MEASUREMENT ON A MULTISTEM DRIFT TUBE STRUCTURE*

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This is a report on a new standing wave structure, operating in the TM_{010} mode, for accelerating protons below an energy of 200 MeV. This structure employs more than one stem to support each drift tube, and unlike the conventional drift tube structure the stems play a significant role in shaping the dispersion curve about the operating TM_{010} mode. For the past year, an investigation into the detuning effects in linac cavities has been conducted at Brookhaven.[1,2] The purpose of this paper is to describe in more detail the operating characteristics of a multistem structure.

The measurements were carried out on a cylindrical cavity, having a length of 36 in. and a diameter of 10.8 in. Of particular interest for the present discussion are the $TM_{01\ell}$ and $TE_{11\ell}$ modes. Figure 1 is a plot of these modes for the hollow unloaded cavity. It should be noted that there are no modes below 650 Mc/sec (650 Mc/sec is the lowest frequency that energy can propagate down this structure).

Figure 2 shows a drift tube structure having a single stem support for each drift tube. This structure is scaled down from 200 Mc/sec for operation at a $\beta \approx 0.43$. The modes of this cavity were measured and are shown in Fig. 3. A comparison between Figs. 1 and 3 reveals a number of interesting differences. The addition of a single stem and drift tube decreases the frequency spacing between the $TE_{11\ell}$ and $TM_{01\ell}$ modes, and in addition, introduces a new set of modes which we shall call the $TS(1)_{10\ell}$ modes, to be discussed in more detail later on. For modes designated TS(N), N indicates the number of stems.

Now consider the structure shown in Fig. 4, which is the same as that shown in Fig. 2 with the exception that there are two stems, 180° apart. Figure 5 is a plot of the $TM_{01\ell}$, $TE_{11\ell}$ and $TS(2)_{10\ell}$ modes for the two stem case. It is interesting to note that there is very little change in either the $TM_{01\ell}$ or the $TE_{11\ell}$ modes, as compared to the single stem case, but the $TS(2)_{10\ell}$ modes are higher in frequency than the $TS(1)_{01\ell}$ modes.

Similar measurements were made on 3, 4 and 6 stem structures with configurations shown in Fig. 6. (Figure 19 is a photograph of the 4 stem experimental cavity.) For the 3, 4 and 6 stem cases it should be pointed out that the $TE_{11\ell}$ modes are all above 1200 Mc. The results for the $TM_{01\ell}$ and $TS(N)_{10\ell}$ modes for the 1, 2, 3, 4, and 6 stem cases are compiled in Fig. 7.

The $TM_{01\ell}$ and $TE_{11\ell}$ modes are conventional modes and are discussed in many textbooks. The $TS(N)_{10\ell}$ or the more general $TS(N)_{nm\ell}$ modes are associated with transverse stem resonances and, as can be seen in Fig. 7, the $TS(N)_{nm\ell}$ modes being considered are lower in frequency than the normal $TE_{11\ell}$ and $TM_{01\ell}$ modes.

The $TS(N)_{nm\ell}$ modes are in some ways similar to those mentioned in the literature for the crossbar structure,[3,4] and for the H-type wave structure.[5] It should be pointed out that to the authors' knowledge, there has been no treatment of these modes in terms of loaded transverse resonances.

To determine the nature of the $TS(N)_{nm\ell}$ modes, first consider a drift tube with a single stem support in an open-ended, long, hollow cavity as shown in Fig. 8a. Figure 8b shows the electric and magnetic field configurations for the $TS(1)_{10}$ mode. The values of N, m and n from Fig. 8b correspond to N = 1 for a single stem, m = 0 since there is no radial variation of the field, and n = 1 since the radial electric field is zero at the stems and maximum midway between the stems. (There can exist higher order modes corresponding to n > 1, where the radial electric field goes to zero between stems.) For the case shown in Fig. 8b, the electric field has a circumferential variation of

$$\left| \sin \frac{n\varphi N}{2} \right| = \left| \sin \frac{\varphi}{2} \right| .$$

Also shown in Fig. 8b are the conduction currents flowing on the stem and on the walls of the cavity. The single stem transverse resonance for this case is 320 Mc/sec. This frequency is well below the normal $TE_{11\ell}$ and $TM_{01\ell}$ modes of the hollow guide and the fields from the transverse stem resonances decay exponentially along the guide.

Now consider a single drift tube with two stems (180° apart) in an open-ended, long, hollow cavity. The transverse field configuration for the two stem case is shown in Fig. 8c, which corresponds to the $TS(2)_{10}$ mode, where N = 2 since there are two stems, and n = 1 since the circumferential field variation goes as

$$\left| \sin \frac{nN\varphi}{2} \right| = \left| \sin \varphi \right| .$$

The transverse resonant frequency for this case is 495 Mc/sec. It is interesting to note that the circumferential field variation does not change sign, as would be the case for a normal TE_{11} mode where the stem would be perpendicular to the transverse electric field. For the three stem case shown in Fig. 8d we have the $TS(3)_{10}$

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mode, which has a resonant frequency of 610 Mc/sec. Figure 9 is a plot of transverse stem and drift tube resonant frequency vs. number of stems for a single drift tube in an open-ended cavity.

