CAVITY TUNING FOR THE LAMPF 805 MHz LINAC*

by

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ABSTRACT

As the construction of the LAMPF 805-MHz side-coupled linac progressed, tools and techniques were developed for tuning the rf cavities making up the structure. Ten thousand cavities were adjusted to precise frequency settings in a manner that limited field deviations to ± 6% from the average. Pre- and post-assembly tuning procedures are described, including the nose-stretching and dinging techniques. A method for correcting field unflatness using a combination of septum bending and the techniques above is given. Selected results are compared with the theory of the effects of frequency and coupling constant errors on the structure field distribution. Refinements to the computerized beadpull measurement system for rapid determination of field flatness are presented.

I. INTRODUCTION

The Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF) 805-MHz linac is designed to accelerate protons from 100 to 800 MeV, with beam intensities up to 1 mA average. The linac has 104 side-coupled cavity chains, called tanks, which are joined together in sets of four or two to form 44 modules, each driven by a 1.25-MW (peak) klystron amplifier. Each tank has a different cavity geometry, in order to match the increasing velocity of the protons and to optimize the shunt impedance of each structure.

Requirements for satisfactory beam dynamics made necessary the custom tuning of each of the cavities as a part of the fabrication and installation of the linac structures. For brevity in this paper, accelerating cavities will be called main cells and side-coupling cavities will be called

coupling cells. Some details of the structure tuning process have been given in a previous paper[1] and will not be repeated here. As the construction of the linac progressed, improvements to the tuning process were incorporated when needed or desirable. The procedure set forth in Part II below represents the final evolution of the tuning process. The 805-MHz linac tuning was started in January, 1970, and completed in April, 1972. Two to four 2-man crews of tuning technicians did the tuning after the proper strategy had been determined.

The two or four tanks comprising one driven module are joined by special cavities called bridge couplers. The bridge couplers are above the beam line and allow space for quadrupole beam focusing magnets. The bridge couplers also vary in geometry along the linac. The design and adjustment of these bridge couplers in order to preserve correct tank-to-tank phase, to present a satisfactory standing wave ratio to the input wave guide, and to suppress unwanted cavity modes is discussed in a companion paper.[2]

In Part III of this paper, the relation of coupling and frequency errors to the field distribution is studied and refinements to the beadpull measurement system for rapid and accurate determination of field flatness are given.

II. CAVITY TUNING

A. Tuning Requirements

Computer studies of beam dynamics indicated that the averages of the field distribution might vary up to ± 2% from tank to tank without seriously degrading the beam. Further, individual cells might be high or low in field as much as 10% without seriously degrading the longitudinal dynamics provided that the tank averages agreed within ± 2%. Also considered was the initial turn-on, at which time the absolute settings for phase and amplitude for each module would not be known. The computer studies indicated that as the tank-to-tank average amplitude tolerance was increased from ± 1% to ± 6%, the probability of acceptable beam acceleration varied from very good to very poor.

The stability of the field distribution in the π/2 mode depends on the products of main cell and coupling cell frequency errors and the amount of power being transmitted along the structure.

Provided the structure is tuned and cooled correctly, the power transmission effects are mainly confined to the coupling cells. Since only one main cell is sampled for the dynamic amplitude and phase control system, it is crucial that the relative field levels in the main cells remain constant over the operating regime. The resonant frequencies for the tanks within any one module should agree since there is but one water cooling system per module.

For the above reasons, it was decided to make the average field agree to ± 2% from tank to tank, to limit the individual main cell field deviation from average to ± 6% within any tank, to tune main cells within ± 10 kHz, and to tune coupling cells such that stopband was less than 40 kHz, and initially not negative.[3] (It appears the stopband tends to move negatively for a time after tuning.) In fact the tank-to-tank averages were made to agree to less than ± 1% for most of the linac.

