ACCELERATING STRUCTURE RESEARCH AT LOS ALAMOS

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I will talk about measurements made on rf structures at Los Alamos in connection with our proposal to build a Linac Meson Factory. The people working on this program at Los Alamos are Bill Shlaer, Don Hagerman and myself. Since the program has been going only a couple of months you must consider the results reported as preliminary. The objective of our measurement program is to determine the optimum structures for use in a linac as a function of energy. This involves determining the shunt impedance, the Q and other rf properties, such as field strengths near the electrodes for breakdown problems, the bandwidth of π-mode structures, and so on. We claim no originality in this work, and are only checking the results of others at the present time.

Like most other groups designing linacs for high energies, we propose to divide the machine into two sections: acceleration to 200 MeV in an Alvarez structure followed by a transition to a periodically loaded waveguide operated at a higher frequency. We have made measurements on drift tube structures operated in the 2π-mode (Alvarez structure) at 50 and 150 MeV. For higher energy, we have only considered π-mode standing wave structures, for reasons which will be discussed later by Jakobson.

We have concentrated on structures which have a wide bandpass characteristic, that is, strong coupling from cell to cell. As mentioned before, we show no originality on the choice of structures. We have investigated one model of a Crossbar structure such as described by the Rutherford group, and we have investigated some of the properties of a Cloverleaf structure such as described by Chodrow and Craig(1) from Stanford and also studied by the Rutherford group.

A diagram of the 200 Mc/sec Alvarez structure is shown in Fig. 1, and the dimensions are given in Table I. In these measurements, we hope to be able to determine experimentally the validity of the various computer codes which calculate the shunt impedance of structures of this type, maximum field strengths on the surface of the electrodes, and Q's. We also hope to be able to determine the amount of power required to make up those losses which do not yield directly to computation, such as stem losses. We have a code of this general nature in the process of being written at Los Alamos by a group in our theoretical division led by Dr. Harry Hoyt. As a guide line to use, before our code is complete, we have used the results of the MURA code for comparison with our results. For the first structure studies we built a cylindrical drift tube on a stem and two half drift tubes on metal septums which terminate the structure at symmetry planes.

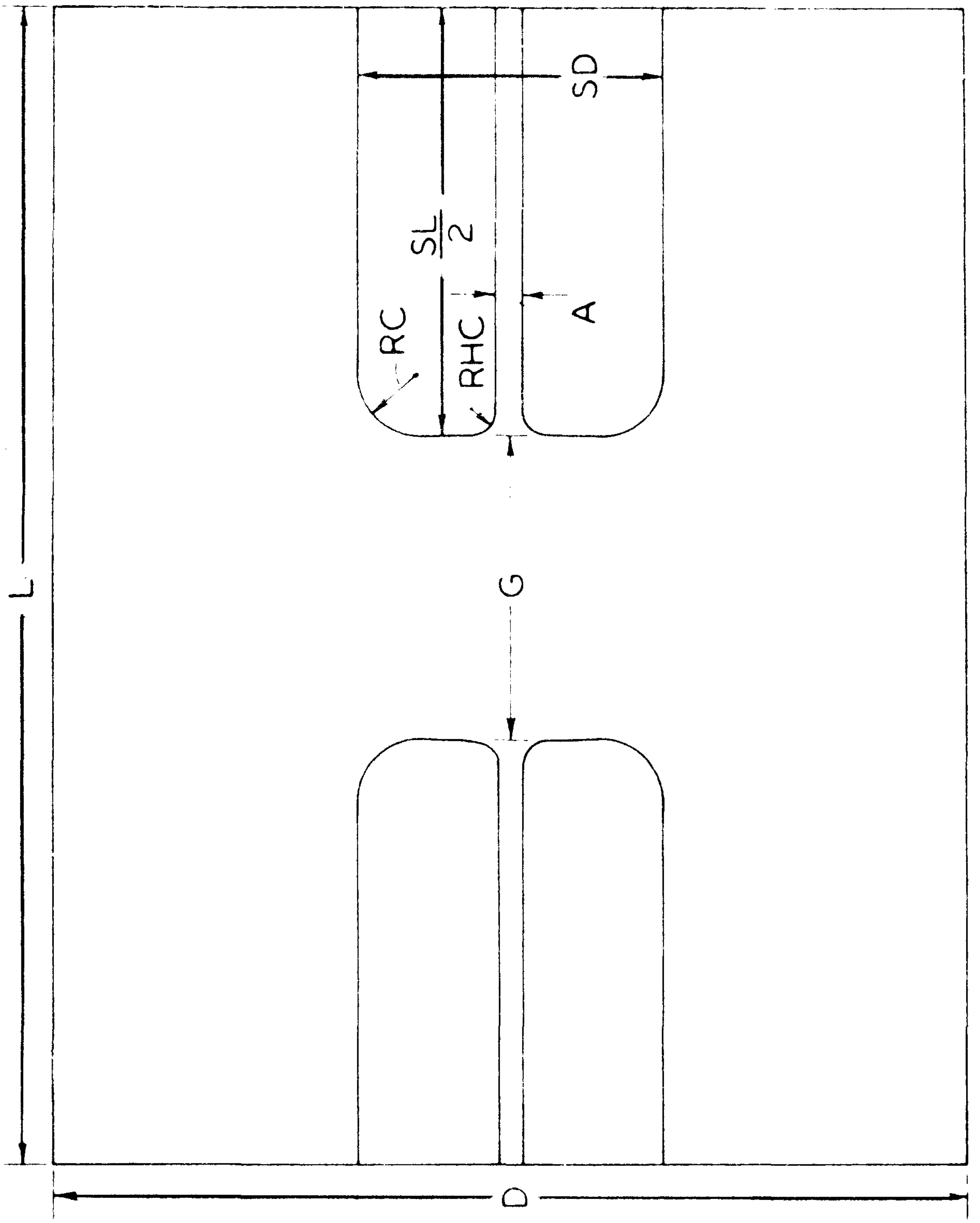


FIG.1 - ALVAREZ DRIFT-TUBE LOADED CAVITY
(MURA NOTATION USED)

