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**LAMPF 805-MHz Accelerator
Structure Tuning and Its Relation to
Fabrication and Installation**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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LAMPF 805-MHz Accelerator Structure Tuning and Its Relation to Fabrication and Installation

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LAMPF 805-MHz ACCELERATOR STRUCTURE TUNING
AND ITS RELATION TO FABRICATION AND INSTALLATION

by

G. R. Swain

ABSTRACT

In the course of construction of the 805-MHz linac, it was necessary to set 10 000 resonant cavities to precise frequencies and to check, and in some cases, to adjust the field distribution along the beam axis of the 104 rf tanks composing the linac. Since this was the first proton linac of the side-coupled type ever built, it was necessary to develop new techniques and instrumentation for structure tuning. An outline of the fabrication and installation process is given, showing how the tuning operations were interwoven with the fabrication steps and indicating the relation of tuning to other installation and check-out activities. The steps of the tuning procedure are then examined in detail. Tools for tuning by dinging, nose-stretching, and septum bending are described. Techniques for frequency measurements and for beadpull measurements of field distribution are discussed. The section on field distribution measurement includes results of research on measurement procedure and theory and observations confirming the low-power stability of field distributions for a three-year period. Selected results from the theory of chains of coupled resonators are given. Coupled resonator model parameters and various measured parameters for the 805-MHz linac are tabulated.

I. INTRODUCTION

A. Scope of This Report

The 805-MHz linac at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF) was the first proton linac employing a side-coupled standing wave structure. The linac is approximately 0.8 km long, and is used for the energy range 100 to 800 MeV. The 805-MHz linac is supplied with particles by three ion sources with Cockcroft-Wilton power supplies (for H^- , H^+ , and polarized H^- beams) and a four-tank drift-tube linac for acceleration from 0.75 to 100 MeV. A general description of LAMPF and its early history are given by Livingston (1972).

This report presents one aspect of the construction of the 805-MHz linac: structure tuning. The process of structure tuning consisted of the steps in the design, fabrication, and initial adjustment of the approximately 10 000 rf cavities making up

the linac such that the proper resonant frequencies and field distributions were obtained. As such a linac had not been built before, it was necessary to develop new techniques and instrumentation (as well as make minor revisions in the design of the accelerator itself in a few cases) as the work progressed.

The structure tuning operations for the 805-MHz linac were very much interlaced with the fabrication process. Thus it is appropriate that this report present an outline of the structure fabrication process and then show how the tuning procedures were embedded in it. The relation of structure tuning to other installation and checkout activities will be shown. However, the report will not attempt to describe the construction of the rf system, the control system, the beam switchyard, etc.; nor give details of auxiliary systems such as vacuum or cooling systems, except as they impinged upon the tuning process.

The report begins by briefly reviewing how the 805-MHz linac was designed, and how certain parameter values and tolerances came out of that design process. Later sections of the report give outlines of the fabrication and tuning procedures (parts II and III), describe in detail the final tuning procedures used (part IV), and give details of the tuning tools and field adjustment procedures (parts V and VI). The section on field distribution measurement in part VI includes results of research on measurement procedure and theory as well as a description of the standard computerized procedure adopted for the tuning of the linac. The observed stability of the low-power field distribution within linac tanks over a three-year period is also discussed. Summaries of 805-MHz linac design and measured parameters are given in the tables in Appendixes A and B. Included are coupled resonator model parameters for each tank in the 805-MHz linac. In addition, selected results from the theory of coupled resonators useful in this report are developed in the appendixes.

B. A Brief Look at Design Considerations

Initial design considerations involved the balancing of desirable beam performance against capital and operating costs. It was desired to have an intense beam with small energy spread but with low beam loss along the machine to keep activation levels low. The choice of the frequencies 201.25 and 805.00 MHz for the drift-tube and side-coupled linacs was based on the technology of drift-tube linacs and the availability of rf drive equipment. Also beam dynamics calculations indicated that the bunch coming out of the drift-tube linac would be compact enough to be accepted by a side-coupled linac operating at four times the frequency. (The factor of 4 was decided upon before it was decided to accelerate both positive and negative beams. An odd factor, such as 3, would have simplified the design of the transition area (Swenson 1972) between the linacs.)

From the point of view of the linac structure, the operating efficiency may be rated by the parameter called effective shunt impedance, ZT^2 , given by

$$ZT^2 = (\Delta\epsilon)^2 / (q^2LP),$$

where Z is the shunt impedance per unit length of structure, T is the transit time factor, q is the

charge of the accelerated particle, P is the power loss and $\Delta\epsilon$ is the particle energy gain in a length L . For the side-coupled linac, the shunt impedance is strongly influenced by accelerating cavity geometry and beam-hole size. Calculations were made using a computer code named LALA (Hoyt et al. 1966, Engel 1968a, Rich and MacRoberts 1969). Mesh calculations were performed for a cylindrically symmetric model. Simple iris-loaded waveguide geometries were analyzed first. Then features such as rounded outside corners and nose cones around the beam holes were added, resulting in an improved shunt impedance. A series of calculations was run to optimize the cavity geometry for a given frequency, particle velocity, and beam-hole size. The predicted shunt impedances and Q 's were checked against the performance of various prototype linac models (E. Knapp et al. 1968). These tests and calculations (Jacobson 1963) indicated that, based on shunt impedance, the appropriate energy to change from the drift-tube structure to the side-coupled structure was 100 MeV. The danger of beam pulse shortening due to excitation of transverse cavity modes was estimated to be small (Gluckstern 1964, Potter 1966).

Beam dynamics calculations indicated that it was reasonable to use a 3.175 cm (1.250 inch) diameter beam hole for 100-211 MeV and a 3.810 cm (1.500 inch) hole for 211-800 MeV, and that it was reasonable to use a stepped-beta structure. (Cavity length is uniform within each of the 104 tanks.) Beam dynamics calculations were also used to explore the types of focusing systems that could be used, and to determine the effects of structure or focusing magnet misorientation, of stray magnetic field, of focusing field strength errors, of tank field unflatness, and of space charge (Jacobson and Visscher 1964, Jakobson et al. 1964, Crandall 1967a, Swenson and Crandall 1968, Jameson et al. 1970, Crandall et al. 1971). The effect of accelerating structure length or spacing errors will be discussed in part III.B.1. of this report.

The energy gain per unit length was limited to about 1.1 MeV per meter in order to avoid cooling and rf arcing problems in the 805 MHz linac. Perhaps this was an overly conservative choice, since side-coupled structures have been successfully operated at over 10 MeV per meter for electron acceleration in commercial units (Livingston 1972, p. 29).

The economy of drive increased with size; the largest practical drive source was selected to be about 1 megawatt. These considerations thus determined the length of side-coupled structure that could be powered from one drive source, and hence how many sources were needed. The tank lengths and spacings and the design particle energy and phase at the input and output of each tank were then calculated using an iterative procedure (Crandall 1974b).

The final 805 MHz linac configuration was based on K. R. Crandall's computer printout (Nov. 2, 1967, see Appendix A) giving number of accelerating cavities per tank, cavity lengths, and spacings between tanks. Additional specifications (Worstell 1968a) were based on economic considerations of the fabrication process and on the need for cooling for high duty factor operation. Tanks were made in sections small enough to fit in a tall (2.13 m, or 84 inches) brazing furnace. Diagrams presenting the nomenclature and illustrating the sequence of assembly of 801-MHz linac parts are given by Koczan et al. (1973). The wall thickness between cavities was made large enough to easily transmit the heat from the nose regions near the beam to the outside diameter, where water-cooling tubes were attached. Based on a balance between copper costs and die costs, it was decided to use nine die sets for forging the accelerating cavity segments, nine more for the clamshells (coupling cavity halves), and two sets for tank heads. Twelve different thicknesses of coupling cavities were used to provide for the required coupling and to maintain clearance at the section joint flanges. A tabulation of geometrical and electromagnetic parameters for accelerating and coupling cavities was prepared (Engel 1968b) using the optimum LALA results as a guide. Figs. 1 and 2 show examples from this tabulation.

In order to keep the work force at LAMPF at a reasonable size, but yet accomplish the fabrication of the 805 MHz linac in a reasonable time, it was decided to subcontract as much as possible of the forging and crude machining to outside firms, but to do all the critical work of finishing, final assembly, and precision tuning at LAMPF. It was also decided to obtain brazing furnaces for the assembly of sections at LAMPF. Among the factors involved in making this decision were problems of transportation, engineering supervision, and the special brazing treatments required (Worstell

1968a-b, 1970, 1971, Worstell et al. 1966).

In order to check certain aspects of the 805-MHz linac design fairly early in the fabrication process, Module 5, the first module of this linac, was first set up and operated with full rf energy (but without beam) at the Equipment Test Laboratory Building (Fig. 3). This permitted some evaluation of the tuning techniques, the module cooling system and the rf control systems (Jameson and Wallace et al. 1970, Jameson and Swain et al. 1970, Swain et al. 1971). The initial development of the computerized beadpull measurement of field distribution also was done during this time. In March 1971, Module 5 was moved in two pieces to its permanent position in the beam tunnel.

Calculations for coupled resonator equivalent circuits were used to investigate the effect of beam loading and the tolerances on frequency and coupling for structure tuning (E. Knapp 1964b, B. Knapp et al. 1965, Swain 1966d, Jameson and Swain et al. 1970). Further discussions of the tuning tolerances used are found in sections III.A.11. and 12., and IV. (particularly IV.C.) of this report.

Some later modifications of the LAMPF 805-MHz linac from its original design will be outlined in part III.B. of this report.

II. PRE-INSTALLATION TUNING PROCEDURE

The tanks of the 805-MHz linac are made up from two or four sections (Fig. 4). This report section deals with the fabrication and tuning steps which occurred before the linac sections and bridge couplers were installed on their support rails in the beam channel. (See Koczan et al. 1973 and references therein, Worstell 1971). Diagrams and nomenclature for the various parts are given by Koczan et al. (1973).

A. Tank Sections

The copper forging and initial machining work were performed by outside shops. As the machined copper forgings for segments and clamshells were received at the Equipment Test Laboratory Building (ETLB), they were gaged by the inspection crew. Those which did not meet the specifications were assigned for rework as necessary. A number of spares of each type were ordered, and unused spares of any type could generally be reworked for use as any previous type, since the parts became larger as

THIS IS THE FINAL EDITION OF GOR4. THE GOSPEL OF RESONANT KAVITIFS....									
PROGRAM	GOR4	SPECIFICATIONS FOR 805 MHZ ACCELERATING CELL DESIGN						ALLPRT	
JOBNAME	ENGLEDA	LISTING BY TANK NUMBER						PAGE	1
DATE	12/03/80								
TANK NUMBER		MODI	11	==	1				
MODULE NUMBER		BETA1	11	==	.43110				
BETA		NACC	11	==	36				
NUMBER OF ACCELERATING CELLS REQUIRED FOR THIS TANK									
GEOMETRICAL PARAMETERS FOR THIS TANK									
BEAM HOLE DIAMETER	AAAI	11	==	1.2500 INCHES	=	3.1750 CENTIMETERS.			
SEGMENT LENGTH	ABAI	11	==	3.1064 INCHES	=	7.9274 CENTIMETERS.			
HALF SEGMENT LENGTH	L/2 ABAI	11	==	1.5502 INCHES	=	3.9637 CENTIMETERS.			
CELL OUTER DIAMETER	ACA1	11	==	10.4850 INCHES	=	26.6522 CENTIMETERS.			
OUTER WALL THICKNESS	ADA	11	==	.4400 INCHES	=	1.1176 CENTIMETERS.			
CELL INNER DIAMETER	ADA1	11	==	10.1000 INCHES	=	25.6540 CENTIMETERS.			
CELL INNER RADIUS	BARA APA1	11	==	5.0500 INCHES	=	12.8270 CENTIMETERS.			
SEPTUM THICKNESS	AJA	11	==	.3740 INCHES	=	.9524 CENTIMETERS.			
SEPTUM HALF-THICKNESS	TW ATWA	11	==	.1870 INCHES	=	.4762 CENTIMETERS.			
DRIFT TUBE NOSE RADIUS	R1 AJA	11	==	.1575 INCHES	=	.4000 CENTIMETERS.			
DRIFT TUBE BASE BLEND R.	R2 AJA	11	==	.3037 INCHES	=	1.0000 CENTIMETERS.			
RADIUS R3	R3 ALA1	11	==	1.3327 INCHES	=	3.5374 CENTIMETERS.			
DRIFT TUBE ANGLE	THETA ANA	11	==	30.0 DEGREES					
LALA DRIFT TUBE LENGTH (NO PADDING)	LOT ADA1	11	==	1.0743 INCHES	=	2.7416 CENTIMETERS.			
DRIFT TUBE HALF-GAP (NO PADDING)	L/2-LOT	11	==	.5371 INCHES	=	1.3708 CENTIMETERS.			
DRIFT TUBE FLAT -- IUS	AWA1	11	==	.8736 INCHES	=	2.2185 CENTIMETERS.			
SLOT LENGTH	APAI	11	==	4.0139 INCHES	=	10.1953 CENTIMETERS.			
COUPLING CELL LENGTH (NO WALL THICKNESS)	2M APCI	11	==	1.1870 INCHES	=	3.0150 CENTIMETERS.			
HALF COUPLING CELL LENGTH (NO WALL THICKNESS)	M AMCI	11	==	.5935 INCHES	=	1.5075 CENTIMETERS.			
B/L RATIO	AOAI	11	==	.31698					
ELECTROMAGNETIC PROPERTIES OF THIS TANK CALCULATED BY LALAP3									
PROTON ENERGY AT MID-TANK ER	AEKE	11	==	101.5809 MEV.					
AXIAL VOLTS	AVAI	11	==	1.1444E+05 VOLTS.					
TRANSIT TIME FACTOR	T ATAC	11	==	.8778					
SHUNT IMPEDANCE	ZT SD AZTE	11	==	38.334E+04 OHMS/METER.					
TANK RESONANT FREQUENCY	AFT	11	==	805.000 MHZ.					
ACCELERATING CELL STORED ENERGY	UT AUTI	11	==	1.3147E+02 JOULES.					
POWER DISSIPATED IN WALLS OF CAVITY	PC APEI	11	==	3.2829E+03 WATTS.					
APPROX. POWER DISSIPATED IN WALLS OF TANK	PT APTI	11	==	1.1710E+05 WATTS.					
QUALITY FACTOR (UNLOADED)	Q AQII	11	==	20.3604E+03					
ZT SD	AQI	11	==	1.8821E+03 OHMS/METER.					
ENERGY GAIN/METER	W AEM	11	==	1.4250 MEV/METER.					

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Fig. 1. Example of tabulation of accelerating cavity parameters.

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PROGRAM GOR4
JOBNAME ENGLEDA
DATE 12/03/80

SPECIFICATIONS FOR 805 MHZ SIDE-COUPLED COUPLING CELL DESIGN
LISTING BY TANK NUMBER

CLMPRT1
PAGE 1

TANK NUMBER		MODI	11	==	1	
MODULE NUMBER		BETA1	11	==	.43110	
TANK BETA		NCCI	11	==	35	
NUMBER OF COUPLING CELLS REQUIRED FOR THIS TANK		CCTI	11	==	1	
COUPLING CELL TYPE						
GEOMETRICAL PARAMETERS FOR THIS TANK						
BOSS DIAMETER	CAC			==	2.9040 INCHES = 7.3800 CENTIMETERS.	
BOSS RADIUS	R0 CBC			==	1.2500 INCHES = 3.1750 CENTIMETERS.	
INNER CAVITY RADIUS	R1 CCC			==	3.2500 INCHES = 8.2550 CENTIMETERS.	
HALF TOTAL CLAMSHELL LENGTH (WALL THICKNESS INCLUDED)	COCI	11		==	.9885 INCHES = 2.4800 CENTIMETERS.	
WALL THICKNESS	CFC			==	.3740 INCHES = .9525 CENTIMETERS.	
HALF INNER CLAMSHELL LENGTH (WALL THICKNESS EXCLUDED)	M CMCI	11		==	.5839 INCHES = 1.5075 CENTIMETERS.	
BOSS CENTER TO BEAM HOLE CENTER OF ACC. CELL	AOCI	11		==	6.7450 INCHES = 17.1196 CENTIMETERS.	
BOSS HEIGHT	CJCI	11		==	.8573 INCHES = 2.1776 CENTIMETERS.	
HALF GAP OF BOSS	B/2 CICI	11		==	.1112 INCHES = .2823 CENTIMETERS.	
SLOT LENGTH	APAI	11		==	4.6139 INCHES = 11.6953 CENTIMETERS.	
CONVERGENCE CRITERIA						
CONVERGENCE LIMITS	* IPS			==	3.000E+03	
B/L INCREMENT PER ITERATION	DFLO			==	1.576E+05 INCHES = 4.000E+05 CENTIMETERS.	
CHI-1	X1 CXI1	11		==	3.230E+00	
CHI-2	X2 CXI2	11		==	3.240E+00	
DEL CHI	X1=X2 COLX1	11		==	5.600E+00	
DEL CHI/CHI-1	CPCTI	11		==	1.740E+00	
NUMBER OF ITERATIONS	ITRI	11		==	1	

00000000

Fig. 2. Example of tabulation of coupling cavity parameters.

Fig. 3. Module 5 under test at ETLB. Module 5 is at the far left, and its drive klystron is at the upper right. Several partly completed modulator assemblies are at right center.

Fig. 4. Schematic of 805-MHz linac modular concept.

One proceeded downstream along the machine. As received by the tuning section at ETLB, the outer radius of each cavity had been machined in the segment or clamshell to the specified final dimensions, but the nose or boss had been left long (Engel 1968b, pp. 1-2) to allow the tuning process to compensate for possible dimensional variations elsewhere in the cavity. (Accelerating segment noses were about 2 mm long and clamshell bosses were about 0.7 mm long.) The segment noses did not have a radius at their tips at this time. The flow of

parts in the pre-installation fabrication and tuning process was as shown in Fig. 5. Parts for the first tank of a new coupling cavity type were handled differently from those for subsequent tanks of the same coupling cavity type. The procedure for subsequent tank segments began at Step 7 below.

1. Crude Initial Segment Half Gap Determined (ETL Tuning Lab.). Approximately eight segments were used to determine the initial segment half-gap dimension. The nose cones of these eight segments were cut back (as will be explained in Step 2) to give a resonant frequency in the range from 800 to 802 MHz for each cavity formed between two segments as measured in the two-segment fixture. This fixture allowed two segments without coupling cavities to be clamped between aluminum end plates faced with plastic (Fig. 6). Two probes on hinged nonconducting blocks were raised to cover the coupling cavity slots, one on each segment, thereby placing the probes in a suitable position to introduce and pick up a rf signal in the cavity formed between the two segments (Fig. 7). For

Fig. 5. Flow of tank section parts in pre-installation fabrication and tuning processes. (Box numbers correspond to the steps described in Section IIA.)

Fig. 6. Tracer lathe experiment being conducted at ETL Tuning Lab. to machine tracer lathe template for the segment nosing fixture. The segment was mounted on the lathe and the tracer lathe was used to machine the template.

Fig. 7. Tracer lathe in ETL Tuning Lab. used to machine segment nosing templates. 2, 4, 8, and 16 segment templates having the nose profile of the segment nosing fixture. The tracer lathe was used to machine the segment nosing fixture at the ETL Tuning Lab. to determine the segment nosing fixture after machining.

Fig. 8. Two-segment fixture being used for initial tank segment frequency measurements (Step 1). Electronic equipment in the rack included sweeper, oscilloscope, signal generator (for a marker), and scaler.

further details on resonant frequency measurement, see Section V.A. of this report.)

2. Initial Segment Noses Machined (ETL Tuning Lab.). The nose cone runout angle for the finished accelerating cavities was 30° (Hoyt et al. 1966, Fig. 4, for example). In order that the two tracer lathes (Fig. 8) available in the ETL Tuning Lab. take off copper only from the tip region of the noses, the tracer lathe templates used had a runout of 35° . Since the initial eight segments required that considerable copper be removed from the noses,

Fig. 9. Prototype Model F tuning equipment in 1965. The vertical stack of segments clamped together with steel bands is similar to the stack used in Step 3 of the LAMPF tank sections procedures.

TUNING DATA SHEET

Check List: Tank 91 Section C

Main cell half gap @ 800-MHz _____, _____ cells to shop,
ball setting 2.400, 6/2 1.315", by (EA)
on _____
(Date)

Average frequency two cell reading _____ MHz.

Stack frequency reading before braze 804.733 MHz. 1.280 10/5/71
1.333 1.280 CM-10

Stack frequency reading after brazing main cell and coupling cells together
_____. If this reading is higher than 805.200-MHz, then I.D.'s
should be re-cut so that stack frequency is ~ 805.000-MHz. New
reading _____ MHz.

If the stack frequency after tank section is brazed is below 804.950-MHz,
then this tank should be Dinged. New reading _____ MHz.

Final coupling cell gap 0.935"

Final main cell half gap 1.333"

Final check: _____
(Date)

Sent to tunnel by _____

Fig. 10. Data record for ETL Tuning Lab. measurements on parts of a tank section. Such records were filed in module notebooks.

these noses came out having a region with $3/16$ mm cut near their tips and a region with $3/32$ mm cut near their bases. In Step 7 below, these segments were remachined, along with other segments for the same tank, to produce a $3/16$ mm cut for most of the nose cone surface. The tracer lathe templates also insured that the tips of the noses were given a uniform radius.

3. Improved Segment Half-gap and Clamshell Half-gap Determined (ETL Tuning Lab.) The eight segments were then stacked vertically and fitted with coupling cavities (pairs of clamshells). The coupling cavity halves were held together and held against the segments by adjustable steel bands. (The steel bands were formed from a standard type of screwdriver-adjusted worm-drive hose clamps. No other supports for the stack were required.) Aluminum plates with probes were used as end plates for the top and bottom of the stack (Fig. 9). The segment half-gaps were machined (Step 4) in order to bring the measured π -2-mode frequency of the stack up to a point in the range 800 to 802 MHz. The frequency and half-gap were recorded on a tuning data sheet, Fig. 10, (Cady and Swain 1972). Next, the coupling cavity gap was adjusted by machining (Step 5) until the stopband of the vertical stack appeared closed (i.e. the stopband was less than 1 MHz). (See Sections V.A.2. and 3. of this report for further details of π /2-mode and stopband frequency measurements.) An earlier procedure was to leave the coupling cavity frequency high to compensate for the drop in resonant frequency (about 1 MHz) when the pump-out hole was drilled in Step 6. Either procedure was satisfactory, since the coupling cavities were easy to adjust in frequency later (Step 9, etc.). The sensitivity of resonant frequency to change in the gap was about 40 MHz per mm (1 MHz/mil). The final coupling cavity gap was recorded on the Tuning Data Sheet.

4. Segment Noses Machined (ETL Tuning Lab.) Copper was removed from the tips of the initial segment noses with a tracer lathe as in Step 2.

5. Initial Clamshell Bosses Machined (ETL Shop). In order to raise the frequency of coupling cavities, copper was machined off the flat end of the clamshell reentrant boss, thus increasing the clamshell half-gap dimension.

Fig. 11. Sketch of ball gage in use to check tank section segment nose thickness (Step 7).

6. Repairing Clamshell Bosses Machined (ETL Shop) and All Clamshells Brazed (ETL Brazing Facility). Once the correct clamshell half-gap was determined from the vertical stack measurement (Step 5), all clamshells of that same coupling cavity type were sent to the ETLB shop, where they were machined (as in Step 5) to the correct half-gap. Pairs of clamshells were then brazed together to form coupling cavities by the Fabrication Section in ETLB. The coupling cavities were returned to the ETLB shop for further machining. The cavities were contoured to match the outside diameter of the segments (only three different outside diameters were used for segments of the 805 MHz linac), a pump-out hole was bored, and one of the two dowel pin holes was drilled. (Two dowel pins were used for alignment in Step 12, when the coupling cavities were brazed to their mating segments. The other dowel pin hole was not drilled until after the coupling cavity gaps were adjusted in Step 9.) The coupling cavities were then sent to the Tuning Lab.

7. Segments For A Tank Machined (ETL Shop). For the initial tank of a given coupling cavity type, the segment half-gap dimension had been determined in Step 5 above. For other tanks with the same coupling cavity type, the half-gap dimension to be used was extrapolated from that of the previous tank, using the tabulation (Fig. 1, p. 4) of the calculated dimensions as a guide (Engel 1968b) and reducing the projected half gap by 0.38 mm

(0.015"). (This procedure left a 0.38 mm pad of copper on the noses to be available as necessary to compensate for variations in other cavity dimensions.) In either case, all segments for a given tank now had their noses machined off (leaving a flat tip) to the required half gap, and had the sides of the noses machined to give a uniform nose thickness. (The latter operation removed the region of 35° runout left in the initial segments by Steps 2 and 4, leaving all noses with a uniform 30° runout.) The thickness of the noses was checked using a ball gage arrangement. A sketch of the gage is use is shown in Fig. 11. The ball gage dimensions used were 5.486 cm (2.160") for segments with a 3.175 cm (1.25") diameter beam hole and 6.096 cm (2.400") for segments with a 3.810 cm (1.50") diameter beam hole. The segments also had their outside diameter machined to mate with the coupling cavity contour. Two dowel pin holes were drilled in each segment to be used later (Step 12) in aligning the coupling cavity over the coupling slot in the segment. The segments were then returned to the Tuning Lab.

8. Identification Marks and Segment Nose Radius Applied (ETL Tuning Lab.) Segments were stamped with a permanent segment number (which indicated the tank number and relative position within the tank) and an arrow indicating the beam direction. After this time, all frequency measurements would be made with the segments arranged in their final sequence, but not necessarily with the coupling cavities that each would eventually receive. Segments not needed were put aside for possible use as spares.

One of the tracer lathes was used to put the radius on the tip of the nose on each side of the segments. Since this did not shorten the noses appreciably, this did not leave the segments with any significant tapered surface with the 35° runout of the tracer lathe template.

9. Gap Set and Identification Stamped On Coupling Cavities (ETL Tuning Lab.) The gap of coupling cavities was set to the dimension found in the vertical stack measurement in Step 3. The copper was soft enough that this was done by tapping on the sides with a mallet to bring the bosses together or tapping in a phenolic wedge inserted between the bosses to force them apart. Figure 12 shows

Fig. 12. Checking coupling cavity (clamshell) gap after halves brazed together and gap set, Step 9.

coupling cavities being checked after this adjustment.

Each coupling cavity was stamped with a permanent identification number which agreed with that of the segment to which it would be joined.

10. Final Segment Half Gap Determined (ETL Tuning Lab.) Frequency measurements were made for a long stack using the long horizontal fixture. A long stack consisted of all the segments, excluding knife-edge and O-ring segments, of a given tank section held together in order by the fixture and with the coupling cavities clamped on. The long horizontal fixture employed a pair of support rails faced with plastic upon which a set of segments could be placed (Fig. 13). The segments were clamped between a fixed aluminum end plate at one end of the rails and a movable aluminum end plate at the other. A set of special clamps was used to hold a coupling cavity in position at the proper side of each segment. (Although the segments were placed in their correct final order and relative orientation, the coupling cavities used for the measurement were not necessarily the same cavities the segments would eventually receive.)

In the Tuning Lab., the temperature was held at 22.2°C (72°F) and the humidity was controlled in order to make precise frequency measurements possible. The $\pi/2$ -mode frequency of the long stack was adjusted to 804.90 ± 0.15 MHz. This figure was arrived at after considerable experience with the effects of the brazing process was obtained. It was

[illegible]

Fig. 14. Data record for ETL Tuning Lab, measurements on a tank section after brazing, Steps 13 and 14. Such records were filed in module notebooks. The printed ticket was the output of a programmable calculator.

Fig. 15. Interior of bridge coupler with iris after final assembly and installation. Three of the seven posts used for mode suppression and field stabilization are visible, two on the sides and one near the far top of the cavity. The bar used to compensate for the shift in resonant frequency caused by the drive iris is seen at the top. Also visible are one of the end tuner slugs in the centers of the cavity ends and one of the coupling slots at the bottom of the cavity where it joins to the tanks below via a special coupling cavity.

the linac tank head segments had their noses machined to have the same half-gap dimension as the segments of the tanks they were to mate.

As received by the tuning section at ETLB, the body unit had post, tuner ports, end tuner holes, and end slots for joining to the coupling cavities already machined. The tuning procedure differed depending upon whether the bridge coupler had an iris for rf drive or not. If the bridge coupler had an iris, the following steps were done:

1. The tank head segments and coupling cavities were clamped to the bridge coupler body.
2. Plates with H-probes (pickup loops) were attached to the tank head flanges. (Care was taken not to scratch or nick the knife-edge O-ring joint area.)
3. Each coupling cavity frequency was measured with all other cavities (two half accelerating cavities, the body cavity, and the other coupling cavity) shorted. The H-probe in the cavity below and an E-probe (electric pickup probe) inserted in the probe hole in the coupling cavity were used to inject and pick up the rf signal. (For further details of frequency measurements, see Section V.A.)

4. The coupling cavity gap was adjusted until the coupling cavity resonant frequency was near 805 MHz as determined in Step 3.

5. The resonant frequency of the whole assembly without shorts was determined, using the H-probes to inject and pick up the rf signal. At this stage, most of the bridge coupler units had an 8.89 cm (3.5") diameter circular iris. For the last few modules of the accelerator, the bridge coupler had an 8.89 x 12.70 cm (3.5 x 5") racetrack-shaped iris at this stage. The iris lowered the resonant frequency, and a length of round copper bar was to be brazed in the top of the bridge coupler (Fig. 15) to bring its resonant frequency back up to about 808.5 MHz. For this measurement the bridge coupler was upside down, and thus a length of bar could be laid in the body unit. The proper length of bar was determined by trial. (See LASL laboratory notebook 15958.) Some of the bridge coupler tuning data is given in Appendix B.

(Later when the completed bridge coupler was installed in the tunnel and the iris enlarged for proper coupling to the input waveguide, end tuners were inserted in the bridge coupler body cavity to bring the resonant frequency down to 805.0 MHz.)

In the case of a bridge coupler without an iris, the resonant frequency was checked to make sure that it was above 805 MHz, and that was all.

There were no further pre-installation frequency checks after the bridge coupler assembly parts were brazed together (Koczan et al. 1973, Fig. 51).

III. 805-MHz LINAC INSTALLATION PROCEDURE

At this point we shift our attention from the manufacturing processes which took place at outside shops and at the Equipment Test Laboratory Building to the installation and checkout processes which took place in the LAMPF beam tunnel and in the cluster of buildings above it. Fig. 16 gives a hint of the many activities taking place within the installation and checkout processes. The final tuning procedures, shown as Step: 11, 12, and 20 in the figure, will be discussed briefly in the sections to follow and again in greater detail in Section IV. See also Swenson (1968) and Tregellas (1969).

A. Initial Installation and Checkout

1. Piers, Rails, Monuments. Piers were bolted to metal plates provided for them in the floor of

Fig. 16. Installation and checkout procedures for 805-MHz linac. (Box numbers correspond to the steps described in Section III.A.)

the beam tunnel. Two structural steel beams were placed on the pier for supporting the accelerator structure, water cooling tender pipes, and the reference drive line. Measurements were established at intervals along the tunnel to provide a reference line for aligning the accelerator (Hart and Colston 1972, Colston and Hart 1972).

