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STABILIZATION OF THE DRIFT TUBE LINAC BY OPERATION IN THE $\pi/2$ CAVITY MODE*

By

D. A. Swenson

E. A. Knapp

J. M. Potter

E. J. Schneider

University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

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The conventional drift tube linac structure, shown on the left side of Fig. 1, can be considered as a series of accelerating cells coupled one to another to form a linac tank. This structure may be analyzed in terms of a simple chain of coupled resonators. A chain of N such resonators can be excited at N different frequencies each corresponding to a different cell-to-cell phase shifts φ. The resonant frequencies and the corresponding phase shifts of these N modes are shown as dots on the mode spectrum at the lower left in Fig. 1. All existing proton linacs operate in the "0" mode indicating a zero phase shift in the accelerating fields from accelerating cell to accelerating cell. It has long been recognized that the field distribution of this particular cavity mode, while having the desired configuration, is very susceptible to perturbations such as mechanical detuning and beam loading. This is primarily due to poor energy propagation characteristics of this mode.

I will now describe the resonantly coupled linac structure[1] shown on the right side of Fig. 1. We have developed resonant coupling devices which when inserted in the sides of the conventional linac strucutre, produce vast improvements in its performance. The resonant couplers are shown here to be mounted on the walls of the cavity directly opposite the drift tubes and alternating from side to side of the cavity. The circuit analogue for this struture takes the form of a biperiodic chain of coupled resonators. The large rectangles represent the main accelerating cells, while the small rectangles represent the resonant coupling devices. In the example given here there are 6 main resonators and 5 coupling resonators for a total of 11 coupled resonators producing a mode spectrum with 11 modes distributed as shown. The field distributions in the $\pi/2$-mode of this structure are very similar to the field distributions in the 0-mode of the conventional linac. In this mode, the accelerating cells are fully excited and the coupling cells are unexcited. Furthermore, the electric fields have the same direction in all accelerating cells, just as in the conventional linac. You might think from the $\pi/2$ terminology, that the electric fields in adjacent accelerating cells would be in opposite directions. There is, however, a phase shift of $\pm\pi$ associated with the geometry of the resonant coupler. The total phase shift from accelerating cell-to-accelerating cell is then $\pi/2 \pm \pi + \pi/2$, giving a total phase shift of 0 or 2π.

The analysis of a biperiodic chain of coupled resonators with nearest and next nearest neighbor couplings[2,3,4] leads to a dispersion relation of the form shown on Fig. 2. This relation often yields a mode spectrum having two passbands separated by a stopband as shown on the left in Fig. 2. In this case, the upper passband corresponds to modes where most of the stored energy is in the main accelerating cells, and the lower passband corresponds to modes where most of the stored energy is found in the resonant coupling cells. If the resonant frequencies of the coupling cells are increased, the lower passband moves up, and at one point, the stopband disappears and the two passbands join together giving the mode spectrum shown on the right in Fig. 2. The coupled resonator theory predicts the stability of the field distributions in the $\pi/2$-mode to be inversely proportional to the stopband. In the case with no stopband, the resonantly coupled linac is vastly superior to the conventional linac from the standpoint of the stability of the fields against perturbations such as mechanical detuning and beam loading, and from the standpoint of cell-to-cell phase shifts associated with power flow.

The resonant couplers must have a geometry such that they are unexcited by the desired field distributions and excited by other field distributions. There is at least one family of resonant couplers that have these properties, two members of which are shown in Fig. 3. The distinctive feature of this family is an inductive stem mounted normal to the outer wall of the linac cavity. The "T-bar" coupler represents one end of this family, where the inductive stem is short and capped with a plate to increase the capacity of the end of the stem to the cavity wall and drift tube. The "post" coupler respresents the other end of the family, where the inductive stem is long and the capacity of the resonant circuit is just the capacity of the end of the stem to the drift tube and cavity wall. In either case, the resonance considered is the one where currents oscillate up and down the stem charging and discharging the end of the stem with respect to the cavity wall and drift tube.

The most favorable location for these couplers seems to be at the points on the outer wall of the linac cavity that are aligned with the centers of the drift tubes and oriented $\pm 90^\circ$ from the drift tube stems. If the latter are in the vertical plane, the couplers would be in the horizontal plane. Furthermore, the nature of the coupling between adjacent resonant couplers is such that adjacent couplers must be located on opposite sides of the cavity as shown in Fig. 1.

We have tested several models of this resonantly coupled linac structure. Our most recent work has been on the 35-cell model shown in Fig. 4. This model consists of a 24-ft long piece of 14-in. diameter aluminum pipe loaded with 34 full drift tubes and 2 half drift tubes. Each cell of this model is of a different length. The cells at the far end correspond to a synchronous energy of 40 MeV and the cells at the near end correspond to a synchronous energy of 100 MeV. The model resonates at about 500 MHz. Figure 5 shows an interior view of this model fitted with post couplers.

