HIGH-POWER TESTING OF THE MULTIPLE-LOOP RADIO-FREQUENCY DRIVE CONCEPT FOR THE FMIT ACCELERATOR*

M. V. Fazio, AT-5, and Robert D. Patton, AT-2, MS-H827
Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA

Summary

The Fusion Materials Irradiation Test (FMIT) accelerator requires several 600-kW rf systems to simultaneously supply rf power to a single accelerator tank. Each rf-system output must be carefully phase and amplitude controlled to achieve the proper system performance. Two 80-MHz, 600-kW rf amplifiers with phase- and amplitude-control systems have been tested into a single, high-Q resonant cavity. Experimental results are presented.

Introduction

The FMIT accelerator will require 13 rf power amplifiers each delivering 600 kW, cw, at 80 MHz. The RFQ will require two amplifiers, one Alvarez section will require six, and the other Alvarez section will require five. Because it is essential to be able to simultaneously drive each of these structures with more than one amplifier, an experiment was performed to investigate the problems associated with the multiple rf-drive concept.

Experimental Configuration

At the time these experiments were performed, the FMIT prototype drift-tube linac tank was available, but the drift-tubes themselves were not available. This tank was a resonant cavity 3.5 m long and 2.5 m in diameter, and had been designed with 15 drift-tubes to accelerate an H_2^+ beam from 2 to 5 MeV. The cavity was resonant at 92 MHz in the TM_{010} mode with an unloaded Q of 131 000. Because the high-power amplifiers were designed to operate at 80 MHz, it was necessary to lower the resonant frequency of the cavity by inserting a dummy drift tube (DDT) as shown in fig. 1. The DDT reduced the tank resonant frequency to 80 MHz. This configuration does not oscillate in the usual TM_{010} accelerating mode, but in a TEM mode. The DDT was suspended by a stem located at each of the two points of zero radial electric field on the DDT. The DDT gap spacing required to produce an 80-MHz resonant frequency would have produced an electric field of 15 MV/m, which is 1.4 times the Kilpatrick limit, with 1200 kW of peak rf input power and an all-copper cavity. To reduce the gap voltage, the DDT was made of stainless steel, which reduced the Q to 44 000 and the gap electric field to 9 MV/m. To simplify the engineering and fabrication of the DDT, 35 kW was chosen as the design specification on average power into the cavity. These specifications greatly reduced the cooling requirement on the DDT while still maintaining the resonant load characteristics of the cavity. Each of two amplifiers used to drive the DDT tank could be pulsed to 600 kW of peak power, as long as the duty factor remained low enough to keep the average power less than 35 kW.

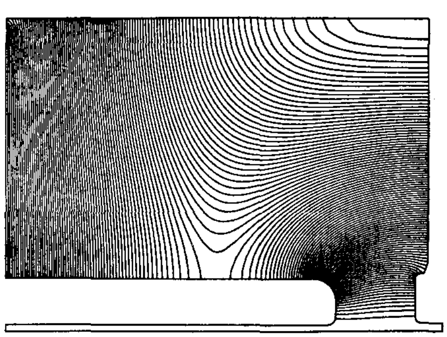

Fig. 1. One-quarter cross section of dummy drift-tube tank showing electric field lines.

The experimental configuration of the cavity and rf amplifier systems is shown in fig. 2. The cavity was driven with two 600-kW rf amplifier chains. Each chain had its own drive loop for coupling rf power into the cavity. The input VSWR of each rf drive loop was about 1.09, overcoupled.

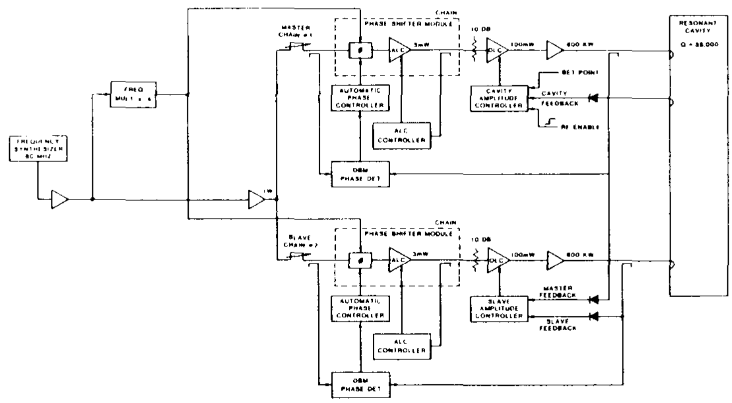

Fig. 2. Simplified schematic for rf control-system experiments.