From measurements made using 1, 2, 3, 4 and 6 stems per drift tube in the cavity of Fig. 2, it is seen from the results plotted in Fig. 7 that the transverse $TS(N)_{10}$ stem resonances form a periodic coupled system having $TS(N)_{10\ell}$ resonances. As an example, a cavity having six drift tubes and three stems per drift tube has the following modes: $TS(3)_{101}$, $TS(3)_{102}$, $TS(3)_{103}$, $TS(3)_{104}$, $TS(3)_{105}$, $TS(3)_{106}$, corresponding to a phase shift per cell (a cell length being defined as the length between the center of two adjacent gaps) of $-\pi/6$, $-2\pi/6$, $-3\pi/6$, $-4\pi/6$, $-5\pi/6$, and $-6\pi/6$, respectively. It should be pointed out that the cell-to-cell variations of the radial electric field ($\vec{E}_r$), along the length (z direction) of the tank varies as $\sin \pi\ell z/L_T$, (where L_T is the length of the tank, and ℓ is the longitudinal mode number), and also the $\vec{E}_z$ field varies as $\cos \pi\ell z/L_T$. The $TS(N)_{100}$ is a degenerate mode due to the boundary conditions, and cannot be excited. Also from Fig. 7, the frequency of the TM_{010} mode is essentially unchanged and independent of the number of stems. The modes adjacent to the TM_{010} mode are affected by the stems, and it is these modes that determine the shape of the dispersion curve about the TM_{010} mode.

Various investigators have discussed the relative merits of 0, $\pi/2$ and π mode structures. To reduce beam loading and tank detuning effects, it is desirable to do either of the following:

1. In the 0 or π mode structure, make the quantity

$$\left| \frac{d^2\omega}{d\beta^2} \right|$$

as large as possible. (The 0 and π modes are normally located at the end of a bandpass.)

2. For the $\pi/2$ mode (which is normally located at the center of a bandpass), make the quantity

$$\left| \frac{d\omega}{d\beta} \right|$$

as large as possible.

In Fig. 7 it is seen that for the one and two stem case the $TM_{01\ell}$ bandpass remains relatively unaffected by the $TS(N)_{10\ell}$ bandpass. In going to 3, 4, or 6 stems the $TM_{01\ell}$ bandpass is influenced by the $TS(N)_{10\ell}$ bandpass. At some region between 4 and 6 stems it may be possible to have the $TS(N)_{01\ell}$ and $TM_{01\ell}$ bandpasses join together and form a continuous dispersion curve, in which case the behavior of the TM_{010} mode would be more like a $\pi/2$ mode.

The six stem case, as seen in Fig. 7, is obviously an overcompensated case and will not be discussed at the present time. The four stem case is obviously undercompensated. The desired operating point should therefore be between four and six stems. The transverse stem resonances (Fig.9) for the four and six stem cases are 700 and 800 Mc/sec, respectively. The desired operating point may more appropriately be described as being where the transverse stem resonance is somewhere between 700 and 800 Mc. The transverse stem resonance is a function of the number of stems and also the width of the stems. The measurements shown in Fig. 9 were made with stems having a diameter of ¼ in. Sheet metal tabs were added to the stem, as shown in Fig. 10, and the flare F was varied from ¼ in. to 3¼ in. Figure 11 shows the transverse stem resonance vs. number of stems for different flare widths.

Figure 12 is a plot of the $TM_{01\ell}$ and $TS(N)_{01\ell}$ modes for a four stem structure with stem flares of ¼ in., ½ in., and 3/4 in. Also plotted in Fig. 12 are the $TM_{01\ell}$ modes for a single stem. It is interesting to note the change in the shape of the dispersion curve in going from a one stem to the four stem structure, and also to note the change in going from a ¼ in. flare to a 3/4 in. flare.

From the above discussion, we see that we have a way of being able to adjust the dispersion curve with the use of multistem supports. We would now like to determine what are the relative advantages and disadvantages of the various configurations considered. Measurements were made on 1, 2, 4 stem ¼ in. flare, and 4 stem 3/4 in. flare structures.

Let us first consider the sensitivity of the various structures to detuning effects. To compare the various structures, we detune the structure by placing a perturbation at one end, and compare the changes in the field variations along its length. Consider the structure shown in Fig. 13, where the size of the perturbation was adjusted to detune the over-all frequency of the structure by 1, 2, 3, and 5 Mc.