The field distributions in our models are measured by the bead perturbation technique. Figure 6 shows the results of a typical bead perturbation measurement. As a metallic bead is pulled along the axis of the tank, the resonant frequency of the tank varies by an amount which is proportional to the square of the electric field at the position of the bead. Figure 6 is obtained by recording the resonant frequency of the tank while pulling the bead along the axis. The absolute field distributions are not too meaningful, since crude alignment of drift tubes and couplers introduces tuning and coupling errors, causing non-flat field distributions in the tuned-up case.

The stability of the fields, however, to programmed errors in the end cells is meaningful, and constitutes our primary test on the performance of the system. We measure the field distribution in the tank with the normal end cell geometry. We then raise the resonant frequency of one end cell by a certain amount, and lower the resonant frequency of the other end cell by the same amount. We then measure the field distributions in the tank, and observe the change in the distributions as a result of the end cell perturbations. As a measure of the field distributions, we define a tank tilt to be the difference between the electric fields in the end cells divided by the average of the fields of the end cells.

On Fig. 7, we see the results of such a series of measurements. In the conventional structure, the tank tilt changed 85% for 1 MHz end cell perturbations. With the post couplers installed and adjusted properly, the tank tilt changed only 4% for 3.5 MHz end cell perturbations. In this case the field stability has been improved by a factor of 75 over the conventional structure. With continued fine adjustment of the post couplers, an improvement in tank stability of 200 was achieved. On the left of this figure, we see a portion of the mode spectrum in the vicinity of the $\pi/2$-mode for the tuned-up case, and indeed the stopband is closed.

It is possible to have high stability end-to-end as described above without having high local stability. In order to achieve high local stability, the individual couplers must be tuned so that the stopband is closed locally along the full length of the tank. A method for adjusting the individual resonant couplers to this condition was developed from the results of the coupled resonator analysis.[5] The method is based on a perturbation experiment of the type described above. A plot of the percentage change in fields in each cell, resulting from the end cell perturbations, as a function of cell number provides information on the local coupler tuning situation. Coupler tuning errors can be related to the slope of this curve. Using this information, it is a straightforward process to achieve high local (and end-to-end) stability in the 35-cell model.

In the case where the stopband is perfectly closed, the field distributions may differ from the desired distribution as a result of the variable cell length and other perturbation such as frequency tuners, drive loops, vacuum ports, etc. Due to the extreme stability of the fields, it is impractical to attempt to change this field distribution by tuning the main accelerating cells. On the other hand, it is reasonable to expect the field distribution to be sensitive to eccentricities in the coupler geometry.

We have tested an eccentric tab on the post coupler which could be rotated to adjust the eccentricity and consequently the field distributions. In Fig. 8, we see a picture of this post and its eccentric tab. At full scale, the diameters of this post would be one inch, and the extension of the tab would be one inch.

With 34 of these posts installed in our 35-cell tank, we obtained the data shown in Fig. 9. With all tabs pointed to the left the fields on the left end went down 50% and the fields on the right went up 50%. With all tabs pointed to the right, the fields tilted the same amount in the other direction.

Prior to this development, a cavity stabilization scheme was developed by researchers at BNL[6] utilizing multiple stems for the drift tube support. This system may be analyzed as a $\pi/2$-mode system in a manner similar to that described above. Either scheme can provide adequate improvements in the stability of the field distributions of the linac structure. We feel, however, that the stabilization scheme described in this paper has several advantages over the multistem scheme. The power dissipation on the post couplers can be quite small, making only a minor change in the efficiency in order to effect the cavity stabilization. The post couplers are readily tunable, have no mechanical interactions with the drift tubes, and allow access to the interior of the linac without disturbing the coupling mechanisms.

References

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2. D. E. Nagle, E. A. Knapp and B. C. Knapp, "A Coupled Resonator Model for Standing Wave Accelerator Tanks," to be published in RSI.

3. J. M. Potter, "An Elementary Perturbation Analysis Applicable to Resonant Coupled Accelerator Structures," (MP-3/JMP-3, June 6, 1967), unpublished.

4. G. R. Swain, "Analysis of Multiply-Coupled Resonators Using a Matrix Formulation," (MP-3/GRS-7, July 10, 1967), unpublished.

5. E. A. Knapp, "On a Method of Tuning the Resonant Couplers in a Drift Tube Accelerator," (MP-3/EAK-1, June 16, 1967), unpublished.

6. S. Giordano and J. P. Hannwacker, "Measurements on a Multistem Drift Tube Structure," Proceedings of the 1966 Linear Accelerator Conference, Oct. 3-7, 1966, Los Alamos, N. Mex., LA-3609, p. 88.

DISCUSSION (condensed and reworded)

E.D. Courant (BNL): In view of the improvement in stability or in mode spacing that you have in this scheme, would you build linac tanks longer and fewer in number than you would using the straight Alvarez structure?