2. Tunnel Wiring, Local Water System.

Cables were pulled into the conduits joining the beam tunnel with the r.f. cluster buildings above. Cable trays were installed along the wall of the beam tunnel behind the accelerator position. Across the aisle from the accelerator position, a wire duct for communications and personnel safety system wiring was installed. (See Step 6.)

A chilled water system in each sector provides the means of removing the heat dissipated in the accelerator structure when in operation. Primary water loops distribute chilled water to the modules. A secondary loop for each module keeps the accelerator tanks at the proper temperature (Rislove et al. 1969, Sharp et al. 1969). The primary loop cooling towers, heat exchangers, pumps, and water lines (Little 1971b) along the tunnel behind the accelerator position were installed at this stage. Pumps for the secondary circulating water loops were put in place and wired to motor controls in the r.f. cluster buildings.

3. R. F. Cluster Building Racks and Wiring.

Cable trays were provided along the service aisle joining the r.f. cluster buildings with each other and with the central control room (CCR) (Case and Parker 1968, Little 1969b). Racks were installed in the r.f. cluster buildings for the local portions of the control systems, and cabinets put in place for the klystron water cooling systems (Doss 1971a).

Extensive use was made of the local control positions during the installation phase for check-out and initial operation. Normal operation of the accelerator at later times was almost exclusively done using the control computer and the remote consoles in CCR (Butler 1967, 1973, 1975, Butler et al. 1971, Gore 1968, Hartway et al. 1973, MP Div. 1971b pp. 21-26, Weber 1969.)

4. Module Installation. When completed tank sections and bridge coupler assemblies were available at the Equipment Test Laboratory Building (ETLB) for one or more complete modules, these would be

rolled to the beam tunnel. Although provision was made to allow such equipment to be lowered from certain r.f. cluster buildings (at sectors B, D, F, and G), these sections were always brought into the tunnel area through one of the truck access doors and rolled along the tunnel on low dollies. It was straightforward to handle the sections with little chance for damage in this way.

The sections were lifted onto their support hardware on the rails and bolted together using the studs provided on the ring points. Transverse alignment was done as the sections were put in place. Longitudinal positioning was accomplished later when several modules might be positioned at the same time. The ring joints were leak-checked as they were made. In the event that the knife-edge did not make a tight vacuum seal on its mating O-ring, a portable grinder assembly was used in the beam tunnel to re-finish the joint another try. This avoided disassembly of previously installed sections and possible damage in transporting sections to the LASL main shop (Hart and Colston 1972, Colston and Hart 1972).

5. Reference Drive Line. The reference drive line was a precision microwave line along the accelerator to provide an 805-MHz reference signal for phase control. This line was installed along the back of the accelerator support rails (MP Div. 1969d p. 13, 1970c pp.12-13, 1970d p.15).

6. Safety, Communications Systems. Wiring and equipment was installed for the following systems: Beam spill monitors and area radiation monitors (Parker 1968b, 1970, 1971a, 1974, Parker et al. 1971, 1972), personnel safety system (warning signs, scram buttons, interlock switches on personnel access doors) (Gore 1969, Little 1971b), interphones (Hartway 1969, 1971, Putnam 1968), closed-circuit television (Parker 1968a, 1969), and rf pulse viewing ("video") system (Criscuolo 1970a, Van Buren and Maddocks 1969, Schaller 1974).

7. Capacitor Bank, Local Klystron Controls and Connections. A capacitor bank used by all the klystrons in each r.f. cluster building was installed in each capacitor room (Doss 1971a). Chassis of control equipment, some of which were mounted in NIM bins, were installed in the racks. Electrical, air, and water connections for the klystron units were put in.

5. Flowing. The majority of the remaining plumbing work for the linac water cooling system was done at this stage. The work to be done consisted of finishing the secondary circulating loop supply and return headers, were run from the pump to each module along the support rails. Connections were made from these headers to the longitudinal flow lines in the tank sections and to the curved join between coupling cavities and to the station and final plasma cavities. Horner (1970), Brown and Swain et al. (1971). A motorized valve was installed to admit chilled water from the primary to the secondary system (Little 1970b, Rishbeth et al. 1969, Sharp et al. 1969). Some of the piping around the bridge couplers was fitted with unions so that pipe could be removed for the installation of a single pinnet at a later date.

The coupling cavities of the 805-MHz linac proved to be somewhat more susceptible to accidental mechanical damage than expected. A light tap might move a cavity 10 kHz in frequency. Therefore it was deemed appropriate to have as much work as possible on the plumbing type complete before final coupling and accelerating cavity tuning was started. This procedure also provided the need for temporary hoses, water carts, and temperature controllers for doing the final tuning.

6. Resonance Controllers. The resonant frequency ($\pi/2$ mode) of each module is kept at 805 MHz by varying the water temperature in the secondary circulating loops. The equipment of the resonance control system was installed at this stage. This permitted the modules to be kept at normal operating temperature, 29.4°C (85°F), for final tuning. Thermistors were installed in the headers to sense the water temperature. Analog control units were plugged in the local control area for each module in the r.f. cluster buildings (Sharp 1968, 1974, Sharp et al. 1969).

Occasionally a connector would be knocked loose or some such event would cause the control system to fail during final tuning. The tuning technicians checked glass thermometers on the linac structure occasionally, but worked an appreciable length of time in some instances before they realized the temperature was no longer correct. In retrospect, it appears that having some audible alarm available if the temperature went out of bounds would have been a good idea.

The resonant frequency changed about 15 kHz per degree change in temperature.

7. Klystron Units. Klystron amplifier tubes were given acceptance tests before leaving the vendor's plant (MCP Division 1971a). Klystrons and modulators were built into amplifier units and tested at LLF (Haderman 1968, 1970, Jameson and Swain et al. 1970, Swain and Liska et al. 1970). The completed amplifier units and control chassis were then installed in the cluster buildings (Knapp 1971). The amplifiers were checked out in the cluster buildings using a dummy load (Boss 1971a-c, Tallierie 1971a,d). (See also section 25 below.)

On completion of rf module manufacturing, part of LLF was converted into a klystron repair facility (Tallierie 1972c).

8. Final Cavity Tuning. In this section we give a brief outline of final cavity tuning. (Further details are given in Sections IV.A., B., and C. of this report.) First an estimate of coupling cavity frequency was made by extrapolating from previous results, and all coupling cavities in the module were set to that frequency. Next the frequencies of all accelerating cavities in the module, as well as the $\pi/2$ -mode frequencies of each tank in the module, were measured. This data was used to calculate the correct accelerating cavity frequencies for interior and end cavities, and the cavities were tuned accordingly. The resonant frequencies were changed using three different types of tools: dinging tools raised the frequency, nose-stretching tools lowered the frequency, and septum-bending tools were used for cavities inaccessible to the other tools or for use in correcting the field distribution within a tank. After the accelerating cavities were tuned, the tank $\pi/2$ -mode frequencies and stopbands were determined. The coupling cavities were then retuned such that the stopband was in the range 0 to +30 kHz. (The stopband had a tendency to decrease at first, dropping perhaps 30 kHz over the first couple months after tuning.)

9. Bridge Coupler Tuning and Module Flattening. In this section we give a brief outline of bridge coupler tuning and module field flattening. (Further details are given in sections IV.D. and E. of this report.) The tuning operations on the bridge coupler had the following objectives:

(a) The module $\pi/2$ -mode frequency was made to

13. Monitor Loops. Magnetic probes were provided at three or more points on each module to provide a feedback signal for the amplitude and phase control systems and to provide signals for determining the stability of the field distribution during initial high-power testing and checkout. These probes were adjusted to deliver approximately 10 W of peak power when the tanks were at design field strength (Cady 1972). The nominal coupling factor was -48.5 dB.

18. Leak Check, Repair Welds. The integrity of the structure and all welded joints was checked

the ion pumps were not able to remove the gas fast enough. The gas was released from the ion pumps and the amplitude was raised to about the design value and the duty factor was slowly raised to 12%. This process took about 20 hours (Wallace 1972). The presence of gas within the module caused x-ray radiation to be produced during conditioning (Parker 1971b). The level was generally about 300 mR/hr at contact with the tanks, or 30 to 50 mR/hr in the aisle. There was sometimes little radiation until the duty factor reached 12%. Initial tests of module 5 in ETLB produced about 700 mR/hr at contact, but this high a level was not seen after that.

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High power was initially delivered at very low amplitude and duty factor. Since the initial operation always released some gas trapped in the inside surfaces of the linac, as this conditioning process proceeded, the ion pumps removed the gas and the amplitude was raised to about the design value and the duty factor was slowly raised to 12%. This process took about 20 hours (Wallace 1972).

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of the machine, and the high intensity beam was not in the center of the linac. It was found that the septum lengths were not correct, the phase angles were off, and the bridge couplers were slightly out of phase. The septum lengths were changed and the bridge couplers were retuned. The lengths of the tanks and the spacings between tanks within modules were remeasured to ± 0.13 mm or better accuracy (Crandall 1974b, MP Div. 1974d p.5). It was found that due to systematic accumulation of errors in tank segment lengths (each of which was within tolerance) and due to longitudinal deformations made when tuning by septum-bending, the lengths of the tanks and the spacing between tanks in certain

modules were not correct. The lengths of the tanks were measured and the phase angles were corrected. The bridge couplers were retuned and the phase angles were corrected. The lengths of the tanks and the spacings between tanks within modules were remeasured to ± 0.13 mm or better accuracy (Crandall 1974b, MP Div. 1974d p.5). It was found that due to systematic accumulation of errors in tank segment lengths (each of which was within tolerance) and due to longitudinal deformations made when tuning by septum-bending, the lengths of the tanks and the spacing between tanks in certain

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B. Later Linac Modifications

Since the 805-MHz linac was completed and first put in operation in June, 1972 (MP Div. 1972c), the following modifications have been made.

1. Bridge Coupler Length Correction. In preparation for the high-intensity tests of LAMPF in 1974, the "delta t" procedure for setting module phases and amplitudes (Crandall and Swenson 1970, Crandall et al. 1972, Jameson and Swenson 1972, Crandall 1974a, 1976) was re-examined, and the lengths of the tanks and the spacings between tanks within modules were remeasured to ± 0.13 mm or better accuracy (Crandall 1974b, MP Div. 1974d p.5). It was found that due to systematic accumulation of errors in tank segment lengths (each of which was within tolerance) and due to longitudinal deformations made when tuning by septum-bending, the lengths of the tanks and the spacing between tanks in certain

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Meanwhile, various approaches for correcting spacings or otherwise compensating for length errors were being explored. Some increase in acceptance could be obtained by raising the amplitudes (and appropriately changing the phases), but the linac was already being run five percent above design and it was felt any other increase should be held in reserve (Jameson 1974). Changing relative amplitude levels from tank to tank within a module was found to fill out the acceptance fish in some regions but to leave peculiar holes in other regions

Fig. 17. Calculated behavior of elliptical beam in linac with module 13 bridge coupler shortened.

Fig. 18. Calculated behavior of elliptical beam in linac with all bridge couplers modified.

Fig. 19. Cross section of a portion of a linear tank showing the coupling cavity probe used in setting coupling cavity frequency, IV.A.2.

and picking up a swept-frequency signal. The probe was inserted along the beam hole, rotated to orient the loops to point toward the cavity being tuned, and moved longitudinally to obtain maximum signal. (See Fig. 19. Further details on frequency measurements are given in Section V.A. of this report.)

If the resonant frequency of the coupling cavity was high, it was lowered by using a lead mallet to tap on the flat sides of the cavity, thus bringing its reentrant bosses closer together. If the resonant frequency was low, it was raised by tapping on a phenolic wedge inserted between the reentrant bosses through the pumpout hole, thus moving the bosses farther apart.

In several instances, coupling cavities were retuned after the vacuum manifolds and caps had been welded on the nozzles at the pumpout holes. In the case of cavities to be lowered in frequency, this was done as above. In the case of cavities to be raised in frequency, one tapped on the rounded sides of the coupling cavity to make a small adjustment (perhaps 50 kHz) or used a special wrench to make a large adjustment, as in Fig. 20. The bottom of the boss was restrained by its proximity to the segment body; pulling on the wrench moved the top of the boss slightly outward. Caution was necessary in using this wrench. In one instance, over-zealous use

Fig. 20. Cross section of coupling cavity showing special wrench inserted in reentrant boss to raise cavity frequency.

Fig. 21. Distances required for FFTD calculation of tool or probe positions, IV.B. step 1.

of the wrench pulled the stainless steel probe tube right off one coupling cavity of the Module 15 bridge coppler assembly.

B. Accelerating Cavity Tuning

This section covers one of the operations briefly described previously in Section II of part III.A. of this report. Accelerating cavities were sometimes called main cells for brevity.

1. Determine Distances. The longitudinal distances from the middle braze joint on the first and last lower coupling cavity in each tank half to the face of the flange at the end of the tank were determined (Fig. 21). A computer program, Form For Tuning Data (FFTD), was then run using this data to generate a Main Cell Data Sheet (see Fig. 22) with appropriate distance information for each accelerating cavity for the tuning tools to be used in step 6 below. Since the tool positions for nose stretching were different from those for septum bending, there were versions of FFTD appropriate

MAIN CELL DATA SHEET				02/29/72
SEGMENT NUMBER	SEGMENT LENGTH	INITIAL C.C. SHORTED	FINAL FREQ. C.C. SHORTED	DATE 2/29/72
26	>---- 145.51	6272	-----	INITIALS
27	>---- 137.53	6272	-----	<i>LS</i>
28	>---- 134.55	6272	-----	MODULE 42
29	>---- 127.55	6272	-----	TANK NO.
30	>---- 121.57	6272	-----	91 CD
31	>---- 115.59	6272	-----	SEGMENT LEN
32	>---- 109.60	6272	-----	5.9854
33	>---- 103.62	6272	-----	22.25m
34	>---- 97.63	6274	-----	TEMPERATURE
35	>---- 91.65	6286	-----	29.5°C
36	>---- 85.66	6286	-----	DEG F DEG C
37	>---- 79.67	6274	-----	PI/2 BEFORE
38	>---- 73.69	6335	-----	TUNING
39	>---- 67.70	6344	-----	80.4377 23
40	>---- 61.72	6377	-----	55.6 55.6
41	>---- 55.73	6293	-----	55.6 MHZ
42	>---- 49.75	6373	-----	TUNE TO THIS
43	>---- 43.76	6151	-----	FREQUENCY
44	>---- 37.78	6328	-----	-----
45	>---- 31.79	6308	-----	MHZ
46	>---- 25.81	6309	-----	TUNE HEAD
47	>---- 19.82	6337	-----	CELLS TO
48	>---- 13.84	6371	-----	-----
49	>---- 7.85	6340	-----	MHZ
50	>----	806538	-----	AFTER TUNING-
HEAD			-----	MODE BELOW
			-----	PI/2 MODE N2
			-----	MODE ABOVE
			-----	-----
			-----	-----
			-----	-----
			-----	-----

Fig. 22. Example of Main Cell Data Sheet used to give probe or tool positions to the tuners and to record final accelerating cavity frequency tuning data, steps 1-4 of IV.B. This sheet covers the downstream half of Tank 91 in Module 42. Such sheets were filed in module notebooks.

for each type of tool (Sharp 1972). Normally the version for dinging and nose stretching was used, and the version for septum bending was used only if the field distribution (as determined in part 1, step 3 below, needed correction. Listings of the computer program are given in Appendix C.

2. Check Temperature. The tuners checked that the water cooling system was operating. The copper temperature was recorded on the Main Cell Data Sheet (Fig. 22). (See also III.A.9.)

3. Measure Cavity Frequencies. The individual accelerating cavity resonant frequencies were measured using a set of main cell probes and shorts. A pinout probe was used. These were units specifically designed to slip into a coupling cavity pump-out nozzle and included a spring-loaded bar to short out the coupling cavity. In addition, two shorting cylinders were inserted along the beam hole to short out the neighboring accelerating cavities. (Further details on these probes may be found in Section V.B.2; on frequency measurements, in Section V.C.1 of this report.) The measured frequencies were recorded on Main Cell Data sheets (Fig. 22) and filed in a notebook furnished for each module.

4. Measure $\pi/2$ -Mode Frequency Before Tuning. The $\pi/2$ mode frequency of each tank was measured with nitrogen atmosphere in the module. Each tank was isolated from the rest of the module by the insertion of shorting pins in holes provided for this purpose in the coupling cavities joining tanks to bridge coupler cavities. The results were recorded on the Main Cell Data sheets as in step 3 above.

5. Calculate Frequencies. The desired individual accelerating cavity frequencies for each tank were calculated using a combination of empirical and theoretical results. Both the individual cavity frequencies before tuning (step 3) and the tank $\pi/2$ -mode frequency before tuning (step 4) were used in the calculation. (Further details are given in Section V.B.2. of this report.) Either a Hewlett-Packard 9100-A programable calculator or a version of program FFTD was used to do the calculation. If the programable calculator was used, the printouts were taped to Checklist 1: Main Cell Tuning (Fig. 23) and filed in the appropriate module notebook. If a version of FFTD was used, new Main Cell Data sheets were generated, showing the desired individual cavity frequencies, the amount of frequency

correction needed for each cavity, and tool positions appropriate for the nose-stretching tool or the septum-bending tool as required. (See Fig. 24.)

A computer program named Sections Compared With Tanks (SCWT) was used for Modules 37 to 48 to compare the final individual cavity measurements made in FTLB with the initial frequency measurements in the tunnel. (See Appendix C for program listing. The tunnel frequencies were usually 0 to 100 kHz lower. One would expect the tunnel frequencies to be about 90 kHz lower due to the change in temperature from 21.2°C (72°F). However, the measured frequency sometimes came out about 50 kHz higher in the tunnel than it appeared to be in FTLB. The cause of this effect is unknown. Perhaps end effects introduced an error in the estimated direct coupling at FTLB. Occasionally, this measured frequency difference was much higher than 100 kHz. All cavities with such unusually high differences were rechecked to ensure that an error in measurement had not occurred. The SCWT printouts (Fig. 25) were filed in the module notebooks.

6. Tune Interior Cavities. Three different tuning methods were employed in tuning interior accelerating cavities: septum bending, dinging, and nose stretching. Septum bending was used for the initial tuning for Modules 5 through 26. Unfortunately, this method was found to affect the field distribution, and was abandoned for initial tuning. (Parts of Modules 15 through 26 were later retuned to correct their field distributions.) Modules 27 through 48 were initially tuned by dinging and nose stretching. Combinations of all three methods were used to flatten the field distributions when necessary. Further information on these matters is given in IV.C.3. of this report. Table II in Appendix B lists the tuning technique used for each linac tank.

a. Septum Bending. In this method, a tool was inserted in the beam hole and a threaded portion expanded to grip the drift tube hole joining a pair of accelerating cavities, as in Fig. 26. A hammer arrangement at the exterior end of the tool was then used to deform the whole septum between cavities, moving the nose regions longitudinally. This lowered the frequency of the cavity on one side of the septum and raised the frequency of the cavity on the other side. By starting the tuning near the

1

Date 8 Mar 72

CHECKLIST: TUNE CELLS

Module # 42

Initials DJ

Tank # 91

- A. 1. _____ °F/°C (temperature OK, N₂ gas)
2. 804.900 MHz (coupling cell frequency) Probe # old
Date 7 Mar 72
- B. 1. DJ done (main cell data sheets)
2. DJ done (read main cells)
3. 804.934 MHz ($\pi/2$ -mode freq. of tank, N₂, before tuning)
4. () Tank 91 (calculate main cell tuning frequencies)

808040	*upstream head cell frequency
805538	*downstream head cell frequency
804934	* $\pi/2$ -mode frequency before tuning, uncorrected
48	*no. of interior cells
51	*total no. of main cells in this tank
805345	*average interior cell frequency
805648	*est. head cell freq. for $\pi/2$ -mode freq. above
804958	* $\pi/2$ -mode frequency before tuning, corrected
805573	* <u>tune both head cells to this freq.</u>
805312	* <u>tune interior main cells to this freq.</u>
8275	*direct coupling constant (times 10 ⁶)

Fig. 23. Example of CHECKLIST 1: MAIN CELL TUNING data sheet, with results of accelerating cavity frequency calculation. (Filed in module notebooks.)

9/30/77

DATE 3-16-77

NO. LOCATION FREQ. DING UP IF

NO.	LOCATION	FREQ.	DING UP IF			
1	>---147.55	806.325	-.065	6345	6319	INITIALS
2	>---141.56	806.350	-.065	6304	6310	<i>JP</i>
3	>---135.58	806.325	-.013	6319	6312	MODULE 42
4	>---129.59	806.256	-.058	6248	6310	TANK NO.
5	>---123.61	806.261	-.055	6558	6318	91 CO
6	>---117.62	806.272	-.040	6266	6312	SEGMENT LEN
7	>---111.64	806.329	-.008	6308	6308	5.9854
8	>---105.65	806.302	-.010	6298	6311	TEMPERATURE
9	>---99.67	806.274	-.038	6266	6312	DEG F DEG C
10	>---93.68	806.286	-.026	6282	6313	PI/2 BEFORE
11	>---87.70	806.286	-.026	6278	6312	TUNING, MHZ
12	>---81.71	806.274	-.038	6265	6310	804.934
13	>---75.72	806.335	-.023	6337	6310	804.834 FPN
14	>---69.74	806.364	-.032	6333	6312	TUNE TO THIS
15	>---63.75	806.317	-.005	6310	6310	FRQUENCY
16	>---57.77	806.293	-.019	6331	6309	806.312
17	>---51.78	806.373	-.061	6373	6314	MHZ
18	>---45.80	806.151	-.161	6153	6311	TUNE HEAD
19	>---39.81	806.328	-.036	6322	6312	CELLS TO
20	>---33.83	806.308	-.004	6304	6312	805.573
21	>---27.84	806.309	-.003	6310	6310	KK= 0.047836
22	>---21.86	806.337	-.025	6333	6312	KD=-0.003675
23	>---15.87	806.371	-.059	6370	6315	AFTER TUNING-
24	>---9.88	806.340	-.028	6346	6312	MODE BELOW
25	HEAD			6536	5523	PI/2 MODE N2
						MODE ABOVE

J=K.E.-O.R.
JOINT FL.

Fig. 24. Example of new Main Cell Data Sheet used in steps 5-8 of IV.B. The amount of frequency correction needed for each cavity is listed in the column under "Ding Up if Positive."

DATE	C	TUNNEL		TUNNEL		TUNNEL		TUNNEL		ERR
		FILE	FILE	FILE	FILE	FILE	FILE	FILE	FILE	
1221	1	805.571	1.000	805.571	1.410	805.571	2.516	805.574	1.507	
1221	2	805.510	-.020	805.510	.102	805.510	-.025	806.313	-.005	
1221	3	805.510	-.015	805.510	.079	805.510	.003	806.313	.018	
1221	4	805.510	-.025	805.510	.072	805.510	.000	806.313	.025	
1221	5	805.510	-.025	805.510	.084	805.510	-.012	806.313	.013	
1221	6	805.510	.310	805.510	.076	805.510	.331	806.313	.021	
1221	7	805.510	-.020	805.510	.080	805.510	-.003	806.313	.017	
1221	8	805.510	-.025	805.510	.085	805.510	-.013	806.313	.012	
1221	9	805.510	-.040	805.510	.085	805.510	-.028	806.313	.012	
1221	10	805.510	-.040	805.510	.085	805.510	-.029	806.313	.011	
1221	11	805.510	-.040	805.510	.085	805.510	.029	806.313	.059	
1221	12	805.510	1	0.000	1	805.510	.513	806.313	1	
1221	13	805.510	-.034	805.510	.070	805.510	-.023	806.313	.017	
1221	14	805.510	.175	805.510	.014	805.510	.244	806.313	.069	
1221	15	805.510	-.034	805.510	.082	805.510	-.030	806.313	.005	
1221	16	805.510	-.034	805.510	.076	805.510	-.024	806.313	.011	
1221	17	805.510	-.034	805.510	.085	805.510	-.004	806.313	.031	
1221	18	805.510	-.019	805.510	.073	805.510	-.005	806.313	.014	
1221	19	805.510	-.034	805.510	.085	805.510	-.013	806.313	.022	
1221	20	805.510	-.034	805.510	.081	805.510	.001	806.313	.036	
1221	21	805.510	-.034	805.510	.085	805.510	-.036	806.313	-.001	
1221	22	805.510	.165	805.510	.050	805.510	.202	806.313	.037	
1221	23	805.510	.051	805.510	.027	805.510	.110	806.313	.060	
1221	24	805.510	-.034	805.510	.052	805.510	.000	806.313	.035	
1221	25	805.510	1	0.000	1	805.510	.344	806.313	1	
1221	26	805.510	-.047	805.510	.104	805.510	-.032	806.313	.015	
1221	27	805.510	-.047	805.510	.027	805.510	.045	806.313	.092	
1221	28	805.510	-.047	805.510	.077	805.510	-.005	806.313	.042	
1221	29	805.510	.023	805.510	.130	805.510	.012	806.313	-.011	
1221	30	805.510	-.047	805.510	.131	805.510	-.059	806.313	-.012	
1221	31	805.510	.264	805.510	.133	805.510	.254	806.313	-.014	
1221	32	805.510	-.047	805.510	.113	805.510	-.041	806.313	.006	
1221	33	805.510	-.047	805.510	.065	805.510	.007	806.313	.054	
1221	34	805.510	-.047	805.510	.083	805.510	-.011	806.313	.036	
1221	35	805.510	-.047	805.510	.111	805.510	-.039	806.313	.008	
1221	36	805.510	-.052	805.510	.094	805.510	-.027	806.313	.025	
1221	37	805.510	-.047	805.510	.099	805.510	-.027	806.313	.020	
1221	38	805.510	1	0.000	1	805.510	-.039	806.313	1	
1221	39	805.510	-.044	805.510	.060	805.510	.022	806.313	.067	
1221	40	805.510	-.039	805.510	.056	805.510	.031	806.313	.071	
1221	41	805.510	-.042	805.510	.080	805.510	.004	806.313	.047	
1221	42	805.510	-.043	805.510	.103	805.510	-.020	806.313	.024	
1221	43	805.510	.046	805.510	.112	805.510	.060	806.313	.015	
1221	44	805.510	-.174	805.510	.114	805.510	-.162	806.313	.013	
1221	45	805.510	-.043	805.510	.068	805.510	.015	806.313	.059	
1221	46	805.510	-.044	805.510	.087	805.510	-.005	806.313	.040	
1221	47	805.510	-.054	805.510	.076	805.510	-.004	806.313	.051	
1221	48	805.510	-.079	805.510	.063	805.510	.024	806.313	.064	
1221	49	805.510	-.019	805.510	.049	805.510	.058	806.313	.078	
1221	50	805.510	-.049	805.510	.050	805.510	.027	806.313	.077	
1221	51	805.510	1	0.000	1	805.510	.964	805.574	1	

Fig. 25. Example of printout from SCWT code for comparing accelerating cavity frequencies measured in ETLB with frequencies measured in the beam tunnel. See step 5.

Fig. 26. Cross section of a portion of a Linac tank showing the septum-bending tool in working position and the magnetic probe and shorts used in IV.B.6.a.

If regions of a tank were either all high in frequency or all low in frequency before tuning, quite large errors could accumulate in the septum-bending process by the time the end of the region was reached. The cumulative frequency error became very large in certain two-tank modules, and it became obvious that pulling or pushing such large errors to the end of the tank produced significant changes in the field distribution. Sometimes the distribution fell very low or hooked up very high at the ends (see Fig. 62, p. 63). Therefore it was decided to abandon septum bending as the primary method for initial tuning.

b. Dinging. Accelerating cavities which were low in frequency were raised by making indentations in the cavity wall along the diameter. It was found that a blunted cold chisel tip would fit between the cooling water passages which covered most of the outer diameter. A single sharp blow on the special chisel with a mallet would change the frequency 10 to 20 kHz. Repeated blows had a reduced effect due to work-hardening of the copper.

Further, it is felt that a part release of this could not be timed by landing, since the aircraft once was released on the jungle. Steel ball flanges for the excitation, the optimizing tools were used to make the frequency error to nearly a vibrating cavity, which were not used in dishing or nose stretching as required.

Nose stretching. To lower the frequency of accelerating cavities that were too high in frequency, a special tool deformed the nose regions of the cavities. The tool made a groove inside the beam hole joining a pair of accelerating cavities. A conical expander forced a cutter wheel to press into the wall of the hole. The groove was made near the end of one of the noses, about 9 mm back from the tip, and deformed the copper nose enough to lower the cavity volume in a high electric field region. (See Fig. 27.) One full application of the tool (rotating the cutter wheel 360°) lowered the frequency 100 kHz or more. Backing the tool into the nose a few millimeters and making a second groove close to the first lowered the frequency as much as 200 kHz more. Thus by applying the tool to both noses, the frequency of a given cavity could be lowered as much as 1.2 MHz. (Further information on the nose-stretching tool is given in V.D.2.)

30

Fig. 27. The neostretching operation. A line drawing showing the use of stretching tool in working position as indicated in Exhibit 1.

The results of the neostretching process were checked using the same magnetic probe-shorts used in step 5. The neostretching tool also served to short the accelerating cavity on the near side to the cavity being tuned. However, even when stretching the near nose, the tool was far into the region for which it perturbed the resonant frequency of the cavity being tuned. While the tool was in use, only the change in frequency might be monitored. The indicated change would be only approximate, however, since the tool sometimes moved longitudinally slightly inward or outward as it was rotated, thus changing the amount it perturbed the frequency. To make the final check of the cavity frequency, it was necessary to loosen and withdraw the tool somewhat.

7. Tune End Accelerating Cavities. The end accelerating cavities (head cavities) of each tank were usually tuned using the septum bending method. Head cavities at the end of the module (no joint ring) and slightly low in frequency (a rare occurrence) were brought up by dinging. In either case, these were tuned to the frequency predicted for end cavities.

An alternate scheme which produced similar (but not identical) results was to tune the head cavities to give minimum field in the first coupling cavity.

This method had the disadvantage that it was practically impossible to detect the field in the first coupling cavity without inserting the probe (which put it in the existing pin hole in the boss) so far that the resonant frequency was perturbed.

8. Measure Coupling Frequency After Tuning. Measure the frequency and stopband of each tank after it was under vacuum atmosphere. Each tank was isolated from the rest of the module by the insertion of the timing pins in the coupling cavities in the three higher assemblies. (See also section 6.4.1.1. of this report.) The results were recorded in the Main Cell Data Sheets (Fig. 24, Exhibit 1) and were filed in the module notebooks.

9. Initial Data Logging Checks

This section describes some of the operational checks noted briefly in Part III.A.11. of this report.

1. Stopband Check. The coupling cavity frequency of each tank was adjusted if necessary so that the stopband under vacuum was between +10 and -10 mHz. (See II.3.2.) The stability of the field distribution is best for a tank with zero stopband. It was decided to tune the tanks to make the stopband slightly high for two reasons:

- The stopband of the tanks tended to move in the negative direction over a period of time. Apparently the coupling cavities might decrease 10 to 30 kHz over the first month or two after tuning. (There is no evidence as yet that this downward trend continues after the first few months, however.)