TABLE I

Dimensions for Cavity of Figure 1

Unit	50 MeV LASL Meas.	150 MeV LASL Meas.	150 MeV MURA Comp.
L	43.0	76.0	76.0
D	84.0	84.0	82.0
G	15.1	25.5	26.0
SL	28.3	50.5	50.0
SD	12.8	8.0	8.0
RC	3.65	4.0	4.0
A	2.74	No Hole	No Hole
RHC	0.92	———	———

We find a Q of 96% of the theoretical value for the empty cavity. We have the capability of looking at the properties of 1/2, 1, and 2 cells of this configuration, and can therefore find the Q of an infinite set of such cells by direct extrapolation. We define the shunt impedance to be

$$ZT^2 = \frac{(\text{Particle Energy Gain (at } \varphi = 0)/\text{meter})^2}{\text{Power dissipated/meter}}$$

$$= \frac{\left(\int_o^L E(z,t)dz\right)^2}{PL}$$

and

$$Z = \frac{\left(\int_o^L E_{max}(z)dz\right)^2}{PL}.$$

where P is the total power dissipated in the cavity, of length L, and φ is the synchronous phase angle. This expression may be easily evaluated by standard cavity perturbation techniques, which yield the quantity ZT^2/Q, together with a separate determination of Q. Figure 2 shows a plot of the axial electric field versus z, the axial dimension. The average axial field is normalized to unity, thus from the curve we see that the peak field on the axis is 5.7 times the average field in the cell. We can compare the results we obtain with those applicable MURA calculations, as shown in Table II.

TABLE II

Measured and Calculated Shunt Impedances
for a 150 MeV Alvarez Structure

	ZT^2/Q	T	Q	ZT^2
LASL (Meas.)	535Ω/m	0.726	40,900	21.9MΩ/m
MURA (Calc.)	614Ω/m	0.716	51,500	31.7MΩ/m

The agreement between the calculated and measured quantities is certainly not outstanding. One might expect the Q of the laboratory cavity to be somewhat smaller than the calculated value, but the deviation of the field distributions from the calculated values is not expected. This particular structure also suffers from a high field gradient on the copper surface, and would probably not be suitable for use as an accelerating structure at the energy gain per meter now planned. This gradient

