

MEASUREMENTS ON A MODEL RF MANIFOLD SYSTEM

Ferdinand Voelker

Lawrence Radiation Laboratory
University of California
Berkeley, California

Abstract

At Lawrence Radiation Laboratory, we have set up a one-tenth-scale rf manifold system with six cavity loads and several amplifiers operating at 200 MHz. The manifold is a 50-ft-long coaxial line, and the cavities are foreshortened quarter-wave resonators with about 25 higher-order resonances below 2GHz. The measurement program consists of three parts. The first part consists of steady-state measurements of amplitude and phase along the system in the principal pass-band. The second part consists of measurements during the rise and fall time in pulsed operation. The third part consists of measurement of higher-order modes of the system which are excited by very short pulses of current (~ 0.25 nsec) in the gaps of the cavities.

Introduction

We propose a system to distribute rf energy by a manifold paralleling a linear accelerator. All the rf amplifiers will supply energy to this manifold, and all accelerator cavities will draw energy from it. This paper describes measurements made on a model that has many of the same parameters as our full-scale device would have.

Figure 1 is a schematic representation of a manifold system. In this case six resonant-cavity loads must be provided with rf energy. Paralleling these cavity loads is a transmission line with both ends short-circuited. Radio-frequency energy is supplied from a number of amplifiers distributed along the system. When the system is operated on the correct frequency, standing waves are set up in the transmission line with a voltage maximum every half wave length. Connection to the transmission line is allowed only at these voltage maximum points, and we refer to them as mesh points.

The loads and amplifiers are connected to the transmission line (or manifold as we will call it) by additional transmission lines which are electrically a multiple of one-half wave length ($\lambda/2$) long. Power can be taken out or fed in at any mesh point in any quantity up to the capacity of the system, so that it is not necessary to have a uniform distribution of loads or sources. It can be shown that the voltages at the mesh points are nearly the same in amplitude and phase if the system losses are low compared to the power being transferred. (There is, of course, a phase difference of π between odd number and even number mesh points.) The amount by which the amplitude

or phase of the voltage at the mesh points changes with various perturbations to the system is predictable, and the model system was built to check that such a system would actually work as expected, and also to look for any transient properties that were not predicted. A description of the actual model (shown in Fig. 2A and 2B) is given at the end of this paper for those interested in details.

The advantages of a manifold system can be summarized as follows. Since a number of amplifiers can be conveniently connected at arbitrary mesh points on the manifold, it is easy and not very costly to add an extra one or two for increased reliability. It is also simple to add more amplifiers for more power later when the beam loading is increased. Similarly, since the linac cavities are divided into smaller units, it is simple to connect these a few at a time when they are first put into service, thus giving a huge surplus of rf power to get through multipactoring as the cavities are baked in. With a manifold system it is not necessary to tailor the individual linac cavity lengths to the size of the rf power package. Since all cavities are "locked" in phase and amplitude, an individual servo system is not necessary to control the phase and amplitude of each linac cavity.

General Observations

When the system is pulsed, the rf envelope of the cavity voltage, the manifold voltage at an unloaded mesh point, and the tank voltage at the amplifier all have a very similar waveform if the system is tuned correctly. There is an exponential risetime, a flat-topped region, and an exponential fall time. Typical waveforms are shown in Fig. 3, A and B. Our monitoring system has a sample and hold circuit which enables us to monitor the pulse at some particular time and to display the amplitude of all six cavities at one time as shown in Fig. 4, A and B.

If the system is correctly adjusted, we can detune the master oscillator or any of the six cavities, and the amplitude of the voltage in the six cavities decreases equally and together. The system can be retuned to resonance by tuning any other of the six cavities or the master oscillator, and the original adjustments can soon be lost even though the system is still tuned to resonance.

If the drive frequency is changed enough to reach the next resonant mode of the system, all

cavity voltages decrease together until they are nearly zero; then they increase separately as the next mode is approached. Figure 4 A and B shows the drive frequency adjusted to the next two resonances (bottom traces.)

