PARALLEL OPERATION OF MAGNETRONS

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by

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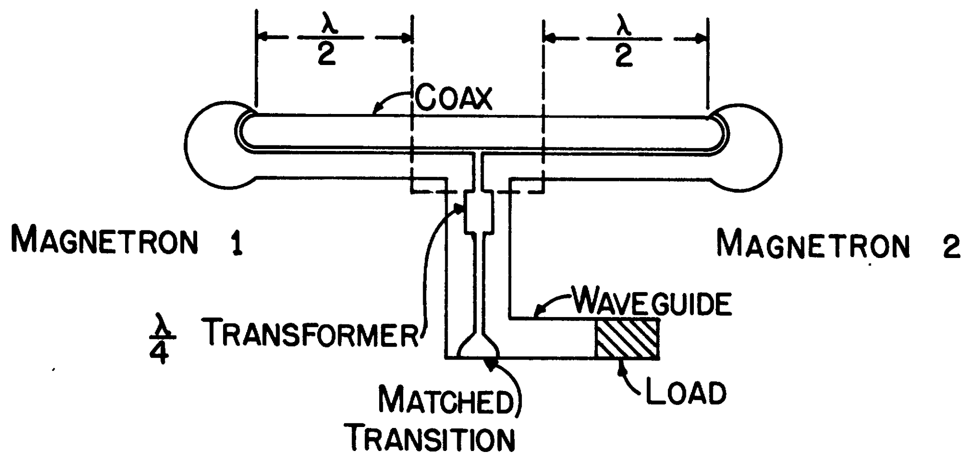
Abstract

As many as three magnetrons have thus far been successfully operated together with coherence in phase and equality of frequency in a repetitive system which promises to permit the operation of n magnetrons into n+1 loads, each of impedance Z_o, the characteristic impedance of the line.

It is sometimes desirable to generate more coherent microwave power than can be obtained from one magnetron. To achieve this objective, it is necessary to consider the possibility of operating two or more magnetrons in parallel in such a way that they are coherent in phase, equal in frequency, and additive in power.

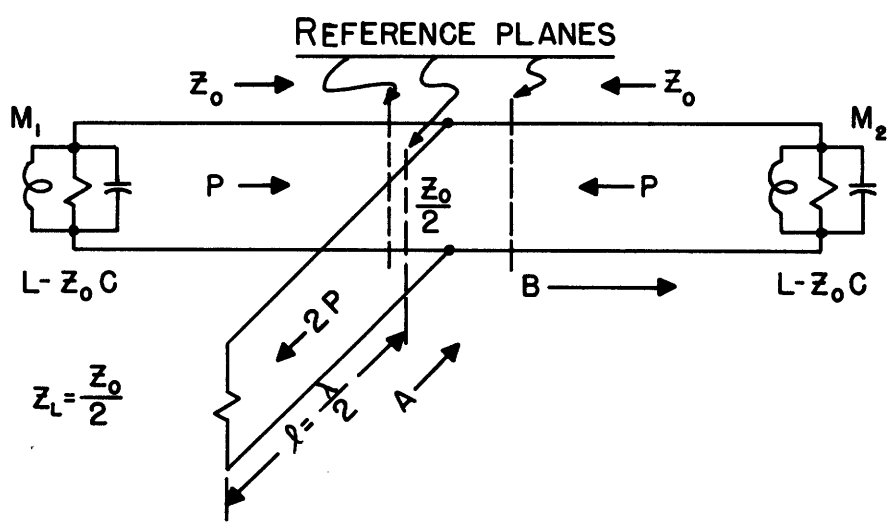
1. Parallel Operation of Two Magnetrons into a Coaxial Load

The first scheme tried in the parallel operation of two magnetrons was that diagrammed in Fig. 1, whose equivalent circuit is shown in Fig. 2.