- Theoretical and experimental results indicated that the transient behavior of the field distribution was better if the stopband was positive rather than negative. (Further information on this point is given in VI.A.1. and Appendix G of this report.)

A portable vacuum roughing pump was used for this and the following vacuum measurements. A rubber hose between the pump and a flange which could be clamped to a coupling cavity pump-out nozzle provided a convenient method for connecting the pump to a module whose vacuum manifold had not been installed.

The following steps were followed when starting a vacuum roughing pump for a module with a vacuum manifold:

- (1) Start fore pump and hold pump flange against tank flange. The flanges will hold together without

bolts and nut on the pump begins to create a vacuum.

(2) Open the vacuum valve to the tank.

(3) After the fore pump starts down, add some liquid nitrogen to the trap and turn turbine pump on.

When pump out nozzles on an unfurnished module are fitted with rubber stoppers, as in previous tuning steps with nitrogen gas in the module, vacuum leaks on temporary probes were backed up by applying a coating of epoxy (Epoxy 9 or equivalent), available from General Electric, along external joint surfaces. At the bridge coupler drive iris, a waveguide spacer and vacuum window were mounted before the waveguide-to-coaxial line transition, since the transition was not vacuum tight. A special waveguide spacer with grooves for rubber O-rings was available for tuning use.

Vacuum levels between 100 and 1000 microns could be reached in this way.

When a vacuum roughing pump was to be shut off after measurements under vacuum were complete, the vacuum valve to the tank would first be closed, then the turbine pump turned off, and finally the fore pump turned off. The module would then be filled with nitrogen gas.

2. Preliminary Bridge Coupler Tuning. The bridge couplers were then tuned such that a preliminary bead pull measurement of field distribution could be made. This involved tuning the bridge coupler to the correct frequency and adjusting the posts such that the phase shift across the bridge coupler was independent of the direction of net energy flow through the bridge coupler. Steps 2 through 7 and 11 through 14 of section D below were followed to do this.

3. Preliminary Beadpull and Field Flattening. The field distribution within each tank was checked using a beadpull measurement. In this type of measurement, a small perturbing object is carried along a string stretched along the beam axis, and the amount of electric field present at each point is deduced from the resulting variation in the $\pi/2$ -mode frequency of the module. Data processing and display were handled by a minicomputer. Further details on this type of measurement are given in section VI of this report.

For a given tank, the maximum acceptable peak-to-peak variation in an accelerating cavity field was ten percent of the average of the cavity field. The choice of ten percent as the tolerance was based on the following considerations. Longitudinal beam dynamic calculations indicated that as long as the tank averages were near their correct amplitude, it would not matter if the amplitude in individual cavities differed as much as 50 percent from the average (Hanson and Leach et al. 1974). This will be discussed further below. Beam dynamics calculations including the transverse motion showed that tanks with non-uniform field distributions produced an almost imperceptibly more diverging beam than tanks with uniform field distributions (M. Perl, 1976a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, p, q, r, s, t, u, v, w, x, y, z). However, it was felt that it would be desirable to be conservative regarding the completeness and accuracy of the beam dynamic model and to try to avoid the possibility that the small increase in transverse motion would cumulate in a significant transverse deflection by the time the beam had traversed the entire machine.

A combination of tuning methods was used to flatten the field distributions within tanks if necessary. When septum bending was employed, a fairly consistent rate of change of field distribution with septum deformation was observed, as in Fig. 28. The field was lowered on the side toward which a septum was moved. Tuning by dinging or nose-stretching, on the other hand, had an insignificant effect on the field distribution. This made possible the following flattening procedure:

Fig. 28. Measured field distribution tilt rates for tilt caused by tuning accelerating cavities by septum bending.

the flattening procedure to correct the field distributions to meet the required flatness. Appendix B indicates how the tanks were retuned.

By Step 11, the tanks in the Flat and Under Vacuum Under Vacuum condition (pressure about 1000 microns) were at the $\pi/2$ -mode frequency, the frequencies were approximately above and below the $\pi/2$ -mode, and the half-power frequencies for each tank were measured and recorded on Checklist #2 (see Fig. 29). The data was used to deduce the stopband and startband frequencies. The equipment layout for measuring the half-power frequencies is indicated in Fig. 30.

By Step 12, the Bridge Coupling and H-Probe Calibration was completed. This section elaborates on the operations mentioned briefly in Part III.A.12. of this report. A summary of the general objectives of bridge coupling tuning, see III.A.12. Further discussion of the objectives is given below and by Potter and Thompson (1970). When tuning a four-tank module, the operation of the coupler and pair of tanks would be adjusted. Then the procedure would be applied to the remaining bridge coupler and pair of tanks. Finally the center bridge coupler would be tuned to match the two halves of the module.

Modules 1 through 4 were initially tuned to the $\pi/2$ -mode frequency and the average field in the tanks was adjusted to the design value. The $\pi/2$ -mode frequency, the tank $\pi/2$ -mode of the cell, were not retuned to correct flattening. The effect of the operation of the tanks was to correct the field distributions in the tanks. The field distributions measured after initial tuning (Glaveson and Swain et al. 1970). The calculated performance was not appreciably degraded from the case with flat field distributions within each tank, provided that the averages of the cavity field amplitudes for each tank fell near the design value. In the actual linac, the averages were adjusted to agree within one percent using the rotatable notched posts in the bridge couplers. (See Section IV.E.)

Tanks in Modules 13 through 26 were retuned or partly retuned when necessary according to the above flattening procedure in order to bring the maximum peak-to-peak amplitude deviation down to approximately ten percent or less for all these modules. The retuning tended to bring severely deformed septums back near their original positions.

Only two tanks (Tanks 71 and 94) in the remainder of the linac, Modules 27 through 48, required

the flattening procedure to correct the field distributions to meet the required flatness. Appendix B indicates how the tanks were retuned.

By Step 11, the tanks in the Flat and Under Vacuum Under Vacuum condition (pressure about 1000 microns) were at the $\pi/2$ -mode frequency, the frequencies were approximately above and below the $\pi/2$ -mode, and the half-power frequencies for each tank were measured and recorded on Checklist #2 (see Fig. 29). The data was used to deduce the stopband and startband frequencies. The equipment layout for measuring the half-power frequencies is indicated in Fig. 30.

By Step 12, the Bridge Coupling and H-Probe Calibration was completed. This section elaborates on the operations mentioned briefly in Part III.A.12. of this report. A summary of the general objectives of bridge coupling tuning, see III.A.12. Further discussion of the objectives is given below and by Potter and Thompson (1970). When tuning a four-tank module, the operation of the coupler and pair of tanks would be adjusted. Then the procedure would be applied to the remaining bridge coupler and pair of tanks. Finally the center bridge coupler would be tuned to match the two halves of the module.

Additional information on $\pi/2$ -mode frequency and stopband measurement procedures is given in V.A.

1. Cut Iris to Initial Size. Most of the bridge couplers (Modules 5 - 43) were delivered to the beam tunnel with only a 8.89 cm dia. hole for the drive iris. This was enlarged at the top and bottom to produce a racetrack-shaped hole. A few bridge couplers (Modules 44 - 48) were delivered with a racetrack-shaped hole. At the start of bridge coupler tuning, those units with a circular hole had the iris cut to 8.89 by 12.70 cm (3.5 by 5.0 inch) dimensions.

2. Install Adjustable Posts. Completed bridge coupler cavities have three kinds of posts: end tuners, fixed post tuners, and center post tuners. (See Fig. 15 on p. 14 and Fig. 31.) The fixed and the center post tuners are water cooled, but the end tuners are not. The end tuners are fixed posts mounted at the flat end faces of the bridge coupler cavity and penetrate along the center line of the cavity. Their lengths were chosen such as to set the bridge cavity TM_{010} mode frequency properly, as will be discussed in Steps 11 and 18 below. At the

2 CHECKLIST 2: FINAL CELL

Set up to read $\pi/2$ mode, stopbands, & Q of each tank.

Before

making measurement, check that coupling cells from tank to B.C. are shorted.

Date 3/16/72 Initials DW + P.B.

Module vacuum 70.2

Module temperature 29.4°C

Tank # 91. Coup. cells tuned to 804.985

Tank # 92. Coup. cells tuned to 804.900

☒ Short under downstream B.C.

☒ Short under upstream B.C.

Mode below 804.422 MHz +20 kHz

Mode below 804.428 MHz +31 kHz

$\pi/2$ 805.005 585

$\pi/2$ 805.002 574

Mode above 805.612 605

Mode above 805.607 605

Stopbands: _____ kHz

Stopbands: _____ kHz

Half-power points: 805.024 MHz

Half-power points: 805.018 MHz

804.989

804.983

Bandwidth (difference): 35

Bandwidth (difference): 35

Q: 23,000

Q: 23,000

BANDW. (kHz)	Q
50	16100
49	16400
48	16800
47	17100
46	17500
45	17900
44	18300
43	18700
42	19200
41	19600

BANDW. (kHz)	Q
40	20100
39	20600
38	21200
37	21800
36	22400
35	23000
34	23700
33	24400
32	25200
31	26000

BANDW. (kHz)	Q
30	26800
29	27800
28	28800
27	29800
26	31000
25	32200
24	33500
23	35000
22	36600
21	38300

Half-power point = (V = 0.71 V at resonance) = 3 dB down

Q = (res. freq.)/(bandwidth) = 805,000/(b.w. in kHz)

8/17/71 GRS

Fig. 29. Example of CHECKLIST 2: FINAL CELL TUNING data sheet used in Step 4 of Part IV.C. (Filed in module notebooks.)

Fig. 31. Equipment layout for measuring half-power frequencies used to determine Q . The oscillator frequency was set for maximum output (30 dBm) in the H_{1112} mode. The frequencies on either side of the H_{1112} mode frequency for which the output voltage was 3 dB down from the maximum voltage ($V_{max} = \sqrt{2} \cdot 0.717 V_0$) were determined. These were the half-power frequencies. For individual tank measurements, probes (1)-(2) or (3)-(4) were used. For module measurement, the shorts in the bridge coupler coupling cavities were removed and the drive placed at (5) and the pickup point at (6). The Q was found from the table of Q vs. bandwidth (difference of half-power frequencies) given on Checklist 2.

Fig. 32. One of the four-tank modules undergoing final tuning in the beam tunnel. A temporary E-probe is bolted to the flange on the beam line at the end of the module. Temporary adjustable end tuners are mounted on the bridge coupler ends.

Fig. 33. Interior view of bridge coupler cavity as seen from the drive iris. The notched center post is at right center. At the left is a fixed post on the near (back) wall, and a fixed post and a blank filling an unused port on the far (front) wall. These posts are at field maxima for the H_{1112} mode. At top left are one of two ports used to suppress a degenerate vertical H_{1113} mode and the bar brazed at the top of the cavity to compensate for the change in frequency caused by the drive iris. At lower left is the slot into the special coupling cavity joining the bridge cavity with the end accelerating cavity of the tank below.

present step in the tuning process, a temporary set of adjustable end tuners was installed (Fig. 32).

The second kind of bridge coupler posts, the fixed post tuners, were installed on the front, back, or top bridge cavity wall as necessary to shift modes to aid in phase compensation or to suppress interfering degenerate modes (Steps 3-10). None of these posts were put in at this time.

The third kind of post, the center post tuner, was mounted at the center of the front wall of the cavity (which is directly opposite the drive iris, for bridge cavities having an iris). This post had a notch in its tip, permitting it to couple differently to the upstream half of the bridge cavity than to the downstream half. Center posts may be adjusted in both penetration and rotation. (See Fig. 33.) Adjustment of the post in or out made the last small adjustment to complete the phase compensation (Steps 3, 6, and 13). Adjustment of the post rotationally controlled the tank-to-tank amplitude behavior (see IV.E.3.). Since the amount of center post penetration adjustment was limited, spacers of various lengths were used between the

Fig. 33. Cross section of a center post coupler. The center post is set for its penetration and rotation by post mounting flange and the flange on the bridge coupler.

At this step in the procedure, only the adjustable end tuner, and the adjustable center post and spacer would be installed. These units were set to the lengths used on the previous module. The slot on the center post was oriented vertically, which left the coupling symmetric. The bridge coupler cavities were manufactured with two other ports for adjustable post tuners along the front wall. These other ports were *not* needed or were at the wrong positions for phase compensation on the LAMPF 805-MHz linac, and were sealed off with copper blanks (as in Fig. 31).

3. Adjust Center Post Penetration. Phase compensation is achieved when the phase between parts of a linac structure is independent of the amount of beam loading. In the case of a single tank operated in the $\pi/2$ mode, phase compensation occurs when the other modes are symmetric about the $\pi/2$ mode, that is to say, when the stopband is closed. In the case of a bridge coupler cavity, the other nearby modes are not symmetric about the desired TM_{010} mode, but the modes can be shifted such that the modes below compensate for the modes

above the TM_{010} mode. For a the plane structure at the TM_{010} mode. The side frequencies for the TM_{010} , TM_{011} , H_{113} , and H_{115} modes for CMB bridge coupler are shown in Fig. 34. The H_{113} mode that is shown is lower than the TM_{011} mode. The adjustable center post and the fixed post (not on the ends) interact strongly with the H_{11n} modes but only weakly with the TM_{01n} modes.

For the shorter bridge coupler (up to about 70 cm in length), the center post alone was adjusted to bring the TE_{11n} modes down such that the TE_{111} and H_{113} modes below the TM_{010} mode compensated for the TM_{011} and higher TE_{11n} modes above. In simplified terms, one might say the TE_{113} mode was brought down until it resonantly coupled the halves of the bridge coupler cavity. If possible, the center post penetration was set to obtain less than one degree change in the phase shift across the bridge coupler as the drive was switched from one end of the module to the other. (See Fig. 35 for measurement equipment layout.) If this could be done, one then skipped down to Step 11 of this procedure.

If the bridge coupler being tuned was longer than about 70 cm, one found that either no setting

[illegible]

For 111 longer bridge couplers (about 80 cm long) a deliberate H₁₁₈ mode with vertical orientation interfered, and two additional posts were added along the top of the bridge coupler cavity to move it frequency away. Thus these bridge couplers have seven posts not including end tuners.

 

those steps for which the iris was not needed as a drive point.

4. Drill For Additional Posts If Required.

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Fig. 36. Equipment layout for determining the input SWR for the module. (See IV.B.8. and 17.)

position of the hole was not very critical, it did need to be perpendicular to the surface so that the post, when installed, would make good contact with the cavity wall.

5. Install Trial Posts. Sets of brass fixed posts varying in length from about 5.7 cm (2-1/4 in.) to about 7.0 cm (2-3/4 in.) in length were used for preliminary measurements. These posts had a diameter of 5.08 cm. One set of four such posts would be installed in the horizontal holes. A pair of small adjustable copper posts (2.54 cm diam) would be installed in the vertical holes if needed. The set of brass posts of 6.35 cm (2-1/2 in.) length would be installed for the first trial on a new module. The post length used was recorded.

6. Find Approximate Center Post Penetration. The penetration of an unattached center post was adjusted by hand and the adjustable end tuners were moved in or out until the $\pi/2$ -mode frequency of the bridge coupler plus linac units on either side was close to the average of the $\pi/2$ -mode frequencies of the individual units, and until the nearest modes of the combined structure were approximately symmetrical about the $\pi/2$ -mode. The required center post spacer length was then recorded.

7. Install Center Post. The center post was installed with a spacer of length determined in Step 6. The center post and the adjustable end tuners were then set under vacuum such that the $\pi/2$ -mode frequency of the bridge coupler plus linac units on either side was within ± 1 kHz of the average of the $\pi/2$ -mode frequencies of the individual units, and

such that there was less than a degree change in phase shift across the bridge coupler as the drive was withdrawn from the end of the combined linac units to the other, as in Fig. 35. (The slot on the center post was left oriented vertically, as before.) The center post position and end tuner penetration were recorded.

8. Measure SWR. For center bridge couplers, the SWR in the input line near the bridge coupler iris was measured and recorded. On some of the early modules, a slotted line was used to determine the SWR in the input waveguide. Later a directional coupler and vector voltmeter was used to measure the forward and reflected power in the coaxial line behind the cone-guide transition (Fig. 36), and the SWR was calculated from this data. The procedure used was as follows:

a. Set the frequency to obtain minimum reflected signal.

b. Set the drive amplitude to give a reading on the 100 scale of the vector voltmeter using Probe A of the meter connected to the forward output of the directional coupler. This reading is V_F .

c. Move Probe A to the reflected output of the coupler and read the signal level on the same meter scale, if possible. This reading is V_R . Then

$$VSWR = (V_F + V_R) / (V_F - V_R).$$

Whether the iris was overcoupled or was undercoupled could be determined by making use of the fact that the impedance locus for the iris and module did encircle the center of a Smith chart plot if the iris was overcoupled, but did not if it was undercoupled, for frequencies near the $\pi/2$ mode. The question was resolved without actually drawing such a graph, as follows: Probe A of the vector voltmeter was connected to the forward output of the coupler and Probe B to the reflected output. The phase meter was set to zero using the largest scale (± 180 degrees). The frequency was then varied from resonance to a point for which a maximum in reflected amplitude was reached. If the phase moved in one direction but then returned to near zero as this frequency variation was being made, the iris was undercoupled. If the phase did not return to zero (but generally kept moving in whatever direction it started), the iris was overcoupled.

Depending on the results of the VSWR measurement, one of the following three courses of action were taken:

(1) If the VSWR was in the desired range between 1.2:1 and 1.5:1 overcoupled, one skipped to Step 10.

(2) If the VSWR was undercoupled or less than 1.2:1 overcoupled, one went on to Step 9.

(3) If the VSWR was greater than 1.5:1 overcoupled, one installed a shorter set of trial fixed posts and Steps 6 through 8 were repeated. If after doing this with the shortest fixed posts, the VSWR was still high, an external iris plate was machined and cut by trial to the proper size. The iris plate was mounted between the waveguide flange on the bridge coupler and the short wave-guide section leading to the rf window.

Generally the procedure went gradually enough that one did not overshoot the desired range of VSWR. It was only on bridge couplers that were changed from one post to five posts (or the like) after the iris had already been enlarged that cases of VSWR more than 1.5:1 overcoupled were encountered.

9. Enlarge Iris. A special fixture bolted to the waveguide flange on the center bridge couplers was used to hold a heavy-duty power drill in position for milling the iris to a larger size. As in Step 4, precautions were taken to prevent chips from entering the linac sections below.

If there was room to enlarge the iris longitudinally, the racetrack was made longer and the length recorded. Steps 6 through 8 were then repeated using the same trial set of fixed posts.

If the iris was already cut to maximum size, with the racetrack extending all the way to the stainless steel waveguide flange at top and bottom, a longer set of trial fixed posts was installed and Steps 6 through 8 repeated. In a few cases, even the longest posts did not bring the VSWR to 1.2 overcoupled. In this event, the iris was cut to approximate a rectangular shape by using a smaller radius to enlarge the four portions of the opening corresponding to corners.

10. Install Permanent Fixed Posts. Four fixed copper posts were cut to the length of the successful trial posts and were installed in the bridge coupler. (The water cooling passage in

these copper posts did not extend all the way to the end in order that they could be cut to length as required.) The vacuum seal for these posts was on the outside of the bridge coupler. Each post had a small passage through its base where it seated against the inside radius of the bridge coupler cavity. This passage eliminated the possibility of a virtual vacuum leak from the mounting hole space to the bridge coupler cavity.

After permanent post installation, Steps 7 and 8 were repeated.

11. Adjust End Tuners. The adjustable end tuners were moved so that the $\pi/2$ -mode frequency of the bridge coupler plus linac units on either side was within 1 kHz of the average of the $\pi/2$ -mode frequencies of the individual units under vacuum.

12. Adjust Coupling Cavities. The change in phase across each of the two coupling cavities in the bridge coupler assembly was measured as the direction of drive was changed. A vector voltmeter and E probes built into the adjustable end tuner of the bridge coupler above and E probes inserted along the beam hole into the first accelerating cavity below were used. (See Fig. 35.)

If the phase change was greater than 2 or 3 degrees, the frequency of the coupling cavity was adjusted. To lower the frequency, the flat sides of the coupling cavity were tapped or squeezed together. To raise the frequency, the side of the cavity towards the middle of the bridge coupler was pulled out, thus moving its reentrant bosses farther apart. Two machine nuts brazed to the outside wall of the cavity together with a special wrench that spanned the side of the cavity were used to do this, as in Fig. 37. If a large upward correction in frequency was required, a hydraulic cylinder was inserted in the bridge coupler through the iris and placed between the coupling cavity bosses. The cylinder was then expanded to force the bosses farther apart.

13. Adjust Phase With End-End Drive. The change in phase between tanks was measured as the drive point was switched from one end of the linac unit to the other. Electric probes were inserted along the beam pipe centerline to pick up signals from each of the end accelerating cavities underneath the bridge coupler to do this, as in Fig. 35. The penetration of the center post in the bridge

Fig. 36. Section showing method used to raise the frequency of coupling cavities in bridge coupler unit.

Coupler was adjusted so that this change in phase was less than 1 degree.

11. Check Phase With Center Drive. For center bridge couplers, the drive was switched to the input iris after the measurement of Step 13. A large change in power level going into the vector voltmeter could affect the indicated phase difference. Thus, it was necessary to reduce the signal generator level when driving the module through the bridge coupler iris. The drive level was reduced until the input level to the vector voltmeter was near the level obtained when driving from one end of the module. If the phase between tanks changed more than 1 degree from the phase observed in Step 13, Steps 12 and 13 were repeated.

15. Recheck Frequency and Phasing. The $\pi/2$ -mode frequency was rechecked (see Step 11) and the phasing with end-end and center drive was rechecked (see Steps 13 and 14) at this point and readjusted if necessary.

16. Measure Stopband. The module stopband was measured with the drive at one end of the module and the pickup point at the other end.

17. Check VSWR.

a. No Fixed Posts Used. If no fixed posts were used in the bridge coupler cavity, the VSWR was measured (see IV.D.8. and Fig. 36) and the iris was enlarged (as in Step 9) until the VSWR was between 1.2:1 and 1.5:1 overcoupled. Steps 15 and 16 were repeated after each cut.

b. Fixed Posts Used. If fixed posts were used in the bridge coupler cavity, the iris had pre-

viously been enlarged at the iris at Step 9, and the VSWR was normally measured at this point.

18. Set Permanent End-tapers. The end-taper end-tapers (set at the input and output) were now removed and the lengths of penetration measured. Permanent copper bridge coupler end-tapers were then cut of the average of these two measured lengths and installed. The lengths of the permanent end-tapers was recorded.

19. Check Final Phase With $\pi/2$ -Mode Drive. The tank-to-tank phase was measured while driving at the iris. (See Step 11 and Fig. 36.) If this phase was greater than 1 degree, it was taken as an indication something was wrong. It was an indication the end-tapers had been the same length, or one of the bridge coupler unit coupling cavities being retuned.

20. Record Final Measurements. The forward final measurements were recorded on Checklist #3 (see Fig. 3-1).

a. Module $\pi/2$ frequency with iris drive. (The resonant point was taken to be the frequency which gave maximum reflected signal in the drive line.)

b. Tank-to-tank phase shift, with end and with iris drive.

c. Apparent module Q.

d. Stopband, measured end-to-end and measured with iris drive.

e. VSWR.

f. Mode spectrum photo. The $\pi/2$ -mode was positioned on the center cross marks. At least six modes on either side were shown. (Photos and other information may usually be found in laboratory notebook R-2229 if not given on the Checklist #3 sheet.)

If the mode spectrum was not symmetrical about the $\pi/2$ mode for several modes, it might indicate the bridge coupler did not have the right number or length of fixed posts. (A spectrum with mode pairing often could be observed before the coupling cavities below the bridge coupler were tuned - Step 12. There should not be mode pairing at Step 20.)

21. Set H-Probes. The monitor loops (H-probes) were part of the tanks, rather than of the bridge couplers, but are included here since they were set at this point in the tuning sequence.

The monitor loops were adjusted to deliver a nominal 10 watts of peak power when the tanks were

CHECKLIST 3 FINAL MODULE MEASUREMENTS

Date 3/22/72
Initial DW+PE

Module No. 42
Module Temp. 29.4°C

A. Module P.I. frequency with center drive 805.000 MHz.

B. Tune-out - tune phase shift

1. In drive 0°.

2. In drive .2°.

C. Module output 805.039 MHz

Drive, amp into 804.958

Load, out (Difference) 81

Q: 9,938

D. Stopband

1. In Drive: Mode below 804.731 MHz +27 kHz

$\pi/2$ 805.004 263

Mode above 805.294 290

Stopband: _____ kHz

2. In Drive: (a) D.20

(b) F.1 [FINAL CHECK AFTER WARMING]

Mode below 804.419 MHz +26 kHz

$\pi/2$ 805.000 581

Mode above 805.607 607

Stopband: _____ kHz

Mode below _____ MHz

$\pi/2$ _____

Mode above _____

Stopband: _____ kHz

E. Loss 1.31 mresampled

F. Paste Mode Spectrum Photo:

Fig. 38. Example of CHECKLIST 3: FINAL MODULE MEASUREMENTS datasheet used in IV.D.20. and IV.F. These sheets were filed in the module notebooks.

operated at design level, the input cable was replaced and actually returned to the probe below the range 3 to 14 watt peak. The nominal voltage factor (probe output with respect to power delivered to input) was 18.5 dB. Since the input of the probe hole to the accelerating cavity varied the probe probe, each H-probe had to be individually calibrated. These adjustments were made by using a probe with different length loops and by opening and closing the tip of the loops. The loop lengths on the probe used varied from 15 to 25 cm, and the distance from the probe tip to the tuning plate. These adjustments were made by rotating the loops. The probes were adjusted to approximately nominal output before being finally tightened down for the vacuum seal and the final calibration measurement.

A 20-watt amplifier and a power meter were used in making the measurements. Additional details are given by Galy (1972). The calibration factor for each probe and the input VSWR for each module were recorded. The values are listed in Appendix B, Table B-VIII.

On many of the probes, the socket to port contact was too large and the individual fingers had to be bent inwards to make good contact. If the socket did not make good contact, the result was a tuned connection, which could deliver a signal up to 13 dB above the nominal power depending very critically on cable and connector positions. The coaxial cable from each probe was a rigid type. Unless these cables were connected very carefully and supported by a brace, the H-probe or the connector on the end of the cable could be broken. Several accidents of both types occurred.

E. Module Field Equalization

These procedures included the final checks and the final adjustments to ensure that the field distribution within each tank was reasonably flat and that the field averages for the tanks within a module agreed to better than one percent. (These procedures were mentioned briefly in Part III.A.12. of this report.) The steps followed were:

1. Do Vacuum Beadpull. A beadpull measurement was done under vacuum in order to determine the field distribution along the beam axis of the module. (See Section VI.B. for details of beadpull measurement.)

Each tank is fitted with a probe. It is not at first a very accurate antenna, but it is used to measure the field distribution along the beam axis. The probe is used to measure the field distribution along the beam axis. The probe is used to measure the field distribution along the beam axis. The probe is used to measure the field distribution along the beam axis.

2. Rotate Bridge Coupler (center post). The center post in the bridge coupler unit was rotated to adjust the field distribution from tank to tank. The posts were rotated one at a time to make the tank averages agree to within one percent under vacuum. Center post rotation could not be done under vacuum. The module had to be let up to air, the post rotated, and a new seal installed. The slot was rotated toward the tank whose amplitude was to be raised. In a few cases, full rotation of the post (the notch oriented at 90° from the vertically) was insufficient to make the averages agree. In such cases, it was necessary to install a post with a larger notch and recheck the bridge coupler adjustments (Steps 3 to 20 of VII.B. above). Changing the notch size affected primarily the required center post penetration. Notches as large as 2.54 cm long by 2.54 cm deep (half way through the diameter of the post) were used.

After the post rotations were completed, a line was scribed on the center post body and mount to indicate the correct position for future reference.

4. Record Data. The final beadpull measurement data were recorded in a laboratory notebook. Notebooks R-2242, R-2284, and R-2229 were used to keep a working record. Notebook 17464 was used to keep a summary of final results. Data saved included a photograph of the graph of cavity peak fields ("peak graph", a list of individual accelerating cavity peak field amplitudes ("peak list"), and a punched paper tape for the beadpull.

F. Final Low-Power Stopband Check.

This section covers the operation mentioned previously in part III.A.20. of this report. This check was performed after plumbing connections to the bridge coupler unit were complete and vacuum manifolds had been welded to the lower coupling cavities and caps welded on the upper coupling cavities (Figs. 39 and 40). The stopband was measured driving at the iris and picking up at the E-probe in the bridge coupler end tuner, or driving

Fig. 39. Exterior view of 7-post bridge coupler. The connector for the 1-probe in the bridge coupler and tuner is visible at the middle of the cavity end face at right. The tank to the left of the bridge coupler has had its vacuum manifold welded or soldered. Top will later be welded on the coupling cavity of the tank on the right; these were still closed with rubber stoppers when the photograph was taken.

at the line and picking up reflected power in the drive line. (See V.1.2. and V.1.4.b.) The stopband can be tall in a specified range, usually -17 to $+10$ kHz, to be accepted. No modules failed this criteria. The stopband information was recorded on Checklist 3 (Fig. 39).

V. TUNING TECHNIQUES AND TOOLS

A. Frequency Measurement Techniques

1. Resonant Frequency. The standard method of measuring single cavity or cavity chain mode frequencies was as follows: Two electric or magnetic probes were positioned so as to be lightly coupled to the cavity or cavities. A swept-frequency signal was introduced with one probe. The response was picked up by the other probe and displayed by vertical deflection on an oscilloscope whose horizontal deflection was synchronized with the frequency sweep. (See Figs. 41 through 43 for examples of equipment set-ups.) The resonant modes appeared as inverted peaks in the horizontal trace (Fig. 44). A marker signal was added to this trace to permit accurate determination of the frequencies of the resonant modes thus displayed. Part of the signal from a stable signal generator was fed to a mixer-detector, along with the swept-fre-

Fig. 40. Exterior view of completed 1-post bridge coupler. The plumbing connections across the front of the bridge coupler had been removed and were then replaced after the quadrupole focusing magnet was put in place. The shrouds over the tanks on either side protect the coupling cavities from accidental mistuning due to falling tools or the like.

quency response, thus producing a "birdie" at the position on the trace corresponding to the frequency of the signal generator. The other part of the signal from the signal generator was sent to a scaler, where the cycles of a suitably heterodyned signal were counted to provide a readout consistent to better than 1 kHz. When the marker was superimposed on the tip of one of the response peaks, the frequency (usually in kHz difference from 800 MHz) was read off the scaler. The positions of the probes might then be adjusted slightly to check that the probes themselves were not perturbing the cavity frequency.

2. Pi/2 Mode Identification. It was often necessary to determine which of a whole family of modes on the swept-frequency display was the $\pi/2$ mode. A convenient way to do this was to introduce a perturbation (e.g., a shorting pin only partly inserted) in the coupling cavity at one end of the chain, and watch how this moved the modes in frequency. Since the $\pi/2$ mode had nearly no field in the end coupling cavity, but all other modes had some field in this cavity, such a perturbation shifted all other modes, leaving the $\pi/2$ mode almost unaffected. Thus the mode that appeared not to move was the $\pi/2$ mode.

Fig. 41. Equipment set-up for coupling cavity frequency measurement.