The high-power amplifiers were built by Continental Electronics[1] and each was capable of generating 600 kW, cw, at 80 MHz. The high-power amplifier consisted of three vacuum-tube stages. All three stages were operated in the grounded-grid configuration so that the output power was a linear function of input drive power.

Each low-power amplifier chain consisted of a varactor-tuned electronic phase shifter,[2] a 100-mW solid-state amplifier for drive-level control (DLC), and a 100-W solid-state amplifier to drive the high-power amplifier. The output of the DLC amplifier was controlled by the bias voltage applied to it; therefore, the output of the final amplifier was a linear function of the DLC amplifier output. In this manner the bias voltage on the DLC amplifier could then be used to control the output of the final amplifier.

The specifications on the FMIT accelerator require the amplitude to be controlled to within ±1% and the phase to be controlled to within ±1°. This control was accomplished by means of the analog feedback-control system shown in fig. 2.

The basic control philosophy accomplishes a dual purpose. The first is to maintain the cavity field's required phase and amplitude. The second is (1) to establish zero phase shift between both chain's rf outputs and (2) to maintain the slave chain's power output equal to that of the master chain. Phase and amplitude

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tracking between the two rf chains is essential to achieve good overall system stability. It will become even more essential in the case of FMIT with six 600-kW chains.

The rf chain, #1, was designated the master chain; the other chain, #2, was the slave. The output of the master chain was determined by the cavity amplitude controller that compared the feedback signal from the cavity to the cavity's amplitude set point to generate an error signal. The controller then used proportional, integral, and derivative compensation to generate a control voltage that biased the DLC amplifier to properly regulate the output of Chain #1. The slave chain was designed to track the master in output power by the slave amplitude controller shown in fig. 2. The set point for this control loop was the detected forward-power level of Chain #1. The feedback signal was the forward-power output from Chain #2. The controller, as in the previous case, appropriately biased the slave DLC amplifier so that the Chain #2 output power equalled that of Chain #1.

The phase shift through each amplifier chain can vary considerably for a variety of reasons such as changes in bias voltage, changes in output power, etc. Each amplifier chain had a phase controller that maintained a constant phase shift across the chain relative to the rf reference signal, regardless of the operating conditions. A double-balanced mixer (DBM), used as a phase detector, measured the phase difference between the reference input and output of each chain. The DBM output was the error signal fed to the phase controller. The phase controller produced a signal used to bias the electronic phase shifter to reduce the phase error to zero.

The phase control loops and the slave amplitude control loop had a bandwidth of about 50 kHz. The cavity's amplitude control-loop bandwidth was about 15 kHz.

Experimental Results

A block diagram of the phase and amplitude controllers is shown in fig. 3. The "EXTERNAL-DEMAND" input was used to introduce a step disturbance into each loop to measure the loop response.

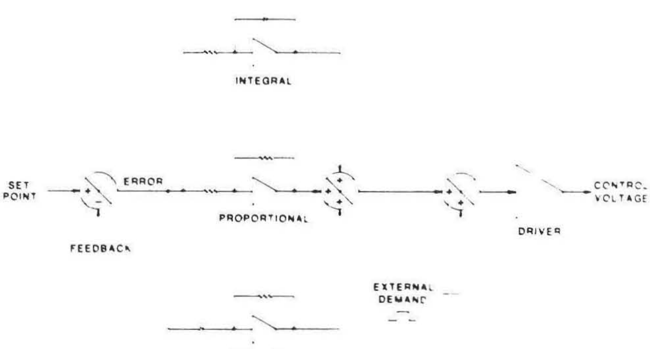

Fig. 3. Basic configuration of feedback controllers.