For each of the above perturbations, the field along the length of the structure was measured using pickup loops. Measurements were made on a one stem, two stem, four stem with ¼ in. flare, and four stem with 3/4 in. flare structures. The results are plotted in Figs. 14, 15, 16, and 17. It is seen that for all of the above-mentioned figures the one stem case gives field tilts between 30% to 50%, and for the four stem 3/4 in. flare case the field tilts are reduced to 5% to 10%. The two stem and four stem ¼ in. flare case gives intermediate values of improvement. Due to the limitation in the accuracy of the measurements, the authors feel that the improvement in the reduction of field tilts is greater than indicated by the measurements.

It is now necessary to determine what effect multiple stems have on the shunt impedance (R_{sh}). For the one, two, and four stem cases being considered, the axial electric field between the drift tubes was measured using a metallic bead perturbation technique, and it was found that there was essentially no change in the axial electric field for the four cases. It can easily be shown that since the axial electric field did not change, then R_{sh} is simply proportional to the Q of the structure being considered.

We will first consider the case of a flat tank (e.g., no tilt in the axial field distribution). Adding additional stems and/or flares increases the losses in the TM_{010} mode. If we assume that the increased losses are simply related to the surface area of the stems, we may write

$$Q = \frac{W}{L_o + L_s} ,$$

where W = stored energy, L_s = stem losses, L_o = all other losses in the cavity. We may now write

$$\frac{1}{Q} = \frac{L_o}{W} + \frac{L_s}{W} = \frac{1}{Q_o} + \frac{L_s}{W} ,$$

where Q_o is the case for no stem losses. If we plot the above equation using 1/Q and L_s as the variables we get a straight line.

We will now consider the measured values of Q to determine whether or not the stem losses are simply related to the surface area of the stems. Measurements of Q were made on the one stem, two stem, four stem ½ in. flare, and four stem 3/4 in. flare (the relative surface area, L_s , for the four cases being considered is 1, 2, 4, and 12, respectively). The results as plotted in Fig. 18 of 1/Q vs. L_s form a straight line within the accuracy of the measurements, showing that the losses of the stem are simply proportional to their surface area. Since the stored energy in the cavity is almost identical for each of the four stem configurations used, the shunt impedance of the cavity is therefore directly proportional to the Q's of the cavity for each of the stem support geometries used. For the case of four stems with 3/4 in. flare, the reduction in Q over the single stem support is 30%, and for the case of a beam-loaded cavity of 100 milliamperes the reduction in Q is estimated to be 15% relative to the single stem support. This additional 15% in rf power requirements appears to be justified when contrasted to the improvement in tank detuning effects. The 3/4 in. flares were attached to the stem by first soldering the two halves of the flare onto two fuse clips and snapping the fuse clips onto the stem. Because of the poor rf design of the flare connection to the stem, the authors believe that, with an improved version of flare mounting, the additional rf power requirement would be reduced from 15% to 10% or less.

As was done in the tank detuning measurements (Figs. 14, 15, 16, and 17) the same tilt was introduced, and for each tilt the Q of the cavity was measured using one, two, and four stems with ½ in. flare, and four stems with 3/4 in. flare. For field perturbations corresponding to Δf of 2 Mc (which in linac cavity design would represent a very large field distortion of the TM_{010} mode) or less, the Q's for each stem geometry remained relatively unchanged with respect to Δf . Having shown that the Q's are independent of tank tilt, therefore, the R_{sh} will also be independent of tank tilt.

The experimental results reported in this paper indicate that a multistem configuration can be designed which will reduce the axial field variations of the TM_{010} mode caused by beam loading and mechanical tolerances. This reduction in axial field variation of the loaded cavity should result in a more stable operating machine and also substantially reduce the energy spread of the beam. The field variation consideration becomes extremely difficult to cope with electronically as the beam currents become more intense, and it therefore seems attractive to reduce the electronic instrumentation by using a multistem structure.

Acknowledgments

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References

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DISCUSSION

S. GIORDANO, BNL

CARNE, RHEL: I should like to point out, sir, that you can probably get coincidence in the two zero modes by not varying the number of stems, but simply taking two stems and varying the diameter of the stems. This can then be very similar to the cross-bar structure in zero-mode.

GIORDANO: Oh, yes, I should have pointed out that the lower modes in the lower dispersion curve are very similar to, in fact they are, the cross-bar modes; only I have treated them as transverse resonances in this particular case.

