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MULTIPLE EXCITATION OF RF CAVITIES WITH AN RF MANIFOLD

F. Voelker
Lawrence Radiation Laboratory

We believe that it is desirable to make our linear accelerator tanks short in order to have better control of the mode problem, because we want to put the quadrupoles in between the cavities instead of in the vacuum and to reduce the mechanical alignment problem. On the other hand, rf amplifiers seem to be most economical in large sizes. If we can devise some scheme so that one amplifier will handle several cavities, it might be reasonable to enlarge the system appreciably so that five amplifiers could be paralleled. We would want four of these amplifiers to be able to power the load. Then in the event of a failure of one of the tubes the other four could carry on. This is what we mean by an rf manifold: a way of tying several rf power amplifiers to a large number of cavities. The following idea has not been completely studied yet, but we believe that it is feasible.

Let me start with a transmission line as an equivalent circuit. I want to make it 100 wavelengths long and to short circuit it at both ends. If I introduce alternating energy to it, I find a standing wave on the line. At the short circuit the voltage is a minimum;

a quarter wavelength away, it is a maximum, and at every half wavelength farther on, the voltage is again maximum. If the line is lossless, each of the voltage maxima will have the same magnitude, and the same phase. The voltage minima are zero. The power, P, being transported has to be

$$P = \frac{V_{max} \; V_{min}}{2Z_o} \qquad (1)$$

Now let me introduce a resistor ($R >> Z_o$) at a

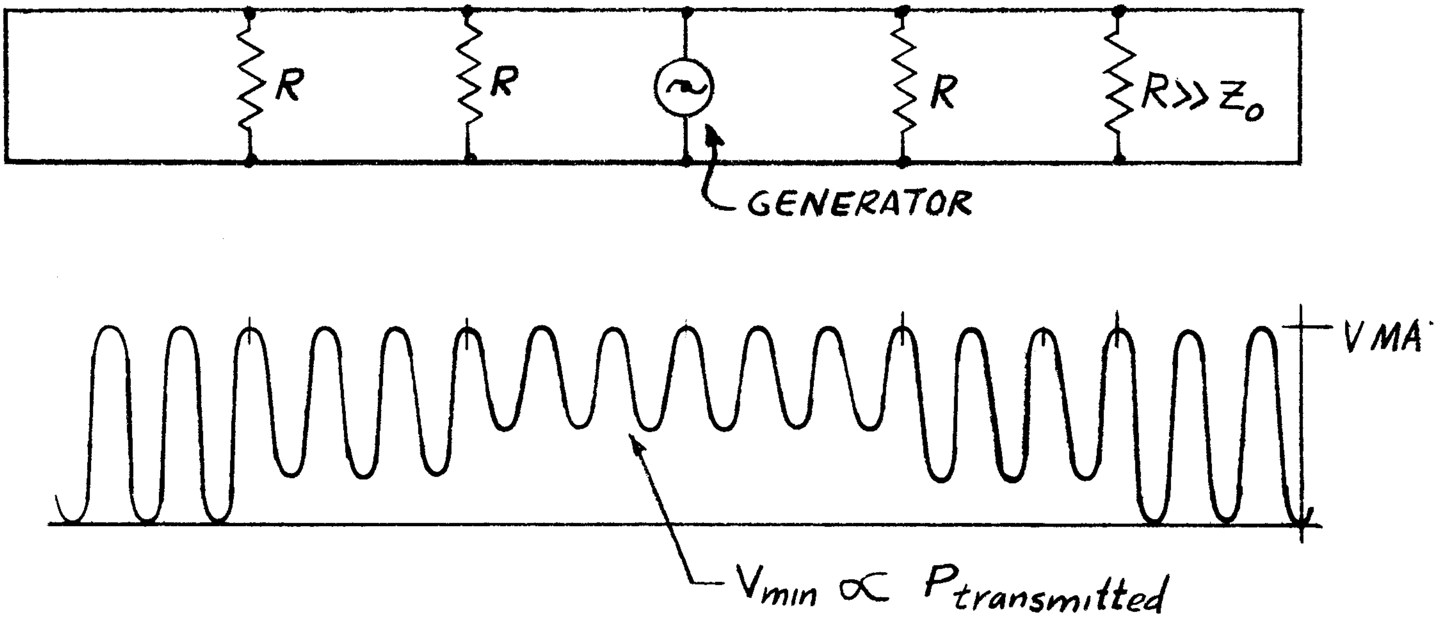

FIG. 1

voltage maximum point as in Fig. 1. As I move down the line to the left of the resistor, power is being transmitted. On the right side of the resistor, the transmission line is not carrying any power. The voltage maxima are still the same, but the voltage minima are proportional to the power being transmitted. Thus the swr (the standing wave ratio) is inversely proportional to the power being transmitted. As long as I add loads at the voltage maximum points, the amplitude and phase at the voltage maxima are all the same, if the transmission line