Fig. 42. Equipment set-up for accelerating cavity (main cell) frequency measurement.

Fig. 44. Equipment for frequency measurements in the beam tune. Top-to-bottom in the rack are a scaler, oscilloscope, frequency sweeper, chart recorder and frequency-to-voltage converter, and signal generator. The coupling cavities on the tank at left have shorting pins held in place with large rubber bands, which was the shorting method used before the combined probe and short for accelerating cavities was invented.

than usual or the tank Q lower, since a poor short usually lowered the Q of the resonance in question.

b. Iris To Bridge Coupler End Tuner Probe Interaction. There is an indication that a signal non-resonantly coupled from the iris to the E-probe in the end tuner of a bridge coupler can perturb the results of stopband or module Q measurements made using the E-probe. Stopbands as measured using this probe may differ up to 10 kHz from stopbands measured using an E-probe in one of the end accelerating cavities.

One may envision the iris to be coupled to the E-probe by means of some spurious low- Q mode in the bridge cavity, perhaps a TE_{113} vertical mode near the module $\pi/2$ mode. The spurious mode has very little energy other than in the bridge coupler, and thus distorts the swept-frequency response observed in the bridge coupler as compared with that observed elsewhere.

Fig. 45. Simplified model of bridge coupler with iris-to-end tuner probe interaction. V_{in} represents the iris drive and V_{out} the end tuner probe response, which has a RLC series resonance plus a term proportional to the drive. The term uV_{in} represents the effect of some spurious mode in the bridge cavity, and if the Q of this mode is much lower than the normal resonant mode, u may be taken to be independent of frequency.

A calculation using the simplified model shown indicates that the resonant peak may be skewed one way or the other, or in the symmetrical case, may be broadened (Petter 1972). (See Fig. 45.)

Distortion of any or all of the three peaks used in a stopband measurement would perturb the result of the measurement. Symmetrical or unsymmetrical broadening of the response peak makes the measured Q lower than when such distortion is not present.

c. Apparatus Too Close to Iris. Special equipment, such as a waveguide-to-coaxial transition, should not be mounted directly upon the flange at the drive iris, since the resonant frequency of the bridge coupler cavity may be perturbed. A special waveguide spacer with grooves for rubber O-rings and a window assembly were generally used between the iris and the transition. This permitted measurements under nitrogen or under rough vacuum as desired. If the iris was not being used as a drive point, a 50 ohm termination was connected to the coaxial end of the waveguide-to-coaxial transition.

d. Humidity Effects. Variations in humidity in air-filled cavities may result in changes in resonant frequency of as much as 30 kHz. For this reason, a trickle of nitrogen gas was kept flowing through the 805-MHz linac modules for all final tuning operations at atmospheric pressure. (See also IV.A.1.)

c. Temperature drift. The effect of causing a failure in the resonant control system was discussed in section III.A.9.

B. Calculation of Desired Cavity Frequencies

The resonant frequency that one measures for a given cavity in a linac with a given $\pi/2$ -mode frequency depends upon the amount of coupling to cavities beyond the nearest neighbors and upon the type of shorting arrangement used to move the resonant frequency of the neighboring cavities far from the frequency of interest. For this reason, the resonant frequencies used to tune cavities individually had to be determined empirically.

1. Coupling Cavities. In the case of the coupling cavities, the coupling to cavities other than the nearest neighbors was very small. This meant that the desired individual cavity frequencies (804.860 to 805.050 MHz) were not far from the desired $\pi/2$ -mode frequency, 804.834 MHz, and did not vary rapidly with change in geometry as one proceeded along the linac. Thus it was possible to obtain a preliminary value for coupling cavity frequency by extrapolation using data from previous modules.

2. Accelerating Cavities. The calculation of desired individual accelerating cavity frequencies was based on selected results from the theory of chains of coupled resonators (Appendix E):

- The $\pi/2$ -mode frequency of a chain of resonators depends mainly on the frequencies of the accelerating resonators, since the coupling resonators contain very little energy in this mode.

- To obtain a stable field distribution, the interior accelerating resonators should all be tuned to a single frequency, f_i , but the end accelerating resonators should be tuned to a different frequency, f_e . These frequencies are related to the $\pi/2$ -mode frequency, $f_{\pi/2}$, and the amount of coupling directly between accelerating resonators (second nearest neighbor coupling), k' , by

$$(f_i/f_{\pi/2})^2 = 1 - k' \quad (1)$$

$$\text{and } (f_e/f_{\pi/2})^2 = 1 - 0.5 k'. \quad (2)$$

- For a chain of resonators in which any one accelerating resonator contains as much energy as any other, the effect of a frequency error in any one accelerating resonator on the $\pi/2$ -mode frequency

is the same as for any other accelerating resonator. For the error in the $\pi/2$ -mode frequency, $\Delta f_{\pi/2}$, the multiple average of the frequency error of the accelerating resonators.

The desired frequencies were determined from the measured frequencies before tuning as follows:

(1) The average interior accelerating cavity frequency was determined from the measured individual frequencies.

(2) A first estimate of the amount of direct coupling was made by solving Eq. (1) for k' , where f_i was the average interior frequency from step (1) and $f_{\pi/2}$ was the measured $\pi/2$ -mode frequency.

(3) The approximate end cavity frequency appropriate for this k' and $f_{\pi/2}$ was estimated by solving Eq. (2) for f_e .

(4) The difference between the actual and cavity frequencies and the above estimate was used to correct the measured $\pi/2$ -mode frequency to account for the actual end conditions:

$$f_{\pi/2} \text{ corr.} = f_{\pi/2} + (2f_e - f_i)^2 / K,$$

where K was the number of accelerating cavities in the chain and f_i and f_e were the measured end frequencies.

(5) A better estimate of k' was found by solving Eq. (1) with the $\pi/2$ -mode frequency found in step (4).

(6) Equations (1) and (2) were then solved to find the desired individual interior and end accelerating cavity frequencies using the value of k' found in step (5) and the desired $\pi/2$ -mode frequency.

The above calculation was implemented in practice by the use of a Hewlett-Packard 9100-A programmable calculator. The algorithm was coded and saved on magnetic program cards. Later, the algorithm was incorporated in a program for generating forms for tuning data (program FFTD).

For nitrogen atmosphere and 22.2°C (72°F), ETL Tuning Laboratory conditions, the desired $f_{\pi/2}$ = 804.930 MHz; for nitrogen atmosphere and 29.4°C (85°F), tunnel tuning conditions, the desired $f_{\pi/2}$ = 804.834 MHz. These correspond to $f_{\pi/2}$ = 805.000 MHz at 29.4°C under vacuum conditions. One magnetic program card was set up for the calculations for ETL, and another card and the FFTD

the phase shift between the fields in the coupling cavity and the adjacent accelerating cavity. The coupling cavity was then adjusted until the stopband was closed.

Another method (E. Knapp 1966) adjusted all coupling cavities together until the stopband was closed as determined from the spectrum of resonant modes of the cavity chain. Another method (E. Knapp 1968, pp. 7-8) examined the phase shift between the fields in the accelerating cavity adjacent to the coupling cavity to be tuned. The coupling cavity was tuned one way to make this phase shift be π radians. Extraneous phase shifts due to the connectors and cables introduced errors in the tuning with this method. Later, a variation of the above method was developed for tuning coupling units in bridge coupler assemblies (see IV.D.3, pp. 36-37). In the terminology of this section, the phase shift between adjacent accelerating resonators was monitored as the drive point was switched from one end of the cavity chain to the other. The coupling cavity between was then adjusted such that this phase shift did not change as the direction of net power flow was changed.

Other indirect methods examined the stopband or the rf field distribution of the whole chain of cavities. One early method (E. Knapp 1966) adjusted all coupling cavities together until the stopband was closed as determined from the spectrum of resonant modes of the cavity chain. Another method

(E. Knapp 1968, pp. 7-8; Knapp 1969a, pp. 7-8) examined the phase shift between the fields in the accelerating cavity adjacent to the coupling cavity to be tuned. The coupling cavity was tuned one way to make this phase shift be π radians. Extraneous phase shifts due to the connectors and cables introduced errors in the tuning with this method. Later, a variation of the above method was developed for tuning coupling units in bridge coupler assemblies (see IV.D.3, pp. 36-37). In the terminology of this section, the phase shift between adjacent accelerating resonators was monitored as the drive point was switched from one end of the cavity chain to the other. The coupling cavity between was then adjusted such that this phase shift did not change as the direction of net power flow was changed.

Another method (Knapp et al. 1967, Knapp 1968, Knapp 1969) tuned coupling cavities to minimize the amplitude step in the accelerating cavity field distribution as one cavity of the coupling cavity being tuned, the variation was done with frequency perturbations in the other accelerating cavities. This was made difficult by the irregularities in field distribution that arose from variations in the amount of coupling from cavity to cavity along the chain. In addition, this and other methods which required a measurement of the field distribution were slow.

Fig. 46. Cross section of sidecoupled linac structure. Introduction of probes at K or at L severely perturbed the frequency of the coupling cavity G. Accelerating cavities are denoted F. The beam-pipe flange at the end of the tank is at H.

Fig. 47. Sketch of a coupling cavity tuning probe as discussed in Sec. 4.5. (this page).

Fig. 48. Various kinds of tuning probes. From top to bottom, a coupling cavity probe, two accelerating cavity probe and short assemblies, and an E-probe for accelerating cavities are shown. The coupling cavity probe and the E-probe are inserted along the beam hole; the accelerating cavity probes are inserted in coupling cavity ports.

The field distribution measurement entailed observing the resonant frequency of the whole cavity chain as a metal bead was pulled along the beam line on a fine string, a time-consuming procedure.

All of these indirect methods (with the possible exception of the closed-stopband method) suffered from the fact that in normal operation of any $\pi/2$ -mode structure, the coupling cavities have very little energy in them, and therefore any measurement on the structure as a whole was relatively insensitive to the resonant frequency of any particular coupling cavity. The motivation for finding a workable direct method was that the tuning could then be done quickly and accurately, with the individual coupling cavity resonant frequencies, as well as their average, set to the desired value. A probe suitable for implementing the direct method was developed (Swain and Manger et al. 1970) in February and March, 1970 (which was after Module 5 was fabricated).

4.5. Description of the Probe and Method of Use. The coupling cavity tuning probe consisted of a cylindrical body (A in Fig. 47), an excitation loop B, a pick-up loop C, and coaxial cables D connecting to these loops. A coupling cavity probe is shown at the top of Fig. 48. When in use, the probe was inserted in the beam hole of the accelerator structure, as shown in Fig. 49. For early versions of the probe as used with the shorter tanks in modules 5 through 12, the coaxial cables D were taped together and were used to position the device. The body of the probe was long enough to extend across and short out the dominant resonant mode (TM_{010}) of the two adjacent accelerating cavities. If on either side of the coupling cavity being tuned. The center part C of the probe body largely plugged the beam hole, and thus prevented any significant rf energy from traveling from loop B to loop C through the beam hole.

Fig. 49 also shows in block diagram form the additional apparatus required for a coupling cavity frequency measurement. A swept-frequency signal was supplied to loop B. The amplitude of the signal transmitted through coupling cavity C and picked up by the loop C is detected and displayed on an oscilloscope. (See V.A. for further details on frequency measurement.) The resonant frequency of cavity C was then adjusted by squeezing in on points M or pushing the reentrant bosses farther apart with a wedge inserted through the port at L.

Shorting pins might be inserted at J to short out the coupling cavities on the opposite side of the structure from the coupling cavity being tuned. It was later found that it was not necessary to short out the coupling cavities on the opposite side, since the probe had a strongly directional characteristic. However, the apparent frequency of a coupling cavity read without shorts on the opposite side was slightly different from the reading with shorts. For example, the coupling cavities on Module 6 when measured without shorts appeared to be about 30 kHz lower than when measured with shorts.

For the low-energy end of the 805-MHz linac, misorientation of the probe in the longitudinal direction until the detected signal fell to half its maximum value resulted in a frequency error of 25 kHz. Misorientation of the probe rotationally

Fig. 49. Coupling cavity probe and other equipment needed to adjust the frequency of a coupling cavity (C).

the frequency of the $\pi/2$ -mode of the cavity being tuned. The frequency of the $\pi/2$ -mode of the cavity being tuned is determined by the position of the electrical shorts in the cavity. The frequency of the $\pi/2$ -mode of the cavity being tuned is determined by the position of the electrical shorts in the cavity.

The first method of tuning accelerating cavities was developed by monitoring the $\pi/2$ -mode frequency of the whole structure and tuning each accelerating cavity in turn such that the field was minimized in the adjacent coupling cavity toward the drive point (G. Enapp 1964a, R. Enapp et al. 1965, L. Enapp et al. 1968, L. Enapp 1970a). This method has the disadvantages that it is difficult to measure small fields in a coupling cavity without severely perturbing its resonant frequency, that the coupling cavity field minimum becomes less sharp as one proceeds away from the end of the structure, and that at least one other cavity besides the cavity being tuned must be adjusted at each step in the tuning process in order to maintain the $\pi/2$ -mode frequency at the desired value.

4. Accelerating Cavity Tuning Probe

a. Historical Note. The original method proposed and used for tuning accelerating cavities involved monitoring the $\pi/2$ -mode frequency of the whole structure and tuning each accelerating cavity in turn such that the field was minimized in the adjacent coupling cavity toward the drive point (G. Enapp 1964a, R. Enapp et al. 1965, L. Enapp et al. 1968, L. Enapp 1970a). This method has the disadvantages that it is difficult to measure small fields in a coupling cavity without severely perturbing its resonant frequency, that the coupling cavity field minimum becomes less sharp as one proceeds away from the end of the structure, and that at least one other cavity besides the cavity being tuned must be adjusted at each step in the tuning process in order to maintain the $\pi/2$ -mode frequency at the desired value.

A second method of tuning accelerating cavities was developed and tested on the Electron Prototype Accelerator (EPA) at Los Alamos (Potter 1969). In the second method, electrical shorts are inserted in the accelerating cavities adjacent to the accelerating cavity being tuned and also in the coupling cavities adjacent to the cavity being tuned. (Various coupling cavity shorts were tried. One of the best schemes was a simple L-shaped copper pin, rounded at the ends, and held in place by a rubber band cut from an automobile tire inner

*Suggested by Oliver Rivera.

†Suggested by Dennis West.

liner. An electric probe inserted in the beam hole of the cavity being tuned introduces a swept-frequency signal, and another electric probe inserted in the beam hole on the other side of the cavity being tuned picks up the signal and transmits it to a detector. The transmission properties of the cavity being tuned reveal its resonant frequency, which can then be quickly and accurately set to a predetermined value. One disadvantage of the second method is that if the electric probes are inadvertently positioned too close to the cavity being tuned, its resonant frequency will be perturbed and the accuracy of the measurement is lost.

The second method was used on the early work on the 805-MHz line and occasionally later when a tank was to be retuned after the vacuum manifolds and caps had already been welded on.)

A third tuning method, which uses the accelerating cavity tuning probes described below, was developed in November and December, 1970 (Manger et al. 1971). The third method is a variation of the second method, but the third method does not suffer from any of the disadvantages indicated above. Again electrical shorts are inserted in the accelerating cavities adjacent to the accelerating cavity being tuned. The accelerating cavity tuning probes (Fig. 48, middle) used in pairs to set the resonant frequencies of accelerating cavities. They are inserted in the vacuum ports of the coupling cavities adjacent to the accelerating cavity being tuned, as in Figs. 26 and 27 (pp. 30-31). One of the pair of probes supplies a swept-frequency signal, while the other picks up the portion of this signal transmitted through the cavity being tuned. At the same time, the probes short out the coupling cavities in which they are inserted, thus preventing the proximity of the dominant resonant frequency of these cavities to interfere with the accelerating cavity measurement.

Tests on December 2, 1970, indicated that devices of this type may be used to set accelerating cavity frequencies with a repeatability of better than ± 10 kHz at 807 MHz. (Further experience showed that frequency measurements were repeatable within ± 3 kHz.)

The third tuning method was used for the initial tuning of Module 14 and modules thereafter. The built-in shorts for the coupling cavities

Fig. 49. Accelerating cavity tuning probe as shown in V.A.(p. 43).

proved to be more reliable than any of the various separate shorting-pin schemes that were used with the second method. The old shorting pin hole in the coupling cavity was not used. This had the advantage that there were no separate shorting pins to keep track of, and the shorting pin hole could be welded shut before segment assemblies were brazed together to form accelerator sections, thus making it easier to leak-check the sections before and after installation. In addition, the positioning of tools and shorts was less critical than the positioning of electric probes required by the previous method.

E. Description of the Probe. Each accelerating cavity tuning probe consisted of a magnetic pickup (or exciter) loop, as shown at A in Fig. 50, an assembly C which electrically short circuited the dominant resonant mode (TM_{010}) of a coupling cavity, and an assembly B which holds the above loop and shorting assembly in proper alignment when in use.

The magnetic loop was fashioned from a length of coaxial cable. One end of the cable led out from the probe as in Fig. 50 to connect the probe electrically with other equipment. The inner conductor and insulation of the other end of the cable were used to form the loop A, the inner connector being attached to the probe body at B. The outer conductor was also grounded to the probe body at B. The loop was turned long enough to extend along side of a tank to the resonant losses of the coupling cavity when the probe was in place. The shorting assembly consisted of a wedge-shaped conductor C which was inserted into the resonant losses of the coupling cavity and held firmly in that position by a spring-loaded pin at C in its supporting shaft. The alignment assembly had a handle B for inserting, extracting, or positioning the device rotationally. A long cylinder D was made with a diameter such that it fit snugly (but without sticking or binding) in the coupling cavity vacuum port. Four spring loaded bars E pressed out against the port, holding the probe firmly in place, even when it was inserted upside-down in one of the lower coupling cavities. Further information on the measurement set-up and the method of using these probes for accelerating cavity frequency measurements is given in V.A.(p. 43) and Fig. 42 (p. 45).

D. Tuning Tools

1. Septum Bending Tool. The septum bending tool was designed^{*} for use in the construction of the Electron Prototype Accelerator. The tool was also used for the early tuning work on the LAMPF 805-MHz accelerator. After the dinging and nose-stretching tools were developed, the septum bending tool was used for cavities which had joint flanges (which prevented use of the dinging tool) and for field flattening within a tank. (See also IV.B.6.a, p. 26.)

The tool was arranged so that the tuners could grip the beam hole walls between accelerating cavities and move the whole septum longitudinally such as to lower the resonant frequency of the accelerating cavity on one side of the septum and raise the frequency of the cavity on the other side (see Fig. 26, p. 30). The tool consisted of an expandable

^{*}The septum bending tool was designed by W. J. Van Dyke.

head, a hammer assembly, and a set of extensions which could be inserted between head and hammer such as to position the head at any desired position in the beam hole of a tank. (See Fig. 51.)

The head was a hollow cylinder, slit at the end to form fingers which could come out and grip the beam hole walls. The fingers had raised sets of ridges, similar to threads, which actually fit into the copper wall of the beam hole to provide a good grip. A conical section fit inside the hollow cylinder and moved longitudinally to make the fingers expand and grip the hole wall.

One extension each consisted of a hollow tube with a rod inside. The outer tube transmitted the force from the hammer to the head piece, and thus to the septum to be moved. The tube had threaded joints at the ends and had marks every 2.54 cm along its length to aid in positioning the head piece as desired in a tank. The inside rods transmitted torque to a threaded piece in the head assembly which moved the conical expander, thus tightening or loosening the head assembly in the beam hole.

The hammer assembly was arranged such that the tuners could bang a slider piece in either direction. Thus septums could either be pushed away from or pulled out towards the end of the tank from which the tuner was working.

Fig. 51. Septum-bending tool parts. From top to bottom, a hammer assembly, an extension interior piece and a handle for tightening the tool, an extension exterior piece, a set of extension pieces, and the expandable head assembly are shown.

2. Nose-stretching Tool. The nose-stretching tool was designed* to deform the nose region of accelerating cavities in a manner that lowered their resonant frequency. It did this by making a groove just back from the nose inside the beam hole, thus forcing the copper aside and lengthening the nose a small amount. The working end of the tool had a cutter wheel and two support wheels. After the tool was slid in place down the beam hole using extensions of the same type as used for the septum-bending tool, a conical expander was used to force the wheels against the wall of the beam hole. (See Fig. 27, p. 31.) A crank handle was clamped to the exterior end of the set of tool extensions, and the tool rotated to produce a groove in the copper wall of the beam hole. Fig. 52 shows accelerating cavity tuning in progress at Module 37. (See also W.B.G., p. 40.)

The critical part of the tool design was the selection of cutter and support wheels and bearings. Early versions of the tool suffered several failures in which bearings broke and parts were lost inside linear tanks and (with considerable effort) were found and retrieved. (A bore scope proved useful in locating parts lost in accelerating cavities in mid-tank.)

The most reliable version of the nose-stretching tool had a hardened steel cutter wheel followed by a hardened and ridged steel follower wheel and then a flat follower wheel. The cutter and first follower used no special bearing; the second follower was a ball-bearing assembly. The stresses on these wheels were very high when the tool was in use. Originally two ball-bearing wheels plus the cutter wheel were used. Replacement of the first ball-bearing wheel by the solid ridged follower wheel had two beneficial effects. It reduced the tendency of the cutter to move in an unwanted helical path instead of the desired circular path when one was enlarging the original groove. It also crushed any ridges or burrs left in the copper by the cutter wheel, thus leaving a smooth surface relieved of stress for the ball bearing to roll on. The reliable design retained the second ball-bearing wheel, since the flexibility of the bearing

*The nose-stretching tool was designed by D. Liska and R. Kandarian.

Fig. 52. Accelerating cavity final tuning in progress at Module 37. The tuning gear was mounted on an elevated platform which could be rolled along the accelerator beam tunnel as needed. The box in the bottom foreground was used to store extensions and parts of the nose-stretching and septum-bending tools when not in use.

produced better tracking than would have been possible with a solid wheel in this position.

The need for the strongest possible ball bearing became evident when several bearings obtained from laboratory stock failed. The ball type bearing was necessary because it was short. A longer needle or roller bearing would have produced more of a perturbation in the cavity resonant frequency when the tool was in place. The best ball bearings available were purchased. (The cost was about nine times that for the similar stock bearing.) These were known as miniature precision bearings (MPB's) and were available from Delco, New Departure, and other manufacturers. The bearings used were size classification SR4RHH, and were rated at a radial load of 290 newtons at 42 radians/second (vs. 200

newtons for the cheaper bearings). The added strength was due to better heat treatment of the steels and greater precision in the rolling parts. Even so, the rated load given was below the requirements of this application. Loads of about 800 newtons (at very low speed, fortunately) were probably encountered in practice.

What made these bearings trustworthy for use on the nose-stretching tool was the excellent ball retainers used. These retainers held the balls in place even when the outer race cracked (which happened once before the ridged solid follower wheel was installed). The cheaper bearings used inadequate retainers which immediately released the balls when the outer race cracked.

The dust covers (grease seals) and the spring rings which held them on were removed from both sides of the MPR's before installation on the nose-stretching tool. Thus the possible loss of these parts in the event of a bearing failure was eliminated, and the tool operated satisfactorily without them.

3. Dinging Tool. The dinging tool was used to raise the frequency of accelerating cavity. It was fashioned from a cold chisel. The tip was blunted and smoothed in order to reduce the possibility of structural damage to linac tanks. When in use, the tip of the tool was inserted between the cooling water passages along the outside of a linac tank at a longitudinal position corresponding to the center of the accelerating cavity to be tuned (that is, near the braze line between segment assemblies), and the head of the tool was given a sharp blow with a mallet. (See also F2.B.6.5., p. 49.)

4. Nose Shaving Tool. A nose shaving tool was also designed for use in raising accelerating cavity frequency. It was never used, however, since it was felt that the tool was likely to leave rough spots or burrs on the cavity noses. This would be undesirable since the region of the cavity near the nose tip has a high field gradient, and hence sparking or sputtering might occur.

VI. FIELD FLATNESS AND ITS MEASUREMENT

A. Overview

1. Causes of Field Unflatness in $\pi/2$ -Mode Linac Structures. We first discuss the need for field flatness measurements. Field unflatness in a $\pi/2$ -mode linac structure may arise in four ways. Only the first two of the four allow diagnosis and treatment using low-power field distribution measurements. The four ways are:

- (1) Variations in coupling between resonators cause variations in amplitude along the structure.

The cavity-to-cavity couplings show negligible power or frequency dependence in the 805-MHz linac, hence a pattern of field variations caused by coupling variations can be considered to be frozen in. Care must be taken in construction to minimize such coupling variations. The tuning and flattening procedure discussed in section IV.C.3. was de-

veloped to reduce the effects of field variations on using the field distribution measurements to tune the beam. The low-power measurements of field distribution to be discussed in following sections were part of this flattening process. We also served to check that gross frequency errors were not present, as we can see from the second inflation measurement.

- (2) Certain combination of individual resonator frequency errors may cause tilt in the field distribution.

In general, it is necessary that one or more accelerating cavities and one or more coupling cavities be detuned to cause tilts in the field distribution. Provided that a $\pi/2$ -mode structure is properly tuned, the field distribution is extremely insensitive to individual cavity frequency errors. (The meaning of "properly tuned" is explored in Appendix E.) Frequency errors tend to increase the power dissipated in coupling cavities, which in turn may lead to power-dependent behavior if the errors are large. Thus it is important to avoid frequency errors.

- (3) The distribution depends to some extent on the amount of beam loading.

An advantage of the $\pi/2$ -mode linac is that it tends to minimize this problem. To first order, the accelerating resonator amplitude and phase are independent of beam loading. The coupling resonator amplitude (but not phase) varies with the amount of power flowing along the structure and into the beam (Skenson et al. 1969), but by design the coupling resonator excitation is always small compared with the accelerating resonator excitation. Again, the structure must be properly tuned. (See Appendix E.) Only when the structure is made extremely long or the beam loading is made extremely heavy might complications arise in this regard. In a long structure, beam loading causes an amplitude droop; and beam loading combined with improper stopband may cause a shift in phase. (See Appendix F for estimates of beam loading effects.)

- (4) Interaction of an improper stopband with an unflat field distribution may produce field distribution variations dependent on average power dissipation in a module.

If the field distribution of a module is not flat, which may be the result of mechanism (1)

above, the measured total field at varying rf power is found to depend on the stopband structure and Swain et al. 1974, Liska 1970). The initial distribution of the rf power dissipation to be larger in the parts of the module that flatten because the cooling system is not a perfect heat sink, the temperature and the accelerating cavity resonant frequency shift. Little for some parts of the module when the rf power is increased. If the stopband is negative (cooling cavity) low in frequency, the accelerating cavity frequency shift causes the field distribution to flatten out or even worse. If the stopband is positive (cooling cavity) high, the field distribution becomes flatter with increasing power. Further discussion of this effect is given in Appendix G. Since the LAMPF accelerator is operated at various duty factors, it was important to minimize this effect. This was done by checking that the cooling system was adequate (Jameson and Swain et al. 1979), by requiring that the tuners leave the stopband of each module near zero or slightly positive, and by adjusting the field distributions to be reasonably flat.

The only way of checking if unflatness from mechanisms (3) or (4) was present during the construction of the LAMPF 805-MHz line was to monitor the signals from a few probes (built into the structure or temporarily inserted along the beam line at the tank ends) as it was operated under varying high-power conditions. (See H1.A.22., High-Power Test.) This type of measurement could detect tilts and the like but did not permit one to examine the complete field distribution. Some work was done to develop a high-power headpull measurement of field distribution (Liska 1970, Liska et al. 1971), but no reliable procedure was found. The field distribution measurements discussed in the following sections are low-power measurements.

More recently a few measurements were made of the beam loading effect (mechanism (3) above). A peak beam current of about 9 mA produced an amplitude droop of one per cent and phase changes of less than one degree (Swain and Jameson 1976, Swain 1976), which are consistent with the estimate of beam loading effect developed in Appendix F. These measurements used the existing pickup loops (one

per tank) to obtain the total field profiles at the 805-MHz cavity. Since, this was not a real-time measurement, the complete field distribution

was obtained by taking Measurements. The measurement of the total field distribution along the beam line of a linear module was to perform a headpull frequency headpull measurement under various conditions of beam current. In this analysis were detected unflatness. In determining unflatness and tank averages, specific reduction of flatness and correction for drift and plotting of tank averages and presentation of the data for future reference in a uniform format.

The headpull method consisted of pulling a probe to perturbation about the beam axis at a constant rate during the change in $\pi/2$ -mode frequency as a function of time. The head pull frequency was prepared by inserting the probe in the feedback loop of an amplifier so that it oscillated at the $\pi/2$ -mode. As the head was moved through the accelerator, the frequency of the oscillator followed the $\pi/2$ -mode as it was perturbed by the beam. The change in frequency was measured by heterodyning the oscillator signal (about 805 MHz) with a very stable signal generator to obtain a frequency of nominally 10 kHz. This 10 kHz signal was presented as data to a computer interface unit which measured the period of the incoming signal by counting a 5 MHz clock for eight periods and presenting the resulting count to the computer.

The computer program converted the incoming period data to frequency data, and recorded the initial frequency with the head out of the tank. As the head moved through the module, the resulting frequency was compared with the initial base-line frequency to determine the change in frequency. Since the head passed through a region of zero field inside the drift tubes between accelerating cavities, the base line could be updated to provide a correction for drift of the unperturbed $\pi/2$ -mode frequency with temperature fluctuations. Two separate measures of the cavity field were recorded, one being the field at cavity center and the other being the integral of the field as the head passed through the cavity. Displays of these measures on a storage scope enabled the tuners to assess flatness within each tank and to adjust bridge coupler posts so as

Fig. 53. A module as part of an oscillating loop for the headpull measurement of field distribution.

to make the tank averages within a module agree. Further details are given in VI.B. below.

In the course of accelerator tuning, a number of other types of headpull measurement were developed in addition to the standard method. The results of these investigations are briefly discussed in VI.C. Measurements indicating the long-term stability of the low-power field distributions are discussed in VI.D.

B. Computerized Frequency Headpull Techniques

1. Electrical Considerations. The bead pull measurement is based on the fact that the introduction of a small metallic or dielectric object in a cavity perturbs the resonant frequency of the cavity (Harvey 1963). The amount of frequency perturbation is proportional to the volume of the small object and to the square of the field intensity at the point occupied by the small object before the object was introduced. Introduction of a metallic object in a region of electric field lowers the frequency; introduction of such an object in a region of magnetic field raises the frequency. In the case of a linac module, the whole module is considered to be the cavity. The field along or near the beam axis is primarily electric. A small metal bead was carried along a string stretched along the beam axis, and the electric field intensity squared at each point was found from the resulting variation in the $\pi/2$ -mode frequency of the module. The bead size was chosen such that the frequency of the module dropped about 2 kHz when

Fig. 54. Computerized frequency measurement equipment set-up for headpull measurements.

the bead was in the center of an accelerating cavity.

The resonant frequency of the module was determined by making the module part of an oscillating loop, as shown in Fig. 53. Phase shifters and a bandpass filter were provided to facilitate making the loop resonate at the $\pi/2$ mode and not at one of the many other possible modes of oscillation of the linac module. The phase shifters were set such as to give a minimum at the reflected signal output of the directional coupler. Two solid-state amplifiers (20 dB each) provided sufficient gain to make the loop oscillate. Isolators reduced the influence on resonant frequency of the equipment external to the linac module.