If one of the lines coupling a cavity to the system is made too long or too short, the voltage in that cavity no longer is "locked" to the others and as any element in the system is tuned, the amplitude of this cavity voltage is no longer proportional to the others. Figure 5 shows this for the coupling line 2 cm too long on cavity 3.

Steady-State Behavior

The steady-state measurements were of two kinds. The first was a search for all resonant modes we could find by using a loosely coupled signal generator and a type-661 Tektronix oscilloscope. We were particularly interested here in resonances above 200 MHz, and we were able to identify about 150 resonances below 2000 MHz.

The second kind of measurement was made with an amplifier coupled to the system through a $\lambda/2$ line. A Hewlett-Packard rf vector voltmeter was used to measure the amplitude and phase of the voltage in the various cavities as a function of frequency for the "ideal" tuned situation, and for several kinds of mistuning. This information was plotted directly on graph paper by using an x-y recorder. Case 1 in on Fig. 6 shows a typical graph of the voltage amplitude of cavities 3 and 4 and the phase of the fields between them as the frequency was varied. In this set of curves the amplifier was located at one end of the manifold and the two cavities at the center were being observed. Notice that the amplitude of the field in both cavities stays almost the same as the system is tuned through resonance, and that phase difference between the fields is not greater than 0.1 deg for frequencies ± 25 kHz from resonance. Case 2 in this figure shows the amplitude and phase of the fields in these same cavities as cavity 3 is detuned by 50 mils on the micrometer.

It can be deduced from this family of curves that the principal effect of changing the tuning of one cavity is to change the resonant frequency of the system. There is a change in phase of only 1 deg because of this detuning. The cavities are $3\lambda/2$ apart, which accounts for the 180-deg difference in phase. Notice that, even in this extreme detuned case, the voltage amplitude of the cavities is "locked" together. Figure 7 shows the relationship between the fields in cavities 3 and 4, when cavity 3 is detuned and the system brought back to the original resonant frequency by tuning cavity 4. Adjusting one cavity ± 50 mils on the micrometer will tune a cavity ± 550 kHz when it is not connected to the manifold. Since the Q of the unloaded cavity is about 5000, this is equivalent to having the cavity tuning about 14 Q-widths from its unloaded resonant frequency. For this very extreme detuned situation, the amplitudes of the fields in the perturbed cavities were still within 1% of each other, and the phase difference was

less than 2 deg.

The most critical adjustment of the system is the length of the coupling line between a cavity and the manifold. Figure 8 shows the relationship between the fields in the cavities as one of the coupling lines is increased 2 cm. The amplitudes now differ by about 1%, and the phase difference between them is increased to 1.5 deg. This was apparent in Fig. 5, where the amplitude in cavity 3 has changed, but the other five cavities are still "locked."

The spectrum of the adjacent modes is shown in Fig. 9 along with the values predicted from the computer simulation. The predicted values for the "ideal" condition are quite close.

The more remote modes are difficult to measure and are more easily perturbed. They do not show on this graph, because appreciable signal strength is required to actuate the servo system in the rf vector voltmeter. We expect 12 modes in this pass-band, but we have never measured all 12 at once. The edges of the pass-band agree with the computed results, however, which increases our faith in the computer simulation. The computed data also show a set of modes, which we designate as $\pm \frac{1}{2}$, $\pm 1\frac{1}{2}$, etc. between the integer numbered modes, and which we have not been able to find on the model. These correspond to modes in which the voltage in the cavity at one end is high and the voltage in the cavity at the other end is low. (The integer-valued modes correspond to symmetry about the center.)