is lossless. The nearest modes on the line are for frequencies that make the line 99λ or 101λ long which means that if the frequency is changed 1 part in 100, another mode will be excited. However, if the frequency is changed only 1 part in 10,000, the voltage is still a minimum at the ends, and the voltage maximum points are unchanged. Now, the generator sees a reactive load and must supply some reactive energy which will pass in and out of the transmission line. The voltage maxima change in amplitude depending on the Q of the system, but their relative amplitudes and positions are unchanged. If we excite the system with a generator at one of the voltage maxima, and introduce a small capacitor at another, the voltage maxima and minima do not change position because there has to be an integral number of quarter wavelengths from these points to either wall. The generator must supply the reactive energy to this small capacity, much as it did when driven off-frequency.

As long as there is a lossless line, and as long as we talk about slowly changing steady state conditions, then each of these voltage maxima is in parallel with the others. The equivalent circuit of this system is a voltage generator in parallel with many loads; if there is more than one generator, then these generators are also paralleled.

Consider what happens when we have some losses in the transmission line. The voltage maxima stay in the same positions, but the relative magnitudes change as in Fig. 2. If α is the real part of the propagation constant, and ℓ, the length of the line, then the voltage maxima increase by $1/2\ (\alpha\ell)^2$. After the first load is reached, an $\alpha\ell/\mathrm{swr}$ term dominates ($\alpha\ell \ll 1$). After n loads at the generator drive point, the amplitude of the voltage maximum is

$$\left[1 + \frac{(\alpha\ell_o)^2}{2}\right]\left[1 + \frac{\alpha\ell_1}{\mathrm{swr}_1}\right]\left[1 + \frac{\alpha\ell_2}{\mathrm{swr}_2}\right] \quad \cdots$$

$$\cdots \left[1 + \frac{\alpha_n}{\mathrm{swr}_n}\right] , \qquad (2)$$

where swr_n = swr in section n.

If α is small enough, the above expression reduces to

$$1 + \frac{\alpha\ell_1}{\mathrm{swr}_1} + \frac{\alpha\ell_2}{\mathrm{swr}_2} + \cdots + \frac{\alpha\ell_n}{\mathrm{swr}_n} , \qquad (3)$$