The frequency of the oscillating loop was monitored by comparing the signal with that from a stable signal generator, as shown in Fig. 54. The difference frequency coming out of the mixer was adjusted (by varying the signal generator frequency) to be about 10 kHz, with the signal generator frequency on the low side. Thus the input signal to the interface unit had a base line at around 10 kHz and dipped to about 8 kHz each time the bead traversed an accelerating cavity. The frequency of this signal was sampled 60 times per second in the following manner. The interface unit contained circuitry for counting cycles of a 5-MHz clock for 8 periods of the input signal. Upon receipt of a pulse from the sampling clock, the interface unit

Fig. 55. Raw data display obtained during a bead-pull measurement. The upper part of the display shows the frequency deviations of the individual samples (many traces superimposed). The lower part shows the base-line levels and cavity center levels for each cavity in the module.

beam to look for the next zero crossing (of one polarization at the input flange). Upon finding the zero crossing, the unit began counting pulses from the beam clock. At the end of eight periods of the input signal, the counting was terminated and the computer sent an interrupt signal. The computer then accepted the number of counts. With the beam traversing a module (approx. 14 meters) in about 150 seconds, and with the sample rate set at 60 per second, approximately 100 data points were accepted for each accelerating resonator. The computer then proceeded to correct for drift in the base line, calculate the square root of the change in frequency for each accelerating cavity, and to display the raw data for monitoring by the operator (Fig. 55).

Various data processing and display options were initiated with pushbuttons on the interface unit or commands via the teletype. Data were recorded and labeled by means of punched paper tape, photographs of storage scope displays, and teletype printouts. Further details of the mechanical arrangements are given in Section 2 and of the computer algorithms and data displays in Section 3 below. Information on teletype commands and on equipment used and electrical connections is given in Appendix H.

2. Mechanical Considerations. The initial method for making a beadpull measurement with the

module under rough vacuum used airtight boxes at each end of the module enclosing drive or idler pulleys (Gruin et al. 1971). The string made an elongated loop around these pulleys, with both the side of the loop with the bead and the return side passing down the beam hole. The extra line going down the beam hole made an unwanted frequency perturbation and tended to get twisted up with the bead string when threading on.

An arrangement was attempted in which only one string from the beam hole was used, with a supply reel in an airtight box at one end and a take-up drum at the box at the other end. This was never satisfactory, since in spite of the various brakes and tension devices tried, the velocity of the bead was not uniform.

A satisfactory single-string vacuum beadpull arrangement was found (Gruin et al. 1972) and is shown in Fig. 56. The string, which was a 44 N (10 lb.) nylon monofilament line of the type used by fishermen, passed through teflon bushings at either end of the module. Nylon with retractable supports were used between tanks within the module. Support and drive pulleys were on frames external to the evacuated area. These frames were held in place on the support rails with C-clamps and permitted the string to be brought back over the module and tied to itself to form a loop.

The end pieces each consisted of an aluminum flange, a short plastic tube, and a pair of aluminum parts holding the teflon bushing. The flange piece bolted to the end flange of the module. The plastic tube permitted one to see when the bead had reached the end of the module. The teflon bushing was easily removed by unscrewing one of the two remaining aluminum parts.

The tubes for use between tanks were also plastic, so that it could be seen if the string was in correct position on its support. Aluminum flanges at each end of these tubes allowed some longitudinal movement of the tube to accommodate the variable inter-tank spacings. Extensions were available to accommodate the larger inter tank spacings.

The following procedure was used to thread up the bead pull apparatus:

(1) Clamp left and right drive bracket to the support rails with C-clamps.

Fig. 56. Mechanical apparatus for making a headpull measurement under rough vacuum for a two-tank module. The drive iris, and an electric probe II in the end tuner of the bridge coupler were used for the rf input and output respectively. The magnetic probe II were not used.

(2) Thread a clean piece of coaxial cable through the module, left to right. (Alternative: use piece of cable long enough to go through one tank.) Clean 6 mm (1/4 inch) diameter copper tubing may be used in place of coaxial cable in this step and the steps below if desired. The tubing may be pushed through a longer section of a module than cable without jamming.

(3) Thread string through right teflon bushing and right end piece and tie to coaxial cable. Pull string into right tank. Bolt right end piece to end flange and insert and clamp teflon bushing.

(4) Pull string to gap between tanks. Cut off from coaxial cable. Tie nut on end of string and drop through center tube with string support retracted. (Do this with extension bolted to center tube, if extension needed.) Remove nut and re-tie end of string to coaxial cable. Pull end into next tank. Bolt one end of center tube in place. (If this is four-tank module, repeat this step for remaining tanks.)

(5) Pull string out of left end of module. Cut off from coaxial cable. Take a yard-long piece of string and thread it from the outside end through the left end piece (with teflon bushing removed) and tie it to the end of the main string. With this, pull the end of the main string through the left end piece and cut off yard-long string and knot. Thread end of main string through teflon bushing and clamp bushing in place.

(6) Pull string around pulleys and back over module to starting place, as shown in Fig. 56. Al-

low enough string to loop around the drive pulleys once and to go over the upper support pulleys. Tie ends together and clip string on pulleys. The string should rest in the groove of the intermediate pulleys (midway along the vertical member of each drive bracket).

(7) Extend the string supports and position the string on the support in each tube between tanks. (If one forgot to retract the supports at the start of this procedure, one may find that the string is hopelessly caught below the support at this time.) Bolt the other end of each tube between tanks to its corresponding flange on the linac.

(8) Position the knot just to the left of the upper right support pulley, and put marker flag over the knot. Back off left teflon bushing and form bead (from aluminum foil, about 6 mm long) around the string between the teflon bushing and the left end piece. Move the string to move the bead through the hole in the left end piece. Re-clamp the teflon bushing to the left end piece.

(9) Pump down for rough vacuum; 13 Pa (1000 microns) or less can usually be obtained.

Vacuum levels in the neighborhood of 4 Pa (300 microns) were avoided, since some kind of rf-plasma interaction appeared there. Perhaps this was because natural ionization occurs around 3 Pa (200 microns). The oscillation would tend to lock to a certain frequency, as seen in Fig. 57. The individual cavity raw data waveforms were distorted from something like that in Fig. 58 to something like that in Fig. 59. When one went to vacuum

told to "fall", plus a constant. Each subsequent offset from this reference frequency was plotted as a point on a "raw data" storage scope display. The sign of the offset was taken such that the frequency display appeared as peaks above the base line, (see Fig. 61). The computer expected a positive value for this offset. For this to be true, the base line displayed should not have gone below the bottom of the screen of the storage scope.

The computer program considered the incoming raw data to be in one of two classes and stored it accordingly. A cut line was used to distinguish peak data from valley data. The points below the cut line on the raw data display (such as the points from A to C on Fig. 61) were considered as valley data and were used to compute the base line. Points above the cut line (C to E on Fig. 61) were considered peak data and were used to find the field at the cavity center.

When the program was first loaded, the cut line frequency was set at 366 Hz. After the program was started, the cut line was set midway between the values for the previous peak and valley. Thus, if a test run was made for a new bead pull setup, the cut line was left in the appropriate place. (If the cut line is not near the midway position, a one percent error may result in the value for the first accelerating cavity only.) If fewer than four points were found above the cut line, or fewer than 16 points below, the computer gave the message "TOO FEW DATA POINTS." The computer would output the message "TOO MANY DATA POINTS" if the raw data storage area became filled to capacity.

After the bead had gone well beyond the center of an accelerating cavity such that the points on the raw data plot began falling below the cut line (such as occurred near E on Fig. 61), the computer was programmed to do the following:

- (1) Interpolate to find the times of the cut-line crossings (at C and E) for the current peak.
- (2) Find the time midway between the times determined in step (1). This is taken to be the time (at D) for which the bead was at the center of the cavity.

- (3) Average the four data points whose times were the closest to the time determined in step (2). This is saved as the peak position.

Later on, the bead passed into a new accelerating cavity and the data points began to fall above the cut line (such as happened near E on Fig. 61). At this time the computer was programmed to do the following:

- (1) Interpolate to find the times of the cut-line crossings (at I and G) for the previous valley.

- (2) Find the time the bead was midway between accelerating cavities (at F).

- (3) Fold the eight nearest points on each side of valley center to the positive side of center, including any fractional offset from center.

- (4) Fit these 16 points to the curve $y = a + bx^2$, where x is the time interval from center, y is the offset, and parameters a and b are chosen for minimum sum of squared errors. The value of the parameter b is then the position of the base line (at F) for this valley.

- (5) Get the position of the cut line next to valley back (at B).

- (6) Calculate the height of the peak (at E) with respect to a linear base line. (Finding a and F); store this value in the peak data area. (This was an estimate of field intensity squared at cavity center.)

- (7) Calculate the integral of the square root of the height of the data above the linear base line (from B to F); store this value in the average data area. (This was thus an estimate of the integrated field intensity, i.e., the relative voltage drop through the cavity along the beam axis.)

Some modifications to the above procedures were necessary at the beginning and ending of each tank. To find the initial base line position (at B) for the first accelerating cavity of a tank, the computer found the time interval H between the first peak (at G) and the following valley (at D), then went back a time interval H from the time of the peak and averaged eight points (near B).

The computer sensed that the bead had left a tank when it found no cut-line crossings for an interval $2H$ seconds long. To find the last base-line position for the last accelerating cavity of a tank, the computer averaged eight points near a time H seconds later than the time of the last peak. After the bead left each tank, the tank average was calculated for the peak data and the cavity average

Fig. 62. Field distribution for Module 17 before retuning as displayed by computerized beam/pull measurement equipment. Note expanded scale on vertical axis.

data. One observed a flick in the raw data plot after the beam had left a tank as this calculation was taking place. The computer accepted data for up to four tanks. It was possible to halt data acquisition after any number of tanks up to four if analysis of only part of a module was required.

The original peak data after halting data acquisition were the frequency shifts in hertz at the center of each accelerating cavity, with a square-root flag not set. If the peak graph option was selected, the following steps were taken:

- (1) The square-root flag was checked. If it was not set, the square root of each cavity value (i.e., the relative field strength) was found and put in the same storage area, and the flag was set.

- (2) The module average was determined as the average of the tank averages.

- (3) All data were then normalized such that the module average was 10 000. (Due to roundoff error, this sometimes left the tank averages such that their average was not exactly 10 000.)

- (4) The individual cavity field strengths and the tank averages were plotted on the storage scope on an expanded scale (0.9 to 1.10). (For examples, see Figs. 62 and 63.)

Fig. 63. Measurement for Module 17 after retuning to flatten field distribution.

The tank averages, rms and peak-to-peak values, and tilt were displayed below the plot, along with the first three items from the last two distributions.

Other options allowed the operator to punch the data on paper tape, to read in data from previous measurements, to plot cavity-by-cavity ratios of different measurements, or to display the data in other ways. Further details are given in Appendix B.

4. Choice of Measurement Parameters and Accuracy. The reproducibility of cavity peak data was found to be about 9.1 per cent peak-to-peak, but that of the integrated cavity field data was a few per cent. Consequently peak data was used as the criterion for field flatness and the setting of tank averages. One of the factors contributing to the poor reproducibility of the integrated data was the need to take the square root of small numbers, thus exaggerating the noise component in these numbers.

The data reduction program assumed that the digital input data rate was uniform. Note that the input rate was not precisely uniform, however, since the counter waited an interval varying from

Fig. 65. Ratio of beadpull measurements for Module 11 with the pickup at different points.

when the pickup point is elsewhere for frequency beadpulls.)

These various results indicate that the standard beadpull method was indeed accurate enough to set the tank averages within a module to better than the 12 per cent accuracy required for proper beam dynamics and easy linac initial turn on.

3. Effect of Beadpull Pickup Point. It has been experimentally determined that the pickup point for a phase or frequency beadpull affects the measured field distribution. This error occurs as a linear tilt between the drive and pickup points in the module and is independent of the bead size. As J. M. Potter has noted (MP Division 1971d), the error results not from an actual change in the field distribution but from a phase shift introduced by the presence of the bead. If part of the structure traversed by the bead is included in the oscillating loop, this phase shift causes an error.

An estimate of the error based on the coupled resonator model with only nearest neighbor couplings is

$$e_{\max} = 4Nn_{dp}/(k^2Q_aQ_c), \quad (3)$$

where N is the total number of accelerating cavities in the structure, n_{dp} is the number of accelerating cavities the pickup point is removed from the drive point, k is the nearest-neighbor coupling, and Q_a and Q_c are the Q 's of the accelerating and coupling cavities. (See Appendix I.) The value of

Fig. 66. Field distribution in Module 12 as measured in 1975, three years after initial installation.

k may be found from Table B-III in Appendix B for the LAMPF structure, or may be estimated from mode spacing as in Appendix J. This error was avoided for the measurements on the 805-MHz linac by both driving and picking up the signal at the center bridge coupler cavities.

Figure 65 shows the ratio of a beadpull with the pickup point midway along the fourth tank to a beadpull with the pickup at the bridge coupler (measured on Module 11, July 23, 1971, runs 1 and 8). Substituting $N = 128$, $n_{dp} = 48$, $Q_a = 20\,000$, $Q_c = 8\,000$, and $k = .946$ in Eq. (3), one finds $e_{\max} \sim 7\%$, in reasonable agreement with the measured difference of 8%.

D. Observed Long-Term Stability of Field Distributions.

In connection with certain bridge coupler length correction work described in section III.B.1. of this report, measurements of 805-MHz linac tank field distributions were made for Modules 12 and 13 approximately three years after the initial tuning was completed. Comparison of the 1975 measurements with the 1972 measurements shows no detectable change in the field distribution within tanks as measured at low power. Fig. 66 shows the field distribution within Module 12 in 1975; only the upstream bridge coupler had been adjusted since 1972. Fig. 67 shows the ratio of the 1975 measurement to

Fig. 67. Ratios of beadpull measurement on Module 12 done in 1975 to measurement done in 1972.

Fig. 68. Field distribution in Module 13 as measured in 1975.

Fig. 69. Ratio of 1975 to 1972 measurements for Module 13.

Fig. 70. Ratio of two beadpull measurements of Module 13 made in 1975.

the 1972 measurement. Figures 68 and 69 show similar results for Module 13, whose bridge coupler was replaced in 1975. The r.m.s. scatter in the ratio of 1975 to 1972 measurements in Figs. 67 and 69 is about one-fourth of one per cent. This is about the same as the scatter in the ratio of different runs made in 1975, as shown in Fig. 70.

The fact that the low-power field distributions remain stable over long time periods indicates that the cavity-to-cavity couplings and cavity frequencies of the 805-MHz side-coupled linac structures remain reasonably stable over long time periods.

Fig. 71. It's done! Persons involved with structure tuning and some of their contributions: (Front row) Bob Cady - probe calibration, Oliver Rivera - tuning and tool improvements, Dave Jones - tuning, Cecil Stark - tuning, Paul Beauchamp - tuning, Bob Romero - tuning, (2nd row) Don Liska - beadpull equipment design and supervision, Jim Potter - bridge coupler stabilization - beadpull improvements, John Zastrow - beadpull equipment, Charlie Manger - prebraze and section tuning and supervision, George Swain - procedure design and supervision, (on I-beam) Don Holcom - rf testing, Bob Patton - rf testing, Mike Dugan - rf testing, Dennis West - tuning and tool improvements, (back rows) Jerry Wallace - rf test design, Buck Hayes - machining, Bob Harrison - tuning and beadpull data processing, Jess Lee - machining supervision, Ed Knapp - structure design and modifications, Joe Van Dyke - tuning tool design, Bob Jameson - coordination and scheduling and rf system design, Rene Mills - data collection, Bob Kandarian - tuning tool design, and Seth Rislove - cooling system installation supervision.

ACKNOWLEDGMENTS

The successful completion of the project to fabricate and precisely tune 10 000 cavities and to check the performance of the 44 modules of the LAMPF 805-MHz linac depended on the conscientious and persevering efforts of a great many people. Some of the persons particularly involved in the structure tuning process are shown in Fig. 71. The

author is especially indebted to E. Knapp and James Potter for developing the theory, to R. Jameson and J. Sharp for refining and documenting procedures, to E. R. Martin for beadpull computer software, and to C. Manger, O. Rivera, and D. West for developing procedures and hardware for various measurements. C. Manger supervised the pre-braze tuning. D. Liska assisted in final tuning supervision.

APPENDIX A
DESIGN PARAMETERS FOR 805-MHz LINAC

The computer printout (Grandall 1967b) for the 805-MHz linac design is given in Table A-1. Some terminology is different from that used in this report. What we call tank is labeled SECT on the printout. The part of a tank from mid-septum on one side of a cavity to mid-septum on the other side is called a CELL. The lengths given are in meters. SPACING is the distance from the end of the last cell of one tank to the start of the first cell of

the next tank. DESIGN PHI gives the range of phase in degrees through a tank for the design particle. Energies are given in MeV. DE/DZ is the energy gain per unit length in MeV/m. Powers are in megawatts (peak) unless otherwise indicated. ZT2 is the assumed effective shunt impedance in M/m. The values shown under H are the quadrupole focusing magnet gradients for the doublers between tanks.

TABLE A-1
805-MHz LINAC DESIGN PARAMETERS

Mod	SECT ENERGY IN	SECT LENGTH ENERGY OUT	ACUM SECT L ENERGY GAIN	TOTAL L DZ/DZ	SPACING POWER CU	NO. CELLS POWER BEAM	CELL LENGTH TOTAL POWER	DESIGN HETA BEAM LOAD	DESIGN PHI ZT2	H (KG/CM)
5	1	2.8899	2.899	2.890	0.00300	36	.0803	.43110	-36.7883,-25.6925	
	109.000	163.192	3.1920	1.1046	.18608	.05298	.2391	.2216	25.055	2.27,-2.27
	2	2.9285	5.818	6.546	.72738	36	.0813	.43687	-36.6355,-25.7723	
	109.192	166.427	3.2345	1.1045	.18643	.05369	.2401	.2236	25.344	2.28,-2.28
	3	2.9669	8.785	10.250	.73701	36	.0824	.44259	-36.4873,-25.8888	
	106.427	169.703	3.2766	1.1044	.18676	.05439	.2412	.2256	25.629	2.30,-2.30
	4	3.0048	11.790	14.001	.74654	36	.0835	.44825	-36.3437,-25.9891	
	109.703	113.022	3.3184	1.1043	.18708	.05509	.2422	.2275	25.913	2.32,-2.32
6	5	2.8724	14.663	17.965	1.09227	34	.0845	.45370	-35.5212,-26.4958	
	113.022	116.193	3.1713	1.1040	.17698	.05266	.2296	.2293	26.185	2.33,-2.33
	6	2.9056	17.558	21.636	.76401	34	.0855	.45895	-35.4070,-26.5696	
	116.193	119.401	3.2078	1.1040	.17725	.05327	.2305	.2311	26.448	2.35,-2.35
	7	2.9386	20.507	25.748	.77256	34	.0864	.46415	-35.2962,-26.6404	
	119.401	122.645	3.2440	1.1039	.17751	.05387	.2314	.2328	26.708	2.36,-2.36
	8	2.9717	23.478	29.101	.78224	34	.0874	.46931	-35.1884,-26.7092	
	122.645	125.924	3.2798	1.1039	.17777	.05447	.2322	.2346	26.965	2.38,-2.38
7	9	3.0035	26.441	33.247	1.14229	34	.0883	.47441	-35.0835,-26.7759	
	125.924	129.240	3.3153	1.1038	.17801	.05506	.2331	.2362	27.221	2.40,-2.40
	10	3.0355	29.517	37.042	.79935	34	.0893	.47947	-34.9413,-26.8406	
	129.240	132.590	3.3505	1.1038	.17826	.05565	.2339	.2379	27.473	2.41,-2.41
	11	3.0672	32.584	40.956	.80778	34	.0902	.48448	-34.8019,-26.9035	
	132.590	135.975	3.3853	1.1037	.17849	.05623	.2347	.2396	27.724	2.43,-2.43
	12	3.0987	35.683	44.871	.81614	34	.0911	.48944	-34.7850,-26.9644	
	135.975	139.395	3.4199	1.1037	.17872	.05681	.2355	.2412	27.972	2.45,-2.45
8	13	3.1298	38.813	49.005	1.00760	34	.0921	.49435	-34.6506,-27.0240	
	139.395	142.849	3.4541	1.1036	.17894	.05738	.2363	.2428	28.218	2.46,-2.46
	14	3.1606	41.973	52.817	.64759	34	.0930	.49922	-34.5986,-27.0818	
	142.849	146.337	3.4879	1.1036	.17916	.05794	.2371	.2444	28.461	2.48,-2.48
	15	3.1911	45.164	56.662	.65391	34	.0939	.50404	-34.5089,-27.1379	
	146.337	149.859	3.5215	1.1035	.17937	.05850	.2379	.2459	28.702	2.50,-2.50
	16	3.2213	48.386	60.543	.66016	34	.0947	.50882	-34.4215,-27.1925	
	149.859	153.413	3.5547	1.1035	.17958	.05906	.2386	.2475	28.941	2.52,-2.52
9	17	3.2513	51.637	64.841	1.04710	34	.0956	.51354	-34.3366,-27.2460	
	153.413	157.001	3.5875	1.1034	.17978	.05961	.2394	.2490	29.177	2.54,-2.54
	18	3.2809	54.918	68.795	.67248	34	.0965	.51822	-34.2536,-27.2979	
	157.001	160.621	3.6201	1.1034	.17997	.06015	.2401	.2505	29.411	2.55,-2.55
	19	3.3102	58.228	72.783	.67855	34	.0974	.52286	-34.1725,-27.3483	
	160.621	164.273	3.6523	1.1033	.18016	.06069	.2408	.2520	29.643	2.57,-2.57

$$A_1, A_2, \dots, A_n \text{ are } n \text{ independent events, then}$$
[illegible]

NO. OF STATIONS	STATION ENERGY IN	STATION ENERGY OUT	STATION ENERGY GAIN	STATION POWER	STATION POWER CO	NO. OF BEAMS	CELL LENGTH TOTAL POWER	SECTION HEAT LOAD	SECTION HEAT	DESIGN HEAT	DESIGN HEAT
											(KKG/CM)
1	65	33,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	66	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	67	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
2	68	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	69	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	70	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
3	71	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	72	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	73	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
4	74	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	75	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	76	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
5	77	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	78	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	79	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
6	80	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	81	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	82	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
7	83	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	84	34,124.4	24,121.7	210,440.4	24,121.7	1,131.1	53	1,131.1	2,774.0	-31,553.5,-26,124.1	34,121.7
	 

Parameter	Table	Column
Accelerating cavity frequency		
Interior cavities (N_i)	I	90
Interior cavities (vacuum)	III	110
End cavities (N_e)	I	89
Accelerating cavities, no./tank	VII	213
Access to beam tunnel		
Entrances to tunnel	VII	205
Gates along tunnel	VII	207
Beam hole diameter	VII	212

Power dissipation, modules (no beam)		
Tanks only	IV	129
Tanks and bridge couplers	V	123
Tanks, b.c.'s, and waveguide	V	124
PI/2-mode freq., tanks, after tuning		
With N	I	141
Under vacuum	I	145
PI/2-mode frequency, tanks,		
before final tuning, N		
Uncorrected for end cavities	II	82
Corrected for end cavities	II	86
PI/2-mode frequency change, N,		
before to after final tuning	II	112
Monitor loop (for beam alignment)		
Upstream loop	VIII	171
Center loop	VIII	173
Downstream loop	VIII	175
PI/2-mode freq., tanks, after tuning		
With N	I	141
Under vacuum	I	145
PI/2-mode frequency, tanks,		
before final tuning, N		
Uncorrected for end cavities	II	82
Corrected for end cavities	II	86
PI/2-mode frequency change, N,		
before to after final tuning	II	112
Power dissipation, modules (no beam)		
Tanks only	IV	129
Tanks and bridge couplers	V	123
Tanks, b.c.'s, and waveguide	V	124


```

NOTE X
A -- END CELLS TUNED INDIVIDUALLY.  VALUE GIVEN IS APPROXIMATE.
H -- ONLY UPSTREAM PART OF TANK RETURNED AT LAST RETUNING.
C -- ONLY DOWNSTREAM PART OF TANK RETURNED AT LAST RETUNING.
D -- END CELL DATA UNAVAILABLE.  VALUE FROM THECHY AND INT. MAIN CELL FREQ.
DU -- DATA UNAVAILABLE.
E -- ESTIMATE BASED ON AVAILABLE DATA.
Q -- DATA UNCERTAIN.

```

										-----142		-----144		-----146		-----148		-----149	
NO.	NAME	UNIT	DATE	TIME	LOCATION	STATUS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS	REMARKS
5	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
6	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
7	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
8	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
9	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
10	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
11	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
12	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
13	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
14	1	101	1971	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
15	37	SC1	804.444	804.444	804.444	-0.033	0.0478	2	-0.00589	.08	10.39	2.76	-3.12	4-13-72					
16	38	SC1	804.447	804.445	804.444	-0.001	0.0466	2	-0.00417	-.08	10.83	3.69	-9.18	4-13-72					
17	41	SC1	804.447	804.445	804.444	0.057	0.0473	3	-0.00591	.25	11.07	2.68	2.14	4-16-72					
18	42	SC1	804.447	804.445	804.444	0.046	0.0434	1	-0.00571	-.25	8.56	2.37	.52	4-16-72					
19	43	SC1	804.447	804.445	804.444	0.036	0.0477	1	-0.00585	.50	7.86	1.78	-.36	5- 2-72					
20	44	SC1	804.447	804.445	804.444	-0.004	0.0471	1	-0.00411	-.50	9.26	2.23	-4.38	5- 2-72					
21	45	SC1	804.447	804.445	804.444	0.055	0.0457	1	-0.00536	-.24	10.52	3.68	-11.08	11- 5-71					
22	46	SC1	804.447	804.445	804.444	0.062	0.0452	1	-0.00572	.30	6.91	2.39	-6.45	11- 5-71					
23	47	SC1	804.447	804.445	804.444	-0.019	0.0439	1	-0.00494	.05	8.65	2.53	7.72	10-27-71					
24	48	SC1	804.447	804.445	804.444	-0.035	0.0443	1	-0.00470	-.04	11.49	4.14	-12.46	10-27-71					
25	49	SC1	804.447	804.445	804.444	-0.072	0.0432	1	-0.00458	.15	9.11	2.98	9.18	12- 2-71					
26	50	SC1	804.447	804.445	804.444	0.087	0.0470	1	-0.00508	-.34	7.69	2.10	1.88	1- 5-72					
27	51	SC1	804.447	804.445	804.444	0.064	0.0457	1	-0.00489	.36	6.38	1.39	-1.65	1- 5-72					
28	52	SC1	804.447	804.445	804.444	-0.055	0.0454	1	-0.00478	.37	11.08	2.81	6.89	1-21-72					
29	53	SC1	804.447	804.445	804.444	0.049	0.0446	1	-0.00461	-.36	8.27	2.16	-4.58	1-21-72					
30	54	SC1	804.447	804.445	804.444	0.044	0.0449	1	-0.00447	.12	7.49	1.98	-5.79	1-19-72					
31	55	SC1	804.447	804.445	804.444	-0.062	0.0439	1	-0.00436	-.12	5.44	1.75	3.60	1-19-72					
32	56	SC1	804.447	804.445	804.444	0.054	0.0498	1	-0.00489	.29	10.85	3.10	1.60	12-20-71					
33	57	SC1	804.447	804.445	804.444	-0.130	0.0490	1	-0.00473	-.28	4.40	.93	-.43	12-20-71					
34	58	SC1	804.447	804.445	804.444	-0.175	0.0486	1	-0.00461	-.07	5.45	1.29	2.87	1-27-72					
35	59	SC1	804.447	804.445	804.444	-0.159	0.0470	1	-0.00448	.07	10.88	3.82	-10.41	1-27-72					
36	60	SC1	804.447	804.445	804.444	0.021	0.0467	1	-0.00437	.13	9.21	2.31	4.42	1- 4-72					
37	61	SC1	804.447	804.445	804.444	-0.115	0.0462	1	-0.00425	-.13	5.88	1.26	-.63	1- 4-72					
38	62	DN1	804.442	804.440	804.440	-0.074	0.0449	1	-0.00412	-.05	6.05	1.74	.75	1-27-72					
39	63	DN1	804.442	804.440	804.440	-0.055	0.0452	1	-0.00409	-.04	3.37	.89	1.01	1-27-72					
40	64	DN1	804.442	804.440	804.440	-0.143	0.0453	1	-0.00396	-.22	6.08	1.52	1.68	1- 7-72					
41	65	DN1	804.442	804.440	804.440	-0.280	0.0449	2	-0.00387	.23	10.19	3.12	8.56	1- 7-72					
42	66	DN1	804.442	804.440	804.440	0.037	0.0479	1	-0.00438	-.01	7.50	1.79	-3.21	2- 9-72					
43	67	DN1	804.442	804.440	804.440	-0.120	0.0486	2	-0.00427	.01	6.54	1.64	-4.57	2- 9-72					
44	68	DN1	804.442	804.440	804.440	0.071	0.0486	2	-0.00417	-.20	5.85	1.12	-2.17	1-18-72					
45	69	DN1	804.442	804.440	804.440	0.023	0.0482	2	-0.00414	.20	6.87	1.99	6.21	1-18-72					

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[illegible]

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NOTES
1 -- FROM MEASUREMENT BEFORE TUNING.
2 -- FROM MEASUREMENT AFTER TUNING.
3 -- FROM MEASUREMENT AFTER TUNING AND WELDING COMPLETED.
UU -- DATA UNAVAILABLE.
E -- ESTIMATE BASED ON AVAILABLE DATA.
O -- DATA UNCERTAIN.