Circuit employed in the operation of two magnetrons in parallel into coax

Figure 1



Equivalent circuit of Fig. 1

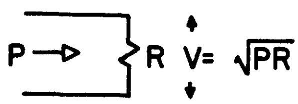
Figure 2

When each magnetron is looking into a matched load of impedance Z_o, the impedance at the resonant frequency of the magnetron seen by an observer looking into each magnetron is $-Z_o$. When both magnetrons are tuned to the same frequency, the desired load impedance Z_L may be computed by reasoning that a magnetron should see at the T-junction a load of Z_o which is formed by the parallel combination of $-Z_o$ and Z_L. Thus:

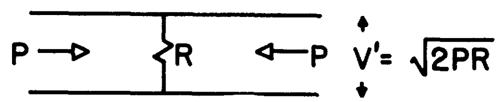
$$\frac{1}{Z_o} = \frac{1}{-Z_o} + \frac{1}{Z_L}\text{, whence } Z_L = \frac{Z_o}{2}\ .$$

It is apparent that when both magnetrons are not operating at the same frequency, the input impedance of one magnetron at the frequency of the other is no longer $-Z_o$, and that each magnetron is therefore not operating into its desired terminal impedance Z_o. Also, if the line length ℓ in Fig. 2 is not $\frac{\lambda}{2}$, the magnetrons are mismatched, for then the impedance of the load arm at the T is no longer $Z_o/2$. For successful operation, therefore, the magnetrons must be tuned to the same frequency and line length ℓ must be an integral multiple of $\frac{\lambda}{2}$ if $Z_L = Z_o/2$. In order to make $\ell = \frac{\lambda}{2}$, it is, of course, necessary to determine accurately the reference plane of the coaxial T and the reference plane of the load.

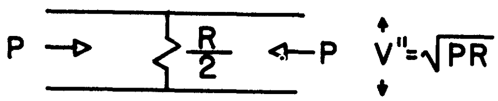
It was necessary to insert a $\frac{\lambda}{4}$ transformer in the position shown in Fig. 1 to make the circuit effectively that of Fig. 2. Without the insertion of this transformer the circuit is effectively that of Fig. 3b in which the power flowing from two magnetrons produces a voltage V' across R which is effectively $\sqrt{2}$ V, where V is the voltage produced across R when the power comes from only one magnetron. This increased voltage V' has an undesirable effect on the operation of the magnetron. The voltage V" across the magnetrons when a load of $\frac{R}{2}$ is used (Fig. 3c) is equal to V, of Fig. 3a and the circuit of Fig. 3c represents the type of operation depicted by Figs. 1 and 2.



Voltage across load R when power comes from one magnetron.
a



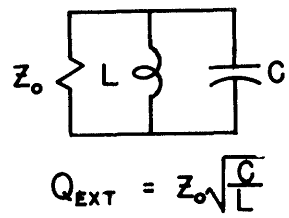
Voltage across load R when power comes from two magnetrons.
b



Voltage across load $\frac{R}{2}$ when power comes from two magnetrons.
c

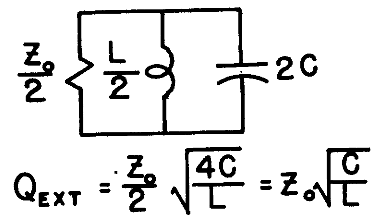
Figure 3

The size and position of the $\frac{\lambda}{4}$ transformer in Fig. 1 was determined through "cold" measurements of standing-wave ratio and standing-wave minimum position as a function of frequency. It may be seen from Fig. 4 that the external Q, $Q_{ext} = Z_o\sqrt{\frac{C}{L}}$, of this system seen by an observer at A (Fig. 2) is the same as that for a single magnetron seen by an observer at B.



Q_{ext} for one magnetron and load Z_o.

a



Q_{ext} for two magnetrons with load shown in Fig. 2.

b

Figure 4

In the experiment here reported, a tunable HK7 magnetron and a fixed-tuned 4J33 magnetron were used. The best tubes of this type can be expected to deliver at the most 1000 kw at a pulse duration of 2 μsec and a repetition rate of 300 cycles. The frequency is 2800 Mc.

Two line pulsers with hydrogen thyratron switches were pulsed simultaneously with a common trigger. It was necessary to pressurize the entire r-f line to 30 lb of dry air to prevent r-f voltage breakdown. The maximum power obtainable from either of the particular tubes alone into a matched load is 800 kw. A maximum power, limited by sparking within the magnetron, of 1470 kw was obtained by operating these tubes in parallel.

It is believed that 2000 kw may be expected from two exceptionally good magnetrons of this type operating in this circuit. In operating two or more magnetrons in parallel it is, of course, necessary to synchronize accurately the pulses arriving at the magnetrons.

It should be noted that this system is not repetitive.