Pulsed Operation

Because the Q of our model is about one tenth that of the full scale system, the rise times are of the order of 10 μ sec rather than 100 μ sec for the full-scale case. Figure 3A shows the envelope of the cavity voltage in the upper trace and the envelope of the amplifier tank voltage in the lower trace. The amplifier is tightly coupled to the system, so that the amplifier voltage rises at the same rate as that of the cavity. The principal difference between the various cavity voltages is in the phase and amplitude of the superimposed transient during the rise and fall time. Figure 3B shows the rf voltage in one of the cavities in the upper trace, and the modulator voltage (going negative) in the lower trace. The amplitude of the voltage is being servoed in this figure, so that the amplitude of the modulator voltage is reduced after the rf envelope in the manifold reaches the servoed level, which decreases the rise time. The modulator voltage has a ripple that tends to cancel the ripple on the amplifier output. Figure 10, A and B, shows the rf envelope of the voltage in cavities 3 and 6 and the amplifier with a higher loop gain in the servo system. In this case there is some overshoot on the front end of the pulse. Figure 10B shows the trailing edge in more detail. The amplifier can interrupt the power being fed to the system more rapidly than it can start power flowing; therefore the transients are excited more strongly. The principal frequency in the falling

waveform is about 2 MHz in cavity 3 and about 3.3 MHz in cavity 6. This corresponds to the ± 2 modes and the ± 3 modes, respectively. Since the amplifier is located near the center of the system, it does not tend to excite the ± 1 modes. The period of the overshoot on the front end of the pulse corresponds to the bandwidth of the servo amplifier. This was made less than the frequency difference between the operating frequency and the nearest modes in an effort to avoid exciting these modes. In Fig. 11 the bandwidth is large enough to cause continuous oscillation at a frequency which is the same as that excited by the transients.

Multiple Drive

All data shown were taken with only one amplifier driving the system. However, we have operated with an amplifier in the center and with additional amplifiers eight and nine half wave lengths on either side of the center one. There has been no difficulty in making them share the load, if the phase to the input of each drive amplifier is correct. If the phase of the drive of one amplifier is reversed, it then lowers voltage on the system. When the power-supply voltage of one of the amplifiers is changed, the voltage level on the system changes accordingly. With one amplifier being servoed, the system level stays approximately constant when the power-supply voltage is changed on another one.

We also have been able to operate the system with one amplifier being driven from the master oscillator and another amplifier being driven from an adjacent mesh point. This is particularly interesting, because it means that we may be able to operate the full-scale system with only one driver and with the other amplifiers driven from the manifold.

Transient Phenomena

We intend to do more work on the transient phenomena of a manifold system, particularly as it pertains to excitation of the adjacent modes by the servo system. Another phase of the study of transients is concerned with their excitation by the beam. We are now in the middle of an experiment in which we are mounting a small micro-wave triode across the gap of one of the cavities. The triode will be operated with the grid grounded to the inner conductor of the cavity and the anode grounded (for rf currents) on the other side of the gap.

We have a small pulse generator using a snap-off diode at the cathode of the triode. With it we can turn on the triode for about 0.25 nsec at 200 MHz and at an arbitrary phase, so that a short pulse of electrons passes through the gap, simulating the beam loading in a linac cavity. We have already driven a loop in the cavity with this same pulse generator and have found, as one would expect, that several of the higher resonances of the manifold system are strongly excited. We hope to arrive at a suitable way to suppress these without disturbing the 200-MHz

properties of the system. Andris Faltens who is carrying out this part of the study will report on this work later.

Description of Model Manifold System

The model manifold system, shown in Fig. 2A consists of three parts: a one-tenth-scale manifold, six resonant-cavity loads with coupling lines, and the amplifier drive system. The rf manifold is made of 18 accurately machined sections of coaxial line that are each 5.7 cm in diameter and 75 cm long. The characteristic impedance of the coaxial line is 35.5Ω . The inner conductor is supported on a continuous Styrofoam insulator, and each section is electrically connected to the next by rf spring fingers. A threaded steel rod through the center pulls all 18 sections of outer conductor together. The two end sections are short-circuited at the outer ends making the manifold 18 half-wave lengths long at 195.770 MHz when the manifold is at 17°C. The overall length of nearly 50 ft has the same attenuation from end to end as the full-scale manifold we have been considering. In the center of each section there is a provision to insert a fitting that allows electrical connection to the inner conductor through a GR 848 connector. These connections are the "mesh-points" of the manifold, and they are at the voltage maximum points of the unloaded manifold.