Swenson: The tank lengths are matched to the power sources at the moment, so I see no reason to change the tank length. But one gains a great deal in terms of field stability with regard to beam loading and phase shifts from cell to cell needed to propagate power for the length of the tank. The field distributions are insensitive to tuning errors in the accelerating cells, so that one may take some advantage of this in the construction of the tank, but I don't count heavily on that.

M. Puglisi (Frascati): What is the variation of the Q of the tank due to the introduction of resonant couplers?

Swenson: It is entirely consistent with the power losses expected just by introducing a rod into the TM_{010} mode.

J.E. Leiss (NBS): These improvements are very impressive, but these are always on the field strength and one can tilt it by changing tabs. Has anyone looked at what happens to the phase shift in the process because π of it is put out through the rods. I wonder what local perturbations in phase shift might be going on.

Swenson: This causes power to flow to redistribute the field so that the coupler itself is no longer excited. For instance, in a short cavity consisting of two half-cells with one drift tube in the center and a coupler underneath, if some eccentricity is introduced by offsetting, the fields in this very short linac tank are 15% higher on one side than on the other. Due to the eccentricity in the coupling constants from one side of the cavity to the other, an excitation sets up fields which pump power such that large fields with a small coupling constant are equal to small fields with a large coupling constant.

We don't intend to use the eccentric tab to introduce a sloping field, but if for instance a drive loop or tuning slug causes local perturbations such that the natural distribution of fields in a resonantly coupled linac is askew, we then use the eccentricities to bring back the uniform distribution. We would use a little controllable eccentricity just to remove other eccentricities which might be inadvertently introduced into the structure.

There is a concern about what happens in a long tank if these things become excited. Do they produce fields which deflect the particles? We have to be concerned about this, as Brookhaven people are. We have measured the field distributions; in the modes when the posts are excited there are very small fields in the gap where the particles are, but there is some little field there. That, however, is an artificial situation because this is a mode where they are excited; in a $\pi/2$ mode the posts are certainly unexcited to a first order. We have not been able to measure any excitation of the posts in a reasonably tuned case.

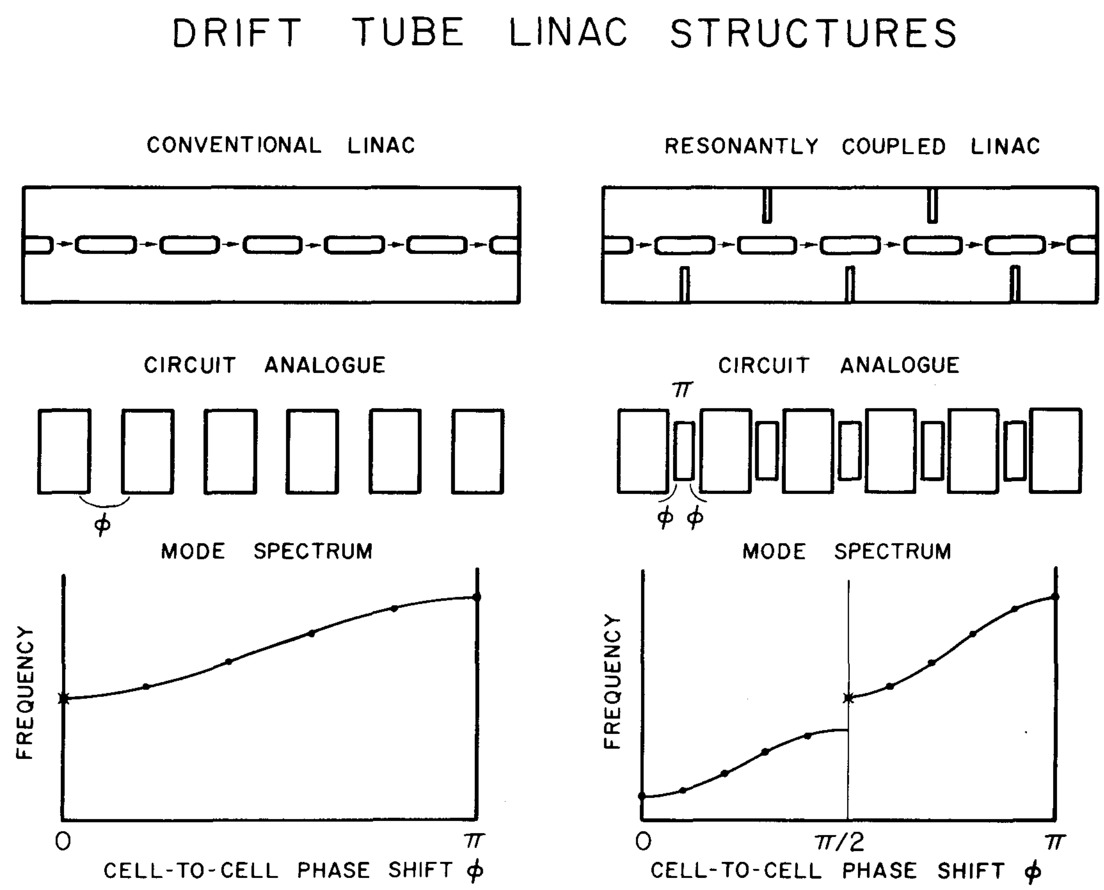

Fig. 1. Conventional and Resonantly Coupled Linac Structures.