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[illegible]

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		---22	---23	-123	-124	--120	---160	---162	---164	---166	---170	---172	---174
	MOD	H.C.	B.C.	PWR	PWR	LEN.	POWER	POWER	POWER	POWER	POWER	POWER	POWER
	NO.	RAW	RAW	TO	TO	OF	SPREAD	AVG.	DEV.	CHANGE	SPREAD	AVG.	DEV.
		LEN.	DIA.	MOD	MOD	NO.	E	E-PRB.	H	DEF.S-1	E	E-PRB.	H
				AVD	AVD		PRHES	OFFSET	PRHES	PRHES	PRHES	OFFSET	PRHES
		(CM)	(CM)	(MM)	(MM)	(M)	(PCT)	(PCT)	(PCT)	(PCT)	(PCT)	(PCT)	(PCT)
B	5	61.0	1.90	550	582	41	4.4	5.5	6.2	7.0	2.0	2.5	3.0
	6	44.3	1.90	575	542	33	4.4	1.3	3.2	0.0	1.7	0.7	1.5
	7	44.3	1.90	540	597	25	14.8	6.0	13.1	5.4	8.2	2.0	7.4
	8	45.5	1.90	599	620	30	2.9	1.5	3.0	3.1	0.9	0.5	1.2
	9	45.5	1.90	542	589	23	7.0	4.4	9.5	3.5	2.8	1.9	3.9
	10	50.4	1.90	545	543	43	1.4	-0.7	0.3	3.5	1.9	-0.4	-0.3
C	11	50.4	1.90	547	622	45	1.2	-2.5	-5.3	3.5	2.8	-1.1	-3.5
	12	54.7	1.90	542	577	35	2.9	-1.0	2.1	3.5	1.0	-0.5	0.7
	13	61.0	1.90	615	635	24	5.5	2.7	1.2	3.1	3.3	1.3	0.8
	14	58.4	1.90	573	611	25	4.3	0.4	1.2	3.4	2.1	-0.2	0.5
	15	63.5	1.90	547	615	25	4.4	0.7	0.5	5.9	2.0	-0.1	-2.4
	16	64.8	1.90	595	614	26	5.3	1.1	1.7	4.5	2.1	0.7	1.2
	17	61.7	1.90	619	648	38	1.5	-1.1	-2.0	5.2	3.0	-0.8	-1.0
D	18	61.0	1.90	614	648	45	2.0	-1.6	-1.6	4.7	1.0	-0.5	0.5
	19	73.7	1.90	574	517	35	4.2	2.2	3.5	0.2	1.9	0.4	0.7
	20	76.2	1.90	632	631	26	1.5	-1.7	-2.1	2.0	0.8	-0.7	-0.8
	21	61.0	1.90	613	632	26	5.5	-0.1	-1.9	2.0	3.4	0.2	-0.7
	22	61.0	1.90	614	631	23	2.4	1.4	7.0	1.8	0.9	0.5	0.0
	23	59.7	1.90	622	647	33	1.1	-2.7	-4.1	5.0	1.0	-0.1	1.4
	24	62.6	1.90	617	648	42	3.3	0.3	0.8	4.3	1.5	0.2	0.5
E	25	73.7	1.90	604	640	43	0.4	-0.9	-1.1	3.4	0.2	-0.4	-0.5
	26	74.3	1.90	625	649	32	3.8	-6.7	-7.0	5.0	1.0	-3.5	-4.0
	27	78.7	1.90	632	650	24	2.0	-1.1	-1.5	-0.5	0.6	-0.4	0.4
	28	74.9	1.90	630	650	27	0.3	0.1	1.1	4.0	0.3	0.0	0.3
	29	73.0	1.90	622	640	25	1.8	1.5	-3.4	5.4	1.1	-0.9	-1.6
	30	75.5	1.90	616	642	37	2.9	1.1	3.0	2.9	1.7	0.4	1.7
F	31	77.5	1.90	644	615	44	4.5	-1.5	-3.8	1.8	2.3	-0.8	-2.0
	32	71.1	2.54	625	649	32	4.9	-3.6	-4.4	3.4	2.7	-1.8	-2.2
	33	75.7	1.90	615	632	24	1.4	-0.6	-0.9	3.8	0.8	-0.4	-0.4
	34	79.4	1.90	621	641	27	1.2	-0.4	1.9	3.4	0.8	-0.2	1.0
	35	80.2	1.90	619	638	25	2.2	0.1	0.4	2.5	0.9	-0.1	0.1
	36	74.5	1.90	657	634	37	0.8	-0.5	-0.6	2.0	0.4	-0.3	-0.2
G	37	81.3	1.90	611	643	43	0.7	-2.4	-2.7	7.2	0.3	-1.5	-1.5
	38	61.6	2.54	655	629	32	3.2	-1.2	-1.4	3.8	1.7	-0.8	-0.8
	39	62.9	2.54	611	628	23	1.5	-0.3	1.4	2.9	0.6	-0.5	0.4
	40	64.8	2.54	625	644	26	0.7	-1.7	-2.1	7.6	0.4	-1.2	-1.3
	41	71.1	1.90	620	639	26	2.1	-1.2	-1.6	4.0	0.7	-0.8	-0.9
	42	61.0	2.54	624	653	38	1.2	-2.0	-1.5	-0.2	0.7	-1.1	-0.6
H	43	68.6	2.54	638	670	41	0.7	-0.9	1.4	4.9	0.3	-0.6	-0.7
	44	63.5	2.54	642	665	30	1.1	-0.6	-1.0	4.0	0.4	-0.6	-0.7
	45	58.4	1.90	612	629	24	2.0	-1.2	-1.1	-1.6	0.8	-0.6	-0.5
	46	74.9	2.54	633	651	24	2.4	-0.2	-0.3	4.7	0.1	-0.1	0.0
	47	71.1	1.90	650	620	27	1.1	-2.3	-2.5	2.7	0.8	-1.5	1.3
	48	56.4	1.90	631	650	33	1.1	0.4	1.7	6.5	0.6	-0.5	0.5

TABLE B-VI

TANK LENGTHS AND SPACINGS

COLA	-----	----	-----177	-----178	-----177	-----178	-----177	-----178	-----177	-----178
MOD NO.	FIRST TANK OF MOD.	LAST TANK OF MOD.	TANK 1 LENGTH (CM)	SPACE TO NEXT TANK (CM)	TANK 2 LENGTH (CM)	SPACE TO NEXT TANK (CM)	TANK 3 LENGTH (CM)	SPACE TO NEXT TANK (CM)	TANK 4 LENGTH (CM)	SPACE TO NEXT TANK (CM)
5	1	4	289.560	71.953	293.599	73.439	296.779	74.585	300.794	108.483
6	5	8	297.515	76.383	290.782	77.236	293.969	78.395	296.774	114.275
7	9	12	300.022	80.033	303.723	80.813	306.771	81.669	310.086	100.353
8	13	16	312.842	65.141	315.567	65.689	318.922	66.210	321.813	105.185
9	17	20	325.062	67.330	327.571	67.899	331.236	68.428	334.048	107.810
10	21	24	317.030	69.680	319.344	70.411	321.638	70.813	324.107	112.240
11	25	28	326.728	71.857	329.113	72.347	331.727	72.898	333.964	115.336
12	29	32	336.446	73.721	338.338	74.648	340.779	75.024	343.339	117.043
13	33	34	661.514	75.440	669.511	120.345				
14	35	36	654.926	78.113	661.954	100.338				
15	37	38	669.554	79.624	677.034	101.933				
16	39	40	683.842	81.432	690.182	104.673				
17	41	42	696.824	83.071	703.341	106.695				
18	43	44	709.564	84.567	715.769	108.585				
19	45	46	697.522	85.997	703.473	109.639				
20	47	48	709.082	87.348	714.108	111.798				
21	49	50	719.653	88.707	725.025	112.997				
22	51	52	730.075	64.287	734.888	115.555				
23	53	54	739.854	65.039	744.502	117.285				
24	55	56	722.681	65.913	726.745	119.291				
25	57	58	731.241	66.739	735.546	119.799				
26	59	60	739.861	67.452	743.684	121.303				
27	61	62	747.751	68.151	751.591	122.718				
28	63	64	755.500	68.859	759.054	124.107				
29	65	66	762.876	69.576	766.425	125.710				
30	67	68	741.540	70.134	744.987	126.665				
31	69	70	748.551	70.709	751.416	127.673				
32	71	72	754.647	71.265	757.723	99.761				
33	73	74	760.557	71.971	763.773	100.246				
34	75	76	766.031	72.423	769.508	101.112				
35	77	78	772.323	72.979	775.018	101.595				
36	79	80	748.452	73.515	750.806	102.403				
37	81	82	753.303	73.927	755.729	102.944				
38	83	84	757.939	74.346	760.316	103.853				
39	85	86	762.366	74.833	764.578	104.343				
40	87	88	766.884	75.331	769.262	104.795				
41	89	90	771.180	75.662	773.387	105.857				
42	91	92	775.277	76.109	777.143	106.009				
43	93	94	779.440	76.551	781.152	107.081				
44	95	96	783.064	76.939	784.868	107.526				
45	97	98	756.171	77.231	757.751	108.102				
46	99	100	759.409	77.549	761.073	108.565				
47	101	102	762.521	78.113	763.935	109.123				
48	103	104	765.863	78.235	767.151	-				

TABLE B-VII

ACCESS, COMMUNICATIONS, AND MISCELLANEOUS DATA

-	---	201	-	--	203	-204	----	205	-----	207	208	-209	210	211	212	---	213
S	C	MOD	FIRST	LAST	ACCESS-	WALL	I	P	T	P	P	C.C.	BEAM	ACC.			
E	O	NO.	TANK	TANK	LARGE	OR	N	M	E	H	O	TYPE	HOLE	CELLS			
C	L		OF	OF	MAZE	GATE	T	O	L	O	S		DIA.	PER			
T	O		MOD.	MOD.	OR		E	N	E	N	T			TANK			
O	R				SM.MAZE		R	E			S						
R					*ELEV.								(CM)				
B	GREEN	5	1	4	.....	GATE D.S.END	YES	....			1	A	3.175	36			
		6	5	8	.....	TRUCK	YES	6097			1	B	3.175	34			
		7	9	12	.....		YES	....			5	C	3.175	34			
		8	13	16	.....		YES	5619			1	D	3.175	34			
		9	17	20	.....	L.MAZE	YES	....			1	D	3.175	34			
		10	21	24	.....		YES	5619			1	E	3.175	32			
C	BLUE	11	25	28	.....		YES	....			1	E	3.175	32			
		12	29	32	.....		-M-	....			1	E	3.175	32			
		13	33	34	.....		YES	....			5	F	3.810	61			
		14	35	36	.....		YES	5619			5	F	3.810	59			
		15	37	38	.....	ELEV. WALL U.S.END	YES	....			7	F	3.810	59			
		16	39	40	.....		YES	....			5	F	3.810	59			
		17	41	42	.....		YES	5620			5	G	3.810	59			
D	VIOLET	18	43	44	.....		NO	....			5	G	3.810	59			
		19	45	46	.....		YES	....			5	G	3.810	57			
		20	47	48	.....		YES	....			5	G	3.810	57			
		21	49	50	.....		YES	5656			5	H	3.810	57			
		22	51	52	.....	L.MAZE	YES	....			1	H	3.810	57			
		23	53	54	.....		YES	....			1	H	3.810	57			
		24	55	56	.....		YES	5656			1	I	3.810	55			
E	RED	25	57	58	.....		YES	....			1	I	3.810	55			
		26	59	60	.....		YES	....			1	I	3.810	55			
		27	61	62	.....		YES	5651			1	I	3.810	55			
		28	63	64	.....	ELEV.	YES	....			1	I	3.810	55			
		29	65	66	.....		YES	....			1	J	3.810	55			
		30	67	68	.....		YES	5651			1	J	3.810	53			
F	ORANGE	31	69	70	.....		YES	....			1	J	3.810	53			
		32	71	72	.....		YES	....			1	J	3.810	53			
		33	73	74	.....		YES	....			1	J	3.810	53			
		34	75	76	.....	L.MAZE	YES	6951			5	J	3.810	53			
		35	77	78	.....		YES	6951			5	K	3.810	53			
		36	79	80	.....		YES	....			5	K	3.810	51			
G	PEACH	37	81	82	.....		YES	....			5	K	3.810	51			
		38	83	84	.....		YES	....			5	K	3.810	51			
		39	85	86	.....		NO	....			5	K	3.810	51			
		40	87	88	.....	L.MAZE	YES	4670			5	K	3.810	51			
		41	89	90	.....		YES	4670			5	L	3.810	51			
		42	91	92	.....	GATE D.S.END	YES	....			5	L	3.810	51			
H	YELLOW	43	93	94	.....		YES	....			5	L	3.810	51			
		44	95	96	.....		YES	....			7	L	3.810	51			
		45	97	98	.....		YES	....			7	L	3.810	49			
		46	99	100	.....	ELEV.	YES	4853			7	L	3.810	49			
		47	101	102	.....		YES	4853			7	L	3.810	49			
		48	103	104	.....	SW.YD.	YES	....			7	L	3.810	49			

TABLE B-VIII

MONITOR LOOP CALIBRATION AND IRIS VSWR DATA

COL#	-220	--221	-222	--223	-224	--225	--234	-----235	--236	-----237	--238	-----239
MOD NO.	TANK NO.	COUP. FACT. U.S. SECT. LOOP	TANK NO.	COUP. FACT. CTR. SECT. LOOP	TANK NO.	COUP. FACT. D.S. SECT. LOOP	VSWR, B.C. TUNING	DATE C-234	VSWR, IRIS, LOW PWR.	DATE C-221 C-223 C-225 C-236	VSWR, W.G., HIGH PWR., 6-PCT	DATE C-238
.	AND	(DB)	AND	(DB)	AND	(DB)	.	(M-D-Y)	.	(M-D-Y)	.	(M-D-Y)
5	1B	DU	2B	DU	4A	DU	1.3	DU	DU		DU	
6	5A	DU	5B	DU	8A	DU	1.4	DU	DU		DU	
7	9A	DU	10B	DU	12A	DU	1.1	DU	DU		DU	
8	13A	91.4	14B	48.6	16A	52.6	1.4	DU	1.3	11-01-71	DU	
9	17A	DU	18B	DU	20A	DU	1.3	5-01-72	DU		DU	
10	21B	DU	22B	DU	24A	DU	1.2	5-01-72	DU		DU	
11	25B	DU	26B	DU	28A	DU	1.4	5-01-72	DU		DU	
12	29B	DU	30B	DU	32A	DU	1.0	5-02-72	DU		DU	
13	33B	53.6	33D	53.2	34C	52.5	1.0	4-12-72	1.2	4-27-72	1.2	8-18-71
14	35C	DU	35D	DU	36B	DU	1.5	4-12-72	DU		1.3	4-25-72
15	37C	48.5	37D	48.7	38B	48.8	1.3	4-21-72	1.6	4-14-72	1.5	4-19-72
16	39C	48.2	39D	48.7 (*)	40B	47.8	1.3	4-11-72	1.2	12- 5-71	1.4	11-16-71
17	41C	52.2	41D	48.5	42B	50.9	1.6	4- 3-72	DU	10-27-71	1.8	5- 1-72
18	43C	49.1	43D	49.4	44B	49.2	1.4	4-28-72	1.3	12-10-71	1.5	1-10-72
19	45C	48.7	45D	48.7	46B	48.8	1.7	11- 4-71	DU	10-29-71	1.5	11-11-71
20	47C	48.3	47D	48.5	48B	48.2	1.3	10-26-71	1.6	12-10-71	1.7	1-11-72
21	49C	48.1	49D	48.6	50B	48.2	1.2	11- 9-71	1.3	1- 6-72	1.6	1-19-72
22	51C	48.3	51D	48.3	52B	48.6	1.2	1- 4-72	1.3	1-17-72	1.5	2- 3-72
23	53C	48.0	53D	48.1	54B	48.4	1.2	1-20-72	1.3	1-17-72	1.3	2- 3-72
24	55C	49.7	55D	50.1	56B	48.4	1.3	12-17-71	1.3	1- 7-72	1.5	1-21-72
25	57C	49.2	57D	48.7	58B	49.9	1.0	1-21-72	1.1	1- 7-72	1.1	1-30-72
26	59C	50.0	59D	48.3	60B	48.4	1.3	1- 3-72	1.3	1-17-72	1.4	1-27-72
27	61C	48.1	61D	48.2	62B	48.2	1.3	1-26-72	1.3	1-17-72	1.6	1-31-72
28	63C	48.1	63D	48.0	64B	48.2	1.2	1- 4-72	1.5	1-17-72	1.5	2- 9-72
29	65C	48.1	65D	48.1	66B	48.2	1.4	DU	1.7	1-27-72	1.7	2-10-72
30	67C	48.1	67D	48.7	68B	48.1	1.4	DU	1.6	1-27-72	1.6	2-11-72
31	69C	48.1	69D	50.5	70B	49.2	1.4	1-18-72	1.6	1-27-72	1.7	2-16-72
32	71C	48.3	71D	48.4	72B	48.4	1.1	2- 1-72	1.2	1-27-72	1.5	2-17-72
33	73C	48.5	73D	51.3	74B	49.8	1.2	1-21-72	1.4	1-27-72	1.3	2-24-72
34	75C	48.3	75D	49.5	76B	48.3	1.3	2-16-72	1.3	2-25-72	1.6	3- 1-72
35	77C	49.0	77D	48.4	78B	48.5	1.3	2-14-72	1.5	2-25-72	1.4	3- 2-72
36	79C	48.6	79D	48.5	80B	48.9	1.3	2-14-72	1.5	2-28-72	2.0	3- 3-72
37	81C	48.3	81D	48.7	82B	48.6	1.3	2-17-72	1.5	2-28-72	1.4	3-13-72
38	83C	48.3	83D	48.5	84B	48.2	1.5	2-29-72	1.8	3-13-72	1.8	3-14-72
39	85C	48.5	85D	48.2	86B	48.5	1.5	3- 1-72	1.6	3-13-72	1.7	1-24-72
40	87C	48.7	87D	48.6	88B	49.0	1.4	3- 3-72	1.5	3-13-72	1.8	4- 4-72
41	89C	48.4	89D	48.5	90B	48.5	1.3	3-15-72	2.0	3-13-72	1.6	3-28-72
42	91C	48.5	91D	48.2	92B	48.5	1.5	5-12-72	1.5	4- 3-72	1.6	4- 6-72
43	93C	48.9	93D	48.4	94B	48.4	1.5	5-19-72	1.3	4- 3-72	1.6	4-10-72
44	95C	48.6	95D	48.8	96B	48.6	1.6	5-19-72	1.6	5- 4-72	1.6	5-17-72
45	97C	48.6	97D	48.6	98B	48.7	1.4	5- 3-72	1.3	4-21-72	1.5	4-27-72
46	99C	48.6	99D	48.3	100B	48.4	1.4	5- 3-72	1.4	4-21-72	1.4	5- 4-72
47	101C	48.6	101D	48.3	102B	48.5	1.6	5-19-72	1.4	4-21-72	1.5	5-10-72
48	103C	48.2	103D	48.8	104B	48.3	1.2	5-19-72	1.1	5- 4-72	1.3	5-17-72

DU = DATA UNAVAILABLE (*) COUP. FACTOR MEASURED 12-13-71.

APPENDIX C

COMPUTER PROGRAM LISTINGS

Table C-I gives a program for finding the average resonant frequencies for interior accelerating cavities of a section or tank. Table C-II gives a program for calculating the frequencies to which end and interior accelerating cavities are to be set. The latter program used the average data found by the former, together with end cavity frequencies and the $\pi/2$ -mode frequency of the whole section or tank. These programs are for the Hewlett-Packard 9100A calculator. The program in Table C-I was recorded on side A of a magnetic program card; in Table C-II, on side B. The tuners were given the following instructions for using these programs:

(1) After calculator has been turned on and has warmed up, check that only ON and y buttons on printer are depressed.

(2) Set DECIMAL DIGITS wheel to 2.

(3) Push GO TO () (), 0, 0.

(4) Insert A end of magnetic program in slot and push in.

(5) Press ENTER button.

(6) Push GO TO () (), 0, 0.

(7) Enter interior cell frequencies for one tank from Main Cell Data Sheet - Freq. Before Tuning in the following manner:

- Key in value in kHz, push CONT. The printer will print in the form 805999.01, where 805999 was the value entered, and 01 designates segment 1 - 2.

- Key in subsequent values, pushing CONT after each. Only the part of the value that is changing needs to be keyed in. For example, if the previous value was 805999 and the present value is 806111, only key 6, 1, 1, 1, CONT.

- If the printer does not print after you have pushed CONT, check the value displayed in the z register.

If the value displayed is correct, push CONT. If the value displayed is not correct, key in correct value (in x register), push CONT.

- If the last value entered and printed is incorrect, it may be corrected as follows. Push CLEAR, CONT. Then key in correct value, push CONT. The procedure works only for the last value entered. If an error is discovered farther back than the last value, you should start over.

After all interior cavity frequencies have been entered, check segment number of last printed value (the 2 digits to the right of the decimal point). This should be 2 less than the total number of accelerating cavities for this tank.

Push the PAPER button on the printer to feed out the tape. Tear off tape, mark tank number and date on it, and file in envelope attached to back of previous page in looseleaf notebook. Then do second part of calculation:

(1) Set DECIMAL DIGITS wheel to 0.

(2) Push CLEAR, GO TO () (), 0, 0.

(3) Insert B end of magnetic program card in slot and push in.

(4) Press ENTER button.

(5) Push GO TO () (), 0, 0.

(6) Key in upstream head cavity frequency in kHz, push $\uparrow$.

(7) Key in downstream head cavity frequency, push $\uparrow$.

(8) Key in $\pi/2$ -mode frequency before tuning, push CONT. Program will print 11 numbers.

(9) Feed out tape, trim off and attach in the box on Checklist #1. An example of a Checklist #1 and the listing printed out by the HP 9100A calculator is shown in Fig. 23 on page 27 of the main text of this report. The checklist gives the meaning of the 11 numbers printed.

The desired $\pi/2$ -mode frequency is found in the program in Table C-II at steps 5.1 through 5.6. This may be changed as required for different temperatures or atmospheres in the cavities.

Tables C-III through C-V list programs for generating forms for tuning data (FFTD) used in the final tuning. The program in Table C-III is for septum bending; in Table C-IV, for nose stretching. These programs are written in FLEA, an extension of

TABLE C-I

HP 9100A PROGRAM TO FIND AVERAGE INTERIOR ACCELERATING CAVITY FREQUENCY

<u>Step</u>	<u>Instruction</u>	<u>Code</u>	<u>Step</u>	<u>Instruction</u>	<u>Code</u>	<u>Step</u>	<u>Instruction</u>	<u>Code</u>
0.0	roll ↓	31	3.0	2	02	6.0	swap x,y	30
0.1	0	00	3.1	rc1	61	6.1	+	33
0.2	x → ()	23	3.2	if x < y	53	6.2	print	45
0.3	a	13	3.3	4	04	6.3	stop	41
0.4	x → ()	23	3.4	0	00	6.4	go to --	44
0.5	d	17	3.5	-	34	6.5	0	00
0.6	x → ()	23	3.6	roll ↑	22	6.6	b	14
0.7	9	11	3.7	swap x,y	30	6.7	stop	41
0.8	x → ()	23	3.8	X	36	6.8	swap y, -	24
0.9	c	16	3.9	roll ↑	22	6.9	9	11
0.a	roll ↑	22	3.a	swap x,y	30	6.a	swap x,y	30
0.b	x → ()	23	3.b	go to --	44	6.b	swap x,y	30
0.c	b	14	3.c	3	03	6.c	if x > y	53
0.d	clear	20	3.d	2	02	6.d	0	00
1.0	b	14	4.0	↓	25	7.0	b	14
1.1	if x = y	50	4.1	b	14	7.1	if x < y	52
1.2	7	07	4.2	+	33	7.2	0	00
1.3	8	10	4.3	e	12	7.3	b	14
1.4	log x	75	4.4	↑	27	7.4	pause	57
1.5	int x	64	4.5	swap y, -	24	7.5	go to --	44
1.6	↑	27	4.6	9	11	7.6	4	04
1.7	1	01	4.7	if x < y	52	7.7	a	13
1.8	+	33	4.8	6	06	7.8	swap y,-	24
1.9	1	01	4.9	7	07	7.9	c	16
1.a	0	00	4.a	x → ()	23	7.a	.	21
1.b	X	36	4.b	9	11	7.b	0	00
1.c	acc +	60	4.c	↓	25	7.c	1	01
1.d	↑	27	4.d	y → ()	40	7.d	-	34
2.0	a	13	5.0	a	13	8.0	y → ()	40
2.1	roll ↓	31	5.1	d	17	8.1	c	16
2.2	if x > y	53	5.2	+	33	8.2	d	17
2.3	3	03	5.3	y → ()	40	8.3	↑	27
2.4	1	01	5.4	d	17	8.4	a	13
2.5	-	34	5.5	swap y, -	24	8.5	-	34
2.6	roll ↑	22	5.6	c	16	8.6	y → ()	40
2.7	swap x,y	30	5.7	.	21	8.7	d	17
2.8	÷	35	5.8	0	00	8.8	go to --	44
2.9	swap x,y	30	5.9	1	01	8.9	6	06
2.a	int x	64	5.a	+	33	8.a	3	03
2.b	roll ↓	31	5.b	y → ()	40	8.b	end	46
2.c	go to --	44	5.c	c	16			
2.d	2	02	5.d	roll ↓	31			

TABLE C-II

HP 9100A PROGRAM TO CALCULATE DESIRED ACCELERATING CAVITY FREQUENCIES

<u>Step</u>	<u>Instruction</u>	<u>Code</u>	<u>Step</u>	<u>Instruction</u>	<u>Code</u>	<u>Step</u>	<u>Instruction</u>	<u>Code</u>
0.0	roll	31	2.b	1	01	5.8	a	13
0.1	acc +	60	2.c	swap x,y	30	5.9	d	17
0.2	rcl	61	2.d	-	34	5.a	swap x,y	30
0.3	print	45	3.0	y → ()	40	5.b	set flag	54
0.4	roll ↑	22	3.1	b	14	5.c	go to --	44
0.5	print	45	3.2	2	02	5.d	2	02
0.6	print	45	3.3	÷	35	6.0	7	07
0.7	x → ()	23	3.4	1	01	6.1	y → ()	40
0.8	a	13	3.5	swap x,y	30	6.2	e	12
0.9	roll ↑	22	3.6	-	34	6.3	1	01
0.a	print	45	3.7	a	13	6.4	swap x,y	30
0.b	c	16	3.8	swap x,y	30	6.5	b	14
0.c	roll ↑	22	3.9	$\sqrt{x}$	76	6.6	-	34
0.d	enter exp	26	3.a	X	36	6.7	a	13
1.0	2	02	3.b	print	45	6.8	swap x,y	30
1.1	X	36	3.c	continue	47	6.9	$\sqrt{x}$	76
1.2	print	45	3.d	continue	47	6.a	X	36
1.3	2	02	4.0	if flag	43	6.b	print	45
1.4	swap x,y	30	4.1	6	06	6.c	y → ()	40
1.5	+	33	4.2	1	01	6.d	f	15
1.6	print	45	4.3	2	02	7.0	b	14
1.7	y → ()	40	4.4	X	36	7.1	swap x,y	30
1.8	c	16	4.5	e	12	7.2	enter exp	26
1.9	swap x,y	30	4.6	-	34	7.3	6	06
1.a	d	17	4.7	f	15	7.4	X	36
1.b	swap x,y	30	4.8	-	34	7.5	print	45
1.c	:	35	4.9	c	16	7.6	print	45
1.d	print	45	4.a	÷	35	7.7	stop	41
2.0	y → ()	40	4.b	a	13	7.8	end	46
2.1	d	17	4.c	+	33			
2.2	continue	47	4.d	print	45			
2.3	continue	47	5.0	print	45			
2.4	continue	47	5.1	8	10			
2.5	continue	47	5.2	0	00			
2.6	a	13	5.3	4	04			
2.7	÷	35	5.4	8	10			
2.8	↓	25	5.5	3	03			
2.9	↑	27	5.6	4	04			
2.a	X	36	5.7	x → ()	23			

FORTRAN which permits top-down structured programming. Table C-V lists a corresponding program for dinging and nose stretching, after the program was translated by the FLEAS preprocessor to standard FORTRAN. (Data cards are not shown. These are similar to the data cards shown in Table C-IV.) See Fig. 22 on page 25 for an example of the form generated by the program in Table C-III; and Fig. 24 on page 28, by Table C-V.

Table C-VI lists a program for comparing measured individual cavity data for sections compared with tanks (SCWT). The section data was from the measurements after brazing; the tank data, from measurements in the tunnel before final tuning. The calculation was made to check for large frequency errors in the measurements before the final tuning was done. For an example of the output, see Fig. 25 on page 29.