LAPOSTOLLE, CERN: I would like to say a few words about what is done at CERN. One and a half years ago, we thought about the importance of stems, although we did nothing until we heard about what Giordano was doing. In fact, we thought about it then mainly in terms of cross-bar structure, and Georges Dome did a lot of work which agrees with what has just been reported. There are only two things that I would like to add. The first is that we find that there are several ways to get the two bands closer. One which was studied first by Giordano is to increase the number of stems. Another way is to use a different disposition of the stems, and the cross-bar is an arrangement which increases the bandwidth in such a fashion that even if the middle frequency remains constant, the upper frequency becomes closer to the Alvarez mode. We rather favor this solution. At low energy, the cross-bar with only two stems is probably enough to get the resonant situation. The third way to get the modes closer has just been mentioned by Allen Carne, and that would be to increase the stem diameter. In the energy range of 10 to 30 MeV, G. Dome found that only a slight increase in the bar diameter of a cross-bar structure provides the resonance. My second point is a question. Theory shows that when one tries to increase the frequency of the lower mode by, for instance, increasing the number of stems to the point where the lower mode frequency should be above the Alvarez mode, the lower mode stops at the Alvarez frequency, and the Alvarez mode starts above at some higher frequency. This has been verified by some of our experiments, although these experiments were sometimes hard to analyze with the long cavity we used. Have you also observed this phenomenon? In one of the figures you had shown a six-bar configuration which was not in accordance with this.

GIORDANO: As I mentioned in my talk, at the point where the $TS(N)_{100}$ mode becomes higher in frequency than the TM_{010} mode, we have a very interesting situation; but I did not discuss this point in my paper. What I believe is happening (but my measurements are not completed as yet) is this: Let me first consider the case where $TS(N)_{100}$ mode is lower in frequency than the TM_{010} mode; then when we excite the TM_{010} mode, we only get energy in that mode; and there is no energy in the $TS(N)_{100}$ mode. If we now consider the case where the $TS(N)_{100}$ mode is higher in frequency than the TM_{010} mode, then, when we excite the TM_{010} mode, we also get some energy in the $TS(N)_{100}$ mode. I should like to point out that, for the above measurements, the stems were adjusted so that the $TS(N)_{101}$, TM_{010}, and TM_{011} modes were all in a straight line. A better method would be if we could actually find the $TS(N)_{100}$ mode. There is a method of finding the $TS(N)_{100}$ modes by the use of a simple perturbation theory, which I did not report on in this paper. In reference to low betas, I have made some preliminary measurements at an energy of approximately 1 MeV. In this region, I found that it may be possible to get an optimum dispersion curve with only two or three stems.

KNAPP, LASL: Is anyone working on a theoretical treatment of the problem when the phase velocity is tapered in this sort of a tank, and the effects that this taper will have on the currents that you may drive in the stems?

GIORDANO: I believe if one looks at this and compares it to, say, side-coupled cavities or to an APS structure, you will find that, at the operating mode, there is no stored energy in these transverse resonances, as is the case where there is no stored energy in the side-coupled cavities. Therefore, there are no stem currents associated with the $TS(N)_{01}$ modes.

KNAPP: I think that is true. You can also apply the equivalent circuit type theory--is anyone doing this?

GIORDANO: No, not that I know of right now. We do have plans for having Nishikawa work on this.

CARNE: I should like to make one more comment in addition to those of Lapostolle. We wrote about the cross-bar structure in terms of transverse modes in the Frascati paper. In the case under discussion, we are interested in a very large group velocity at the zero mode. In addition to coincident zero modes, we are thus also interested in the bandwidth of the lower passband. You can get the maximum bandwidth by having a configuration which is exactly that of the cross-bar structure; that is, two sets of stems alternate sets of right angles.

GIORDANO: I believe this is true at low betas, but at higher betas there are other options.

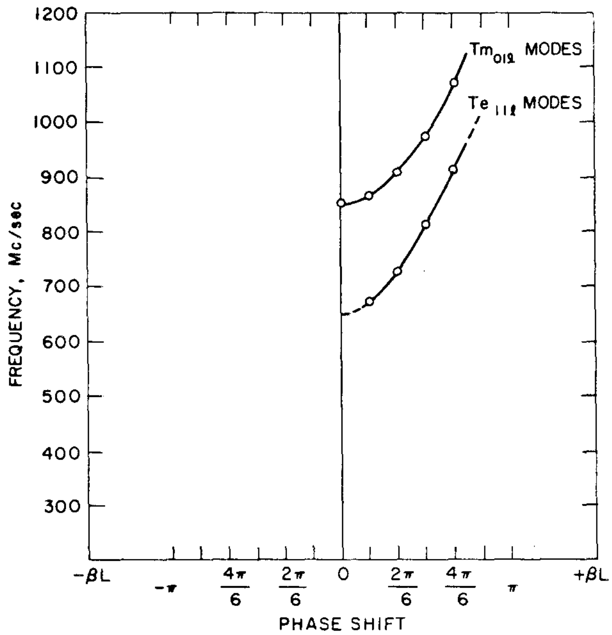

Fig. 1. Hollow cylindrical cavity.

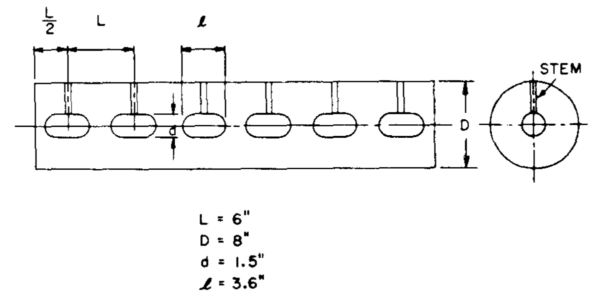

Fig. 2. Single stem drift tube cavity.