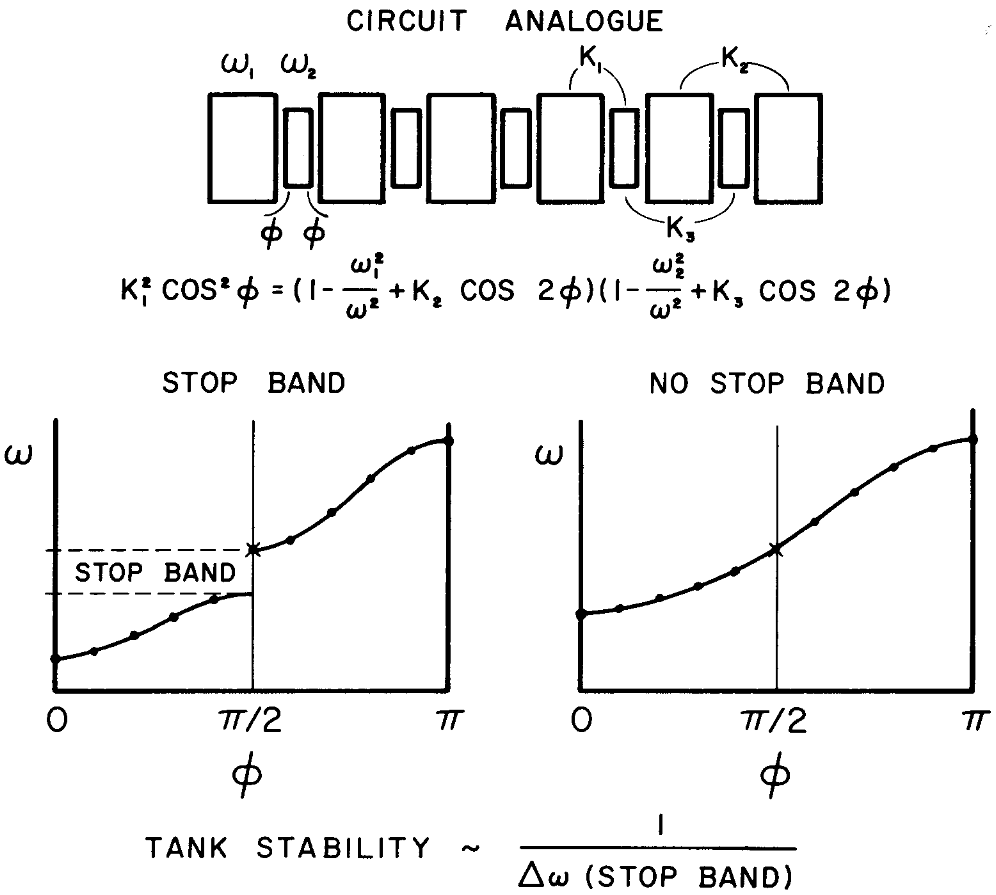

Fig. 2. Dispersion Relation and Mode Spectra for Biperiodic Chain of Coupled Resonators.

