POWER-COMBINING AND INJECTION-LOCKING MAGNETRONS FOR ACCELERATOR APPLICATIONS*

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ABSTRACT

Single magnetrons are commonly used to drive accelerator cavities, but many applications require multiple sources which can provide phase control operating into multiple cavities. Conventional injection locking techniques provide the means to phase lock magnetrons to within 1° rms phase error but these techniques use circulators. Where weight is a concern or when high power is used, circulators are not feasible or available. We are investigating a number of approaches to achieve phase locking and power combining without the use of circulators. A series of experiments have been undertaken where two magnetrons are injection locked and power combined, first operating into a matched load, second operating into a tunable short, and third operating into X-band cavities.

I. INTRODUCTION

Multiple magnetrons were used to drive high Q linear accelerators prior to the advent of ferrite isolators [1]. It was found that either tuning or some degree of isolation was required to prevent oscillation from starting and remaining in a useless mode [2]. This tuning can be provided by an injected signal within the appropriate locking bandwidth.

In the method described here, an X-band waveguide 3 dB hybrid coupler provides the avenue for both injection locking and power combining of magnetron pairs.

The experimental configuration, shown schematically in Figure 1, has been described previously [3]. The high Q (Q_L = 1600) magnetrons were run in parallel off of the same modulator. The variable phase shifters after the magnetrons were used to optimize the relative phase relationship between the injection locked signals returning to the hybrid. Unfortunately, the phase shifters have a 0.8 dB insertion loss which reduced the system efficiency. The circulator was included to protect the TWT driver against fault conditions. Identical operation was observed with the circulator removed.

The load was connected to port 4 of the hybrid after a variable phase shifter. An E-H tuner was used to provide a load of variable impedance. All components between the magnetrons and the load were WR-90 X-band waveguide components to minimize circuit loss and VSWR.

Phase measurements of the signals incident on the load and reflected from the load were made relative to the output of the driver amplifier chain using two phase bridges.

Two cavity loads were used, each a section of WR-90 waveguide with a tunable short on one end and a quarter-wave transformer on the other. Cavity Q measurements gave the following parameters at 8.96 GHz for the overcoupled cavity: $Q_o = 5700$, $Q_E = 4100$, $Q_L = 2400$, coupling factor = 1.4, and cavity fill time constant = 43 ns. For the critically coupled cavity, Q_L = 2700.

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II. EXPERIMENTAL RESULTS - VARIABLE Z LOAD

The impedance of a cavity changes as the cavity is filled [2]. Therefore, the effect of load impedance upon coupled power phase coherency was investigated by using an E-H tuner to vary the load impedance. The variable phase shifters prior to each magnetron were adjusted for conditions of optimum power combining and maximum isolation into a matched load. With these path lengths set, the E-H tuner was adjusted to provide a purely real impedance, referenced to the output of port 4 of the hybrid. Results of this experiment are shown in Figures 2 and 3. Figure 2 gives the rms phase error for several real load impedances as defined above. The phase error was measured well after the phase lock time and at the same time during each pulse. The rms phase error is a measure of inter-pulse phase coherence. For comparison, a typical klystron has an rms phase error of 0.2°. Figure 3 shows how the phase of the combined signal changes as the load impedance changes.

Unstable operation was observed for normalized load impedances less than unity. It should be noted that a simple change of 90° in the electrical length prior to the load translates the load impedance to a real value in the stable regime.

III. EXPERIMENTAL RESULTS - CAVITY LOADS

Operation of the magnetrons into the cavity loads at long pulse lengths is shown in Figure 4. The forward power (power out of hybrid arm 4 and incident upon the load), the reverse power (power out of hybrid arm 1 and incident upon the driver), and the reflected power (power reflected from the load) are shown at the top of Figure 4 for a 9 us pulse. The phase of the signal incident on the cavity is shown at the bottom. Once the magnetrons have filled the cavity, the phase stays constant within 0.4° for the 9 us pulse. When operated for a pulse length of 18 us, a monotonic 5° phase change was observed across the pulse. This phase change has not yet been explained.

The cavity has been filled when the reflected signal returns to a minimum as the reflected power and the power radiated from the cavity cancel one another. Complete cancellation occurs only for a critically cavity at resonance. For the data shown, the magnetrons were operating 0.5 MHz away from the cavity resonant frequency.

The spike at the beginning of the reverse power pulse correlates with the magnetron phase lock time given in Table 1. During the phase lock time the magnetrons are oscillating incoherently with respect to each other and the hybrid provides no isolation between the driver and the load. Table 1 summarizes the operating conditions for the data of Figure 4. Note that the magnetron phase lock time is greater than the cavity fill time.

IV. CONCLUSIONS

We have demonstrated that injection-locked magnetrons can be used to drive a moderate Q cavity at long pulse without a circulator with excellent phase coherency. The cavity transient impedance does not preclude the magnetrons from filling the cavity, at least when the cavity fill time is less than the magnetron phase lock time.