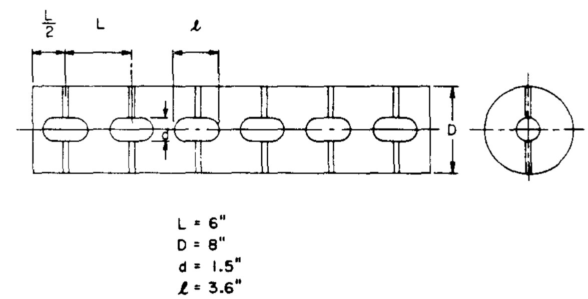

Fig. 4. Two stem (180°) drift tube cavity.

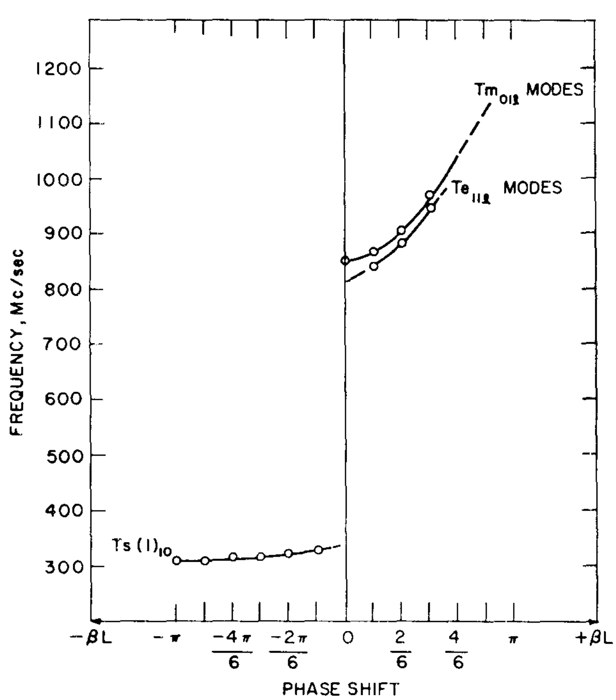

Fig. 3. Modes of the single stem drift tube cavity.

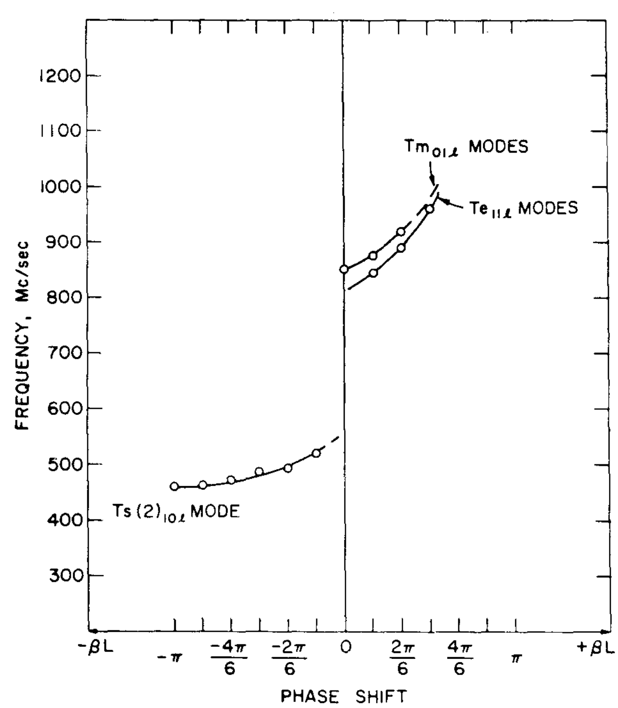

Fig. 5. Modes of the two stem (180°) drift tube cavity.

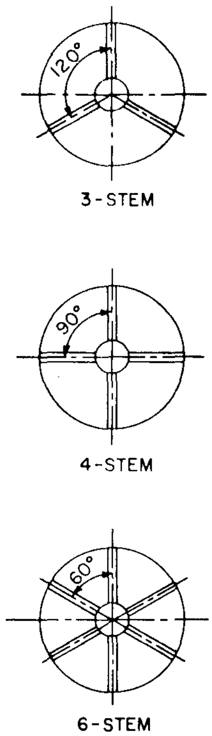

Fig. 6. Multistem configurations.