TABLE C-III

PROGRAM FFTD, VERSION FOR SEPTUM BENDING LASL Identification No. LP-1070

```

$INIITATE FORM FOR TUNING DATA
  DIMENSION HOLD(70,66), INFO(70), ID(8)
  INTEGER HOLD
  $A.
  $(FORM LENGTH=1, 6 2, 1)    $- MODULES 24-48
  $GO INITIALIZE.
105 FORMAT(1H1,9X8A10)  $ READ 105,(ID(J),J=1,6) $ CALL DATE1( ID(7) )
111 FORMAT(10X,70A1)  $ READ 111,HOLD $- GENERAL LAYOUT OF FORM
120 PRINT 105, (ID(J),J=1,7) $ LINE=1 $ N=11
122 FORMAT(13,F8.3,14,F7.3,7X13,5XF6.3) $ READ 122,NM,DM,NE,DE,NTANK
  1 ,OFFSET $ IF( NM.EQ.0 )RETURN
  NCELLS=55-(NTANK/67)*2-(NTANK/79)*2-(NTANK/97)*2 $ N ADJ=0
  IF( NM.GT.NE )
  1 $GO UPSTREAM HALF.
  IF( NM.LT.NE )
  1 $GO DOWNSTREAM HALF.
  SEGS=NM-NE $ SEG LEN=(DM-DE)/ABS(SEGS) $ TOOL LOC = DM + OFFSET
  IF( N ADJ.NE.0 )
  1 $GO MAKE ADJUSTMENTS.
  $FOR(FORM LENGTH). $ $GO COPY LINE.
    IF( NREM.LT.0 )
    1 $GO ERASE LEFT PART OF INFO.
    IF( NREM.EQ.0 .AND. MOD(LINE,2).NE.0 )
    1 $GO INSERT QUOTE HEAD.
    IF( LINE.GT.4 .AND. MOD(LINE,2).NE.0 .AND. NREM.GT.0 )
    1 $GO INSERT SEGMENT NUMBER IN INFO.
    IF( LINE.GT.4 .AND. MOD(LINE,2).EQ.0 .AND. NREM.GT.0 )
    1 $GO INSERT TOOL LOCATION IN INFO.
    IF( LINE.EQ.9 )
    1 $GO INSERT MODULE NUMBER IN INFO.
    IF( LINE.EQ.11 )
    1 $GO INSERT TANK NUMBER IN INFO.
    IF( LINE.EQ.15 )
    1 $GO INSERT SEGMENT LENGTH IN INFO.
    PRINT 111, INFO
  GO TO 120
$BLOCK INITIALIZE. $ LINE=1 $ N=11 $ $(LINE= 1, 7 0, 1)
$DECLARE N D,1H0,1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9 $
$BLOCK UPSTREAM HALF. $ NSEG=NM+1 $ NREM=NSEG $ NDIF=-1
  IF( 2*NREM.LT.NCELLS .AND. MOD(NTANK,2).NE.0 ) N ADJ = 1
  IF( 2*NREM.GT.NCELLS .AND. MOD(NTANK,2).EQ.0 ) N ADJ = -1
$BLOCK DOWNST HALF. $ NSEG=NM-1 $ NREM=NE+2*MOD(NE,2)-NM $ NDIF=1
  IF( 2*NREM.GT.NCELLS .AND. MOD(NTANK,2).NE.0 ) N ADJ = -1
  IF( 2*NREM.LT.NCELLS .AND. MOD(NTANK,2).EQ.0 ) N ADJ = 1
$BLOCK MAKE ADJUSTMENTS. $ NREM=NREM+NADJ
  NSEG=NSEG+NADJ*NDIF $ TOOL LOC=TOOL LOC+SEG LEN*FLOAT(NADJ)
$BLOCK COPY LINE. $ $FOR(LINE). $ INFO(17)=HOLD(17,LINE)
  LINE=LINE+1
$BLOCK INSERT QUOTE HEAD. $ INFO(1)=1HH $ INFO(2)=1HE $ INFO(3)=
1 1HA $ INFO(4)=1HD $ NREM=-1
$BLOCK ERASE LEFT PART OF INFO. $ DO 555 J=1,58

```



```

555      INFO(J)=IH
      $BLOCK INSERT SEGMENT NUMBER IN INFO. $ N=3 $ NDIG=2 $ NFRAC=0
      VALUE=NSEG $ $GO INSERT VALUE IN INFO. $ NSEG=NSEG+NDIF
      NREM=NREM-1
      $BLOCK INSERT TOOL LOCATION IN INFO. $ N=11 $ NDIG=3 $ NFRAC=2
      VALUE=TOOL LOC $ $GO INSERT VALUE IN INFO. $ TOOL LOC=TOOL LOC
1      - SEG LEN
      $BLOCK INSERT MODULE NUMBER IN INFO. $ N=66 $ NDIG=2 $ NFRAC=0
      VALUE=(NTANK+1)/2-4 $ $GO INSERT VALUE IN INFO.
      $BLOCK INSERT TANK NUMBER IN INFO. $ N=60 $ NDIG=3 $ NFRAC=0
      VALUE=NTANK $ $GO INSERT VALUE IN INFO.
      IF(NDIF.LT.0) INFO(64)=IHA $ IF(NDIF.LT.0) INFO(65)=IHB
      IF(NDIF.GT.0) INFO(64)=IHC $ IF(NDIF.GT.0) INFO(65)=IHD
      $BLOCK INSERT SEGMENT LENGTH IN INFO. $ N=60 $ NDIG=2 $ NFRAC=4
      VALUE=SEG LEN $ $GO INSERT VALUE IN INFO.
      $BLOCK INSERT VALUE IN INFO. $ POWER=10.0** (NDIG-1)
      VALUE=ABS(VALUE)+0.5*(10.0**(-NFRAC)) $-ROUND LAST DIGIT $ M=0
777      IF(POWER.LT.1. .AND. POWER.GT.0.05) INFO(N)=IH.
      IF(POWER.LT.1. .AND. POWER.GT.0.05) N=N+1 $ J=VALUE/POWER
      IF(J.GT.0)M=1 $-PAST 1ST NONZERO DIG $ IF(M.GT.0) INFO(N)=
1      ND(J+1) $ IF(J.GT.9) INFO(N)=IH* $ N=N+1 $ VALUE=VALUE-
2      FLOAT(J)*POWER $ POWER=POWER/10.0
      IF(2.0*POWER.GT. 10.0**(-NFRAC) ) GO TO 777
C      TO INSERT 9.99, SET NDIG=1 NFRAC=2 VALUE=9.99 (POS. VAL. ONLY)
      $END
      SUBROUTINE STARTER(DUMMY) $ RETURN $ END
      $-STOP PROCESSING

```

1 MAIN CELL DATA SHEET

01	02	SEGMENT	TOOL	FREQ.,	FREQ.BEFORE	FINAL FREQ.	DATE
03	NUMBER	LOCATION	C.C.SHORTED	TUNING	C.C.SHORTED		
04	29						-----
05	>----	11.11					INITIALS
06	28		-----	-----	-----		
07	>----	11.11					-----
08	0		-----	-----	-----		MODULE
09	>----	11.11					TANK NO.
10	0		-----	-----	-----		
11	>----	11.11					
12	0		-----	-----	-----		
45	>----	.11					SEGMENT LEN
47			-----	-----	-----		
47	>----						-----
45			-----	-----	-----		
13	>----	11.11					TEMPERATURE
14	0		-----	-----	-----		
15	>----	11.11					-----
16	0		-----	-----	-----		DEG F DEG C
17	>----	11.11					
18	0		-----	-----	-----		PI/2 BEFORE
19	>----	11.11					TUNING
20	0		-----	-----	-----		
21	>----	11.11					-----
22	0		-----	-----	-----		MHZ
23	>----	.11					
24	0		-----	-----	-----		TUNE TO THIS
25	>----	.11					FREQUENCY
26	0		-----	-----	-----		
27	>----	.11					-----
28	0		-----	-----	-----		MHZ
29	>----	.11					
24	0		-----	-----	-----		TUNE HEAD
25	>----	.11					CELLS TO
26	0		-----	-----	-----		
27	>----	.11					-----
28	0		-----	-----	-----		MHZ
29	>----	.11					

30	0		-----	-----	-----	AFTER TUNING-
31	>----	.11	-----	-----	-----	MODE BELOW
32	0		-----	-----	-----	PI/2 MODE N2
33	>----	.11	-----	-----	-----	MODE ABOVE
34	0		-----	-----	-----	
35	>----	.11	-----	-----	-----	
37	0		-----	-----	-----	-----
37	>----	.11	-----	-----	-----	-----
39	0		-----	-----	-----	-----
39	>----	.11	-----	-----	-----	-----
41	0		-----	-----	-----	-----
41	>----	.11	-----	-----	-----	-----
43			-----	-----	-----	-----
53	>----		-----	-----	-----	
55			-----	-----	-----	
55	>----		-----	-----	-----	
57			-----	-----	-----	
57	>----		-----	-----	-----	
59			-----	-----	-----	
59	>----		-----	-----	-----	
61			-----	-----	-----	
61	>----		-----	-----	-----	
63			-----	-----	-----	
63	>----		-----	-----	-----	
64			-----	-----	-----	
65						
66						

24	143.680	2	13.480	TANK 87 AB	0.250 OFFSET
26	149.550	50	7.500	TANK 87 CD	0.250 OFFSET
25	150.060	1	7.580	TANK 88 AB	0.250 OFFSET
27	144.080	49	13.500	TANK 88 CD	0.250 OFFSET

000000000000000000000000

TABLE C-IV

PROGRAM FFTD, VERSION FOR NOSE STRETCHING

```

$INITIATE FORM FOR TUNING DATA
  DIMENSION HOLD(70,66), INFO(70), ID(8)
  INTEGER HOLD
  $(FORM LENGTH=1, 6 2, 1)  $- MODULES 24-48
  $GO INITIALIZE.
105 FORMAT(1H1,9X8A10)  $ READ 105,(ID(J),J=1,6) $ CALL DATE1( ID(7) )
111 FORMAT(10X,70A1) $ READ 111,HOLD $- GENERAL LAYOUT OF FORM
120 PRINT 105, (ID(J),J=1,7) $ LINE=1 $ N=11
122 FORMAT(13,F8.3,14,F7.3,7X13,5X6.3) $ READ 122,NM,DM,NE,DE,NTANK
1  ,OFFSET $ IF( NM.EQ.0 )RETURN
  NCELLS=61-(NTANK/35)*2-(NTANK/45)*2  $ IF( NTANK.GT.54 )
1  NCELLS=55-(NTANK/67)*2-(NTANK/79)*2-(NTANK/97)*2 $ N ADJ=0
  IF( NM.GT.NE )
1  $GO UPSTREAM HALF.
  IF( NM.LT.NE )
1  $GO DOWNSTREAM HALF.
  SEGS=NM-NE $ SEG LEN=(DM-DE)/ABS(SEGS)
  TOOL LOC=DM + 0.5*SEG LEN - HG(4*NTANK-160) + 1. - 3./8. $-T41-84
  IF( N ADJ.NE.0 )
1  $GO MAKE ADJUSTMENTS.
  $FOR(FORM LENGTH). $ $GO COPY LINE.
    IF( NREM.LT.0 )
1    $GO ERASE LEFT PART OF INFO.
    IF( NREM.EQ.0 .AND. MOD(LINE,2).NE.0 )
1    $GO INSERT QUOTE HEAD.
    IF(LINE.GT.4 .AND. MOD(LINE,2).NE.0 .AND. NREM.GT.0)
1    $GO INSERT SEGMENT NUMBER IN INFO.
    IF(LINE.GT.4 .AND. MOD(LINE,2).EQ.0 .AND. NREM.GT.0)
1    $GO INSERT TOOL LOCATION IN INFO.
    IF( LINE.EQ.9 )
1    $GO INSERT MODULE NUMBER IN INFO.

```

```

      IF( LINE.EQ.11 )
1    $GO INSERT TANK NUMBER IN INFO.
      IF( LINE.EQ.15 )
1    $GO INSERT SEGMENT LENGTH IN INFO.
      PRINT 111, INFO
      GO TO 120
$BLOCK INITIALIZE. $ LINE=1 $ N=11 $ $(LINE= 1, 7 0, 1)
$DECLARE N D,1H0,1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9 $
$- TANKS 41 - 84 $DATA HALF GAP,
      .949, .949, .949, .949, .960,
      .960, .960, .960, .969, .969,
      .969, .969, .981, .981, .981,
      .981, .987, .987, .987, .987,
      .992, .992, .992, .992, 1.000,
      1.000, 1.000, 1.000, 1.009, 1.009,
      1.009, 1.009, 1.028, 1.028, 1.028,
      1.028, 1.035, 1.035, 1.035, 1.035,
      1.043, 1.043, 1.043, 1.043, 1.051,
      1.051, 1.051, 1.051, 1.058, 1.058,
      1.058, 1.058, 1.066, 1.066, 1.066,
      1.066, 1.096, 1.096, 1.096, 1.096,
      1.103, 1.103, 1.103, 1.103, 1.110,
      1.110, 1.110, 1.110, 1.115, 1.115,
      1.115, 1.115, 1.120, 1.120, 1.120,
      1.120, 1.129, 1.129, 1.129, 1.129,
      1.134, 1.134, 1.134, 1.134, 1.141,
      1.141, 1.141, 1.141, 1.147, 1.147,
      1.147, 1.147, 1.155, 1.155, 1.156,
      1.155, 1.167, 1.167, 1.167, 1.167,
      1.174, 1.173, 1.172, 1.172, 1.177,
      1.178, 1.178, 1.178, 1.1845, 1.1845,
      1.1845, 1.1845, 1.1905, 1.1905, 1.189,
      1.189, 1.195, 1.195, 1.195, 1.195,
      1.200, 1.200, 1.200, 1.200, 1.205,
      1.205, 1.205, 1.205, 1.211, 1.211,
      1.211, 1.211, 1.215, 1.215, 1.215,
      1.215, 1.220, 1.220, 1.220, 1.220,
      1.224, 1.225, 1.225, 1.225, 1.268,
      1.268, 1.2675, 1.2675, 1.272, 1.272,
      1.272, 1.272, 1.278, 1.278, 1.278,
      1.278, 1.283, 1.284, 1.284, 1.284,
      1.288, 1.287, 1.2885, 1.2885, 1.291,
      1.291, 1.291, 1.291, 1.295, 1.293,
      1.293, 1.293, 1.296, 1.296, 1.297,
      1.297 $
$BLOCK UPSTREAM HALF. $ NSEG=NM+1 $ NREM=NSEG $ NDIF=-1
      IF( 2*NREM.LT.NCELLS .AND. MOD(NTANK,2).NE.0 ) N ADJ = 1
      IF( 2*NREM.GT.NCELLS .AND. MOD(NTANK,2).EQ.0 ) N ADJ = -1
$BLOCK DOWNST HALF. $ NSEG=NM-1 $ NREM=NE+2*MOD(NE,2)-NM $ NDIF=1
      IF( 2*NREM.GT.NCELLS .AND. MOD(NTANK,2).NE.0 ) N ADJ = -1
      IF( 2*NREM.LT.NCELLS .AND. MOD(NTANK,2).EQ.0 ) N ADJ = 1
$BLOCK MAKE ADJUSTMENTS. $ NREM=NREM+NADJ
      NSEG=NSEG-NADJ*NDIF $ TOOL LOC=TOOL LOC+SEG LEN*FLOAT(NADJ)
$BLOCK COPY LINE. $ $FOR(LINE). $ INFO(I7)=HOLD(I7,LINE)
      LINE=LINE+1
$BLOCK INSERT QUOTE HEAD. $ INFO(1)=1HH $ INFO(2)=1HE $ INFO(3)=
1    1HA $ INFO(4)=1HD $ NREM=-1
$BLOCK ERASE LEFT PART OF INFO. $ DO 555 J=1,58
555    INFO(J)=1H
$BLOCK INSERT SEGMENT NUMBER IN INFO. $ N=3 $ NDIG=2 $ NFRAC=0
      VALUE=NSEG $ $GO INSERT VALUE IN INFO. $ NSEG=NSEG+NDIF
      NREM=NREM-1
$BLOCK INSERT TOOL LOCATION IN INFO. $ N=11 $ NDIG=3 $ NFRAC=2
      VALUE=TOOL LOC $ $GO INSERT VALUE IN INFO. $ TOOL LOC=TOOL LOC
1    - SEG LEN
$BLOCK INSERT MODULE NUMBER IN INFO. $ N=66 $ NDIG=2 $ NFRAC=0
      VALUE=(NTANK+1)/2-4 $ $GO INSERT VALUE IN INFO.
$BLOCK INSERT TANK NUMBER IN INFO. $ N=60 $ NDIG=3 $ NFRAC=0
      VALUE=NTANK $ $GO INSERT VALUE IN INFO.
      IF(NDIF.LT.0) INFO(64)=1HA $ IF(NDIF.LT.0) INFO(65)=1HB
      IF(NDIF.GT.0) INFO(64)=1HC $ IF(NDIF.GT.0) INFO(65)=1HD

```


57							
57		>----		-----		-----	
59				-----		-----	
59		>----		-----		-----	
61				-----		-----	
61		>----		-----		-----	
63				-----		-----	
63		>----		-----		-----	
64				-----		-----	
65							
66							
28	140.800	2	11.580	TANK	49 AB	0.250	OFFSET
30	135.830	56	6.620	TANK	49 CD	0.250	OFFSET
27	136.830	1	6.630	TANK	50 AB	0.250	OFFSET
29	141.830	55	11.660	TANK	50 CD	0.250	OFFSET
28	142.860	2	11.780	TANK	51 AB	0.250	OFFSET
30	137.800	56	6.700	TANK	51 CD	0.250	OFFSET
27	138.700	1	6.710	TANK	52 AB	0.250	OFFSET
29	143.760	55	11.810	TANK	52 CD	0.250	OFFSET
28	144.740	2	11.910	TANK	53 AB	0.250	OFFSET
30	139.570	56	6.750	TANK	53 CD	0.250	OFFSET
27	140.480	1	6.800	TANK	54 AB	0.250	OFFSET
29	145.620	55	11.930	TANK	54 CD	0.250	OFFSET
26	137.750	2	12.100	TANK	57 AB	0.250	OFFSET
28	143.010	54	6.860	TANK	57 CD	0.250	OFFSET
27	143.780	1	6.900	TANK	58 AB	0.250	OFFSET
29	138.520	53	12.160	TANK	58 CD	0.250	OFFSET
26	139.320	2	12.250	TANK	59 AB	0.250	OFFSET
28	144.610	54	6.950	TANK	59 CD	0.250	OFFSET
27	145.380	1	6.960	TANK	60 AB	0.250	OFFSET
29	140.090	53	12.330	TANK	60 CD	0.250	OFFSET

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904 CONTINUE%IF (NM.LT.NE)GOTO955
905 CONTINUE%SEGS=NM-NE%SEGLE= (DM-DE)/ABS(SF65)%TOOLLOC=DM*0.5%SEGLE*
1-HG(4*NTANK-128)*1.-3./8.%IF (NADJ.NE.0)GOTO956
906 CONTINUE%DO80211=1.62,1%GOTO957
907 CONTINUE%IF (NREM.LT.0)GOTO958
908 CONTINUE%IF (NREM.EQ.0.AND.MOD(LINE*2).NE.0)GOTO959
909 CONTINUE%IF (LINE.GT.4.AND.MOD(LINE*2).NE.0.AND.NREM.GT.0)GOTO960
910 CONTINUE%IF (LINE.GT.4.AND.MOD(LINE*2).EQ.0.AND.NREM.GT.0)GOTO961
911 CONTINUE%IF (LINE.EQ.9)GOTO962
912 CONTINUE%IF (LINE.EQ.11)GOTO963
913 CONTINUE%IF (LINE.EQ.15)GOTO964
914 CONTINUE%N=60%NDIG=3%NFRAC=3%VALUE=FPU%IF (LINE.EQ.25)GOTO965
915 CONTINUE%VALUE=FPU%IF (LINE.EQ.27)GOTO966
916 CONTINUE%VALUE=FIN%IF (LINE.EQ.31)GOTO967
917 CONTINUE%VALUE=FEN%IF (LINE.EQ.36)GOTO968
918 CONTINUE%IF (LINE.EQ.39)GOTO969
919 CONTINUE%IF (LINE.EQ.40)GOTO970
920 CONTINUE%PRINT111,INFO
802 CONTINUE
199 NTANKL=NTANK%GOTO120
803 JUMP1=JUMP%LINE=1%N=11%ND(1)=1H0%ND(2)=1H1%ND(3)=1H2%ND(4)=1H3%ND(
15)=1H4%ND(6)=1H5%ND(7)=1H6%ND(8)=1H7%ND(9)=1H8%ND(10)=1H9%HG(1)=.8
156%HG(2)=.856%HG(3)=
14%HG(286)=1.373%HG(287)=1.372%HG(288)=1.372%NCPE(1)=18%NCPE(2)=1
17%NCPE(3)=16%NCPE(4)=16%NCPE(5)=14%NCPE(6)=15%NCPE(7)=13%NCPE
15(8)=14%NCPE(9)=12%NCPE(10)=13%NCPOS(1)=18%NCPOS(3)=
116%NCPOS(4)=15%NCPOS(5)=15%NCPOS(6)=14%NCPOS(7)=14%NCPOS(8)=13%NCP
105(9)=13%NCPOS(10)=12%JUMP=JUMP1%GOTO9900
804 JUMP2=JUMP%FP1=FMC(NCELLS*4)%IF (FMC(NCELLS*2).NE.FLOAT(NTANK))GOTO
1199%CC=2.*CELLS*(FMC(NCELLS*3)-FMC(NCELLS*5))/(3.14159*SQRT(FMC(NC
1ELLS*3)*FMC(NCELLS*5)))%FI=SUM1%FPU=FP1%F1CELL=FMC(1)%FNCELL=FMC(N
1CELLS)%JUMP=JUMP2%GOTO9900
805 JUMP3=JUMP%FP2=FMC2(NCELLS*4)%IF (FMC2(NCELLS*2).NE.FLOAT(NTANK))
1GOTO199%CC=2.*CELLS*(FMC2(NCELLS*3)-FMC2(NCELLS*5))/(3.14159*SQRT
1T(FMC2(NCELLS*3)*FMC2(NCELLS*5)))%FI=SUM2%FPU=FP2%F1CELL=FMC2(1
1)%FNCELL=FMC2(NCELLS)%JUMP=JUMP3%GOTO9900
806 JUMP4=JUMP%NSEG=NM*1%NREM=NSEG%NDIF=-1%IF (2*NREM.LT.NCELLS.AND.MOD
1(NTANK*2).NE.0)NADJ=1%IF (2*NREM.GT.NCELLS.AND.MOD(NTANK*2).EQ.0)NA
1DJ=-1%JUMP=JUMP4%GOTO9900
807 JUMP5=JUMP%NSEG=NM-1%NREM=NE*2+MOD(NE*2)-NM%NDIF=1%IF (2*NREM.GT.NC
1ELLS.AND.MOD(NTANK*2).NE.0)NADJ=-1%IF (2*NREM.LT.NCELLS.AND.MOD(NTA
1NK*2).EQ.0)NADJ=1%JUMP=JUMP5%GOTO9900
808 JUMP6=JUMP%NREM=NREM+NADJ%NSEG=NSEG-NADJ%NDIF%TOOLLOC=TOOLLOC+SEGL
1FN*FLOAT(NADJ)%JUMP=JUMP6%GOTO9900
809 JUMP7=JUMP%DO801017=1.70,1%INFO(17)=HOLD(17,LINE)
810 CONTINUE%LINE=LINE*1%JUMP=JUMP7%GOTO9900
811 JUMP9=JUMP%INFO(1)=1H%INFO(2)=1HE%INFO(3)=1HA%INFO(4)=1HD%NREM=-1
JUMP=JUMP9%GOTO9900
812 JUMP8=JUMP%DO555J=1.58
555 INFO(J)=1H %JUMP=JUMP8%GOTO9900
813 JUMP10=JUMP%N=1%NDIG=2%NFRAC=0%VALUE=NSEG%GOTO971
921 CONTINUE%NSEG=NSEG+NDIF%NREM=NREM-1%JUMP=JUMP10%GOTO9900
814 JUMP11=JUMP%N=7%NDIG=3%NFRAC=2%VALUE=TOOLLOC%GOTO972
922 CONTINUE%TOOLLOC=TOOLLOC-SEGLE%N=NSEG%IF (NDIF.LT.0)N=N+1%VALUE=FM
1C(N)%J=N%IF (MOD(NTANK*2).EQ.0)J=NCELLS+1-N%IF (MOD(J-NCPE(NGROUP),
1NCPOS(NGROUP)).EQ.0)INFO(5)=1HJ%IF (MOD(NTANK*2).EQ.0)VALUE=FMC2(N
1)%N=16%MSIGN=1H %IF (FIN.LT.VALUE)MSIGN=1H-%CHANGE=ABS(FIN-VALUE)%N
1DIG=3%NFRAC=3%GOTO973
923 CONTINUE%INFO(24)=MSIGN%VALUE=CHANGE%N=25%NDIG=1%NFRAC=3%GOTO974
924 CONTINUE%JUMP=JUMP11%GOTO9900
815 JUMP12=JUMP%N=66%NDIG=2%NFRAC=0%VALUE=(NTANK*1)/2-4%GOTO975
925 CONTINUE%JUMP=JUMP12%GOTO9900
816 JUMP13=JUMP%N=60%NDIG=3%NFRAC=0%VALUE=NTANK%GOTO976
926 CONTINUE%IF (NDIF.LT.0)INFO(64)=1H%IF (NDIF.LT.0)INFO(65)=1H8%IF (ND
1IF.GT.0)INFO(64)=1HC%IF (NDIF.GT.0)INFO(65)=1HD%JUMP=JUMP13%GOTO990
10
817 JUMP14=JUMP%N=60%NDIG=2%NFRAC=4%VALUE=SEGLE%GOTO977
927 CONTINUE%JUMP=JUMP14%GOTO9900
818 JUMP17=JUMP%N=63%NDIG=1%NFRAC=6%VALUE=DC%GOTO978
928 CONTINUE%JUMP=JUMP17%GOTO9900

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819 JUMP16=JUMP$N=63$NDIG=1$IFAC=5$VALUE=CC$GOTO979
929 CONTINUE$JUMP=JUMP16$GOTO9400
820 JUMP15=JUMP$POWER=10.69*(NDIG-1)$VALUE=ABS(VALUE)*0.5*(10.0*(-NFR
1AC))$M=0
777 IF(POWER.LT.1..AND.POWER.GT.0.05)INFO(N)=1H.$IF(POWER.LT.1..AND.PO
WER.GT.0.05)$M=1$IF(POWER.LT.1..AND.POWER.GT.0.05)$N=N+1$J=VALUE/POW
ER$IF(J.GT.0)$M=1$IF(M.GT.0)INFO(N)=ND(J+1)$IF(J.GT.9)INFO(N)=1H*$N
1=N+1$VALUE=VALUE-FLOAT(J)*POWER$POWER=POWER/10.0$IF(2.0*POWER.GT.1
10.0*(-NFRAC))GOTO777$JUMP=JUMP15$GOTO9400
951 JUMP=1$GOTO803
952 JUMP=2$GOTO804
953 JUMP=3$GOTO805
954 JUMP=4$GOTO806
955 JUMP=5$GOTO807
956 JUMP=6$GOTO808
957 JUMP=7$GOTO809
958 JUMP=8$GOTO812
959 JUMP=9$GOTO811
960 JUMP=10$GOTO813
961 JUMP=11$GOTO814
962 JUMP=12$GOTO815
963 JUMP=13$GOTO816
964 JUMP=14$GOTO817
965 JUMP=15$GOTO820
966 JUMP=16$GOTO820
967 JUMP=17$GOTO820
968 JUMP=18$GOTO820
969 JUMP=19$GOTO819
970 JUMP=20$GOTO818
971 JUMP=21$GOTO820
972 JUMP=22$GOTO820
973 JUMP=23$GOTO820
974 JUMP=24$GOTO820
975 JUMP=25$GOTO820
976 JUMP=26$GOTO820
977 JUMP=27$GOTO820
978 JUMP=28$GOTO820
979 JUMP=29$GOTO820
9900 GOTO(901,902,903,904,905,906,907,908,909,910,911,912,913,914,915,9
16,917,918,919,920,921,922,923,924,925,926,927,928,929),JUMP$END
SUBROUTINESTARTER(DUMMY)$RETURN$END

```

TABLE C-VI

PROGRAM SCWT

```

PROGRAMSCWT(INPUT,OUTPUT,TAPE9=OUTPUT,TAPE10=INPUT,TAPE8)$COMMON/O
UT6C/NOUT6C,NOCOLS,NOHEAD,NAMECOL(6,7),NDUMMY(19)$DIMENSIONFMC(66)
1,HOLD(12),FAE(66),TEE(4),TTE(4),DA(4)$CALLSKIPLT$CALLSTARTER(20HSC
1WT 02/15/72 1$NTRACE=200$NOUT6C=0$FPN=804.930$NTANKL=105
111 LINE=LINE+1
112 FORMAT(I4,R1,A5,14F5.0)
READ112,NTANK,LS,DATE,FPU,DCC,HOLD$IF(NTANK.EQ.0)RETURN$SUM=0.$CN=
10.
114 FORMAT(40X*TANK*I4)
IF(NTANK.GT.NTANKL)CALLPAGER$IF(NTANK.NE.NTANKL)PRINT114,NTANK$IF(
1NTANK.NE.NTANKL)$NSTORE=0$IF(NTANK.NE.NTANKL.AND.MOD(NTANK,2).EQ.0)
1NSTORE=NSTORE+1$IF(NTANK.NE.NTANKL.AND.MOD(NTANK,2).EQ.0)FAE(NSTOR
1E)=0.$NICELLS=1$D080011=3,12,1$IF(HOLD(11).GT.0.)NICELLS=NICELLS+1
800 CONTINUE$N=NICELLS+1$D080111=1,N,1$HOLD(11)=.001*HOLD(11)+800.$NST
1ORE=NSTORE+1$FAE(NSTORE)=HOLD(11)
801 CONTINUE$NSTORE=NSTORE+1$FAE(NSTORE)=0.$FPU=.001*FPU+800.$DCC=.000
1001*DCC$D080211=2,NICELLS,1$SUM=SUM+HOLD(11)$CN=CN+1.
802 CONTINUE$FI=SUM/CN$DCE=1.-(FI/FPU)**2$FEE=FPU*SQR(1.-.5*DCE)$FPC=
1FPU+(2.*FEE-HOLD(1)-HOLD(N))/(CN+2.)$DC=1.-(FI/FPC)**2$FEN=FPN*SQR
1T(1.-.5*DC)$FIN=FPN*SQR(1.-DC)$DA(LS)=DATE$TTE(LS)=FIN$TEE(LS)=FE
1N$N1=1$IF(LS.EQ.1.AND.MOD(NTANK,2).NE.0)$N1=2$N2=N$IF(LS.EQ.4.AND.M
1OD(NTANK,2).EQ.0)$N2=N-1$IF(LS.NE.4)GOTO300$NCELLS=61-(NTANK/35)*2-
1(NTANK/45)*2$IF(NTANK.GT.54)$NCELLS=55-(NTANK/67)*2-(NTANK/79)*2-(N

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```

      ITANK/97)*2%NADJ=0%NICELLS=NCELLS-1%CN=0.%$NGROUP=10-(NCELLS-49)/2%
      IELLS=NCELLS$NREAD=NCELLS+5$READ125,(FMC(I),I=1,NREAD)
125  FORMAT(16F5.0)
      DO803I1=1,NREAD,1$IF (FMC(I1).GT.830.)FMC(I1)=.001*FMC(I1)+800.
803  CONTINUE$SUM1=0.%SUM2=0.%DO804I1=2,NICELLS,1$J=I1$SUM1=SUM1+FMC(J)
      CN=CN+1.
804  CONTINUE$SUM1=SUM1/CN$SUM2=SUM2/CN%DCE=1.-(SUM1/FMC(NCELLS+4))*2
      FEE=FMC(NCELLS+4)*SQRT(1.-.5*DCE)$FPC=FMC(NCELLS+4)*(2.*FEE-FMC(I)
      1-FMC(NCELLS))/(CN+2.1$DCT=1.-(SUM1/FPC)*2$FET=804.834*SQRT(1.-.5*
      1DCT)$FIT=804.834*SQRT(1.-DCT)$TIT=FIT$TET=FET
243  FORMAT(10X*DATE C TUNE TO ERROR FREQ., FREQ. FREQ., ERROR
      1 TUNE TO ERR*/10X* NO ETLB ETLB ETLB DROP TUNNE
      2L TUNNEL TUNNEL DIF*/10X*--- -- --- -- --- --
      3-- --- --*)
      PRINT243$LS=1$DO805I1=1,NCELLS,1$IF (FAE(I1).EQ.0..AND.I1.NE.1)$LS=L
      1S+1$TE=TTE(LS)$IF (I1.EQ.1.OR.I1.EQ.NCELLS)$TE=TEE(LS)$TT=TTT$IF (I1.
      1EQ.1.OR.I1.EQ.NCELLS)$TT=TET$EE=FAE(I1)-TE$FD=FAE(I1)-FMC(I1)$ET=FM
      1C(I1)-TT$D=DA(LS)$ED=ET-EE$IF (FAE(I1).EQ.0.)ED=0./0.$IF (FAE(I1).EQ
      1.0.)D=5H $IF (FAE(I1).EQ.0.)EE=0./0.$IF (FAE(I1).EQ.0.)FD=0./0.
      PRINT244,D,I1,TE,EE,FAE(I1),FD,FMC(I1),ET,TT,ED
805  CONTINUE
244  FORMAT(9X*5,14,F9.3,F7.3,F9.3,F6.3,F9.3,F7.3,F9.3,F6.3)
300  NTANKL=NTANK$GOTO11$END

      SUBROUTINE PAGER
      PAGE=CURRENT PAGE NUMBER
      LINE=FREE LINES REMAINING ON THIS PAGE
      COMMON /PAGES/ LINE, PAGE, INFO PG(16), IIOTPT
      PAGE=PAGE+1.
      WRITE(9,11) (INFO PG(J),J=1,16),PAGE
11  FORMAT(1H1,A9,7A10,7A10,A7,F3.0/1H )
      IIOTPT=0
      LINE=59
      RETURN
      END

      SUBROUTINE SKIPLT $ RETURN $ END
      SUBROUTINE STARTER(INFO)
      COMMON /OUT T6/ IN STARTER,OUT T6F,OUT T6H,OUT T6V
      COMMON /OUT T6/KT6,NR T6,INFO T6(6),TYPE T6(6),FMT T6(8)
      COMMON /PAGES/ LINE, PAGE, INFO PG(16), IIOTPT
      DIMENSION INFO(5)
      INFO PG( 1)=1H
      WRITE (H)INFO PG(1)
      BACKSPACE H
      BACKSPACE H

