FAST RF CONTROL WORK AT LASL*

R. A. Jameson, W. J. Hoffert, and N. A. Lindsay
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

Abstract

Fast closed loop control of rf phase and amplitude is necessary to maintain stable acceleration in the LAMPF proton linac. The results of a closed loop rf phase control system using a coaxitron power amplifier driving a full-scale accelerator structure are presented, demonstrating correction bandwidths greater than 200 kHz. Overall rf control system design and component development is discussed, and the proposed interplay between the fast rf control system and the central, digital computer based, machine control system is outlined. A review of current work to evaluate the control characteristics of various types of high-power rf amplifiers concludes the discussion.

Closed Loop RF Phase Control

Experimental Results

Recent experiments at LASL have demonstrated the feasibility of the design approach[1] proposed for controlling the phase of the rf field in the LAMPF linac to the required tolerances.[2] This work was done with the full-scale 805-MHz rf system shown in Fig. 1, using a coaxitron high-power amplifier with a cloverleaf accelerator structure as a resonant load.

The compromises between this configuration and a proposed final 805-MHz coaxitron rf system are as follows: (1) The TWT amplifier will be replaced by a solid-state or tube-type amplifier. (2) The coaxitron was constrained to run at 20 kV plate voltage to insure reliable operation during the experiment. This plate voltage resulted in about 400 kW peak power into the cloverleaf structure, which, while less than half of the coaxitron's rated output, is at or above rated power for the cloverleaf structure. In the final version, the coaxitron will provide 1 MW of peak power to a resonantly coupled side cavity accelerator system. It is felt that the coaxitron behavior will not differ greatly at full power as far as the phase control system is concerned. (3) The cloverleaf tank will be replaced by a side-coupled structure. This should not increase the difficulty of control. Some simulation of the mode spacing which can be expected from the side-coupled structure was obtained by driving in the center cell and sensing the tank field in a cell halfway between the center and the end, resulting in mode reduction by a factor of four.

The open-loop phase modulation transfer function of each of the loop components was measured prior to closing the loop. The characteristics of the power chain through the field in the WR-975 waveguide and through the field in the cloverleaf structure are shown in Fig. 2, corresponding to system tuning for best matching at various points in the chain with maximum output from the coaxitron.

In the first experiment, the phase control loop was closed as shown in Fig. 3. Since the machine is pulsed, low frequency ac coupling can be used to minimize drift problems in the control circuits, and integrator gating is provided since the loop is open when a signal from the tank is not present.

The transfer functions which explain the action of this loop are shown in Fig. 4. The measurement of $\Delta\phi_E/\Delta\phi_D$ (response of the phase error, $\Delta\phi_E$, to a change in the reference phase, $\Delta\phi_D$) was made by inserting another varactor phase shifter in the reference arm of the phase bridge, and $\Delta\phi_E/N$ was measured by adding an extra sinusoidal "noise" modulation to the bias voltage ΔV_B at the driver amplifier.

The noise, N, simulates a phase disturbance in the power amplifier, for instance, that due to a change in transit time when the power output is increased to compensate for beam loading. The curve $\Delta\phi_E/N$ shows how much of N shows up as phase error as a function of the frequencies contained in N. When the loop gain, G_1G_2, is large, the phase error, $\Delta\phi_E$, is attenuated by that part of the loop gain ahead of the point where the error is introduced, in this case by G_1. As the loop gain falls below one, the noise is passed on to the output in an essentially open-loop manner, through G_2. In other words, the frequency components of the "noise" which fall within the correction bandwidth of the loop are attenuated. As the band edge is approached, the attenuation becomes less and less. In this particular case, the edge of the correction band and the frequency at which the cloverleaf tank itself begins to attenuate phase modulation are at nearly the same frequency, so $\Delta\phi_E/N$ turns down again and follows G_2. The noise, Q, simulates a disturbance in the accelerator cavity, such as beam loading; its effect on $\Delta\phi_E$ is given by $\Delta\phi_E/Q$ in the same manner There is good agreement between the measured and theoretical performance.