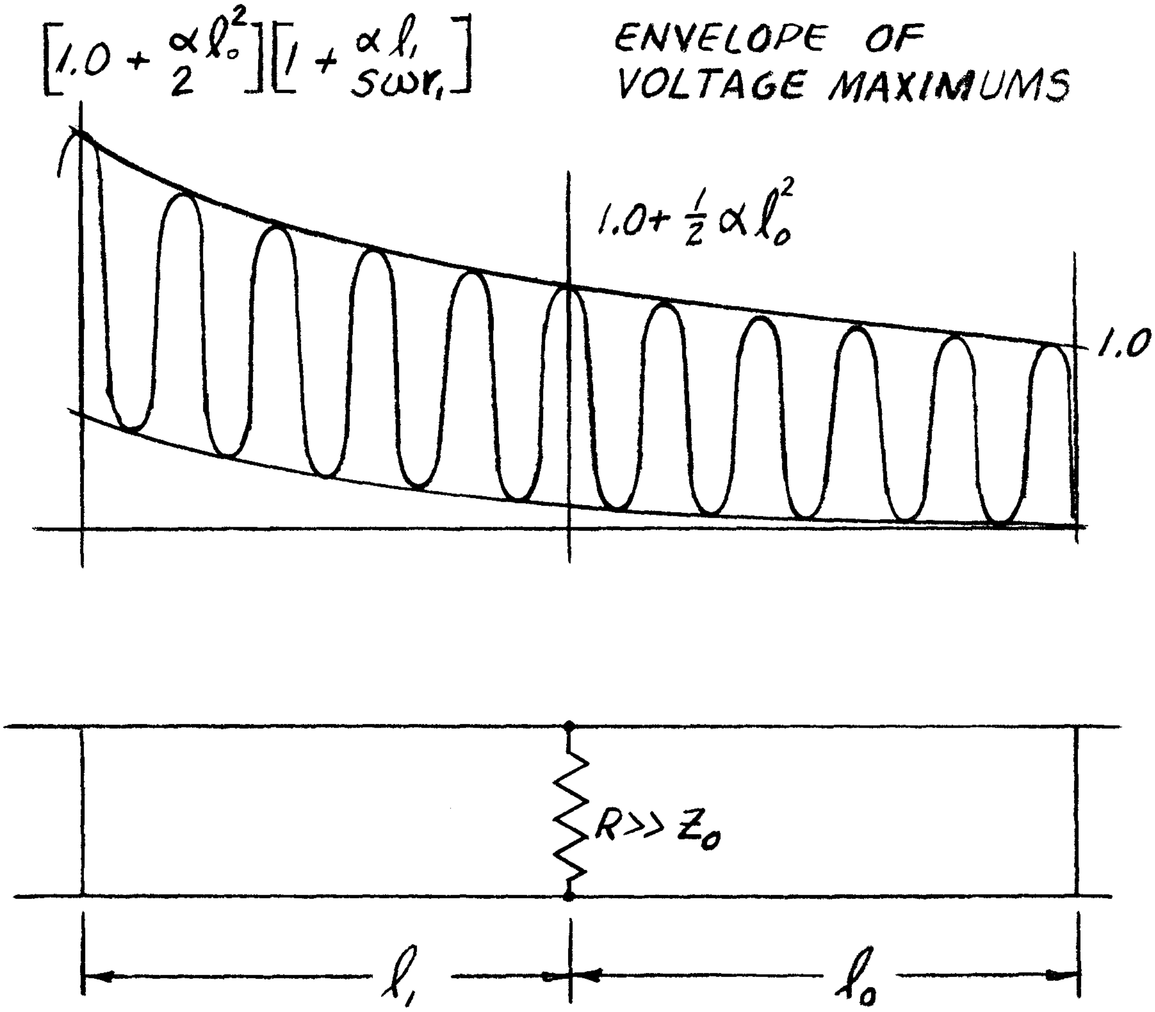
$\left[1.0 + \frac{\alpha \ell_0^2}{2}\right]\left[1 + \frac{\alpha \ell_1}{SWR_1}\right]$
ENVELOPE OF VOLTAGE MAXIMUMS
$1.0 + \frac{1}{2}\alpha \ell_0^2$
1.0
$R >> Z_0$
ℓ_1
ℓ_0

FIG. 2

and gives the relative magnitude at a generator with respect to the magnitude $\lambda/4$ from the short circuited end. To be considered "lossless:"

$$\alpha \left[\frac{\ell_1}{swr_1} + \frac{\ell_2}{swr_2} + \frac{\ell_n}{swr_n} \right] \simeq 0.01 \text{ to } 0.001 \qquad (4)$$

depending on how much "amplitude locking" we are asking of the manifold.

These are governing facts relating to the attenuation allowable in the line, and to the standing wave ratio in each section. The attenuation in the line is a function of the energy density in the line. Making the transmission line larger in cross-sectional area causes the losses to go down. So, in principle, the losses can be made as small as desired. But there is a limit to the cross-sectional area, because we don't want to allow higher order modes to propagate. Also, the length of the rf manifold is limited because as

$$\sum_n \frac{n}{swr_n}$$

increases, the "amplitude locking" decreases.

Now I want to talk about "phase locking." If I plot phase vs. $\beta\ell$ (β is the imaginary part of the propagation constant) and if the line is flat (swr = 1), then we see that the phase change is linear with the distance. (See Fig. 3.) It's easy to show that the