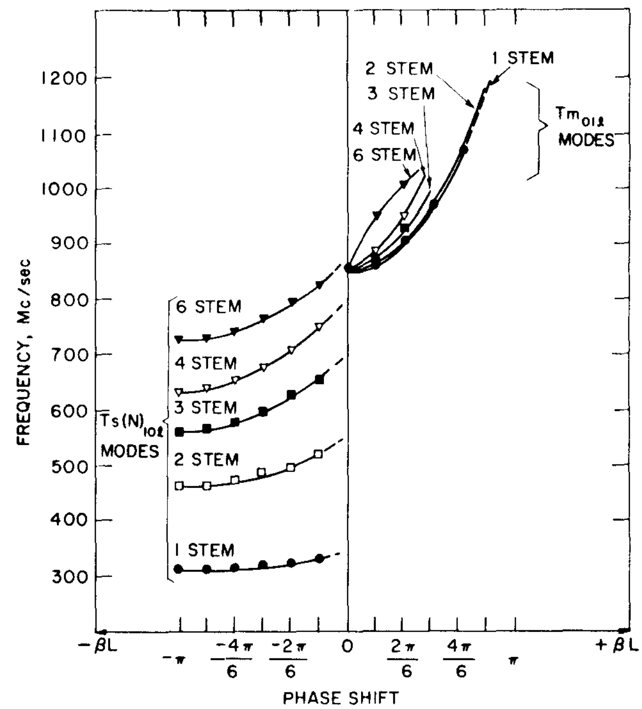

Fig. 7. M᎒des of multistem drift tube cavities.

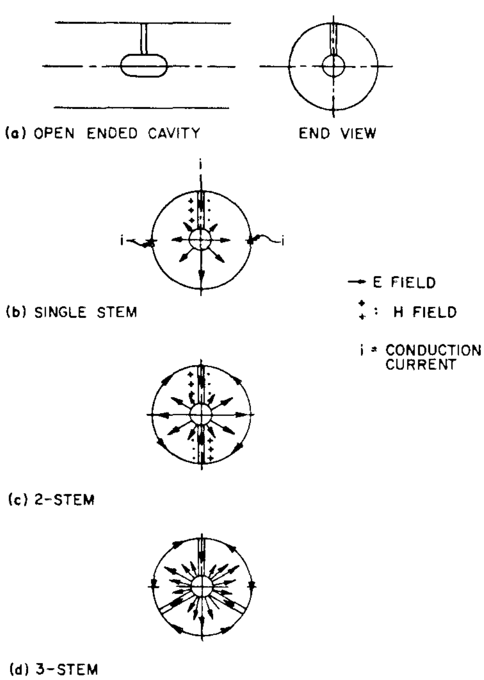

Fig. 8. Stem resonances.

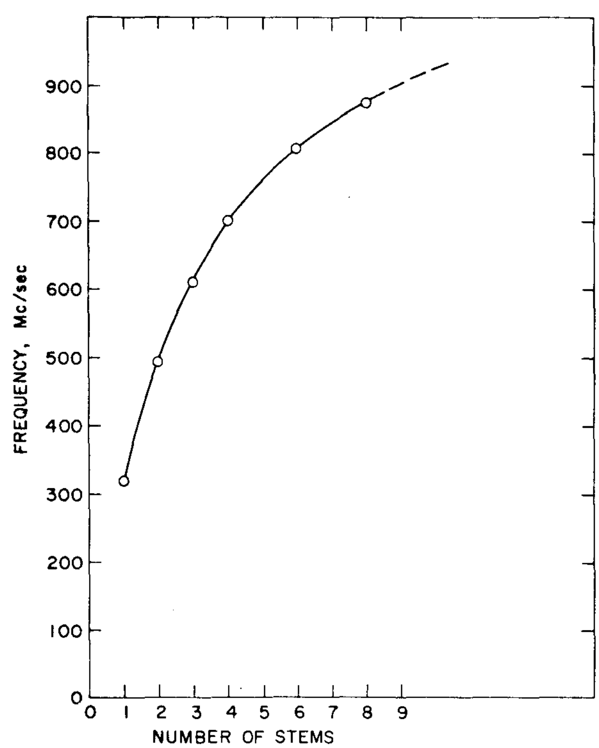

Fig. 9. Transverse stem and drift tube resonances of a single drift tube in a long open-ended cavity ($\frac{1}{4}$ in. diam. stems).

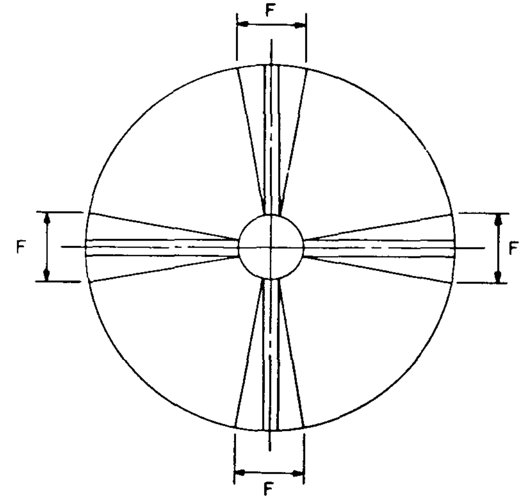

Fig. 10. Flared stems.