B. Tuning Procedure

1. **Pre-braze Tuning.** Each main cell is formed by the void between pairs of machined copper forgings, called segments. Initially, main and coupling cell parts for a chain of about 11 cavities were clamped and stacked together, and the gap dimension was found to place the stack π/2-mode frequency between 800 and 802 MHz. The dimensions of the coupling cell parts, called clamshells, that brought the stopband to 1 MHz or less were determined. All coupling cells of the same type were then machined to the same gap dimension. (The linac used 12 different sizes of coupling cells.) The sensitivity of coupling cell frequency to gap dimension was of the order of one MHz per mil.

The tanks were made in sections short enough to fit in the brazing furnaces, about 1.8-m (70-in.) long. After the main cell segment noses had been machined to a uniform profile with the half gap determined above, the segments for a complete section were stacked in a long fixture and the half gap remachined as necessary to bring the π/2-mode frequency up to 804.9 ± 0.15 MHz at 72°F before brazing. The sensitivity to change in gap was about 100 kHz per mil at the high energy end of the linac. In a few cases it was necessary to reduce the frequency to enter the above range. For these cases, either the cell inside diameter was slightly enlarged (which has about the same sensitivity), or

the segments were shortened (which lowers the frequency about 5 kHz per mil). The latter was done only for groups of segments which were initially longer than nominal length.

2. Post-braze Tuning Before Installation. After brazing, each section was measured to determine the $\pi/2$-mode frequency and individual main cell frequencies at 72°F. Because of the presence of direct coupling, that is coupling directly between adjacent main cells, the $\pi/2$-mode frequency differs from the average of the main cell frequencies. Information from the above measurements was used to calculate the amount of direct coupling and thus infer what the individual cell frequency should be such that the $\pi/2$-mode frequency would be 804.930 MHz. (A section filled with nitrogen gas at atmospheric pressure resonating at 804.930 MHz at 72°F resonates at about 804.834 MHz at 85°F, the design operating temperature, and at about 805.000 MHz at 85°F under vacuum.)

The pre-braze procedure insured that most main cells would be low in frequency. Brazing caused a shift in frequency, usually down. A downward shift of over 400 kHz was found in a few cases. Occasionally some cell frequencies would be left too high in frequency after brazing. Main cells which were low were brought up to 30 kHz below the calculated individual cell frequency. Main cells which were high in frequency were left high until final tuning, explained below.

Main cells were raised in frequency by making smooth indentations (known at LAMPF as dings) in the outer surface along the diameter thus reducing the cell volume in a predominently magnetic field region. The dinging tool used for this incorporated a small hydraulic press. The dings were usually obliterated when the sections were milled for installation of cooling water channels.

3. Final Tuning. After the completed sections were installed in the support rails in the beam tunnel and the connections to the cooling system were plumbed in, the coupling cells were tuned by wedging the bosses farther apart or tapping the cells with a lead mallet to bring the bosses closer together.[1] By this means, the cell frequencies were set within 10 kHz of a desired individual cell frequency obtained by extrapolation from previous data. The stopband had to be left

high by an empirically determined amount (60 to 200 kHz) to compensate for the fact that coupling cells deformed slightly when evacuated, lowering their frequency.

The $\pi/2$-mode frequency and individual main cell frequencies for each tank were then measured at 85°F. A new calculation of the desired individual main cell frequency corresponding to a $\pi/2$-mode frequency of 804.834 MHz was made using this data. The individual cell measurements were also checked against previous measurements at this time to detect gross errors. The main cells were tuned within 5 kHz of the calculated individual cell frequency by one of two methods, dinging or nose stretching, as explained below. Fig. 1 shows the individual main cell frequencies used along the linac. Within a region having the same coupling cell type, the individual cell frequency varies fairly slowly with change in geometry along the accelerator. The direct coupling variation responsible for this behavior was not smooth enough, however, to permit extrapolation of main cell tuning frequency.

a. Dinging. Main cells which were low in frequency were raised by making indentations in the cell wall along the diameter. It was found that a blunted cold chisel tip would fit between the cooling water passages. A single sharp blow on the special chisel with a mallet would change the frequency 10 to 20 kHz. Repeated blows had reduced effect due to work-hardening of the copper. A total frequency shift for a single main cell as much as 500 kHz was achieved in a few cases. For approximately 1000 cells tuned in this manner, only one instance was encountered in which dinging may have caused a vacuum leak. The leak was very small.