The resonant-cavity loads are sections of a coaxial line which are foreshortened by a gap that can be adjusted with a micrometer head. The outer diameter is 6 in. and the cavity has an unloaded Q of approximately 5000. Electrically, the cavity is a quarter wave long, and near the short-circuited end are two coupling loops which have been rotated to give 50Ω and 300Ω input impedance respectively at resonance. Since the shunt impedance of the cavities is about $500\text{ k}\Omega$, this is equivalent to a turns ratio of 100 and 41 respectively between the gap voltage and the loops. The micrometer allows a fine adjustment of the unloaded resonant frequency of $\pm 550\text{ kHz}$ with ± 50 mils of motion.

The cavities are normally adjusted to have the same resonant frequency as the unloaded manifold. The next higher resonance is at 585 MHz, and there are about 23 additional resonances below 2000 MHz. Each cavity has six turns of 1/4-in. diam copper water tubing soldered to its outer diameter, and the cavities are mounted in thick styrofoam jackets so that they will come to the temperature of the circulating water. The six water circuits are connected in series, so that all the cavities stay at the same temperature. The cavities are connected to the manifold by an adjustable GR 50- Ω coaxial line. During the process of adjusting the coupling loops, the length from the cavity to the detuned short position on the coupling line is determined. When the cavity is connected to the manifold, the coupling-line length is adjusted so that the detuned short position falls at the center of the manifold.

Figure 2B is a closer view of one end of the system showing a cavity load and an amplifier connected to the manifold. The drive amplifiers are transistorized and are built on printed-circuit boards. The drive-amplifier board has two class-C radio-frequency stages with strip line tank circuits. There is also a modulator with a closed-loop regulator, so that the supply voltage to the rf amplifier may be controlled in time and amplitude by a low-level pulse. The low-level rf stage is furnished with a continuous-wave drive voltage of about 1V rms at the desired rf frequency, and the bandwidth of the drive amplifier is about 5 MHz.

Tuning the Model

We postulate that the system is ideally tuned (1) when it is driven at the resonant frequency of the unloaded manifold; (2) when the length of coupling line is such that the detuned short position on the line is connected to the mesh point on the manifold, and (3) when the cavity is tuned to minimize the reactive energy exchanged between the cavity and the rest of the system. This is most easily accomplished on the model by unloading the manifold and tuning the drive frequency for resonance; then the cavities are added (with the pre-measured line length) one at a time. Each cavity is retuned to bring the system to resonance before the next is added.

The amplifiers are connected to the system in one of two ways. When going through the tuning-up procedure described above, the amplifier drives a small loosely coupled loop at one end, while a similar loosely coupled loop at the other end is connected to a 661 sampling scope to monitor the resonances. When the system is correctly adjusted, the amplifier is connected to a mesh point through a half-wave-length coupling line. When the system is pulsed, the rf envelope at several points is monitored by crystal detectors. By observing the pulse envelope at the amplifier tank circuit and at a cavity simultaneously, one can easily adjust the amplifier coupling line for the tightest coupling, although this is not a critical adjustment.

Acknowledgments

Others working on this model program are Andris Faltens, and Frank Tirimacco who assembled and operated many parts of the system.

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Bibliography

1. Ferdinand Voelker, A System for Multiple Excitation of R-F Cavities, Lawrence Radiation Laboratory report UCID-10103, January 6, 1964.
2. Ferdinand Voelker, Thoughts on Mode Distribution in R-F Manifolds, Lawrence Radiation Laboratory report UCID-10107, May 25, 1964.

DISCUSSION

F. VOELKER, LRL

SMITH, BOB, LRL: Ferd, one thing that would worry me on a manifold system like this is that, if you are operating at full scale with reasonable voltages on these drive lines and if a cavity became detuned, is there danger of so shifting the standing wave pattern that you would have serious spark-over problems?