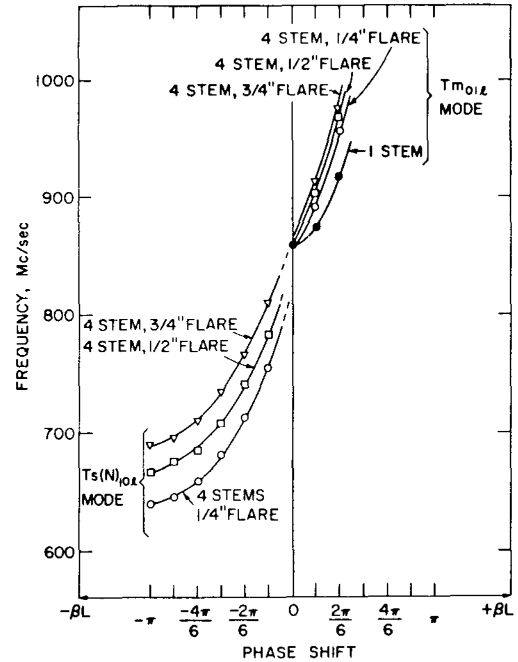

Fig. 12. Four stems with flares.

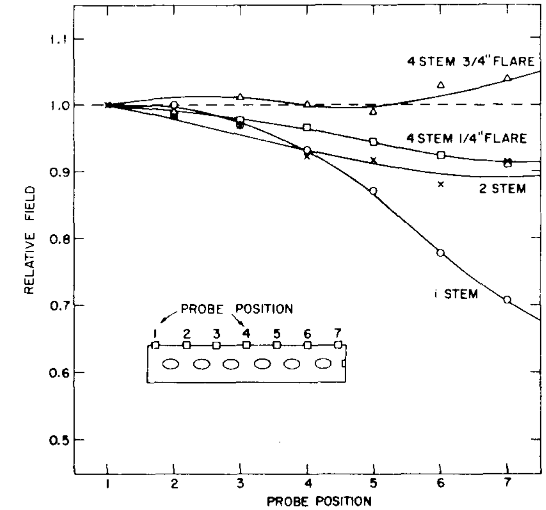

Fig. 14. Field tilt for Δf = 1 Mc.

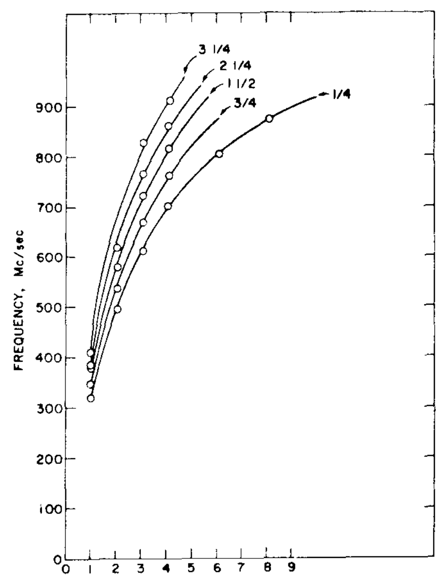

Fig. 11. Transverse stem and drift tube resonances for a flared stem.

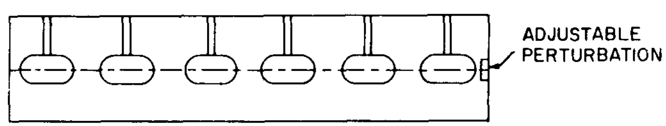

Fig. 13. Cavity with perturbation tuner.

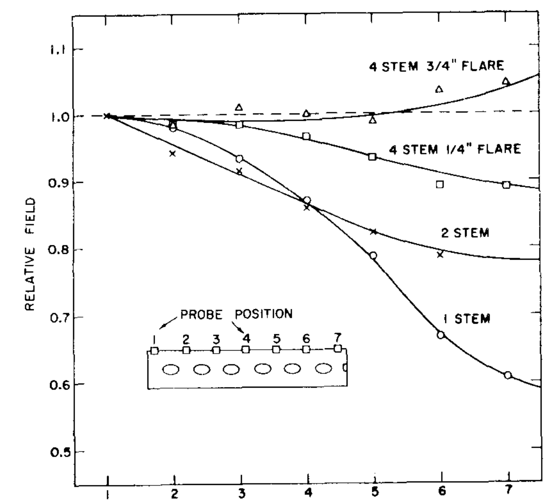

Fig. 15. Field tilt for Δf = 2 Mc.