It was necessary to retune coupling cells in areas where severe main cell dinging had been done.

b. Nose Stretching. A new tool was designed to lower the frequency of main cells which were too high in frequency. The tool makes a groove inside the beam hole joining a pair of main cells (see Fig. 2). A conical expander forces a cutter wheel to press into the wall of the hole. The groove is made near the end of one of the noses, and deforms the copper nose enough to lower the cell volume in a high electric field region. One full application of the tool lowered the frequency 400 kHz or more. Backing the tool into the nose and

making a second groove lowered the frequency as much as 200 kHz more. Thus by applying the tool to both noses, the frequency of a given cell could be as much as 1.2 MHz.

The frequency was measured by inserting a swept-frequency signal by means of the loop on one of the magnetic-probe-and-short assemblies and picking up and detecting the peak response from the other probe-and-short. Since the nose stretching tool perturbs the cell frequency when it is in working position, it was necessary to loosen the expander (using extention rods fitting inside the extensions of the tool itself) and to back out the tool slightly to obtain an absolute frequency measurement.

c. Field Flattening Strategy. In a few cases the random variation in the field amplitudes due to coupling constant variations within a tank resulted in a peak-to-peak amplitude variation of more than 10%. In addition, it was desired to re-tune certain two-tank modules previously tuned by septum bending[1] alone, some of which had peak-to-peak variations in excess of 10%. For these cases, a combination of dinging, nose stretching, and septum bending was used to flatten the field dis-tribution. Septum bending affects the ratio of nearest-neighbor coupling constants and hence the local tilt in the field distribution by about one-quarter percent per MHz correction by septum bend-ing (Fig. 3). Dinging and nose-stretching have little effect on the local coupling. Thus by in-troducing deliberate frequency errors by dinging and nose stretching and then removing the errors by retuning by the septum-bending technique, the frequencies were left at correct values and at the same time the local field distribution was made to tilt in a direction such as to flatten it. The appropriate strategy was developed prior to the commencement of metal bending in each case. One or two iterations of this flattening procedure was always sufficient to bring the maximum deviation within the desired tolerance.

After tuning, each module's field distribution was checked by a beadpull measurement under rough vacuum (to be discussed in Sec. III-B), and if the distribution was not satisfactory, further tuning would be done to bring the maximum deviation from average down within ± 6%. In addition, the final

beadpull measurements included the setting of a notched post in the bridge couplers to force the different tank averages within a module to agree within ± 2%. Usually agreement to less than ± 1% was achieved. An example of the field distribution before and after tuning main cells is shown in Fig. 4.

III. FIELD DISTRIBUTION IN CAVITY CHAINS
A. Use of the Theoretical Coupled Resonator Model to Study Field Distribution

1. Assumptions. A simple lumped element circuit model with mutual inductance representing the coupling between resonators has been extensively analyzed.[4-7] When this model has been employed for the understanding of side-coupled accelerator struc-ture behavior at LAMPF, the following assumptions were made:

(a) The coupling between resonators was a slow function of frequency.

(b) If the resonators were not deformed near the coupling slot, changes in cell frequency would not change the resonator-to-resonator coupling appreciably. (The form of the equations of the model may change if this assumption is not valid.[8])

(c) The variation remaining in the field dis-tribution after the individual resonators were correctly tuned in frequency was the result of variations in coupling along the structure.

