{2U} (v_{\text{bead}}) ,$$

where v_{bead} is the volume of the bead and ϵ is the permittivity. Solving for E and substituting in the equation for R/Q yields

$$\frac{R}{Q} = \frac{[f(\Delta f)^{1/2} d\ell]^2}{3\pi\epsilon v_{\text{bead}} f^2} \quad (1)$$

The phase shift between an rf drive to the cavity and the cavity field as a function of the oscillation frequency is¹³

$$\tan \phi = \frac{Q(\omega_0^2 - \omega^2)}{\omega_0 \omega} = \frac{Q(\omega_0 + \omega)\Delta\omega}{\omega_0 \omega} ,$$

which simplifies, if small frequency shifts are assumed, to

$$\tan \phi \cong \frac{2Q}{f_0} \Delta f .$$

Substituting for Δf yields a relation for R directly.

$$R = \frac{[f(\tan \phi)^{1/2} d\ell]^2}{6\pi\epsilon v_{\text{bead}} f} ,$$

which, for small ϕ , can be written

$$R = \frac{[f(\Delta \phi)^{1/2} d\ell]^2}{6\pi\epsilon v_{\text{bead}} f} \quad (2)$$

This phase bead-pull measurement can be made using the modified bead-pull apparatus shown in Fig. 21.

By taking the ratio of the phase bead pull to the frequency bead pull, we get a direct measurement of Q , in which all the details regarding permittivity, bead, and other experimental factors cancel out.

$$Q = \frac{f}{2} \frac{[f(\Delta \phi)^{1/2} d\ell]^2}{[f(\Delta f)^{1/2} d\ell]^2} \quad (3)$$

Fig. 21.

Equipment setup for phase bead-pull measurement.

We had to use scale factors to convert Δf and $\Delta \phi$ into frequency units for the bead-pull computer. The final equation becomes

$$Q = \frac{f}{2} \frac{[f(\Delta \phi)^{1/2} d\ell]^2}{[f(\Delta \omega)^{1/2} d\ell]^2} \frac{K_f}{K_\phi} .$$

The Q thus obtained is the "loaded" Q of the cavity and includes the effects of any input or output coupling ports.¹⁴ If these ports are connected to impedances R_i , and the coupling is represented by perfect transformers with turns ratios n_i^2 , the measured Q_0 is related to the Q cavity being tested by

$$\frac{Q_0}{Q} = 1 + \sum_i \beta_i , \text{ where}$$

$$\beta_i = \frac{n_i^2 R_i}{R_{\text{cav}}} .$$

The requirement for knowing the β 's complicates making absolute measurements. The bead-pull

method, however, offers a new tool for studying and developing structures. For example, it is easy to obtain the relative Q of the individual cells in multicell structures like those of the LAMPF accelerator.

ACKNOWLEDGMENTS

We wish to thank the many people who were involved in the total program of measurement and analysis. Our special thanks to James M. Potter, J. L. Johnson, R. E. Lomax, E. Harvey, R. Wiley, J. Zastrow, G. R. Swain, K. R. Crandall, W. E. Jule, C. Coppersmith, and M. D. Johnston.

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