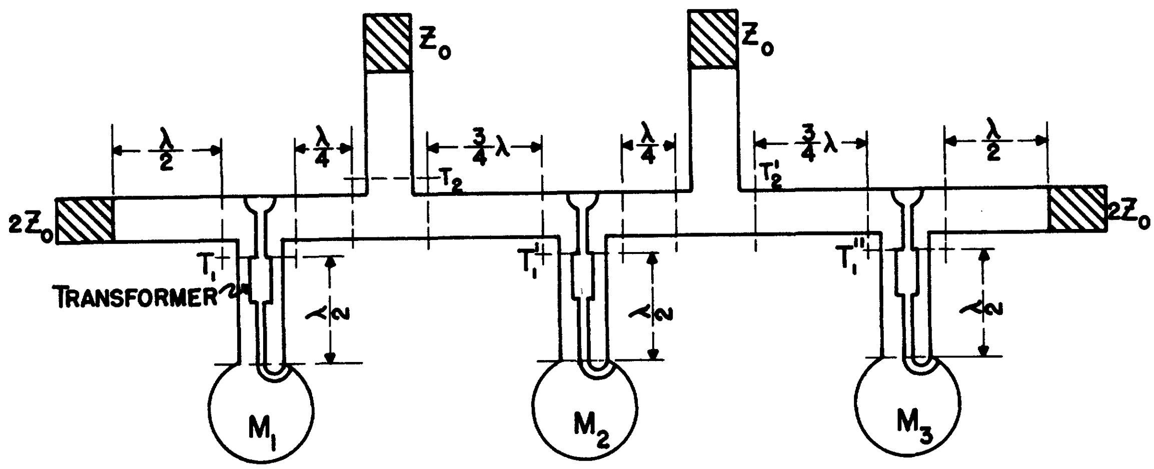
2. Operation of n Magnetrons into a Repetitive System Employing Waveguide

2.1 Operation of n Magnetrons into n-1 Loads of Z_o and Two Loads of $2Z_o$.

A diagram of the first system constructed for the operation of three magnetrons in parallel is shown in Fig. 5 and its equivalent circuit is shown in Fig. 6. The experiment was performed with loads of Z_o and $2Z_o$, but the analysis holds for loads of arbitrary value Z and 2Z.

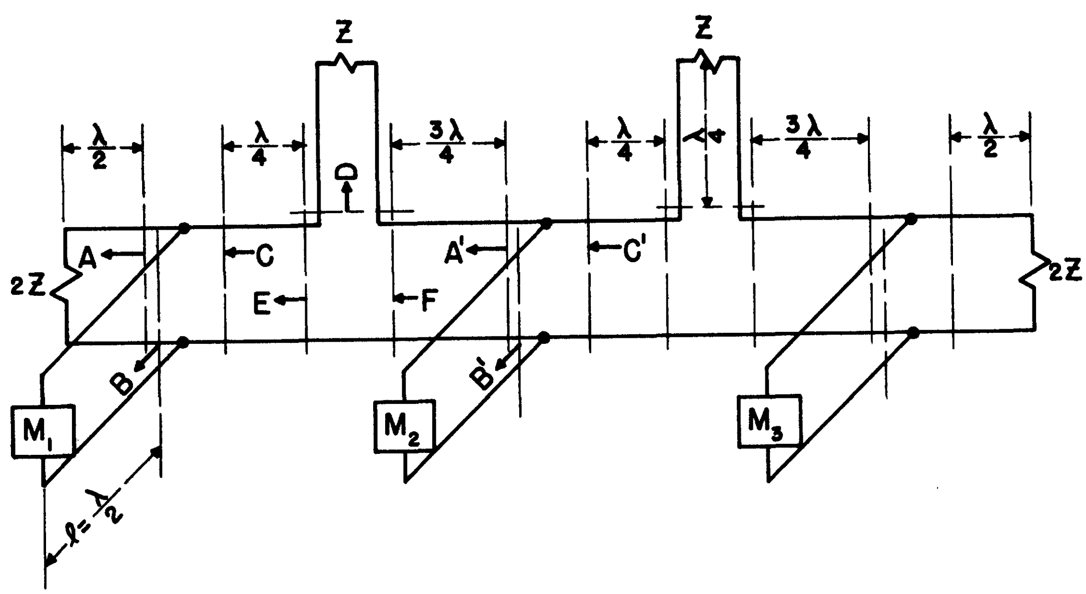
If the r-f power from each of the three magnetrons is to be in phase at each of the loads Z_o and if the r-f power in the two loads $2Z_o$ is to be in phase, the line lengths must be as indicated in Figures 5 and 6. If the $\frac{3}{4}\lambda$ section is replaced by $\frac{\lambda}{4}$ section, the phases in the adjacent loads Z_o will differ by π.