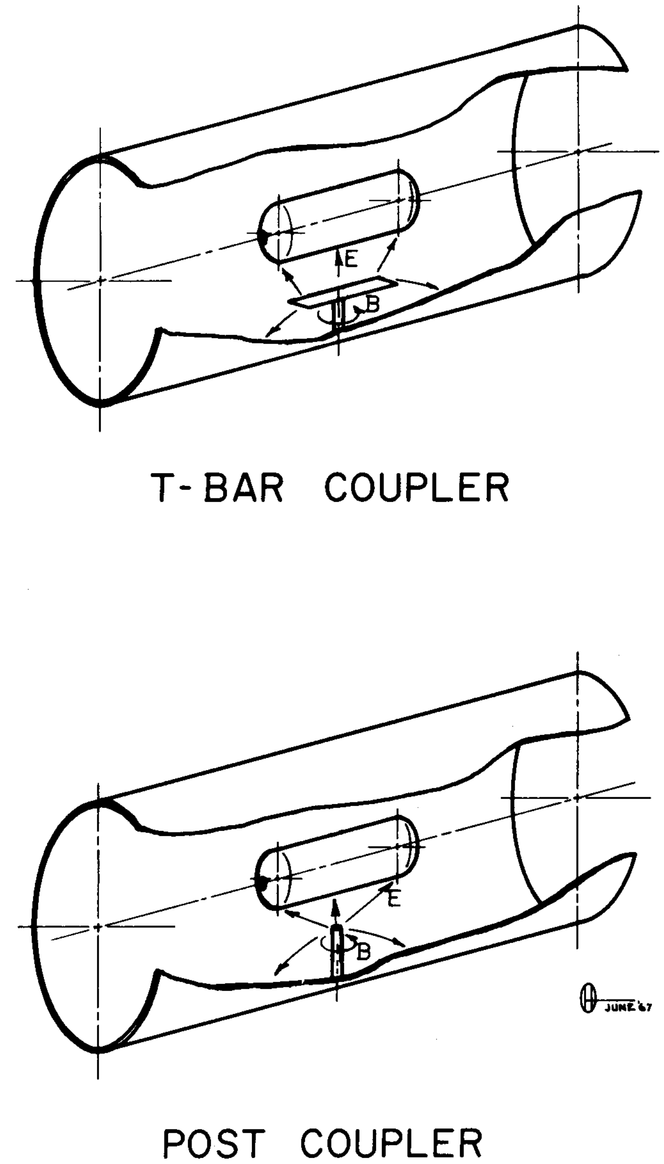

Fig. 3. Resonant Couplers.

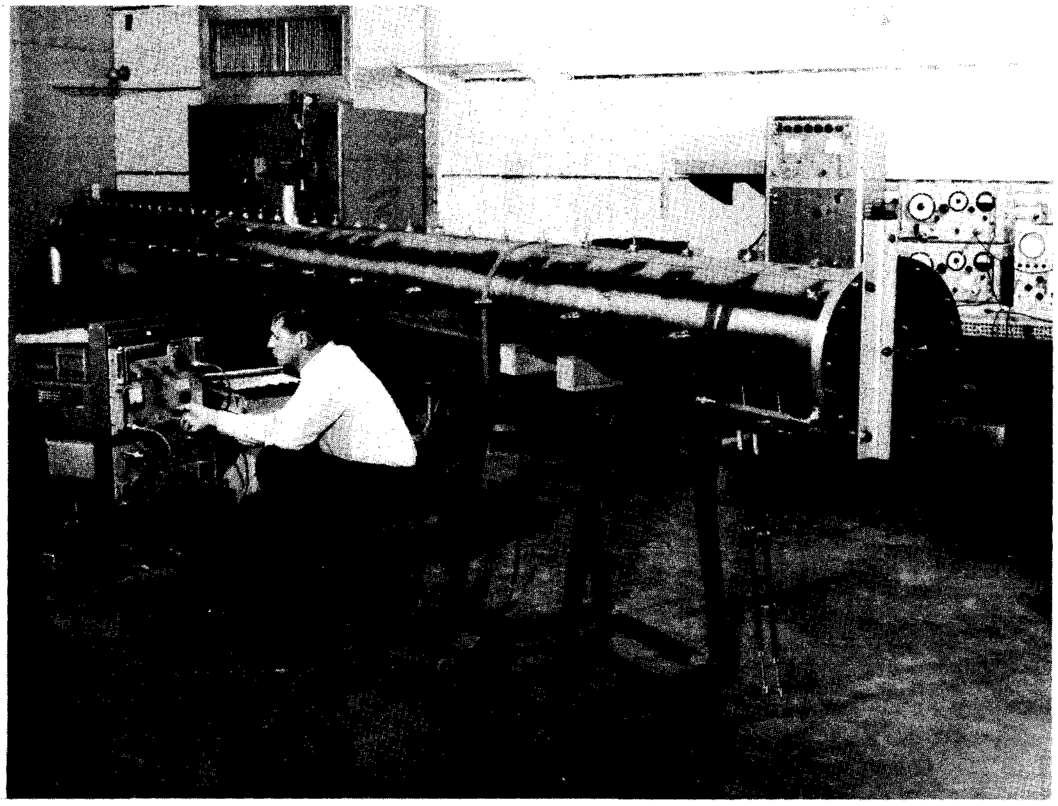

Fig. 4. 35-Cell Linac Model.