Oscilloscope traces of the loop in operation are shown in Figs. 5 and 6. The "flat" part of the pulse is of interest--the leading edge transient is too fast for this particular loop to follow, and the trailing edge transient is meaningless because the accelerator field is decaying to zero.

In order to provide more compensation for intra-loop disturbances in the 10-kHz range, further compensation must be added. One such design was tested as shown in Fig. 7, adding rate and proportional terms to the integral

*Work performed under the auspices of the U. S. Atomic Energy Commission.

compensation of Fig. 3 in a feed-forward arrangement. Figure 3 shows the performance of this loop. The response, $\angle\phi_E N$, now shows an attenuation of all frequencies by at least 10 dB. The correction bandwidth has been increased to at least 200 kHz, as evidenced by $\angle\phi_E/Q$. The peak at 400 kHz, not predicted by the model of Fig. 7, is due to high-frequency effects somewhere in the loop. Efforts to improve performance in this range can fruitfully be undertaken when a final amplifier system is chosen.**

RF Control System Design--Computer Interface

Component Development[3,4]

Considerable effort has been made to improve all of the control loop components. A vacuum tube multiplier chain developed at LASL for the stable rf reference source demonstrates better than 70-dB suppression of all spurious components below the desired outputs. Other chains using varactor multipliers and solid-state amplifiers are under construction, and studies on the detailed phase stability of these chains near the carrier frequencies are planned. These chains use only low-order multiplication stages of X2 to X3 in order to avoid the flywheel effects of higher order multiplication. A new stripline four-arm bridge and tuned detector mount package has been developed which demonstrates directivity approaching 40 dB and ten times better sensitivity than earlier versions. Three types of 805-MHz varactor phase shifters have been procured for evaluation, and a 201.25-MHz varactor phase shifter is on order.

System Design

Detailed system layouts have been prepared and the hardware is being assembled for evaluation in the mockup facilities. Where necessary, special attention to radiation resistance has been given to the components which will be located in the accelerator tunnel.

A module permissive logic system has been developed which will signal the central control system when the module rf phase and amplitude control systems have successfully locked these parameters within their respective tolerances at the start of each pulse. Upon receipt of a permissive signal from each module, the central system may then turn on the proton beam. If the permissive signal from any module is lost during the pulse, a signal will be generated to turn off the beam for the remainder of that pulse.

Central Computer Control System Interface

The fast rf control system, in itself a very fast, self-contained analog system, has been designed to use the central control system, which is based on a real-time digital control computer, as a supervisor and, in certain areas, as a direct controller. Figure 8 shows the interconnecting links.

There are four classes of interfaces:

1. Supervisory Control--The machine operator can command changes in the reference settings. Digitally actuated positioning elements will be used.
2. Data Gathering--Various quantities, including tank amplitude, phase error and reference setting or position will be monitored and the information converted to digital form for the operator's use, or for processing into control information for closed loop systems. In addition, tank amplitude and phase error may be displayed on the video system.
3. Alarms--The central control computer will be cognizant of the condition of the module permissive signal mentioned above. The computer can be used to count missed pulses and generate a non-clearable fault if more than a preset number are missed in a given time. This would shut down the machine and signal for operator action.
4. Closed-Loop Control--It is planned to have the control computer close two auxillary loops which aid the fast-phase loop in its operation. The first will keep the accelerator tanks on resonance by using phase error information between the waveguide feed and the tank to correct the accelerator coolant temperature. This will eliminate a major source of long-term phase drift. Other effects such as aging will still cause slow drifts. These are undesirable because the varactor phase shifters operate best when biased to the center of their dynamic range. Therefore, a second loop will compare the dynamic varactor phase shifter bias voltage with the optimum value and generate compensating signals which will reposition a mechanical phase shifter in the main loop.