VOELKER: In the cases I showed, where the cavities were detuned $1/4$ Q-widths, the voltage between mesh points becomes several times the voltage at the mesh points, and you certainly could not operate under those conditions. The line would spark every time, and so you have to restrict your detuning of the cavities to a fraction of a Q width. Under the latter conditions then, the voltage minimum never gets as high as the voltage at the mesh point, and the voltage maximum on the transmission lines always stays the same. You would have to take care that you didn't get accidentally on another mode or that you didn't detune a cavity a very large amount, as would occur, for example, if a servo were to run away.

SMITH, BOB: Do you think that would be difficult or easy?

VOELKER: Well, we would just have to have adequate protection so that you didn't get into a detuned situation like this at a high power. The crowbars would have to shut you off if you did.

LAPOSTOLLE, CERN: I had a somewhat similar question about the use of an rf manifold. How well will it work when you have different cavities to feed which are possibly operating at quite different power levels, having different Q values, or things like that?

VOELKER: This makes no difference whatsoever. It's just like an ac power main--you can plug a heater in one socket or you can also plug in a light bulb, it doesn't matter. There is some effect due to power distribution which the computer shows up more clearly than the model, if you draw a large amount of power from one mesh point, or if you have some other large asymmetry. We are designing to hold the voltages to $1/10$ of a degree in phase and 0.1% in amplitude. It looks like we can do this, even with our linac cavities which vary in power required by 3 to 1 along the length of the linac. Symmetry is not required of this rf manifold system.

KEANE, BNL: You have said that if the line length between the manifold and the cavity changed, that the voltage gradient in the cavity dropped. All the voltages at the output of the manifold are equal, but if there is a different input impedance from cavity to cavity, wouldn't this now force a different voltage in the cavities in a similar manner?

VOELKER: I didn't mention this, but the transmission line between each cavity (and each amplifier) is also a multiple of a half wave-length, so you also have phase and amplitude locking between the manifold and the cavity fields. If, however, you did allow a coupling line to be the wrong length, the voltage would vary with change in loading. We are planning on 50-ohm lines in the coupling lines between cavities and manifold, but a 30-ohm line on the main manifold. The impedance doesn't matter as long as the lines are a multiple of half wavelengths.

BROWN, Raytheon: What standing wave ratio do you have on the manifold?

VOELKER: It varies from infinity near the ends to about 3 to 1 at the most heavily loaded point. This is a design value. The standing wave ratio inverts if we inadvertently load one cavity too much. I didn't mention it, but we can load a cavity down by inserting resistance into it, and we can actually invert the standing wave ratio. That is, the voltage becomes larger between mesh points than at the mesh points. The standing wave ratio is a measure of the power flow and the voltage at the mesh point stays constant under normal conditions.

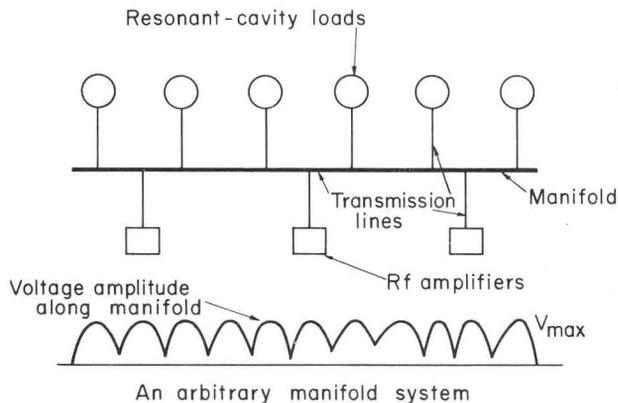


Fig. 1. Schematic of a manifold system.