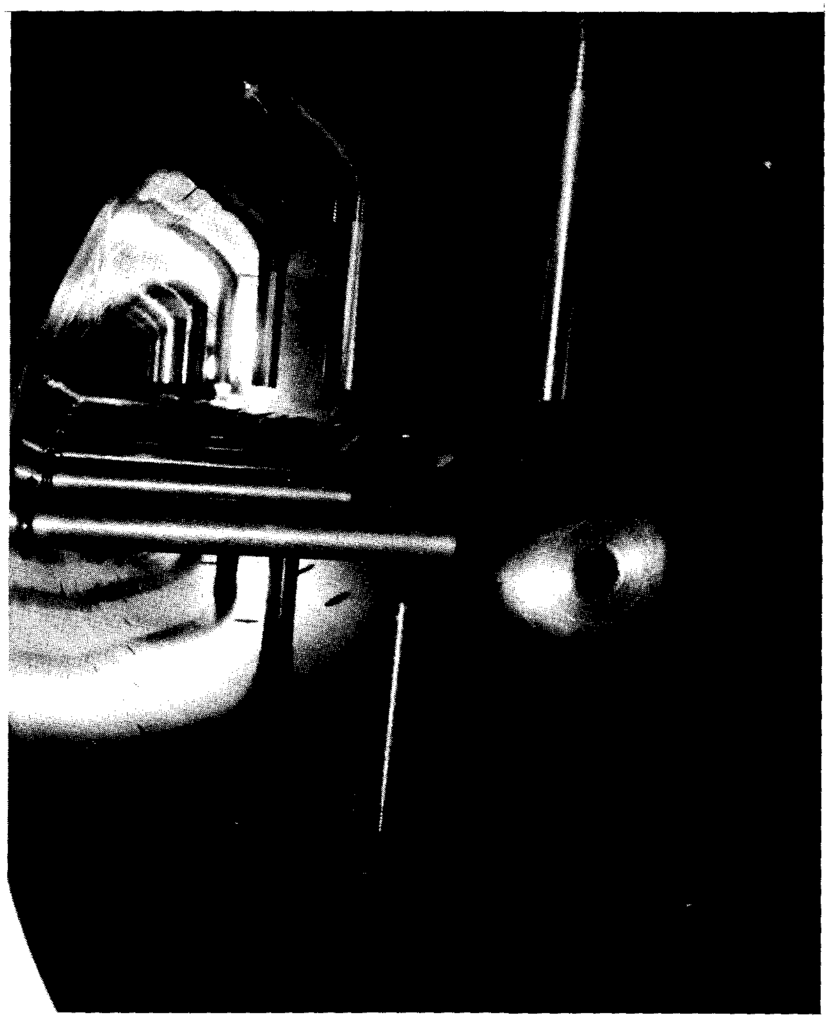

Fig. 5. Post Couplers in 35-Cell Linac Model.

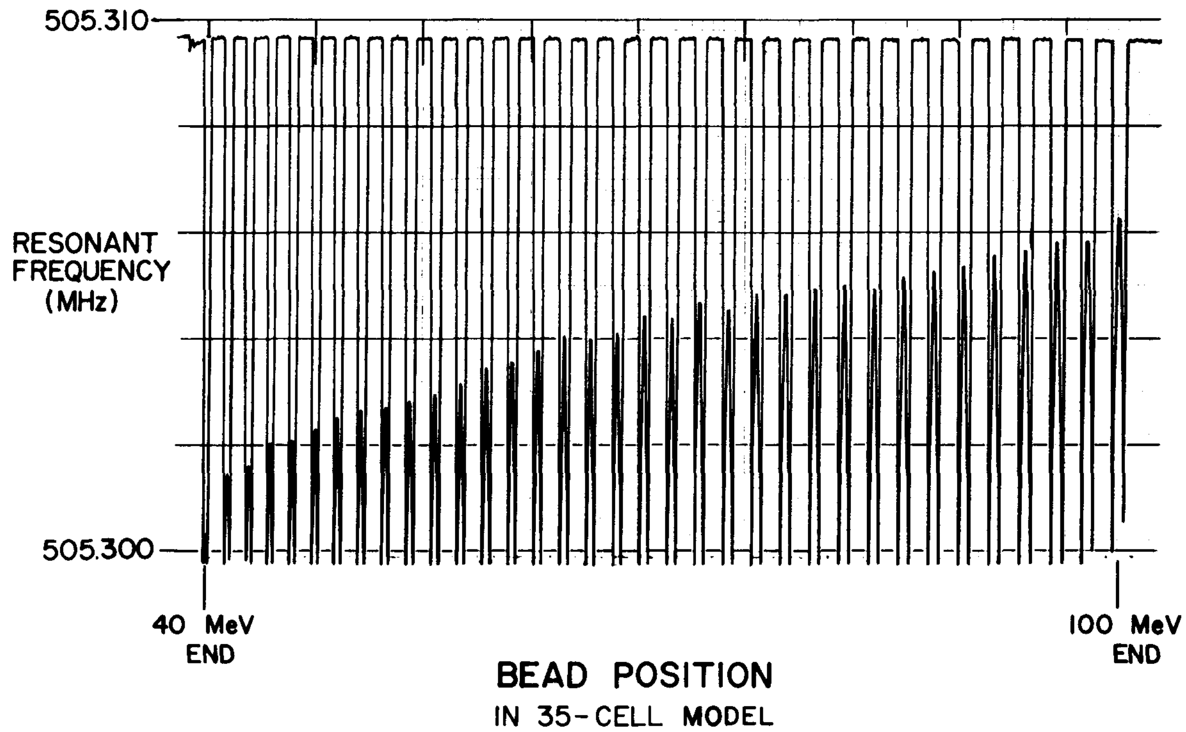

Fig. 6. Bead Perturbation Measurement in 35-cell Linac Model.