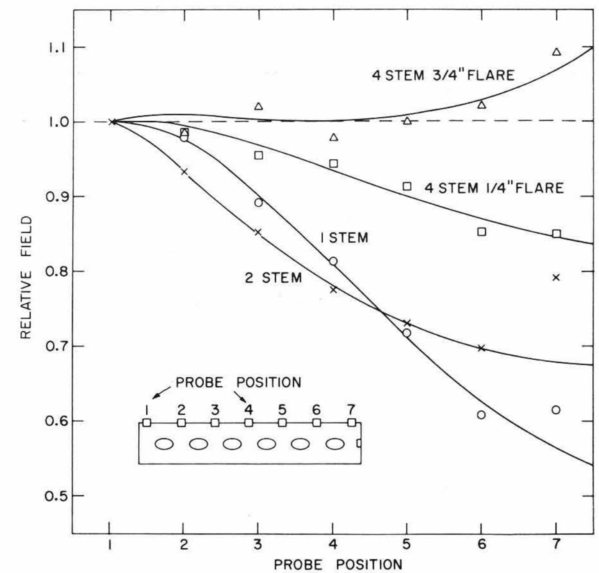

Fig. 16. Field tilt for Δf = 3 Mc.

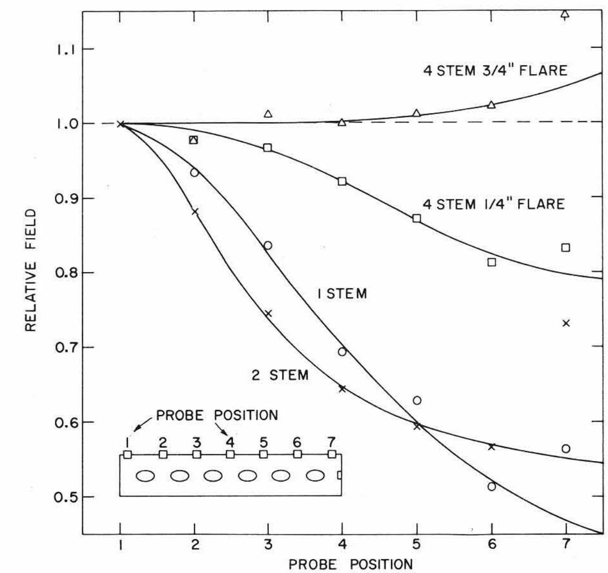

Fig. 17. Field tilt for Δf = 5 Mc.

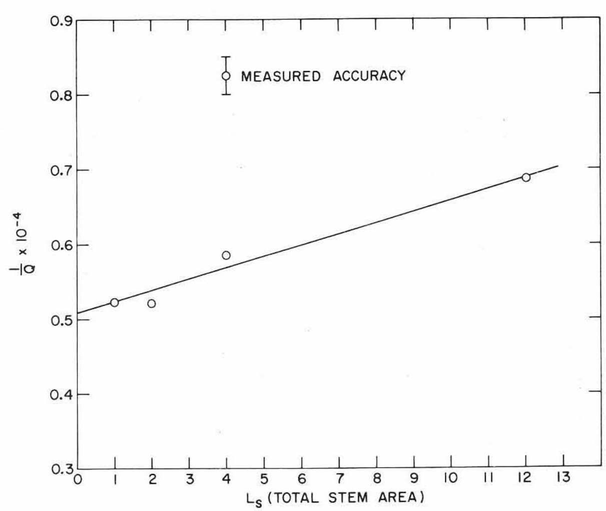

Fig. 18. 1/Q vs stem area for a flat tank in the TM_{010} mode.

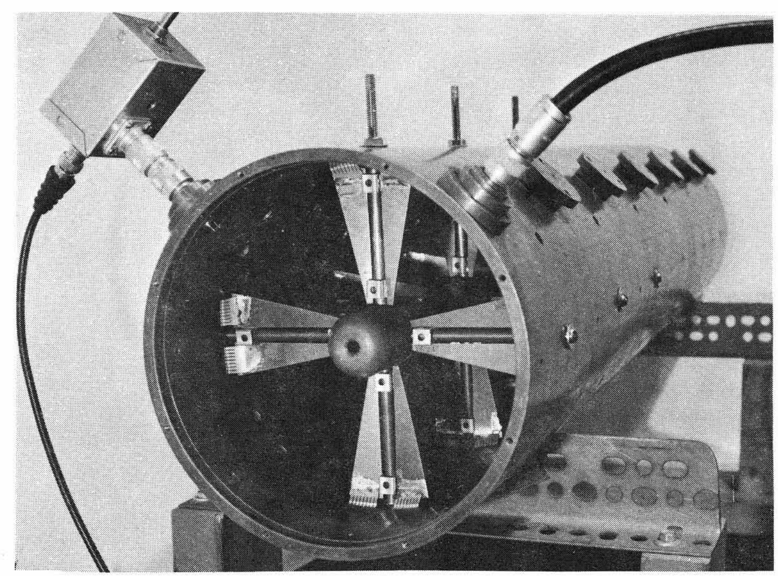

Fig. 19. Photograph of typical structure.