The reference planes of the T's and the magnetrons were carefully measured, and the line lengths were adjusted to the values shown.



System used for operating three magnetrons into two loads of Z_o and two loads of $2Z_o$

Figure 5



Equivalent circuit of Fig. 5

Figure 6

Since this system represents a repetitive circuit, any number of identical sections can be inserted. The power from the magnetrons splits at each T. It may be noted that power from the equivalent of one magnetron is lost to the two loads of 2Z each.

The assumption is made that each magnetron is operating into a load Z and has therefore a source impedance of -Z. It remains to be shown that the circuit is now self-consistent. The characteristic impedance of the line is denoted by Z_o. From Fig. 6, it is evident that at A,

$$Z_A = 2Z,$$

at B,

$$Z_B = -Z,$$

and thus at C,

$$Z_C = \frac{Z_A Z_B}{Z_A + Z_B} = -2Z \ .$$

When -2Z is transformed down a quarter wavelength of line to E there results

$$Z_E = -\frac{{Z_o}^2}{2Z} \ .$$

At D, a quarter wavelength away from Z the impedance is

$$Z_D = \frac{{Z_o}^2}{Z} \ .$$

Therefore, the impedance at F is

$$Z_F = Z_E + Z_D = \frac{{Z_o}^2}{2Z} \ ,$$

which, when transformed to A', gives

$$Z_{A'} = 2Z.$$

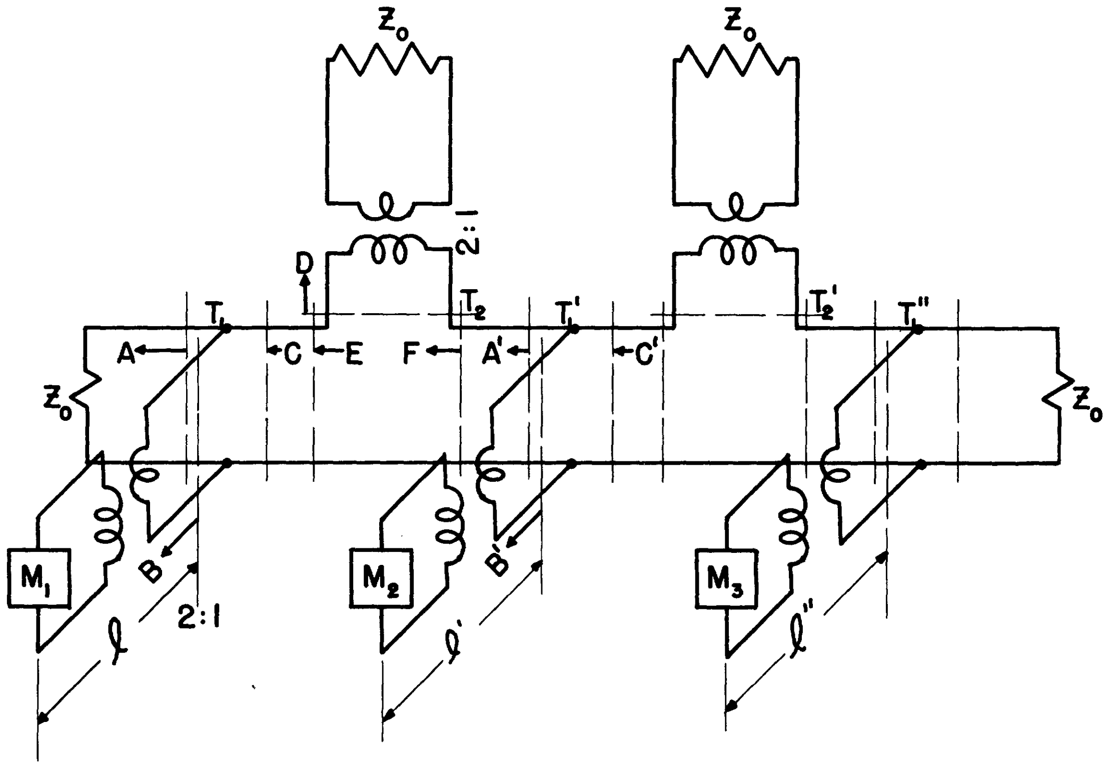
Since $Z_{A'} = Z_A$, the circuit is repetitive and self-consistent.