2. Frequency Error Effects. The usefulness of the model for determining frequency tuning strategies is explored by the following comparison of calculated and measured results. The field distribution for the second tank of module 28 was calculated from the individual main cell resonant frequencies, measured before final tuning, and assuming uniform coupling. The actual pretuning field distribution was also measured using the beadpull method. Final frequency tuning was then done by dinging and nose stretching; septum bending was not used. (Recall that septum bending deforms the cells near the coupling slot, while dinging and nose stretching do not.) The calculated pre-tuning field distribution was then compared with the ratio of the measured pretuning distribution to the measured distribution after tuning. Under the above assumptions, taking this ratio is equiva-lent to eliminating any non-uniformity in coupling.

The individual cell ratios in the ratio of measured distributions varied up to 22%, which agreed with the calculated result to within ± 3%. This includes measurement error, estimated at ± 0.5%. This result indicates that the assumptions are reasonably valid in actual practice with the use of selected tuning techniques. While the agreement is not precise enough to allow prediction of a field distribution to within ± 2% from frequency measurements, one may certainly use the model with some confidence to explore general trends. For example, it appears reasonable to use the model to estimate the order of unflatness caused by given main cell frequency errors and stopbands, as has been done previously.

A simple formula is available for estimating the effects of frequency errors on the field distribution of the $\pi/2$ mode for a simply coupled chain of resonators. With proper normalization, the coupled resonator equations may be cast in the form

$$-\alpha_n X_n + X_{n-1} + X_{n+1} = 0 \quad , \qquad (1)$$

where the X_n are normalized cell amplitudes ($X_0 = 0$), and the α_n contain the various circuit parameters. (This model assumes the chain ends with a full cell, not a half cell.) For uniform coupling,

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

in which ω is the operating frequency, k is the coupling, and ω_n and Q_n are the cell frequencies and Q's. The index n increases going toward the drive point. The normalization factors for the X_n depend only upon the coupling constants for cases where the coupling is not necessarily uniform. For the $\pi/2$ mode, the α's are small, and one may use the assumption $\alpha_i \alpha_j \ll 1$ with Eq. (1) to obtain the distribution for the main cells (odd n):

$$X_{2n+1} = \left(1 - \sum_{p=1}^{n} \alpha_{2p-1} \sum_{m=p}^{n} \alpha_{2m}\right)\left[(-1)^n X_1\right] \quad . \qquad (2)$$

In the absence of frequency errors or losses, the right side of Eq. (2) consists only of the term in the square brackets, a flat distribution in the normalized X_n. The factor in the large parentheses in Eq. (2) tilts the distribution from its idealized

flat state. It can be seen that it takes non-zero α terms both for one or more main cells and for one or more coupling cells to produce a tilt.

Equation (2) is a very compact statement of the effects of frequency errors. An example of its usefulness is given in Section B-2.

2. Coupling Constant Error Effects. Similar analysis of coupling constant effects is possible. Figure 4 illustrates assumption (c) above. In a few tanks, these remaining field variations after tuning, the result of manufacturing tolerances, were unacceptable. However, the septum-bending technique, which violates assumption (b), can be employed as explained above to achieve a satisfactory distribution.

B. Measurement of Field Distribution.

The field distribution for each module at LAMPF was checked after tuning by the beadpull method[1,9] at low power. The stability of the field distribution as indicated by the field detected at 7 or more main cells was also checked at design power for various duty factors. The following remarks concern the beadpull measurement. The field along the axis of the beam hole is calculated from the measured change in resonant frequency of the module due to a short conducting needle suspended at the point of interest. The resonant frequency is determined by making the module part of a loop which includes sufficient amplification to oscillate.

1. Physical Arrangement. After the vacuum manifolds were installed, the string would be threaded through a tuned-up module as shown in Fig. 5. In order to permit the measurement to be done with the module under rough vacuum (1000 microns or less), the string passes through teflon bushings at each end of the module. This arrangement was easy to set up, as the string passed only once through the beam hole, and ran smoothly as a continuous loop. Various schemes with the string moving between reels entirely in vacuum were tried and proved to be jerky in operation. The single-string scheme finally adopted has less frequency perturbation due to the string and was easier to thread up than the double-string scheme[1] initially used.