150 MEV CYLINDRICAL DRIFT TUBE
E FIELD ON AXIS NORMALIZED TO
$E_{AVE}=1$ $T=0.73$ $\frac{ZT^2}{Q} = 545$ OHMS/m

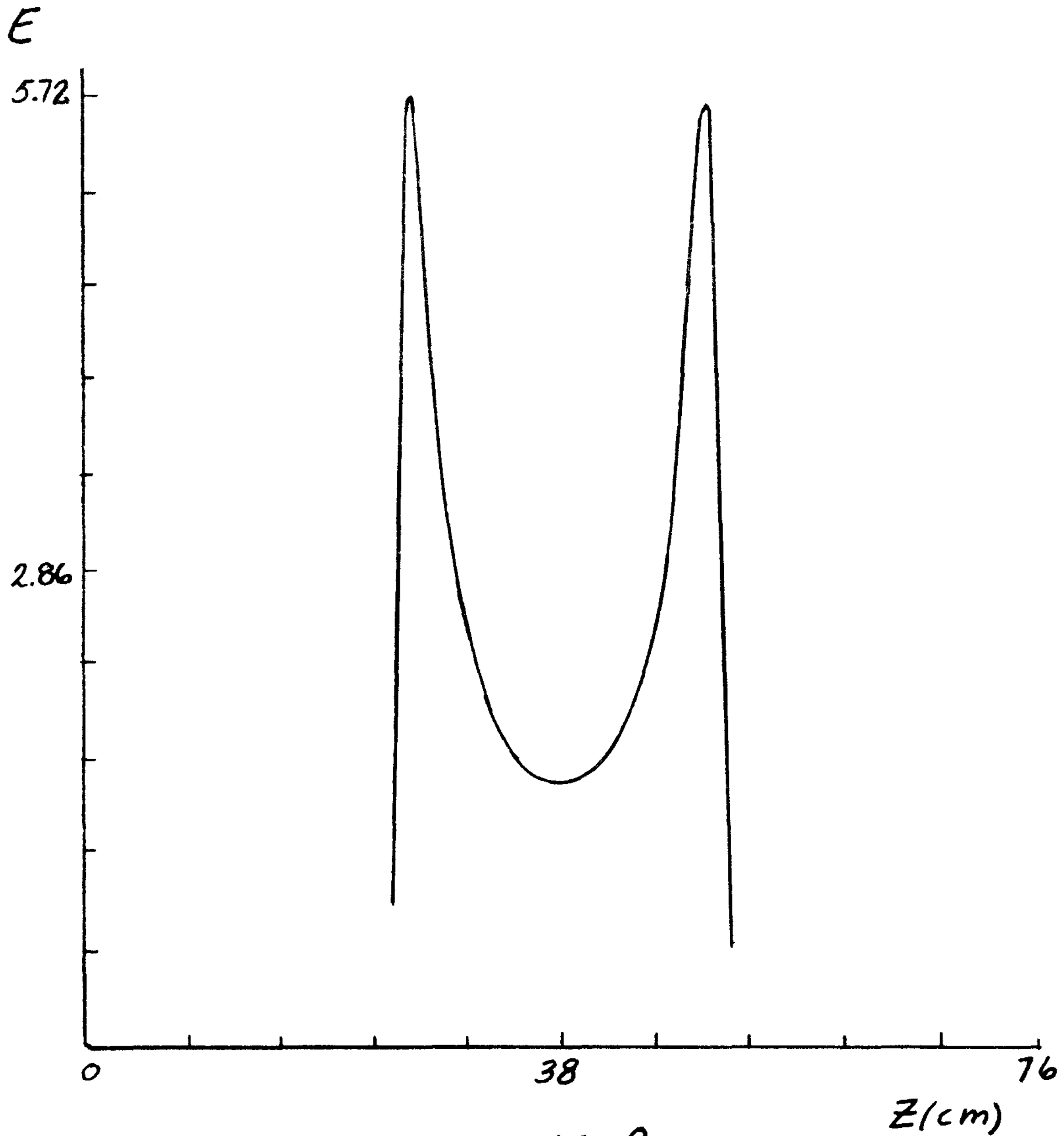


FIG. 2

was determined experimentally with a 1/4 inch diameter dielectric sphere moved on the surface of the drift tube, the maximum frequency shift point being the point of maximum electric field. This measurement yields a peak gradient of $E_{peak} = 9.3\ E_{avg}$ in the region of the sharp break into the hole. This value agrees very well with the MURA calculated value, even though in the calculation, no hole was included in the drift tube. For a particle energy gain of 1 MeV/m we have an average accelerating field of

$$\frac{1\ \text{MeV/m}}{T\ \cos\varphi} = 1.53\ \text{MV/m}$$

and we then have a peak gradient $E_{peak} = 14.3$ MV/m which is essentially the sparking limit, if one believes the Kilpatrick criterion. For a particle energy gain of 1.3 MeV/m we would be considerably above this limit.

We have under construction two more drift tube shapes at this energy, being built to the contours given us by Yale. We also have made measurements on an Alvarez structure at 50 MeV. We are considering a cylindrical drift tube for which, again, MURA has made calculations. Because the diameter of our tank is fixed, we scaled a MURA calculated shape for our tank, and thus are a little off frequency. The dimensions used are those listed in Table I. These measurements were done at a frequency of 220 Mc/sec and scaled at 207 Mc/sec for comparison to the calculated values. Figure 3 shows the axial field distribution measured. In Table III we again compare our measurements with the MURA calculations.

TABLE III

Measured and Calculated Shunt Impedances
for a 50 MeV Alvarez Structure

	ZT^2/Q	T	Q	ZT^2
LASL (Meas.)	555Ω/m	0.800	75,500	41.9MΩ/m
MURA (Calc.)	508Ω/m	0.771	88,200	41.86Ω/m

In this case, to obtain the extrapolation for Q we could not rely upon a 1 cell-2 cell difference, for we had only two half drift tubes completed at the time we made the measurements. So we took the calculated ratio of total losses to septum losses given by MURA for our extrapolation. Thus, the value of Q given may be in some doubt. However, we see again a small disagreement between the calculated and measured values of ZT^2/Q, this time in the opposite direction from that of the 150 MeV model. The agreement for the value ZT^2 is excellent, but somewhat fortuitous.

YOUNG: Why do you end up with a difference in the T factor?

KNAPP: I'm not quite sure. It seems that they would be almost independent of whatever the field did in the gap.

MILLS: How did you estimate the wall and end plate losses?

KNAPP: If you have one cell, then put another one on, take the wall out and add a drift tube in the middle, the wall losses are half as much in the latter case as in the