To more closely model an accelerator application it is still necessary to test the magnetron system without the isolation provided by the variable phase shifters. Beam loading should also be simulated. Presently, we are duplicating the magnetron system at S-band with two 3 MW magnetrons in order to phase lock two low Q, 50-100 MW HPM magnetrons without using a circulator [4].

V. REFERENCES

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[3] T.A. Treado, et al, "Experimental results of power combining and phase-locking magnetrons for accelerator applications," IEDM Tech. Digest, San Francisco, C.A. Dec. 1990.
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TABLE 1 Operating Conditions for Figure 4

Frequency	= 8.964 GHz
Gain	= 13 dB
Isolation	= 23 dB
Return Loss	= 10 dB
Phase Variation	< 0.5°
Magnetron Q_L	= 1600
Cavity Q_o, Q_E, Q_L	= 5100, 4100, 2400
Magnetron Phase Lock Time	= 400 ns
Cavity Fill Time Constant	= 43 ns

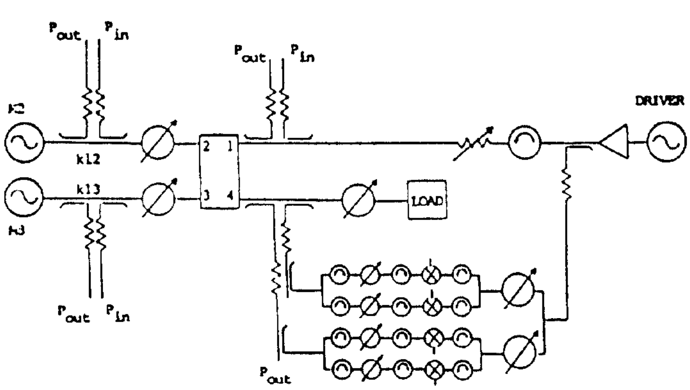

Fig 1 Schematic of Injection Locked, Power Combined Magnetron Experiment.

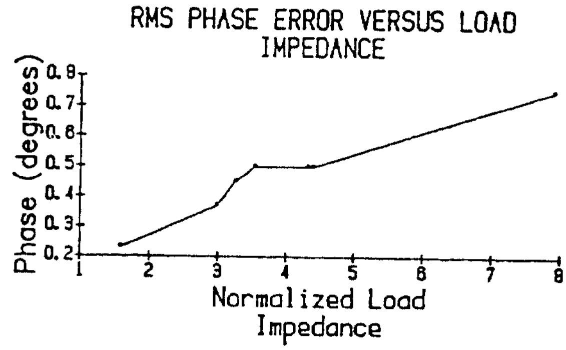

Fig 2 Combined Magnetron RMS Phase Error vs. Normalized Load Impedance.

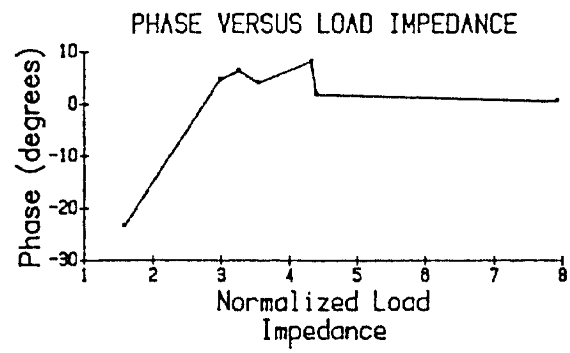

Fig 3 Combined Magnetron Phase vs. Normalized Load Impedance.

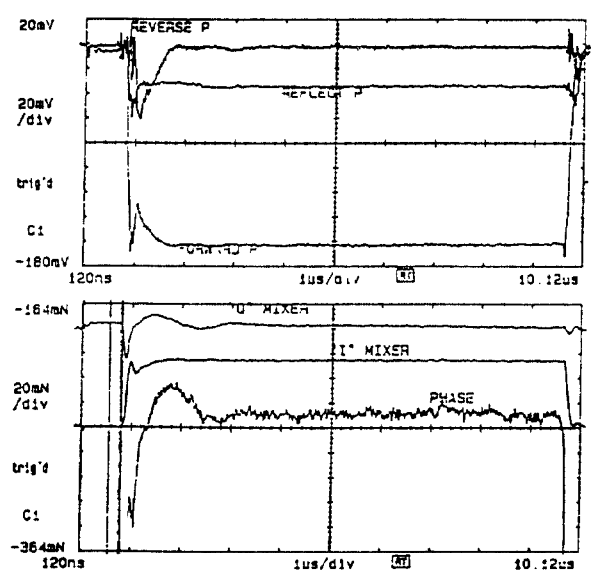

Fig 4 Cavity Filling Experiment, 9 us pulse. Phase (bottom) scale is 0.4° per division.