In the initial tests, when the system was pulsed-on in the closed-loop mode, arcing occurred in the output cavity of the final power amplifier, caused because the final amplifier gain depended on the load impedance presented by the cavity. During the cavity fill at the beginning of the pulse, the cavity amplitude controller would drive the final amplifier to saturation. The final amplifiers had been designed for 600-kW peak and average power, but because of the load mismatch during the cavity's fill time, the final amplifier output soared to 1 MW, causing arcing in the anode cavity. To eliminate this arcing, initial turn on occurred with the cavity amplitude control open loop. After about 125 µs, the cavity fill time, the loop was closed. It was later found that by using the master chain's forward power as a feedforward signal to the cavity amplitude controller, the power overshoot and arcing could be eliminated.

The Cavity Amplitude Control Loop

The top trace in fig. 4 shows the diode-detected forward power of the master chain operating in the open-loop mode at 115 kW, with an EXTERNAL-DEMAND step input to simulate beam-loading injected into the cavity's amplitude controller at about t = 250 µs. With the control loop open, this disturbance drives the output to 475 kW. The second trace is the detected output power of the slave chain operating in a closed-loop mode. The slave is tracking the output of the master chain. Figure 5 shows the output power of both chains with the cavity amplitude control-loop closure being initiated at t = 125 µs and the external demand injected at t = 275 µs. The transient at t = 125 µs is caused by closing the cavity's amplitude loop and the one at t = 275 µs is caused by the EXTERNAL DEMAND disturbance. The signals for the cavity amplitude error, slave amplitude error, and phase errors for both chains are shown in fig. 6. It should be noted in fig. 6 that the peak cavity amplitude error is about 8%, and within 70 µs it settles to well under 0.3%. The cavity rf field (undetected) on an expanded vertical scale is shown in fig. 7.

(a)
(b)

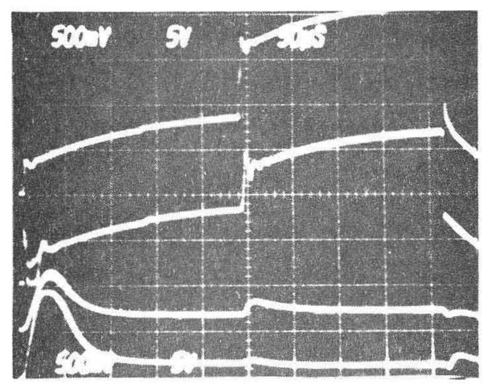

Fig. 4. (a) Master chain forward power (open loop).
(b) Slave chain forward power (closed loop).
(100 kW/DIV, 50 µs/DIV)

(a)
(b)

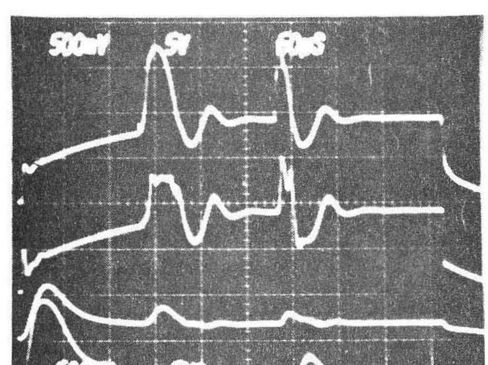

Fig. 5. (a) Master chain forward power (closed loop).
(b) Slave chain forward power (closed loop).

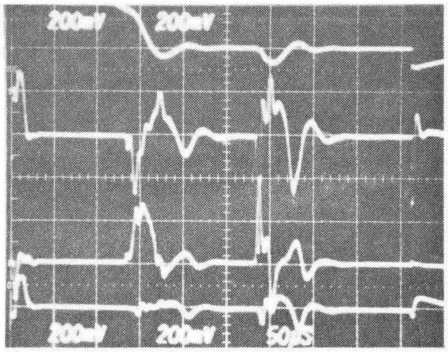

Fig. 6. (a) Cavity (Chain #1) amplitude error 20%/DIV.
(b) Chain #1 phase error 8°/DIV.
(c) Chain #2 amplitude error 20%/DIV.
(d) Chain #2 phase error 8°/DIV.