50 MEV CYLINDRICAL DRIFT TUBE
E FIELD ON AXIS. NORMALIZED TO
$E_{AVE}=1$ $T=0.80$ $\frac{ZT^2}{Q}=595$ OHMS/m

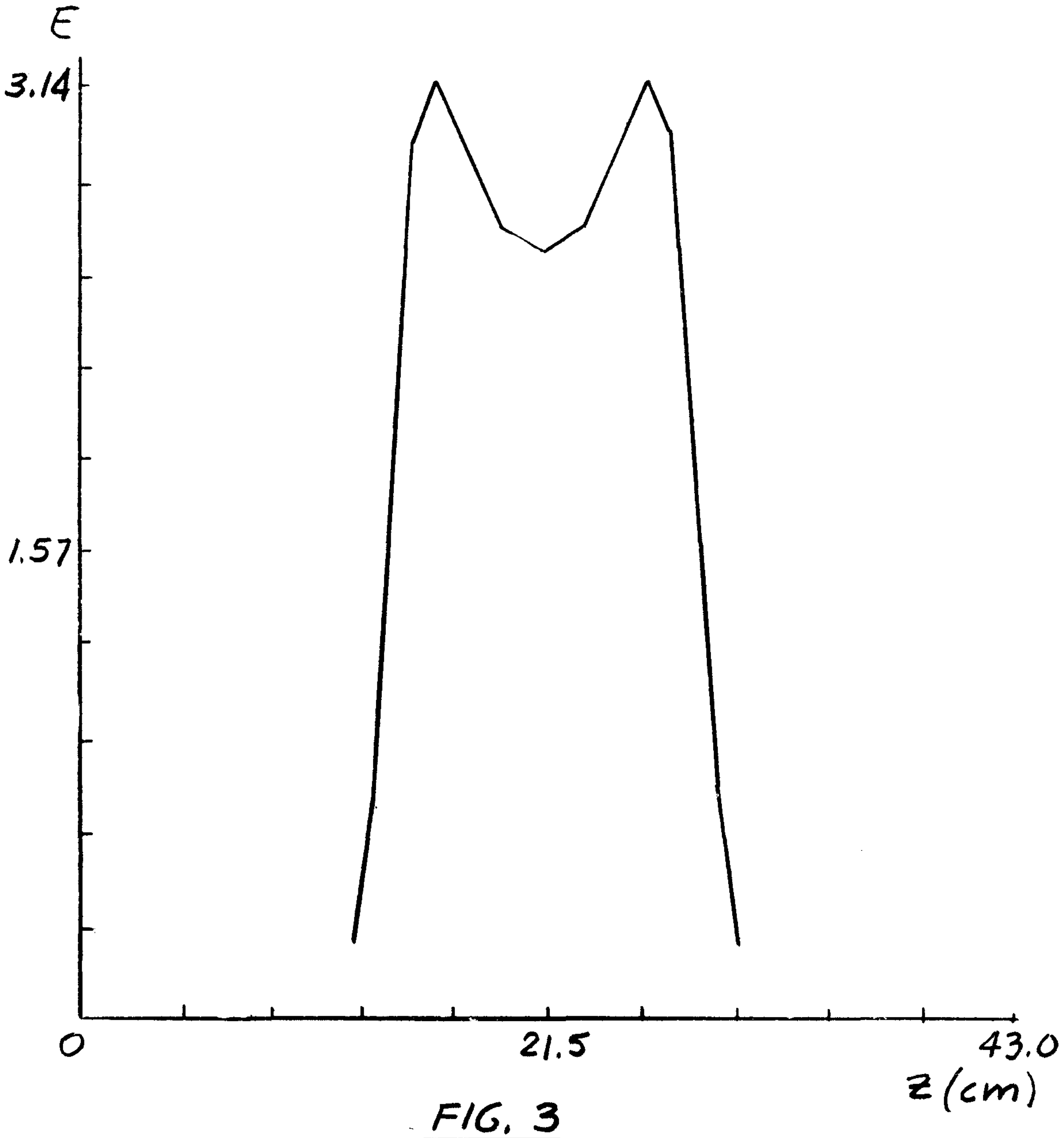


FIG. 3

former case. You then can write down an expression which gives the differences between these two cases and the case where there is no septum when they enter the cell. We couldn't do this for the 50 MeV case because we didn't have a two-halves cell and a one plus two-halves cell model. We had a one-half cell and a one cell model and the losses for the half cell are different.

BLEWETT: I don't think Kilpatrick's criterion ought to be invoked in the case of rf fields.

KNAPP: I don't think we really do either. Bob Featherstone has made a calculation using the Minnesota linac and he feels that they have fields possibly as high as 40 MV/m in their machine and they have no breakdown problems at all.

BLEWETT: There was a test on this subject 3 or 4 years ago in which they got up to 4 times Kilpatrick's limit.

CARNE: I think you can always get beyond Kilpatrick's limit in certain instances, but you've got to have some criterion to design against. Kilpatrick's is pessimistic, but it is something to work against.

BLEWETT: And it gets more pessimistic as the gap gets bigger.

HUBBARD: It's not intended to be an upper limit on what you can get. It's a number at which you don't have any breakdown trouble at all.

CARNE: Do you think that with conditioning you can increase the limit? I'm thinking of the case of the Los Alamos electron machine.

KNAPP: It's true that we don't necessarily believe that 14 MV/m is a limit either.

We are also making measurements on structures for higher energy operation. In these measurements we hope to determine which of the many proposed structures for the high energy end of the accelerator we believe to be superior. Many considerations come in when one must choose a structure for use in this part of the machine. Several of these have been treated by others at this meeting, and a partial list might include efficiency, freedom from breakdown, simplicity of construction, ease of flattening, etc. At the present time, I will discuss only efficiency, but we feel that bandwidth is equally important to the operation of the machine in that it affects the rf tolerances very strongly. We feel that standing wave operation is preferable to travelling wave operation in that the optimum tuning of the tank is independent (to first order at least) of beam loading. Efficiency is what rules out continuing the Alvarez structure for the complete length of the machine. Thus, we want structures which are considerably more efficient than the Alvarez structure at high energies. A search of the available literature suggests that an investigation of the Crossbar structure, as discussed by Carne, would be a reasonable starting place, with the frequency chosen at 400 Mc/sec. Also, an investigation of the Cloverleaf structure is in order. For the Cloverleaf, we envision operation at 800 Mc/sec, and have done our modeling at that frequency.

We have constructed a small Crossbar structure very similar to the one which was discussed by Carne. Our model resonates at a frequency of 560 Mc/sec in the π-mode, and has a bandpass of 53%. Within the bandpass are almost innumerable resonances from a number of undetermined modes of this very complex structure. This model is made to scale to 400 Mc/sec, the drift tube hole scaling to 1 inch at this frequency. If beam dynamics studies show that a smaller hole would be justified, the structure might be suitable at higher frequencies, with a corresponding increase in shunt impedance. It appears that a substantial increase of the ratio of drift tube size to tank size appreciably lowers the effective shunt impedance.

Perhaps it might be reasonable at this time to review the field configurations of this structure. We want the π-mode between like support bars, that is, we have the field between two adjacent gaps in one direction and the field between the next two gaps in the opposite direction. Heavy currents are carried on the horizontal bars, and no currents are carried on the vertical bars as shown in Fig. 4. We define the shunt impedance as before, where now, from general considerations, we can show that $\varphi = 0$ corresponds to the particle being in the center of the middle drift tube at the time of peak field. Thus, the shunt impedance becomes:

$$ZT^2 = Q \, \frac{\left(\int_o^L E(z) \cos \frac{\pi z}{L_c} \, dz\right)^2}{\omega UL}$$

in which

$U =$ total stored energy in the cavity

$\omega =$ angular frequency of the rf

$L_c =$ periodic cell length

$L = nL_c =$ length of the cavity.