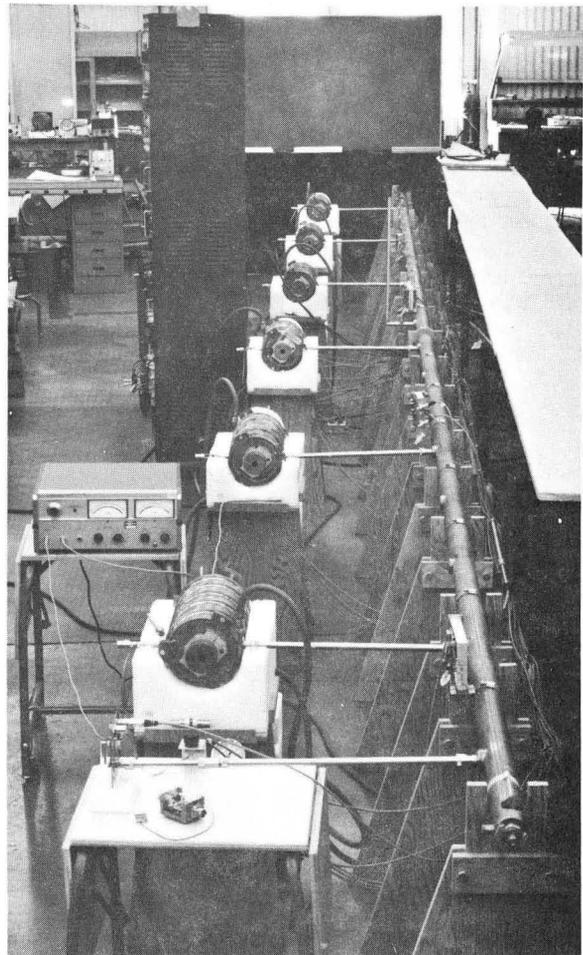


Fig. 2a. One-tenth scale model rf manifold.

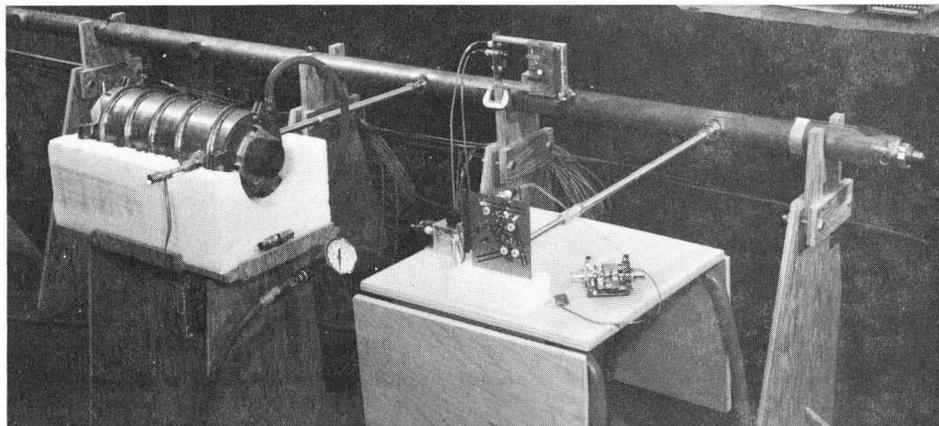


Fig. 2b. Resonant-cavity load and amplifier connected to rf manifold.

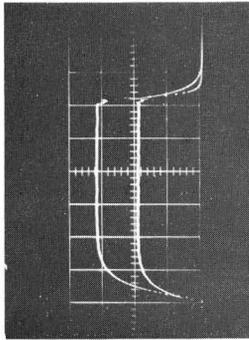


Fig. 3a. RF envelope. a. cavity voltage.

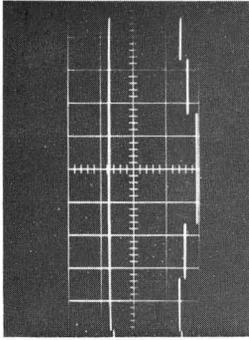


Fig. 4a. Amplitude in all six cavities. a. operating frequency, b. +1 mode.

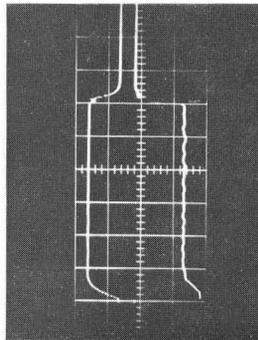


Fig. 3b. RF envelope. a. cavity voltage, b. modulator voltage with amplitude servo.