It is to be noted that with this system there are standing waves set up in the line since $Z_A = Z_{A'} = Z_{A''} = 2Z$ instead of Z_o, and since $Z_C = Z_{C'} = Z_{C''} = -2Z$ instead of $-Z_o$. Also, if for example, magnetron M_1 effectively becomes an r-f short because of a spark inside, $Z_C = 0$, and a condition of severe mismatch prevails because this short circuit appears at C as a short circuit.

It was possible after delicate tuning of the magnetrons and adjustment of the line length and power level to operate successfully a system of this type with two magnetrons. When a system employing three magnetrons was tried, it was impossible to coalesce the various resulting spectra seen on a spectrum analyzer. The lack of success with this system is attributed to the existence of the standing waves which make wavelengths very critical and to the severe r-f mismatches occuring when one magnetron sparks.

2.2 Operation of n magnetrons into n+1 loads of Z_o.

The physical layout of this system is very similar to that depicted in Fig. 5, but its equivalent circuit for three magnetrons is that shown in Fig. 7.



Equivalent circuit for the operation of three magnetrons into four loads of impedance Z_o

Figure 7

Since it is desired that the impedance Z_C, for example, be equal to $-Z_o$ (power is flowing to the right) in order to eliminate standing waves, and since $Z_A = Z_o$,

$$\frac{1}{Z_C} = \frac{1}{Z_A} + \frac{1}{Z_B} = \frac{1}{Z_o} + \frac{1}{Z_B} = -\frac{1}{Z_o} ,$$

or

$$Z_B = -\frac{Z_o}{2} .$$

It is then necessary to alter T_1 with a transformer with an impedance stepup of 1:2 as one goes from B into the magnetron line so that although the magnetron source impedance is $-Z_o$, the impedance seen by the observer looking into the magnetron from the coaxial line at B is $-Z_0/2$.

Since $Z_C = -Z_o$, Z_E will also be equal to $-Z_o$. Also it is desired that $Z_F = Z_o$. Then

$$Z_F = Z_o = Z_E + Z_D = - Z_o + Z_D \quad ,$$

or

$$Z_D = 2Z_o \ .$$

It is then necessary to construct an iris transformer in T_2 to give a 2:1 impedance stepdown as one goes from D to the load Z_o in order that there be no standing waves in this part of the system.

Since $Z_{A'} = Z_F = Z_A$, the system is repetitive.

Although experiment was performed with loads of value Z_o, the analysis holds, and the system is repetitive for, loads of arbitrary value Z. With loads of value Z, however, line lengths again become critical and the system cannot be expected to operate so successfully.

This system with both two and three magnetrons and the same line lengths as shown in Fig. 6 was successfully operated, with a relatively small amount of magnetron tuning and adjustment of line length. The resultant spectra were coalesced into one spectrum as observed on the spectrum analyzer. Since the system was unpressurized, the maximum amount of power obtainable was limited by the breakdown in the $\frac{\lambda}{4}$ transformers situated at the coaxial T's.

In the experiment performed the line lengths $\ell = \ell' = \ell''$ (see Fig. 7) were made equal to $\frac{n\lambda}{2}$ where n is an integer. However, it would seem more advantageous to have $\ell = \ell' = \ell'' = \frac{n\lambda}{4}$, where n is odd, because then for a two-magnetron system an r-f short in magnetron M_1 makes M_2 see an impedance of $2Z_o$ instead of Z_o. This mismatch of $2Z_o$ is much less severe than the short circuit which will be seen if $\ell = \frac{n\lambda}{2}$ and M_1 becomes an r-f short. For a three-magnetron system with $\ell = \frac{n\lambda}{4}$ the effective termination impedance for M_2 and M_3 should become $1.5Z_o$ if there is an r-f short in M_1. As the number of magnetrons in the system in increased, it is, therefore, believed that the severity of mismatch when one magnetron sparks will decrease.