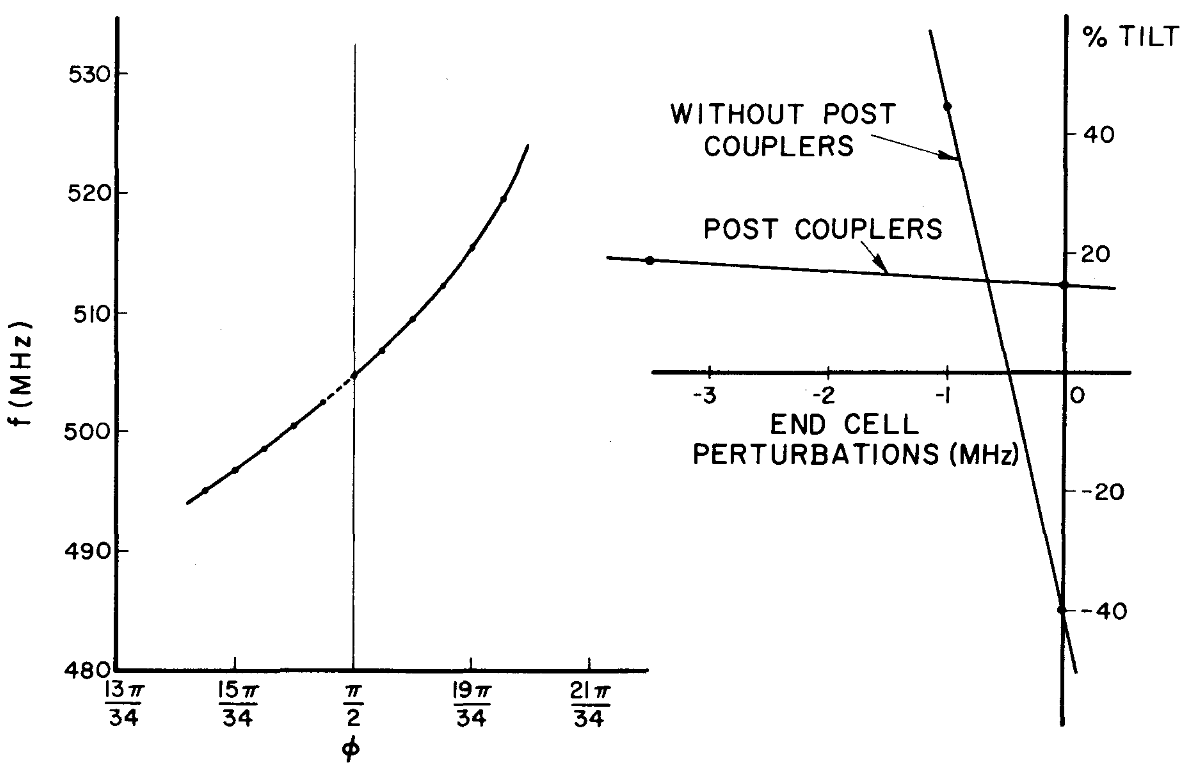

Fig. 7. Partial Mode Spectrum and Field Stability Data for 35-cell Linac Model.