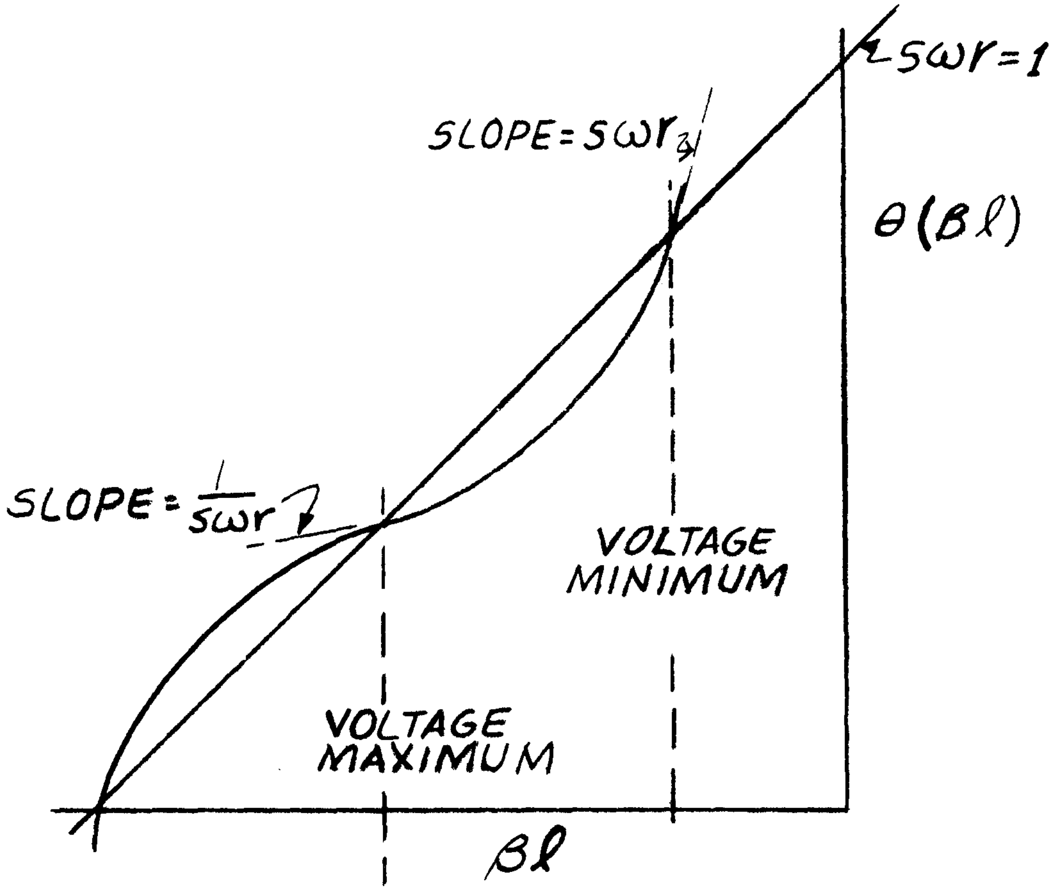
SWR = 1
SLOPE = SWR
θ(βl)
SLOPE = 1/SWR
VOLTAGE MINIMUM
VOLTAGE MAXIMUM
βl

FIG. 3

phase is given by $\theta(\beta \ell) = \tan^{-1}(\text{swr} \cdot \tan \beta \ell)$. The slope at the voltage maximum is 1/swr. As long as the frequency is controlled by a "clock," then phase errors along the manifold are caused by errors in position. If swr = 10 in a given section of rf manifold, the errors are 1/10 as sensitive to position as on a flat line. Phase errors due to change in frequency are likewise reduced, but unfortunately they accumulate along the length of the manifold.

Now, if any given cavity is off a little bit in frequency from what it should be, there will be some reactive energy flowing between it and the manifold. The amplifiers must supply this reactive energy. There also may be some other cavity that is off frequency the other way, and then there will be flow of reactive energy from this cavity to the first. However, as long as the system is driven from a stiff source, the fields in the cavity are proportional to the voltage on the input loop, which is determined by the voltage at the maximum and that is the same in amplitude and phase as at every other input loop. If the cavity loading changes, more current is drawn from the system, but the voltage is unchanged.

Changing the loading of one cavity, or the distribution of the sources of power, will change the swr distribution along the manifold, but the amplitude and phase at each of the voltage maximum points will not be changed more than

$$\sum_n \frac{\alpha\ell_n}{\mathrm{swr}_n}$$

A model, which is 12λ long at 100 Mc/sec, has been built using these ideas. There are five resonant loads and one signal generator that can be connected to any of the voltage maximum points. A dual-beam sampling scope is used to compare amplitude and phase at points along the manifold. To the accuracy that one can obtain with the sampling scope, the amplitude and phase are tightly locked, regardless of where the generator and the resonant loads are placed, or where we compare the signals. The system is still amplitude and phase locked when we detune the resonant loads a substantial amount.