The bead was formed from aluminum foil, about 5-mm long. Such a bead caused a perturbation of about 2 kHz in module frequency.

2. Electrical Considerations. In order to obtain 0.5% accuracy in the measurement of field distribution, elements which have a nonlinear phase shift variation with frequency must not be included in the oscillating loop. For example, a bandpass filter must have a linear phase shift behavior over the range of frequencies produced by the bead as it traverses the structure. Furthermore, any part of the structure traversed by the bead should not be on the main path of the oscillating loop, since the bead produces a phase shift along the structure itself as well as perturbing the oscillating frequency. When Eq. (2) is used to estimate this phase shift, one finds that depending on bead position, a relative error from zero up to

$$e_{max} = 4Nn_{dp} \left/ \left(Q_a Q_c k^2\right)\right. \qquad (3)$$

is produced, where N is the total number of main cells, n_{dp} is the number of main cells 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 main and coupling cells. This error was avoided for the measurements at LAMPF by both driving and picking up the signal at the center bridge couplers (pickup at probe E in Fig. 5).

Figure 6 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. Substituting N = 128, n_{dp} = 48, Q_a = 20000, Q_c = 8000, and k = .046 in Eq. (3), one finds e_{max} = 7%, in excellent agreement with the measured difference of 8%.

3. On-line Computer Reduction of Beadpull Data.

Because of the enormous amount of data to be analysed and the time involved in making a beadpull determination of tank tuning, it was deemed desirable to computerize the reduction of data as the beadpull was being made. A minicomputer with 8000 words of memory was used.

The input to the computer consists of a difference frequency between a stable reference oscillator and the resonant frequency of the amplifier-tank loop. This difference frequency (which is normally around 10 kHz) is perturbed a maximum of about 20% by the metallic bead.

The computer plots this difference frequency as the bead is pulled at a uniform rate through the tank. When the bead is between tank cells, this difference frequency is simply the baseline value. With the bead in the center of a cell, the change in the difference frequency reaches a peak. In practice, the data rate to the computer is adjusted so that approximately one hundred samples of difference frequency per cell are taken. The peak values for each cell are determined by averaging the top four peak points. The peak field values are determined by taking the square roots of these peak frequency differences. In addition to the peak values, it is desirable to know the accelerating field averaged over each cell, which is proportional to the summed square roots of each frequency difference value for the entire cell. The computer keeps a running total of the sum of the square root values of this difference frequency for each cell. Because this is a sum of square roots, it is obviously very sensitive to the contribution of small frequency differences when the bead is near the edge of the cell at each end (i.e., is near the baseline frequency), and great care must be taken in determining the baseline value to be used for each cell. Unfortunately, this baseline value tends to drift slowly due to temperature fluctuations, so the computer must also compensate for this drift. The baseline value is determined anew for each cell, and drift correction is applied, by fitting the sixteen lowest frequency difference points to a parabolic curve at the valley points of the plot. In this way, extremely reproducible and accurate results are obtained.

The computer then plots on a storage scope the peak field values for each cell, the weighted cell averages, and the average values of these parameters for each tank in the module.[9]

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tures," IEEE Trans. Nuclear Sci., NS-18, No. 3, 614-618 (June 1971).

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7. G. R. Swain and L. D. Scott, "Calculation of the Transient Response of Long Chains of Slightly Lossy Coupled Resonators," IEEE Trans. Nuclear Sci., NS-17, pp. 10-13 (Aug. 1970).

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Fig. 2. Cross-section of side-coupled linac with nose-stretching tool and probes for cell frequency measurement in place.