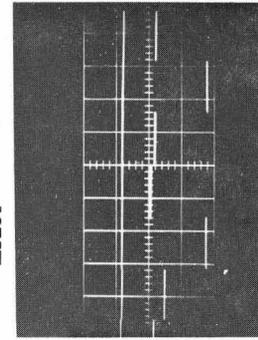


Fig. 4b. Amplitude in all six cavities. a. operating frequency, b. +2 mode.

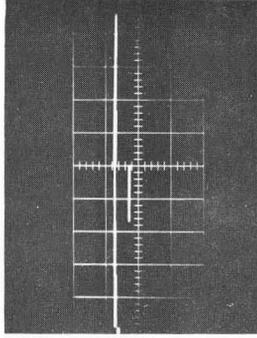


Fig. 5. Amplitude in all six cavities. a. normal, b. coupling line on cavity No. 3 two cm too long.

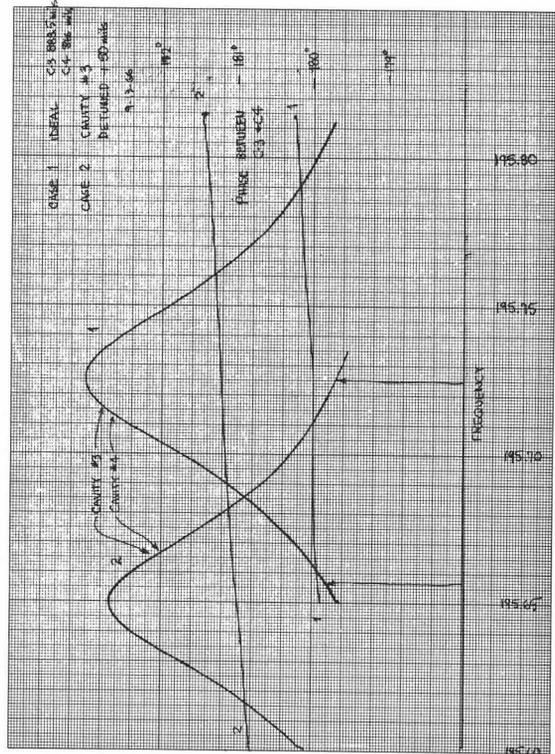


Fig. 6. Amplitude and phase of voltage as one cavity is detuned.

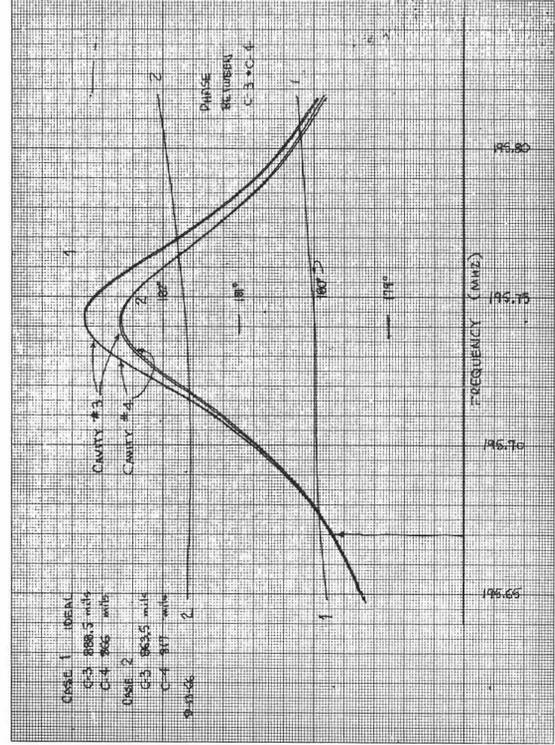


Fig. 7. Amplitude and phase of voltage as two cavities are detuned.