BLEWETT: Are you talking about a fairly short manifold and then long lines into the various cavities?

VOELKER: No, I'm talking about a section of small cavities, 2 to 6 meters long, and, for 100 meters of this, I'll put a long manifold waveguide along side. There will be loops in the manifold and short transmission lines, each half a wavelength long, so that I just reflect the input impedance of the cavity across the load. I must choose these feed points to be at the voltage maxima, as I first described. Then along the manifold periodically, there will be generators.

BLEWETT: The manifold will run the full length of the machine?

VOELKER: The full length of one block of power supplies, for a total of 60 MW. For our injector, we're talking about 300 MW total power, so there would be 5 or 6 manifolds.

BLEWETT: What are the total of losses in the system?

VOELKER: They're related to the expression (4) and because you have to keep losses low in order for it to work, you're talking about 1/1000, or so.

LIVDAHL: Are you thinking of this scheme both at 200 and 800 Mc/sec?

VOELKER: Primarily at 800 Mc/sec, because if we can't get the rf cost down, we won't be able to build a linac, but we'll have to build a booster ring instead. Something like this might be applicable at 200 Mc/sec.

HAGERMAN: You show these transmission lines between the manifold and the cavities with no isolation. If you do this, all these cavities are tightly tied together, so now you have the moding problem of a long cavity.

VOELKER: Well, not quite, in the long cavity, all the short are in series. In this case they're all in parallel. As long as you drive your manifold at a given frequency, no matter which particular mode you're on in this cavity, it looks like either an RC or an RL circuit.

HAGERMAN: True, but what bothers me is that now the modes are so closely spaced you don't know which one is right. Another question is, what happens when we want to change and phase of one of the individual sections?

VOELKER: All of your drive points are locked. In this particular method you have to arrange your mechanical device so that you are at the right phase point.

There isn't really any mechanism to change it once you've chosen where you are unless you can tune your cavities off to one side all the time.

HAGERMAN: Will this make an appreciable difference in your rf amplifier cost?

VOELKER: It will let us use power packages which are very much larger than we would have for an individual cavity. It's just a question of how many 15 or 20 MW packages you need compared to how many 1 1/2 MW packages. We think the cost will be substantially less for thirty 15 MW tubes then it would be for one hundred and thirty 1 1/2 MW tubes. We think this would be at least a factor of two cheaper. It looks as though when you get up to a certain size of tube the cost doesn't increase very fast.

WHEELER: What bothers me here is that you've apparently lost the ability to adjust both voltage and phase in the individual cavities.

VOELKER: You can adjust voltage wherever you want.

WHEELER: Not during the pulse. You can set these up when you tune the machine by a mechanical process, but you have no way of introducing control devices which can operate within the duration of one pulse.

VOELKER: You can't do that here, but you're hoping that it's so stiff that it stays where you set it, and that's all you need. You can't change the individual settings.

PARKER: In your model, what ratio of Z_ℓ to Z_o did you use?

VOELKER: I had 150 Ω loads on a 50 Ω coax model. I might point out that the line is so lossy for 30 sections that it looks like 500 Ω when you look in with a bridge on the unloaded line, and it still seems to work.

PARKER: It's unfortunate that you can't work it out somehow so you could couple to a given line at the zero crossing point, where the derivative of phase with respect to βl is zero.

VOELKER: You do. That's the voltage maximum point. I believe that this is what we call phase locking, the fact that you are working around that point.

FEATHERSTONE: Do you care whether you get your high standing wave ratio by having your loads very much lower or very much higher than the line impedance.

VOELKER: Well, you like to have as high a standing wave ratio as you can get, but in order to get it you've got to push the voltage maximum up and then the losses go up.

LIVDAHL: How are you planning to protect this thing, with a spark gap?

COMMENT: I'm thinking of an rf crowbar in the manifold so that you can get rid of the energy rapidly. There are about 1000 joules in a 60 MW system.

NAGLE: What ratio of Q's do you anticipate between the cavity and the waveguide?

VOELKER: I don't know what the Q's are, but the energy lost in the waveguide is about 0.1% of the energy lost in all the cavities.