Making the usual measurements we obtain the field distribution shown on Fig. 5. Carrying out the integration indicated for the shunt impedance yields the value, after scaling the measurement to 400 Mc/sec,

$$ZT^2/Q = 1380\ \Omega/m$$

and scaling the measured Q (at 560 Mc/sec) of 6500 to 400 Mc/sec gives

$$Q = 7650 \qquad \text{or}$$

$$ZT^2 = 10.6 M\Omega/m.$$

This was for $\beta \simeq 0.45$. This value of shunt impedance is almost ridiculously low compared to the previously reported value at this β of 34.6 MΩ/m, even assuming that the Q of our structure was poorer due to the method of construction (silver-plated brass with soft-soldered joints). Assuming the Q, quoted by Carne in the Rutherford report, gives a shunt impedance of only 16.4 MΩ/m, half of the quoted Rutherford value. The discrepancy in these numbers is not understood at the present time. We are in the process of constructing more Crossbar models of copper

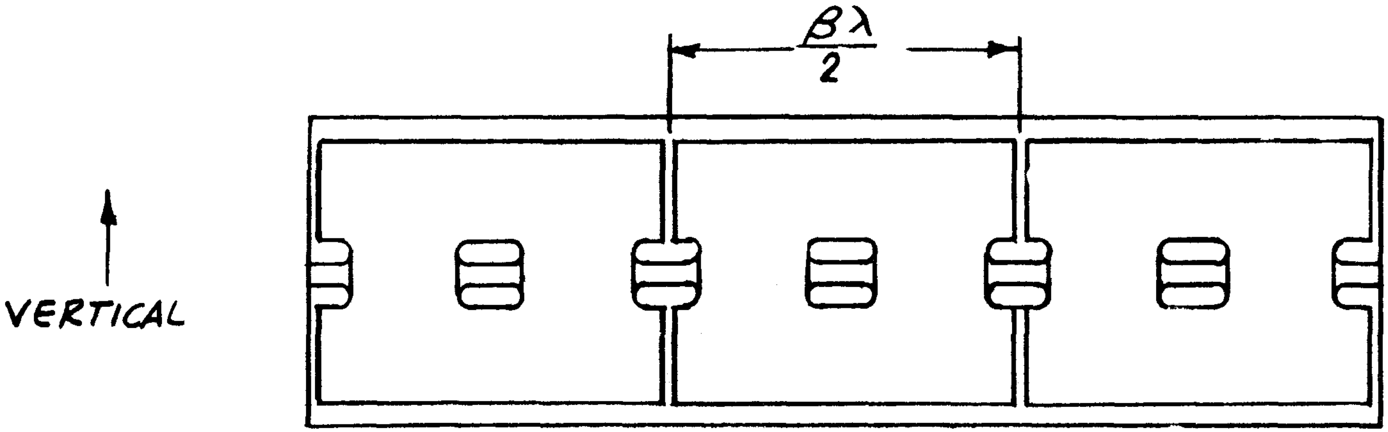


FIG. 4
CROSS-BAR STRUCTURE

"E" FIELD ON AXIS
CROSS BAR - π MODE $\beta = 0.45$
$T = .67$ $\frac{ZT^2}{Q} = 1920$ OHMS/m