Fig. 3. Field tilt per frequency change when tuning main cells by septum bending; empirically determined.
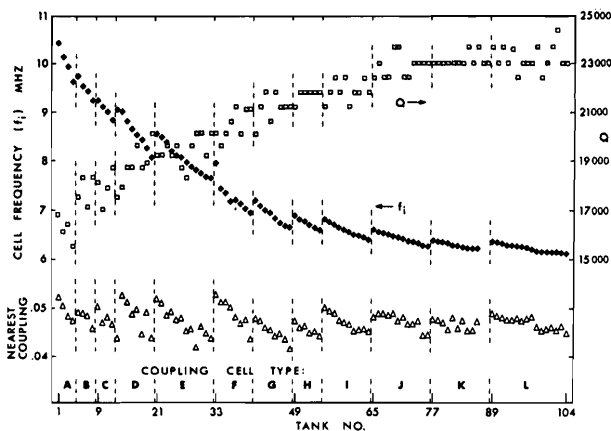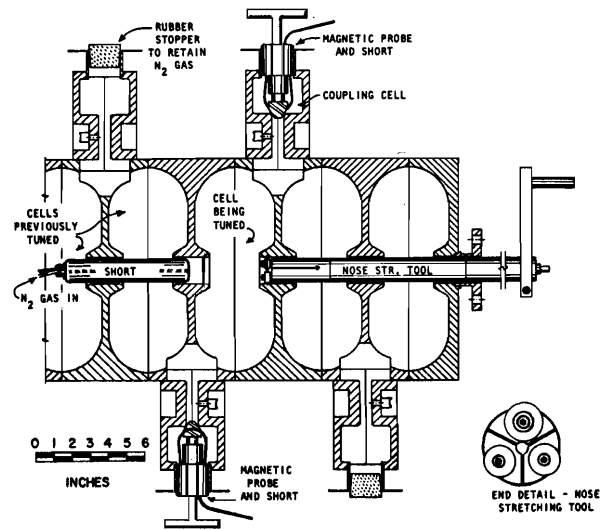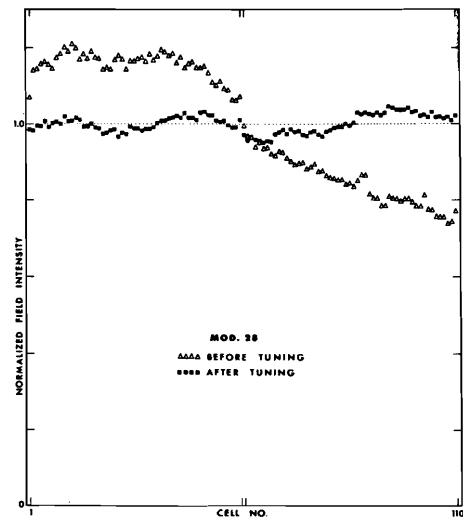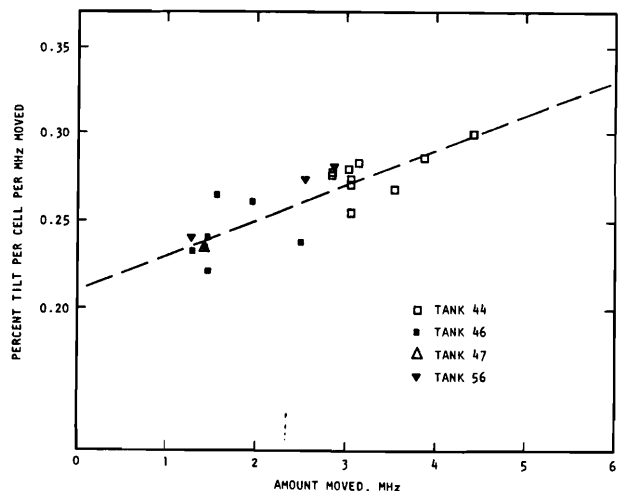

Fig. 1. Variation of tank parameters along the LAMPF 805 MHz linac. Beta varies from 0.43 for tank 1 to 0.84 for tank 104.