      READ 11,(INFO PG(J),J=2,8)
11  FORMAT(7A10)
      INFO PG( 9)=1H
      CALL DATE1 ( INFO PG(10) )
      CALL CLOCK1( INFO PG(11) )
      INFO PG(12)=10H CODE=
      INFO PG(13)=INFO(1)
      INFO PG(14)=INFO(2)
      INFO PG(15)=10H$WAIN MP=9
      INFO PG(16)=7H PAGE
      FMT T6(1)=3H(8X
      FMT T6(8)=1H)
      LINE=1
      PAGE=0.
      CALL PAGER
      RETURN
      END

```


APPENDIX D

COUPLING OF DRIVE LINE TO BRIDGE COUPLER CAVITY

The following derivation is based on a note by E. Knapp (1968). The coupling coefficient of a transmission line system to a resonant cavity is outlined in many microwave texts, and is given by

$$\kappa = \frac{Q_0}{Q_{\text{ext}}},$$

where Q_{ext} is the equivalent loss to the resonant cavity system introduced by the matched generator driving the line. For cavity match $\kappa = 1$. For a cavity system with beam loading, Q_0 varies as a function of beam current and energy gain as

$$Q_0 = \frac{V^2/R}{(V^2/R) + IV \cos \phi} = 1 - \frac{IV \cos \phi}{(V^2/R) + IV \cos \phi}$$

where V is the effective cavity voltage, R is the shunt impedance, I is the beam current, and ϕ is the phase between V and I . If α is defined as a beam loading parameter

$$\alpha = \frac{IV \cos \phi}{(V^2/R) + IV \cos \phi} = \frac{\text{Beam power}}{\text{Total power}};$$

then

$$\kappa = \frac{1}{1 + V/(IR \cos \phi)}$$

and

$$Q_0 = (1 - \alpha);$$

thus the coupling parameter varies as

$$\kappa = \frac{1}{1 - \alpha}.$$

In terms of the usually measured cavity parameters, field levels and current,

$$\kappa = \frac{1}{1 + (E_0 T)/(ZT' \cos \phi_s \cdot I)}$$

where E_0 is the spatial average of the peak cavity field

$$E_0 = \frac{1}{L} \int_0^L E(z) dz,$$

T is the transit time factor, and ϕ_s is the synchronous angle; $E_0 T$ is the rate of energy gain for a particle crossing the center of the gap at peak field.

Then for LAMF we have $E_0 T = \text{constant} = \frac{1.1 \text{ MeV/meter}}{\cos \phi_s} = 1.27 \text{ MeV/meter}$ for $\phi_s = 30$ degrees.

For $I = 17 \text{ mA}$ we want $\kappa = 1.000$:

$$Q_0 = \frac{1}{(1 - \alpha)} = 1 + \frac{ZT' I \cos \phi_s}{E_0 T} = 1 + 0.0116(ZT').$$

Table D-1 indicates Q_0 required to produce this condition.

TABLE D-1

COUPLING FACTOR

$ZT' (M/m)$	Q_0
20	1.23
25	1.29
30	1.35
35	1.41
40	1.46
45	1.52

The coupling hole should be cut to give a VSWR = Q_0 , overcoupled, and varied along the accelerator to match the local shunt impedance.

TUNING CONDITION FROM COUPLED RESONATOR THEORY

Various models have been proposed for analysis of linac field behavior. Coupled resonator models are based on strings of lumped-element resonant circuits coupled by means of mutual inductance between coils. (See Fig. E-1 for an example.) Extensive analysis has been done on the steady-state behavior of these models (Knapp et al. 1968, Smith 1968, Lee-Whiting 1968, Swain 1969a, Gluckstern 1969, Knapp 1970a). Schriber (1972) gives a method for obtaining exact solutions for bi-periodic models with n th-neighbor couplings using finite difference techniques. The transient response has also been studied (Jameson 1964a-d, 1965; Scott 1968, Knapp 1969, Swain 1969b, Swain and Scott 1970). Although coupled resonator models are phenomenological in nature, they have proved to be a useful analog of structure behavior (Jameson 1965, Knapp 1970a, Swain and Scott 1970, Fraser et al. 1972, Schriber 1975).

In another approach, equivalent circuits have been derived from Maxwell's equations with the field expanded in appropriate normal modes (for example, Gluckstern 1965a-b, Jule and Gluckstern 1973). These models are designated field models in this report. For the 805-MHz linac, the passbands of the structure at or near the operating frequency are narrow enough that the choice of model is not critical - similar results are obtained. Further information on the various equivalent circuit approaches may be found in the survey by Dôme (1970) and the references therein.

Fig. E-1. Coupled resonator equivalent circuit with nearest and next-nearest neighbor coupling and full resonator terminations.

If each resonator in a chain representing part of a linac structure is assumed to be coupled only to its nearest neighbor (a simply coupled chain), either a coupled resonator model or a field model leads to a set of equations of the form

$$-i_n X_n + X_{n-1} + X_{n+1} = 0, \quad n = 1, 2, \dots, \quad (E-1)$$

in which the X_n are normalized phasors representing the resonator amplitudes and phases, and the i_n contain various frequency and circuit parameters. Odd numbered resonators represent accelerating cavities; even numbered resonators, coupling cavities. Resonator number one is the end of the chain; the drive is considered to be at a resonator with n greater than the range used in Eq. (E-1). At the end of the chain, the first resonator is coupled to other resonators only on one side and thus $X_0 = 0$ in Eq. (E-1) for $n = 1$. (This is known as a full-resonator termination, as opposed to the half-resonator termination in which the last resonator ends at a plane of reflective symmetry. Half resonator terminations are not considered in this report. Half-resonator terminations were considered by Potter (MP Division 1971d).)

The dependence of i_n on the parameters varies with the approach or model chosen. For the 0-mode field model (losses neglected),

$$i_n = \frac{1 - (1 - k)(\omega_0/\omega)^2}{(k/2)(\omega_0/\omega)^2} \quad (E-2)$$

while for the coupled resonator model with uniform coupling

$$\alpha_n = (2/k)[1 - (\omega_n/\omega)^2 - j\omega_n/(\omega Q_n)], \quad (E-3)$$

where ω is the operating frequency, ω_0 or ω_n characterize the individual resonator frequency, and k is the amount of coupling between resonators.

For the $\pi/2$ -mode, α is small. Then one may use mathematical induction to verify that the approximate values of the phasors X_n at any position along the chain in terms of X_1 at the end are

$$X_{2m} = \sum_{r=1}^m \frac{1}{2r-1} (-1)^{m+1} X_r \text{ and} \quad (\text{E-4})$$

$$X_{2m+1} = 1 - \sum_{s=1}^m \frac{1}{2s} \sum_{r=1}^s \frac{1}{2r-1} [(-1)^m X_r] \quad (\text{E-5})$$

where terms greater than second order in the x 's have been neglected. An alternative form of (E-5) may be obtained by summing the terms in a different order:

$$X_{2m+1} = 1 - \sum_{r=1}^m \frac{1}{2r-1} \sum_{s=r}^m \frac{1}{2s} [(-1)^m X_r] \quad (\text{E-6})$$

In the absence of frequency errors or losses, the right side of either Eq. (E-5) or (E-6) consists only of the term in the square brackets, a flat distribution in the normalized X_n . The factor in the large parentheses may tilt the field distribution from its idealized flat state. It can be seen that it takes non-zero x terms both for one or more accelerating resonators and one or more coupling resonators to produce a tilt.

Note that since the x 's are small, Eqs. (E-4) and (E-5) show that $X_{2m} \approx X_{2m+1}$, at least when m is small. In other words, the stored energy in the coupling cavities is small compared with the stored energy in the accelerating cavities provided the structure is not made too long.

When the resonators are coupled to neighboring resonators beyond just the nearest resonator in the structure, it is more difficult to calculate the form of the field distribution for the $\pi/2$ -mode (Swain 1969, Lee-Whiting 1968, Schriber 1972). However, one finds that if the resonator frequencies are set correctly, a nearly flat field distribution in the normalized X_n can again be obtained. In particular, for the coupled resonator model with nearest and next nearest neighbor coupling only, one has

$$-\alpha_n k X_n + k(X_{n-1} + X_{n+1}) + K_n(X_{n-2} + X_{n+2}) = 0, \quad n = 1, 2, \dots, \quad (\text{E-7})$$

where α_n is as in Eq. (E-3), k is the nearest neighbor coupling, and

$$K_n = k_a, \quad n \text{ odd},$$

$$K_n = k_c, \quad n \text{ even},$$

with k_a representing the coupling between accelerating cavities and k_c , the coupling between coupling cavities. It is noted that for the desired conditions

$$X_{2m+1} = (-1)^m X_1 \quad (\text{E-8})$$

and

$$X_{2r} = X_{2s+1},$$

then the real part of Eq. (E-7) leads to the tuning conditions

$$X_{2m+1} = 1 - k_a, \quad m = 1, 2, \dots, \quad (\text{E-9})$$

for interior accelerating cavities and

$$X_1 = 1 - 0.5 k_a \quad (\text{E-10})$$

for the end accelerating cavity.

A more complete analysis (Swain 1969) shows that a relation similar to Eq. (E-9) holds for the coupling cavities:

$$X_{2m} = \sqrt{1 - k_c} \quad (\text{E-11})$$

In general, the field distribution is found to be stable if the dispersion curve is linear in the vicinity of the $\pi/2$ mode (Dôme 1970, Andreev et al. 1973, Beringer and Gluckstern 1964). This makes nearby modes approximately symmetrical about the operating point. The coupled resonator model with resonators tuned according to Eqs. (E-9), (E-10), and (E-11) is found to have such a dispersion curve.

Values for the various coupled resonator model parameters for the 805-MHz linac are given in Table B-III of Appendix B. The model used assumes full-resonator terminations, and includes next-nearest as well as nearest neighbor couplings.

FIELD DISTRIBUTION DEPENDENCE ON BEAM LOADING

We use a simple coupled-resonator equivalent circuit (Fig. F-1) to study the effect of beam loading on the amplitude and phase of the field distribution in a linac structure. We let the voltage drop V_b represent the effect of the beam. When we sum the voltage drops around the n th loop we find

$$\begin{aligned} j\omega L I_n + j\omega M I_{n-1} + I_n / (j\omega C) + R I_n \\ + j\omega L I_n + j\omega M I_{n+1} + V_b = 0. \end{aligned} \quad (F-1)$$

We find an alternate form of Eq. (F-1) by dividing every term by $2j\omega L$:

$$\begin{aligned} \left[1 - j\omega_n / (\omega Q_n) - \omega_n^2 / \omega^2 \right] I_n \\ + \frac{1}{2} k I_{n-1} + \frac{1}{2} k I_{n+1} - jV_b / (2\omega L) = 0 \end{aligned} \quad (F-2)$$

where $\omega_n^2 = 1/(2LC)$

$$Q_n = 2\omega_n L / R$$

and $k = M/L$.

Now

$$\begin{aligned} V_b / (2\omega L) &= \left[V_b I_n^* I_n / (2\omega L I_n^* I_n^* R) \right] \\ &= \left[\omega_n V_b I_n^* / (\omega Q_n |I_n|^2 R) \right] I_n, \end{aligned}$$

where I_n^* is the complex conjugate of I_n . Since $|I_n|^2 R$ is the power lost in the cavity, P_c , and $\text{Re}(V_b I_n^*)$ is the power transferred to the beam, P_b , we may write

Fig. F-1. Equivalent circuit for the n th resonator in a linac structure.

$$V_b / (2\omega L) = \left[\frac{P_b}{P_c} (1 + j \tan \phi) / (Q_n P_c) \right] I_n, \quad (F-3)$$

where ϕ is the angle between V_b and I_n in the complex plane.

We now combine Eqs. (F-3) and (F-2) to get

$$\begin{aligned} \left[1 - \omega_n^2 / \omega^2 - j\omega_n / (\omega Q_n) (1 + P_b / P_c + jP_b \tan \phi / P_c) \right. \\ \left. + \frac{1}{2} k I_{n-1} + \frac{1}{2} k I_{n+1} \right] I_n = 0. \end{aligned} \quad (F-4)$$

The effective Q of the resonator when the beam is on is lowered from its value when the beam is off:

$$Q_{eff} = Q_n / (1 + P_b / P_c + jP_b \tan \phi / P_c).$$

Comparing Eq. (F-4) with Eq. (E-1) of the previous appendix, we find

$$\begin{aligned} \omega_n = (2/k) \left[1 - \omega_n^2 / \omega^2 + \frac{1}{2} \frac{P_b}{P_c} (\tan \phi) / (Q_n P_c) \right. \\ \left. - j\omega_n / (\omega Q_n) (1 + P_b / P_c) / (Q_n P_c) \right]. \end{aligned} \quad (F-5)$$

When there is no beam loading, $P_b = 0$, and Eq. (F-5) reduces to Eq. (E-3).

From Eq. (E-6) of Appendix E, we find the field distribution is given by

$$X_{2m+1} \doteq (1 + S_m)(-1)^m X_1,$$

$$\text{where } S_m = - \sum_{r=1}^m \alpha_{2r-1} \sum_{s=r}^m \alpha_{2s}.$$

If $|S_m| \ll 1$, we may interpret

$\text{Re } S_m$ = amplitude droop of X_1 with respect to X_{2m+1} ,

$-\text{Im } S_m$ = phase error (radians) of X_1 with respect to X_{2m+1} .

We assume all accelerating cavities are alike and all coupling cavities are alike. Then using the accelerating cavity α_{2r-1} given by Eq. (F-5) and the coupling cavity α_{2s} given by Eq. (E-3), we find the droop ΔA and phase error $\Delta \phi$ are approximately given

$$\Delta\omega_n = \omega_n + \frac{1}{2} \left(\frac{\omega_a}{Q_a} + \frac{\omega_c}{Q_c} \right)$$

$$= \frac{1}{2} \left(\frac{\omega_a}{Q_a} + \frac{\omega_c}{Q_c} \right)$$

$$+ \frac{1}{2} \left(\frac{P_b}{P_c} \right) \left(\frac{\omega_c}{Q_c} - \frac{\omega_a}{Q_a} \right)$$

$$+ \frac{1}{2} \left(\frac{P_b}{P_c} \right) \left(\frac{\omega_c}{Q_c} - \frac{\omega_a}{Q_a} \right) \left(\tan \phi \right) / (k^2 Q_a Q_c) \quad (F-6)$$

and

$$\begin{aligned} \Delta\omega_n &= \omega_n + \frac{1}{2} \left(\frac{\omega_a}{Q_a} + \frac{\omega_c}{Q_c} \right) \\ &+ \frac{1}{2} \left(\frac{P_b}{P_c} \right) \left(\frac{\omega_c}{Q_c} - \frac{\omega_a}{Q_a} \right) \\ &+ \frac{1}{2} \left(\frac{P_b}{P_c} \right) \left(\frac{\omega_c}{Q_c} - \frac{\omega_a}{Q_a} \right) \left(\tan \phi \right) / (k^2 Q_a Q_c) \\ &+ \frac{1}{2} \left(\frac{P_b}{P_c} \right) \left(\frac{\omega_c}{Q_c} - \frac{\omega_a}{Q_a} \right) \left(\tan \phi \right) / (k^2 Q_a Q_c) \quad (F-7) \end{aligned}$$

where ω_a and ω_c are the accelerating cavity and coupling cavity angular frequencies, $\omega_a = \omega_n + \omega$, and $\omega_c = \omega_n - \omega$. The accelerating and coupling cavity Q's are denoted by Q_a and Q_c respectively.

$$\Delta\omega_n = \omega_n + \frac{1}{2} \left(\frac{\omega_a}{Q_a} + \frac{\omega_c}{Q_c} \right)$$

$$\text{and } \frac{\omega_a}{Q_a} = \frac{\omega_c}{Q_c}$$

were used to simplify the results in Eqs. (F-6) and (F-7).

We now consider the contributions to droop of the various terms in Eq. (F-6). The term

$$\Delta A_1 = 2m(m+1)/(k^2 Q_a Q_c)$$

represents a droop that is independent of beam loading. In practice, this droop is masked by the variation in field due to non-uniformities in the couplings k between resonators. The term

$$\Delta A_2 = -8m(m+1) \Delta\omega_a \Delta\omega_c / (k^2 \omega_c^2)$$

may be ignored for the 805-MHz linac since $\Delta\omega_c$ is small (small stopband) and $\Delta\omega_a$ is very small. (Since most of the stored energy is in the accelerating cavities, the resonant frequency, and hence the operating frequency, is very close to the accelerating cavity frequency.)

To estimate the size of the term

$$\Delta A_3 = 4m(m+1) (P_b/P_c) / (k^2 Q_a Q_c)$$

We use $m = 72$ (number of accelerating cavities on each side of the Drive of Module 5), $k = 0.050$, $Q_a = 16,000$, $Q_c = 9,000$, and $P_b/P_c = 0.29$. We find $\Delta A_3 = 0.0085$, that is, about one percent droop at full current. For Module 48, Q_a is higher and m is smaller, and $\Delta A_3 = 0.0051$, about one-half percent droop.

The term

$$\Delta A_4 = 4m(m+1) (P_b/P_c) (\tan \phi) / (k^2 Q_a Q_c)$$

also depends on beam loading, but will be small if the stopband is small.

We next consider the contributions to phase error. The first term of Eq. (F-7),

$$\Delta\phi_1 = 4m(m+1) \Delta\omega_c / (k^2 Q_a Q_c)$$

will be small if the stopband is small. The second term,

$$\Delta\phi_2 = 4m(m+1) \Delta\omega_a / (k^2 \omega_c Q_c)$$

may be neglected, since $\Delta\omega_a$ is very small, as we saw above.

To estimate the effect of the term

$$\Delta\phi_3 = 4m(m+1) \Delta\omega_c (P_b/P_c) / (k^2 \omega_c Q_c)$$

we take $m = 72$, stopband = 50 kHz, $\Delta\omega_c/\omega = 0.05/805$, $P_b/P_c = 0.29$, $k = 0.05$, and $Q_a = 16,000$. We find the phase error for this beam loading is about 0.5 degree.

The final term,

$$\Delta\phi_4 = -2m(m+1) (P_b/P_c) (\tan \phi) / (k^2 Q_a Q_c)$$

also depends on beam loading. For $|(P_b/P_c) \tan \phi| < 0.29$ for Module 5, $|\Delta\phi_4| < 0.0085$ radians, which is less than 0.5 degree.

STOPBAND AND HIGH-POWER STABILITY

It has been observed on Module 5 of the LAMPF accelerator structures that optimum high-power stability appears to be achieved with the stopband set slightly high. A possible explanation of this effect and some crude estimates of the magnitude of the effect are discussed in this Appendix, which is based on work by E. Knapp (1970b).

Using Eqs. (E-6) and (E-3) for a lossless coupled resonator model, we find the tilt sensitivity for a tank with end cavity perturbations is

$$X_{2n+1} = (-1)^n \left[1 - n \alpha_1 \alpha_c' \right] X_1,$$

$$\text{where } \alpha_c' = -4 \frac{\Delta \omega_c}{k \omega_c},$$

$$\Delta \omega_c = \omega_c - \omega = \text{stopband},$$

$$\alpha_1 = -4 \frac{\Delta \omega_1}{k \omega_1},$$

$$\Delta \omega_1 = \omega_1 - \omega = \text{end cavity frequency error}.$$

The field distribution for various combinations of frequency errors is shown in Fig. G-1. The field at cavity $2n+1$ is held constant by the rf amplitude control system. With a negative stopband, a negative frequency error $\Delta \omega_1$ tilts the distribution toward the $n = 1$ end cavity, which induces a greater field in that cavity. This, in turn, can induce an additional negative frequency error due to excess power dissipation in that cavity. Thus if the stopband is negative, a feedback mechanism exists

Fig. G-1. Field distributions for $\Delta \omega_1 < 0$ and various stopband conditions.

to increase tilt, and if the stopband is positive, a feedback mechanism exists to decrease tilt. Now the initial tilt may be produced by unbalance in coupling, rather than frequency errors. In this case, the original frequency errors may be zero except for a stopband. Then the addition of power will produce relative frequency errors in the cavities which would not be present in a flat tank at high-power. If the stopband is high, the frequency errors will be such as to reduce the fields in accelerating cavities which have high initial fields, and raise the fields in cavities with low initial field values, offsetting the effects of coupling errors. With the stopband low, the coupling constant field errors are increased by the frequency errors. In the case of stopband opened high (positive), the tanks are driven to a flat distribution, e.g., stable. In the stopband low (negative) case, the situation may become divergent and large tilts develop.

To estimate the order of magnitude of the effect under consideration, consider the field distribution produced by a tank which has a frequency distribution as shown in Fig. G-2: one-half the module $\Delta \omega_a$ high in accelerating cavities, other half $-\Delta \omega_a$, stopband $\Delta \omega_c$. Then

$$\alpha_{2r-1} \approx \alpha_a = \frac{4 \Delta \omega_a}{k \omega_a} \quad \text{for } r = 1, 2, \dots, n;$$

$$\alpha_{2s} \approx \alpha_c = \frac{4 \Delta \omega_c}{k \omega_c} \quad \text{for } s = 1, 2, \dots, n;$$

Fig. G-2. Assumed frequency distribution in a module.

and we find using Eq. (I-6) that

$$X_{2n+1} = \left[1 - (n(n+1) \frac{\epsilon_a}{\epsilon_c}) \right] (-1)^n X_1$$

Suppose that we now consider the case where $\epsilon_a = 0$, $\epsilon_c \neq 0$, and we have a coupling constant error in the center cavity so that one-half the module is initially high, the other half initially low, by 10% for a numerical case. Then, the differential heating will produce a frequency error distribution as indicated in Fig. G-2. The magnitude of the frequency error can be estimated from the water temperature versus average rf power data from Module 5. A temperature shift of 4°C (7°F) is required for 100 kW average power operation and a 4°C temperature shift corresponds to a 50 kHz change in cavity frequency. Thus

$$\Delta \omega_a = 50 \text{ kHz} \quad \frac{P_{\text{cavity}}}{P_{\text{average}}} = 10 \text{ kHz}$$

$$2n + 1 = 145,$$

$$n = 72 \text{ accelerating cavities to center of module}$$

$$k = 0.04,$$

and for a 100 kHz stopband we find the accelerating cavity amplitude is changed by 4.1%. Now if the stopband is positive, this reduces the frequency error, and a second iteration (assuming the end cell perturbation is in every cell in the system, which is definitely not true, but which can be used easily in calculations) yields a shift from zero power of 2.5%.

If the stopband is negative, the frequency error is increased. Doing this iteration with the same assumptions gives a final field shift of 7.5%.

The results for several stopbands are shown in Fig. G-3.

While these estimates are very crude, they do seem to give at least order of magnitude agreement

Fig. G-3. Field distribution change for half the module initially ten per cent high and half ten per cent low.

with the observed behavior. These calculations can be made on a digital computer without the assumptions made here, and may lead to a more complete understanding of the effect. It appears that:

(1) Removing initial coupling cavity errors would reduce the stopband offset effect.

(2) Setting the average value of the tanks accurately will help alleviate this problem.

(3) Some additional stability will always be afforded by operating with a small positive stopband.

(4) The stopband in each tank should be set, for this can be a local, as well as a general effect.

(5) As we progress to higher n modules, the effect should decrease as heat transfer from the drift tubes in the accelerating cavities becomes better, and the number of cavities per module decreases.

Calculations of this effect using the coupled circuit model including rf losses confirmed the type of behavior shown in Fig. G-3, but indicated the amplitude changes were smaller than shown above (Swain 1970c).

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The input and output impedances are shown in Fig. 10. The input and output impedances of the amplifier are shown in Fig. 11. The external output impedance is, since the raw data is plotted on the voltage-current characteristic, that will give the potential in μ Vol/cm. The input and output impedances are shown in Fig. 12. The minimum external impedance to the voltage fluctuations,

particular, the effect of a head on the fields in the accelerating cavities is of great importance. In this section, the effect of a head on the fields in the accelerating cavities is studied. The results are given in Appendix F.

1.1.1.1. The effect of a head

Consider a structure with a head and a tail. The head is a cavity of length L_h and the tail is a cavity of length L_t . The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t .

The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t .

APPENDIX F

1.1.1.1.1. The effect of a head on the fields in the accelerating cavities

In the present treatment, each cell is considered as a separate resonator. The fields in the head and tail are treated separately. The following analysis is a simplified one, and is valid only for a head and tail which are small compared with the wavelength of the fields. The dependence of the fields on the structure parameters and estimates for the magnitude of the effects. The analysis is based on work by Slater (1969, p. 11-12), but it is not a full analysis. The situation for the structure, at least, is as assumed by him.

For a structure with N accelerating cells, and with a head causing a perturbation of ϵ_h near the entrance of the first accelerating cavity, it passes through, the perturbation in the resonant frequency of the whole structure is

$$\Delta \omega = \Delta \omega_h / N, \quad (F-1)$$

We may use Eq. (E-6) from Appendix E to find the effects of these frequency perturbations on the fields in the structure,

$$X_{2n+1} = \left(1 - \frac{\epsilon_h}{\epsilon_t} \right) \frac{\epsilon_h}{\epsilon_t} \epsilon_{2r-1} \epsilon_{2s} \left[(-1)^n X_1 \right], \quad (F-2)$$

provided one can determine ϵ_{2r-1} and ϵ_{2s} . Primed quantities are used in the expressions to follow

because of the perturbation in the fields. The fields in the head and tail are treated separately. The following analysis is a simplified one, and is valid only for a head and tail which are small compared with the wavelength of the fields.

The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t . The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t . The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t . The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t .

The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t . The head is connected to the tail by a neck of length L_n . The head is filled with a dielectric material of permittivity ϵ_h and the tail is filled with a dielectric material of permittivity ϵ_t .

$$X_{2n+1} = \left(1 - \frac{\epsilon_h}{\epsilon_t} \right) \frac{\epsilon_h}{\epsilon_t} \epsilon_{2r-1} \epsilon_{2s} \left[(-1)^n X_1 \right], \quad (F-3)$$

where ϵ_{2r-1} and ϵ_{2s} are small.

$$\epsilon_{2r-1} = \epsilon_h / \epsilon_t \quad \text{and} \quad \epsilon_{2s} = \epsilon_h / \epsilon_t, \quad (F-4)$$

With the head present,

$$\epsilon_{2r-1} = \epsilon_h / \epsilon_t, \quad \text{and} \quad \epsilon_{2s} = \epsilon_h / \epsilon_t, \quad n \neq 2s-1.$$

$$\text{Then } \epsilon_{2r-1} = (2/k) \left[1 - \epsilon_h / \epsilon_t \right] (1 - 2 \epsilon_h / \epsilon_t)$$

$$= 1 - \epsilon_h / \epsilon_t (1 - \epsilon_h / \epsilon_t) / (1 - \epsilon_h / \epsilon_t)$$

and

$$\epsilon_{2r-1} = 4 \epsilon_h / \epsilon_t (k) = 2j / (kQ_m), \quad (F-5)$$

For $\epsilon_h = 0.002$ MHz, $k = 0.05$, $\epsilon_t = 805$ MHz, and $Q = 20,000$, the magnitude of the second term in Eq. (F-5) is about 10 times that of the first. These values are typical for accelerating cavities. For coupling cavities, the Q is lower, and the ratio of the terms is even larger. Consequently, from Eqs. (F-4) and (F-5)

It is important to note that the above results are based on the assumption that the data are stationary. If the data are non-stationary, the results may be biased. However, the results are robust to the assumption of stationarity.

[illegible]

The presence of the load has introduced a perturbation of the phase and amplitude of the accelerating cavities from the head to the drive. The change in amplitude is not significant if the head is small, but the phase shift can be significant. Ex. figs.

(1-8) and (1-9) the magnitude of the phase shift is approximately

$$z = a_{-b}(n - b + 1)/(k + Q_G), \quad n = b, \quad (4-16)$$

as observed in cavity $2n + 1$ with the bead in cavi-

1. The first step is to identify the key components of the system. This includes understanding the hardware, software, and data involved.

point is determined by the value of $\tan \alpha_{\text{eff}}$. The maximum relative error in this case is a small measurement of the "sensitivity" of the calibration.

$$0.038 \pm 0.003 \text{ g/g} = 0.038 \text{ g/g} \cdot (1 \pm 0.08), \quad (11-13)$$

where K is the total number of accelerating cavities in the structure, n_{dp} is the number of accelerating cavities the pickup point is removed from the drive point, K is the nearest-neighbor coupling, and α_a and α_c are the Q 's of the accelerating and coupling cavities.

$$\left(\begin{array}{c} \cdot \\ \cdot \\ \cdot \end{array} \right) \left(\begin{array}{c} \cdot \\ \cdot \\ \cdot \end{array} \right)$$

()

It is important to note that the above results are based on the assumption that the data are stationary. If the data are non-stationary, the results may be biased. Therefore, it is important to test for stationarity before conducting the regression analysis.

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^a The number of subjects who were included in each group was determined by the number of subjects who completed the study.

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is presented in Appendix F.

 

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the 1990s, the number of people in the world who are illiterate has increased from 1.2 billion to 1.5 billion. The number of illiterate people in the world is expected to increase to 1.7 billion by the year 2015. The number of illiterate people in the world is expected to increase to 1.7 billion by the year 2015. The number of illiterate people in the world is expected to increase to 1.7 billion by the year 2015.

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the 1990s, the number of people in the United States who are 65 years of age or older has increased by 50% (U.S. Census Bureau, 1997). The number of people aged 65 and older is projected to increase to 20% of the total population by the year 2020 (U.S. Census Bureau, 1997). The increase in the number of people aged 65 and older is expected to be even more dramatic in other countries. For example, the number of people aged 65 and older in Japan is projected to increase from 15% of the total population in 1990 to 25% of the total population by the year 2020 (U.S. Census Bureau, 1997). The increase in the number of people aged 65 and older is expected to be even more dramatic in other countries. For example, the number of people aged 65 and older in Japan is projected to increase from 15% of the total population in 1990 to 25% of the total population by the year 2020 (U.S. Census Bureau, 1997).

1. *Phylogenetic relationships*. The relationships of the members of the subgenus *Phylloscopus* are not clear. The subgenus is monophyletic, but the relationships among the species are not clear. The species *Phylloscopus collybita* is the most closely related to the subgenus, and the species *Phylloscopus trochilus* is the most distantly related.

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the 1990s, the number of people in the world who are illiterate has increased from 1.2 billion to 1.5 billion. The number of illiterate people in the world is projected to reach 1.7 billion by the year 2015. The number of illiterate people in the world is projected to reach 1.7 billion by the year 2015. The number of illiterate people in the world is projected to reach 1.7 billion by the year 2015.

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1. The following is a list of the names of the persons who have been appointed to the various committees of the National Council on the Status of Women, established by the Executive Order of the President, dated June 1, 1961, and the subcommittees thereof, and the names of the persons who have been appointed to the various committees of the National Council on the Status of Women, established by the Executive Order of the President, dated June 1, 1961, and the subcommittees thereof, and the names of the persons who have been appointed to the various committees of the National Council on the Status of Women, established by the Executive Order of the President, dated June 1, 1961, and the subcommittees thereof.

1. The first step is to identify the problem. In this case, the problem is that the company is not meeting its sales targets. The second step is to analyze the data. The third step is to develop a plan. The fourth step is to implement the plan. The fifth step is to evaluate the results.

1993, p. 106). Indeed, "the facilitator for the group is not the 'facilitator,'" says the *Journal of Interpersonal Violence*.

10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846,

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