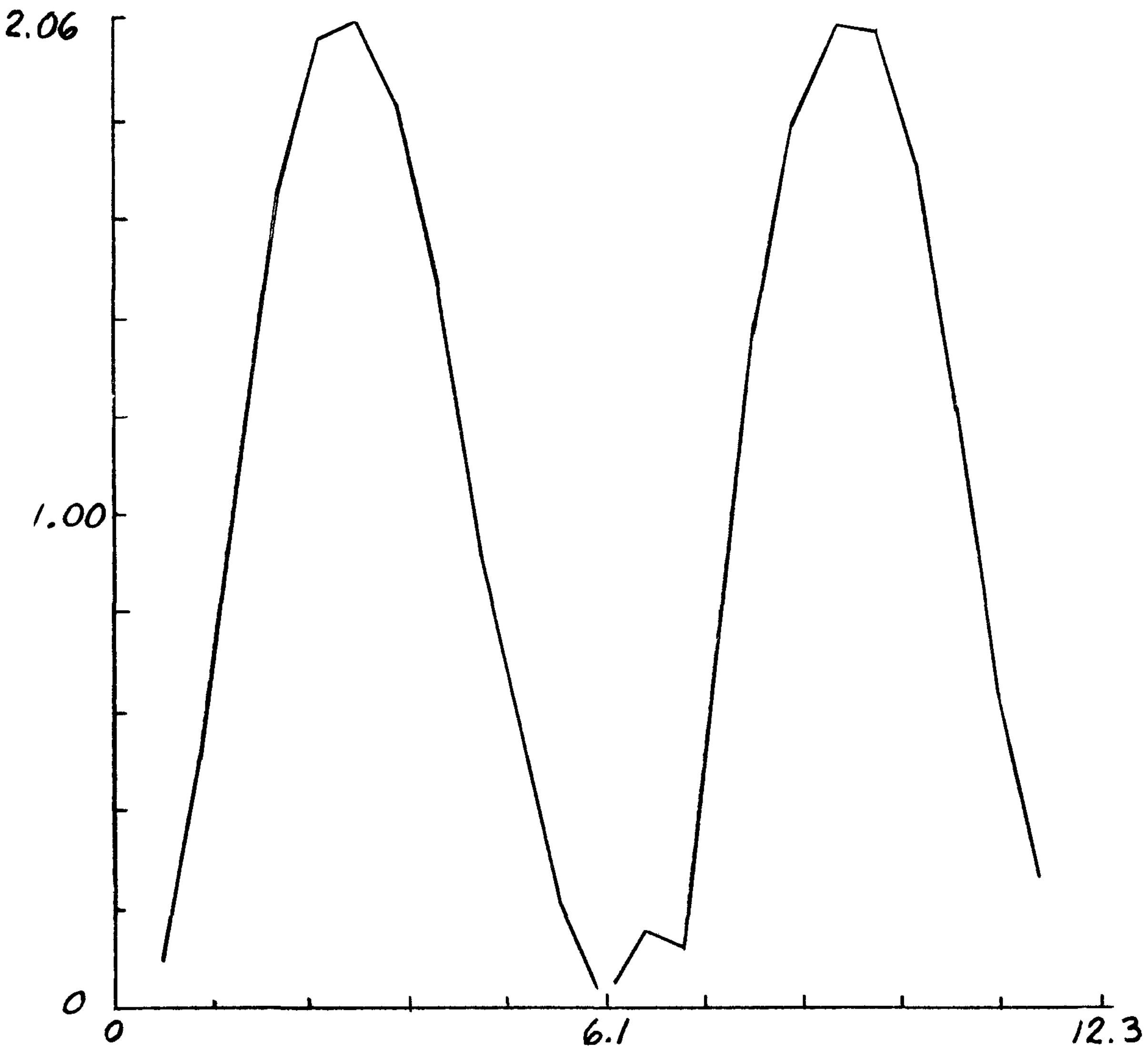


FIG. 5

with better joints to check the Q value. It would seem that in a very long structure, there could be a degeneracy between the mode in which the vertical bars carry no current and those in which the horizontal bars carry no current. I don't quite see how one can drive a long structure in such a way as to avoid this.

The Cloverleaf is essentially an iris-loaded waveguide operated in the TM_{010} mode with the coupling from cell to cell accomplished by inductive slots rather than by the electric field through the hole. The coupling is accomplished by introducing radial magnetic field components which are in the same direction on both sides of the septum. In the π-mode, these radial magnetic fields accomplish the coupling by allowing a current interchange between adjacent cells. I will not go into the details of the coupling because it has been adequately covered.(1)

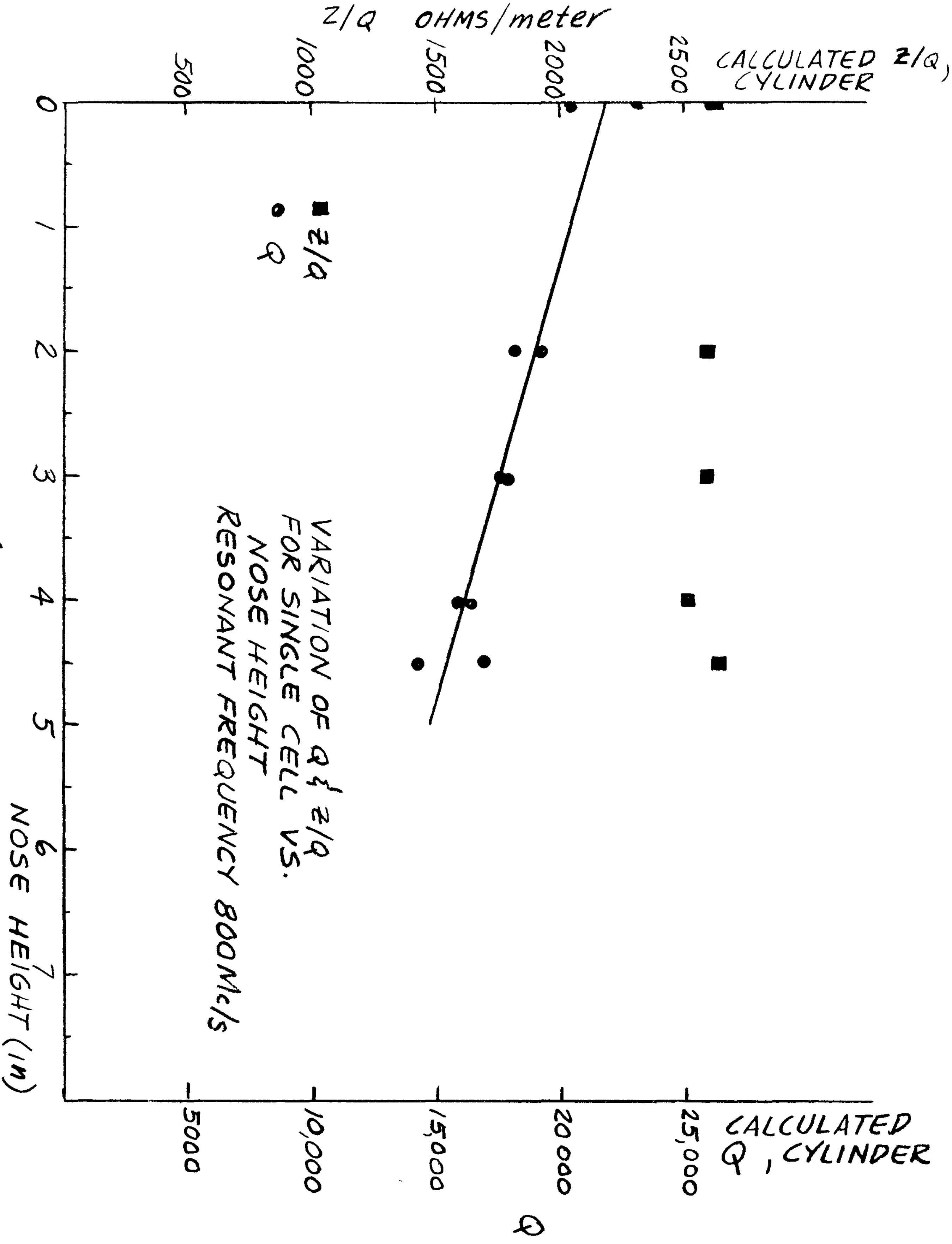
We have chosen to operate at 800 Mc/sec because of beam dynamics considerations, the frequency transition being much easier at this harmonic ratio. In order to investigate the effects of the noses on the field distribution in the cavities we constructed wooden models lined with copper sheet which had varying amounts of nose protrusion into the volume. We attempted to keep the frequency of these cavities around 800 Mc/sec by increasing the outer diameter of the cavity as the noses were made longer. We start with a cylinder, whose field distribution and Q we can calculate exactly, and work up to 5-inch nose protrusion. In practice, the top and bottom lids were secured tightly with large clamps, and the Q of the cylinder was about 80% of theoretical. Results of these measurements are shown in Fig. 6. These indicate that in the absence of slots, the field distribution, (that is, the ratio of stored energy to axial field) remains constant as the noses are increased in size, but the Q goes down more or less linearly. This is certainly a reasonable behavior, and would indicate that a large loss from a cylinder is not experienced in producing the radial fields necessary for the coupling.