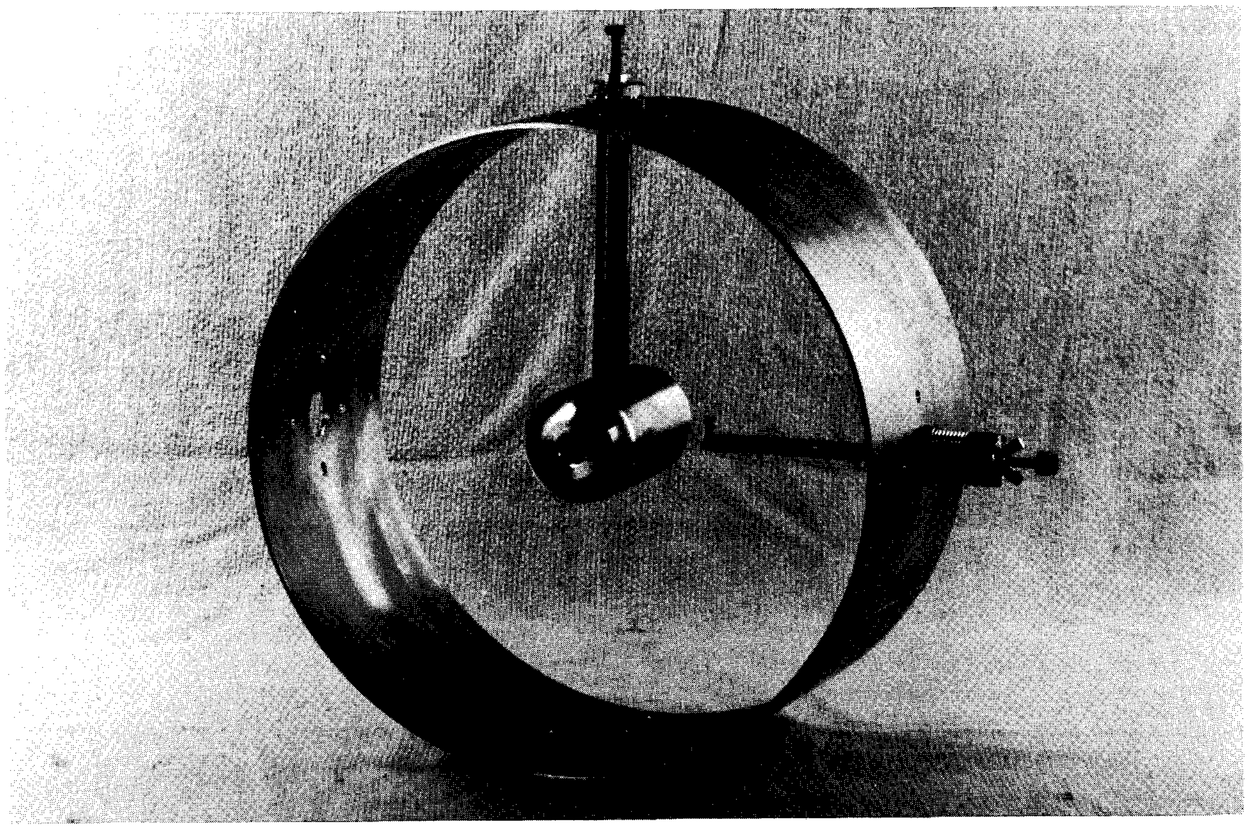

Fig. 8. Post Coupler With Eccentric Tab in Section of Linac Model.

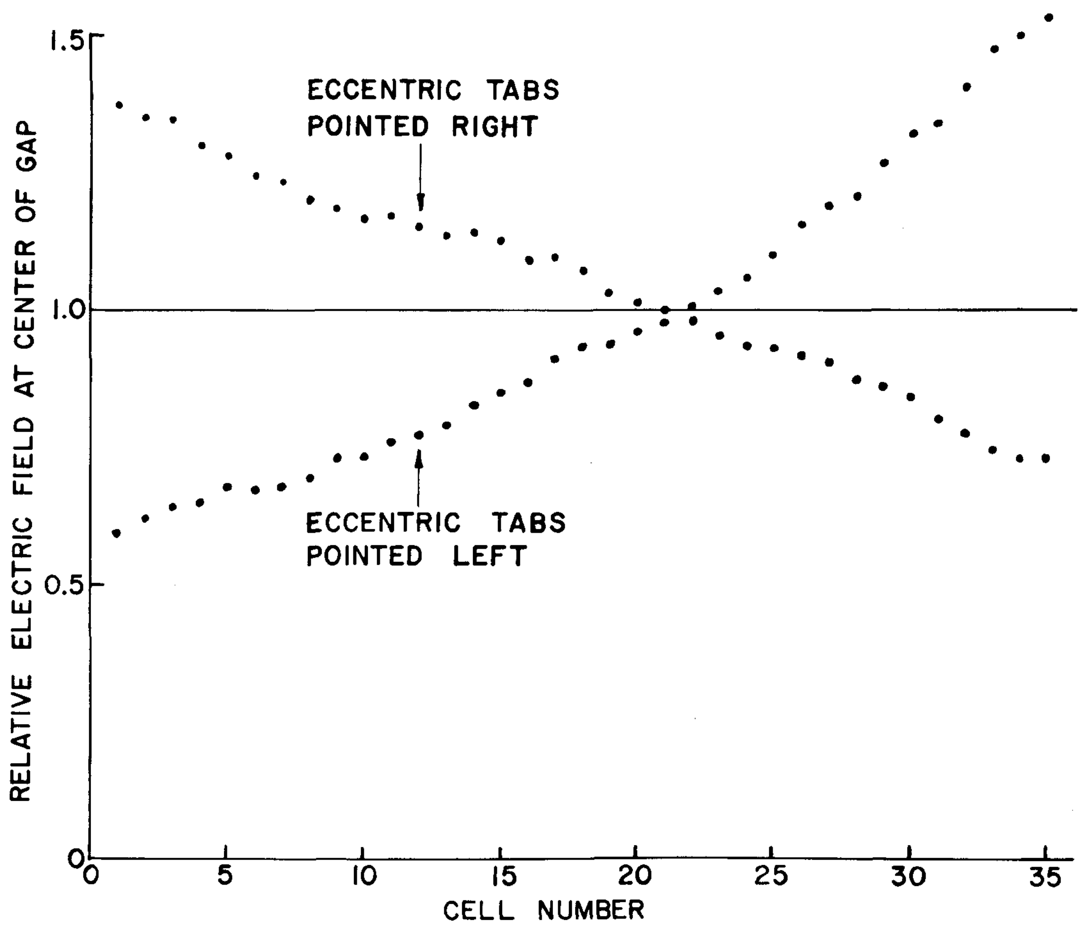

Fig. 9. Performance of Eccentric Tabs in 35-cell Linac Model.