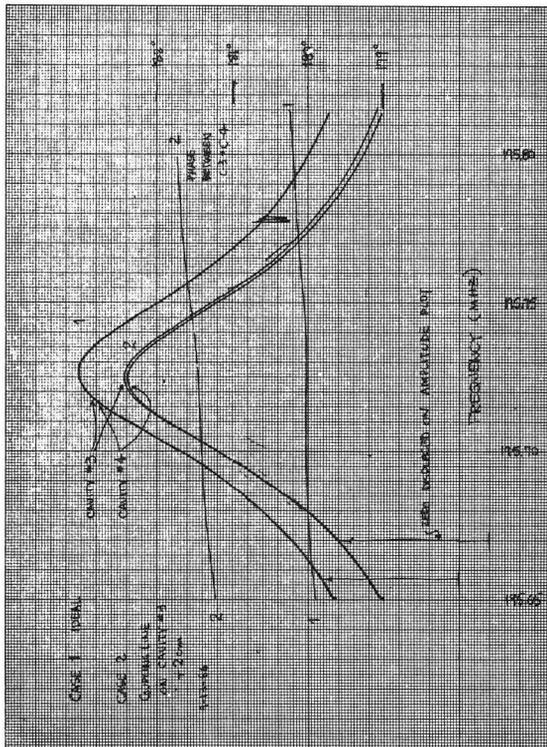


Fig. 8. Amplitude and phase of voltage as coupling line length is changed.

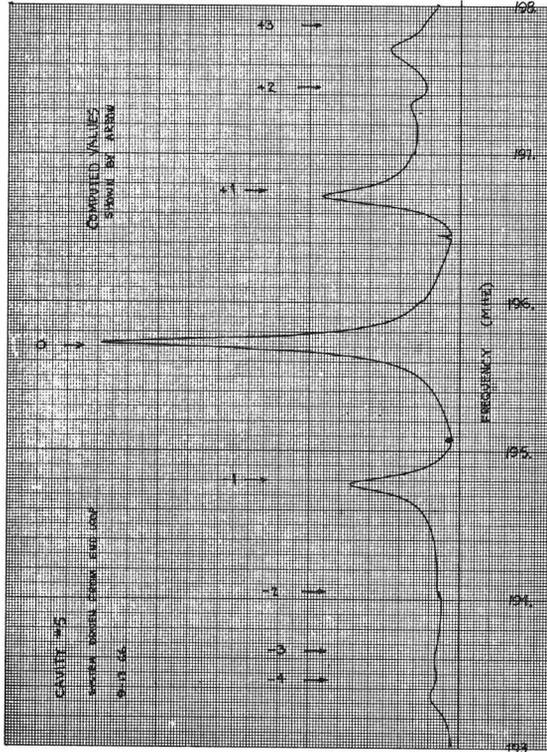


Fig. 9. Adjacent mode structure.

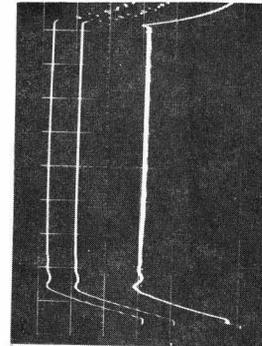


Fig. 10a. RF envelopes with servo on.
 a. cavity No. 3 voltage,
 b. cavity No. 6 voltage,
 c. cavity voltage 5 μ sec/cm.

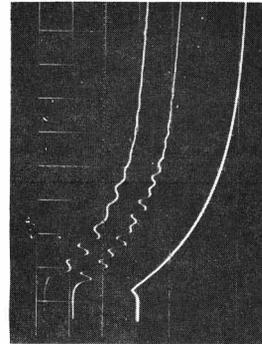


Fig. 10b. Trailing edge of pulse.
 a. cavity No. 3 voltage,
 b. cavity No. 6 voltage,
 c. amplifier voltage,
 1 μ sec/cm.

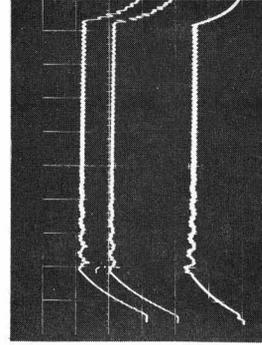


Fig. 11. RF envelopes with higher gain
 and more bandwidth. a. cavity
 No. 3 voltage, b. cavity No. 6
 voltage, c. amplifier voltage,
 5 μ sec/cm.