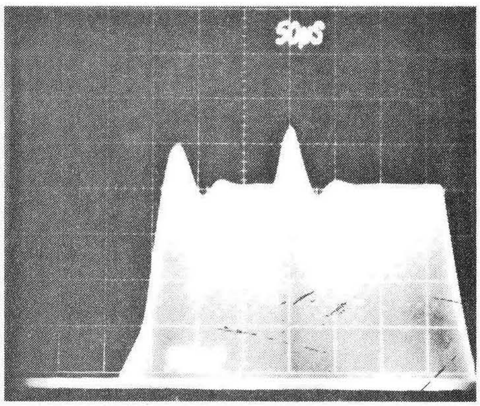

Fig. 7. Vertically expanded cavity rf field (total peak-to-peak voltage = 18 V) (500 mV, 50 µs/DIV).

Slave Amplitude Control

With the cavity amplitude loop closed and each amplifier delivering 115 kW, an EXTERNAL DEMAND disturbance was applied to the slave amplitude controller, so that if the loop were open, the slave's output power would go to 500 kW. In fig. 8, the top trace is the master chain's output; the second is the slave chain's output with the EXTERNAL DEMAND applied at t = 275 µs. The error signals are shown in fig. 9. The maximum amplitude error on the slave chain is about 30%. Within 100 µs, this error drops to well under 1%.

(a)

(b)

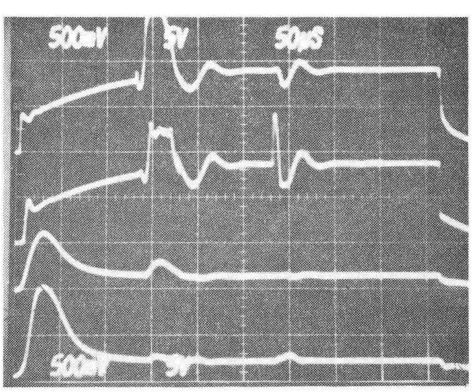

Fig. 8. (a) Chain #1 forward power.
(b) Chain #2 forward power.
(100 kW, 50 µs/DIV.)

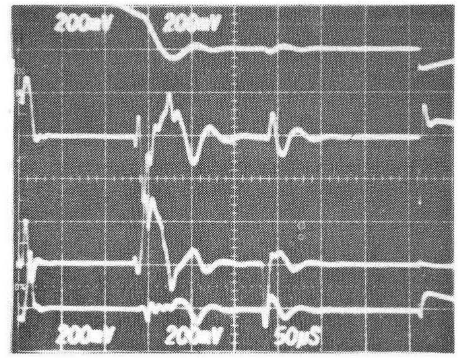

Fig. 9. (a) Cavity (Chain #1) amplitude error 20%/DIV.
(b) Chain #1 phase error 8°/DIV.
(c) Chain #2 amplitude error 20%/DIV.
(d) Chain #2 phase error 8°/DIV.

Phase Control

A 45° phase disturbance was applied to Chain #1 at t = 325 µs. Figure 10 shows the phase-loop error signal for both chains. On Chain #1, the peak phase error is about 16°. This error settles to less than 0.5° in about 50 µs. The same 45° phase disturbance was then applied to Chain #2. In this case the peak phase error also was about 16°. The error settled to less than 0.5° in 50 µs.

(a)

(b)

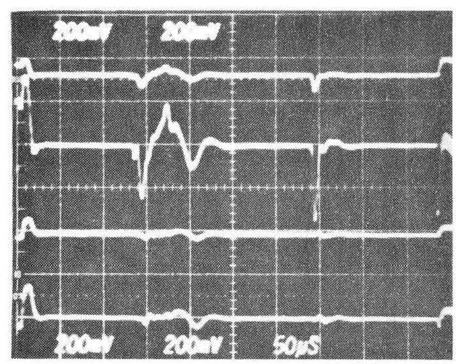

Fig. 10. (a) Chain #1 phase error 8°/DIV.
(b) Chain #2 phase error 8°/DIV.

Conclusions

The master/slave configuration is a viable approach for multiple-loop rf drive. It is also essential for successful operation to have the amplifier outputs phase locked to each other. With this approach it is quite easy to control cavity field amplitude to within ±1%, and phase to within ±1°.

References

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2. H. Johnson, and D. Riggin, "Developments of the RF System for the Fusion Materials Irradiation Test Accelerator," Proc. 1979 Linear Accelerator Conf., Montauk, New York, September 10-14, 1979, Brookhaven National Laboratory report BNL-51134, 356 (1980).