We also have a two cell plus two-half cell model of the Cloverleaf with nose protrusion of 4 1/2 in. at a resonant frequency of 838 Mc/sec. The dispersion curve for this model is shown in Fig. 7. It has a bandwidth of about 10%, its mode spectrum being very clean with no other resonances detectable within its passband. The resonant frequency is 838 Mc/sec giving a β of 0.71 for its periodic length of 5 in. The value of the electric field versus z through the two center cells is shown in Fig. 8. Of course, the field at any one instant of time is reversed in one cell to the next, which is not shown in the figure. Carrying out the required numerical integration yields the value (scaled to 800 Mc/sec) of:

$$ZT^2/Q = 929\Omega/\mathrm{m}$$

The measured Q is 19,000, which scaled to 800 Mc/sec is 19,500, giving a shunt impedance of:

$$ZT^2 = 18.1\ \mathrm{M}\Omega/\mathrm{m}.$$



VARIATION OF Q & Z/Q FOR SINGLE CELL VS. NOSE HEIGHT
RESONANT FREQUENCY 800Mc/s

FIG. 6

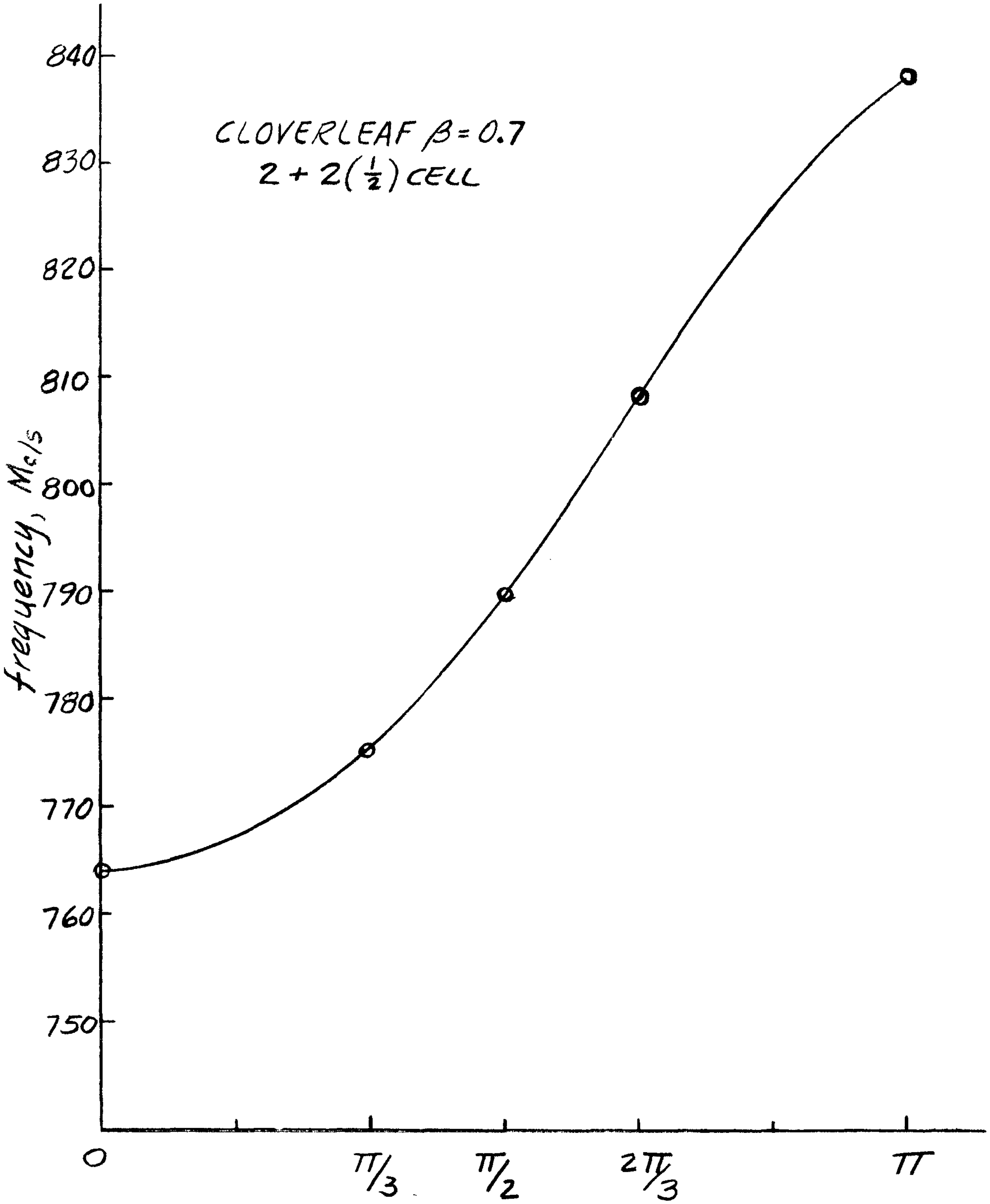

CLOVERLEAF β = 0.7
2 + 2(½) CELL
840
830
820
810
800
790
780
770
760
750
frequency, Mc/s
0
π/3
π/2
2π/3
π
MODE

FIG. 7

CLOVERLEAF AT $\beta = 0.7$
E FIELD ON THE AXIS
$T = 0.69$ $\frac{ZT^2}{Q} = 978$ OHMS/m