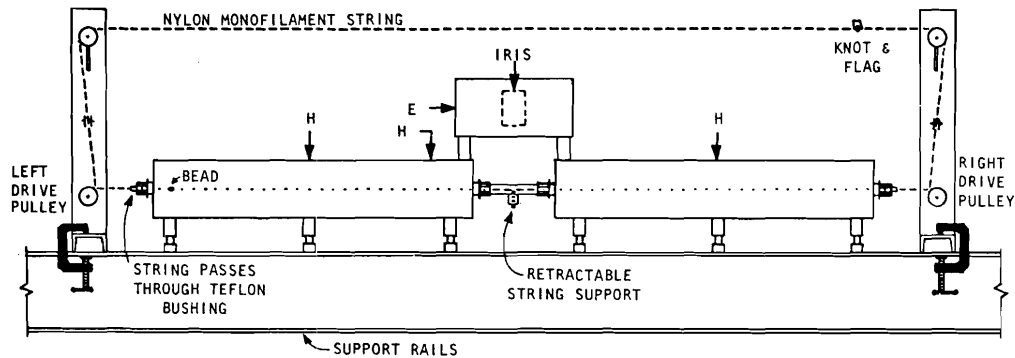Fig. 4. Measured field distribution before and after tuning main cells for module 28 of LAMPF.

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Fig. 5. Beadpull apparatus for measuring the field distribution in a linac module under rough vacuum. RF drive is supplied at the center iris; pickup is at electric probe E. Magnetic probes H are not used.
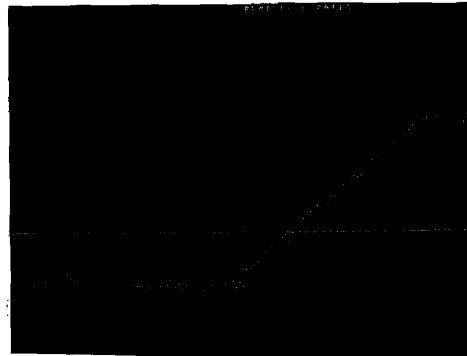

Fig. 6. Point-by-point ratio of a beadpull with pickup point midway along the fourth of four tanks to a bead pull with pickup point at the center bridge coupler. The range shown is from 90% to 110% of average.

DISCUSSION

Loew, SLAC: What would you do if you were starting to build all over again?

Swain, LASL: We would change the inspection procedures to improve the uniformity of the coupling. We would consider adding adjustable parts to control the coupling or correct the field distribution.

Low: What were the tolerances on the coupling aperture and how tight would they have to be to completely avoid tuning?

Swain: The tolerances were 5 or 10 mils, but some of the curvatures were not measured or specified.

Rosen, LASL: It would be too costly to build this type of structure with such high tolerances that no tuning would be necessary.

Schriber, AECL: Were any rf tests done to directly check the symmetry of the coupling to each main cell?

Swain: No, but we feel that the septum-bending technique indirectly checked the symmetry.

Bobylev, ITEP: If you were to start over again, what type of structure would you use?

Swain: We would reconsider all the possibilities, but we are happy with the structure which we used.

Miller, SLAC: Could you review the procedure used to decide on the structure?

Livingston, LASL: Most of these answers are in the "History of LAMPF," which I have recently written.

Joho, TRIUMPH: Would you rather have an odd frequency ratio such as 5:1, or the 4:1 ratio actually used?

Swain: Yes, I think so.

Wilson, SLAC: What sort of tolerance on the coupling constant is found to be required from the coupled cavity model?

Swain: The coupling errors cause variations in field amplitude. Most of our field variations are acceptable after a single tuning and the remaining ones are corrected as outlined above.

Potter, LASL: We found about a 0.1% average variation in each cell, but there were systematic effects which were cumulative and which could have been eliminated by modifying the assembly procedure.

Swain: Yes, for example, the cells could be machined in a consistent fashion and then assembled alternately to eliminate these cumulative effects.