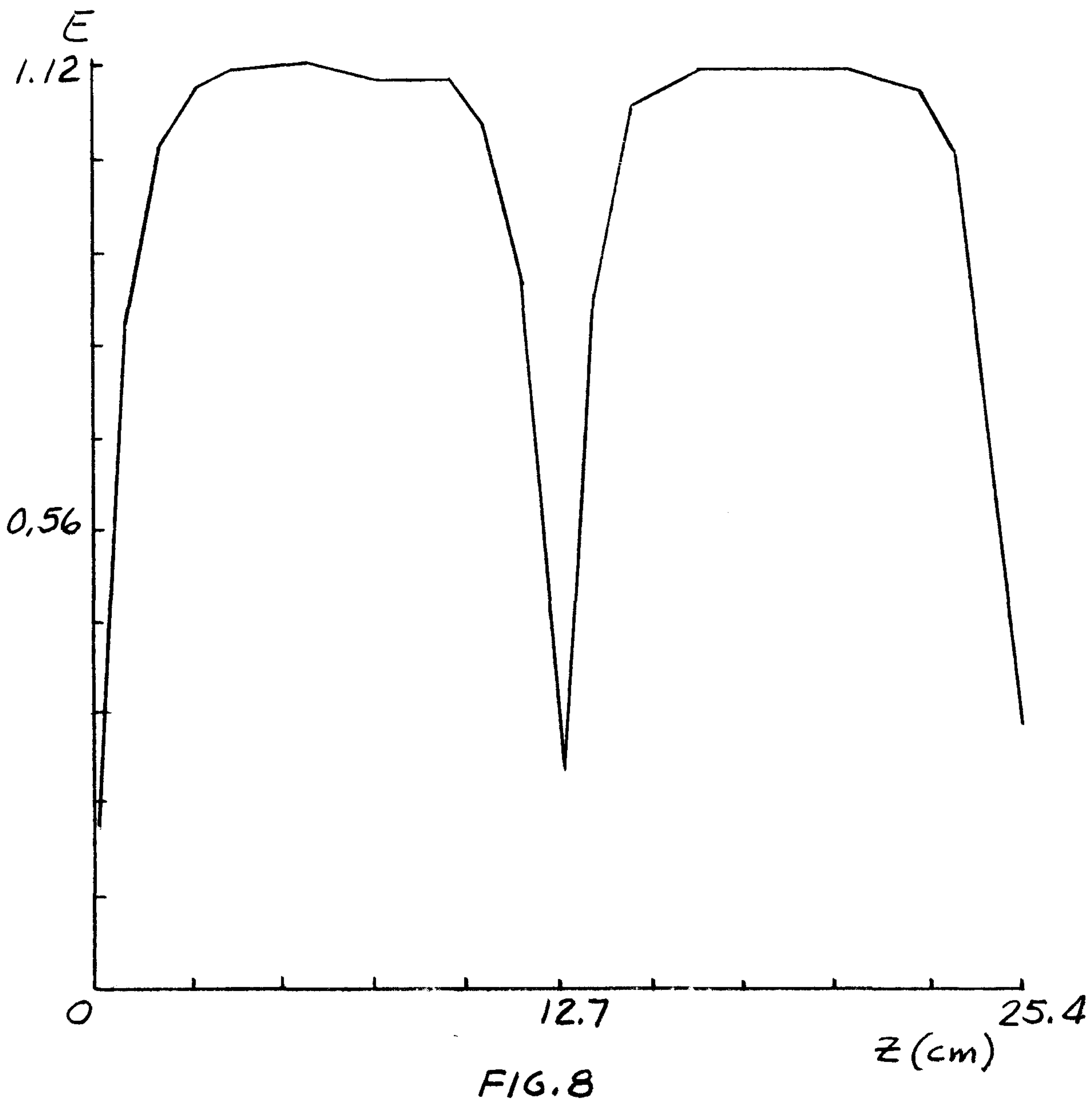


FIG. 8

We have not considered the effects of making the slots resonant at this frequency. Resonant coupling has been investigated by the Rutherford group and found to be desirable from the point of view of bandwidth, however it is not apparent at the present time what effects this might have on the breakdown characteristics of the cavity. Presumably the resonant slots would have large electric fields built up in them and this might bring with it all the problems of coupling through irises. We also hope to consider the effects of different nose shape on the Q of the circuit. It is not obvious that the round end nose is optimum.

In summary, we have measured the shunt impedance of four structures suitable for use in an accelerator, two for use in the Alvarez part of the machine, and two for use in the iris-loaded part of the structure. We find substantial agreement with the results of other linac builders for the values of shunt impedance in the Alvarez part of the machine, but disagree somewhat in detail with the computations of the group at MURA. In the iris-loaded section of the machine, we find quite a disagreement with the work of the Rutherford group. This disagreement is not understood at the present time.

POLK: How large would the drift tube part in the Crossbar structures have to be before they would really start affecting what is going on inside the structure? These appear to be quite small.

KNAPP: I think they effect what goes on in the structure strongly, because there's a large capacity between adjacent drift tubes. Electrically, they are very important.

POLK: But they didn't seem to effect things like losses or shunt impedance, according to what Alan Carne said.

KNAPP: I haven't made any measurements on that. I don't know how they effect losses.

POLK: I was wondering how large the drift tubes and the holes in them have to before you would start seeing some real effect on the Q and shunt impedance of the structure?

CARNE: Well, I think that, in general, it's a bit difficult to say. Of course, the larger the aperture, then the larger the I_o term in the transit time factor, and the shunt impedance would go down. But these are only generalizations, we have not done any measurements, and these are some of the things we are going to do.

Reference

(1) M. Chodrow and R. A. Craig, Proc. IRE 45, No. 8, 1106 (1957).