The combined systems will be evaluated in the mockup facility.

RF Power Amplifier System Analysis

A continuing program of measurement has been in effect to determine the control characteristics of the various types of 805-MHz high-power rf power amplifiers now under evaluation--the coaxitron triode, klystron, and Amplitron crossed-field amplifier. Detailed parameter variation studies have been made on a 100-kW klystron amplifier[5] and on a 100-kW Amplitron system;[4] investigating such characteristics as rf power out vs rf power in, volt-amp curves, change in phase shift across the device as a function of rf power in and beam voltage, and so on. Similar measurements are planned on an improved 100-kW Amplitron, and on 1-MW versions of all three amplifier types.

At the present time, these studies indicate the best control to be the following:

1. Phase control will be accomplished identically on all three types by modulating the rf power input at low power levels with a fast varactor phase shifter, as outlined in the first section of this paper.
2. Amplitude control of the Amplitron or

** Similar experiments with closed-loop rf amplitude control and the combined amplitude and phase control systems are planned using modulators under development at LASL. See paper, "Modulator Development at LASL," R. W. Freyman et al, these proceedings, p. 191.

coaxitron will be accomplished by modulating the high dc voltage with a hard-tube modulator. This approach is considered feasible because of the availability of modulator tubes and the relatively small amount of AM-PM conversion evidenced by these amplifier types.
3. Amplitude control of the klystron amplifier will be accomplished in two steps. The tube being fabricated to LAMPF specifications at the present time will operate at approximately 80 kV and has a modulating anode with a gain of about one. Thus, the mod anode will also swing about 80 kV and is, therefore, not particularly convenient for continuous modulation. For this reason, the mod anode will be used as a switch for on-off control, and the closed loop amplitude control will be accomplished by modulating the rf drive to the high-power amplifier. This implies modulation of about 10-20 watts of rf.

These ideas will be investigated during the next year on test stands now under construction.[6]

References

[1] R. A. Jameson, "Analysis of a Proton Linear Accelerator RF System and Application to RF Phase Control," LA-3372, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[2] R. A. Jameson, T. F. Turner, and N. A. Lindsay, "Design of the RF Phase and Amplitude Control System for a Proton Linear Accelerator," IEEE Trans. on Nucl. Science, V. NS-12, No. 3, June, 1965.

[3] "Quarterly Status Report on the Medium Energy Physics Program for Period Ending April 30, 1966," LA-3521-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[4] "Quarterly Status Report on the Medium Energy Physics Program for Period Ending July 31, 1966," LA-3587-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[5] "Quarterly Status Report on the Medium Energy Physics Program for Period Ending September 30, 1965," LA-3419-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[6] D. E. Nagle, "RF Sources," this conference, p. 449.

DISCUSSION

R. A. JAMESON, LASL

BATCHELOR, RHEL: What sort of interaction do you expect between your rf amplitude and phase control loop?

JAMESON: That's an interesting question and one that we plan to know a lot more about by next spring. There are two major sources of interaction: One is in the accelerator cavity, and the expressions which show the extent of those have been discussed in earlier papers. The interaction in the cavities is mainly due to the beam coming on. There is another interaction in the high-power amplifier when we have to increase the output power for beam loading, and this depends on the transfer functions of the particular tube--klystron, triode, or Amplitron. I don't think the interactions will be serious. If they are, we will have to resort to some strategism to separate the two loops, probably in response time, by making one loop somewhat slower than the other. Which one is to become slower is a function of which one is the hardest to make faster.

LAPOSTOLLE, CERN: I would like to ask you, at what rf power level can the varactor phase shifters be operated?

JAMESON: The ones we presently have are designed to operate at 100 mW. They can be operated at higher power levels than that. The main problem in designing of varactor phase shifters to operate at high powers is that, as you go up in power, the rf in the system tends to buck the bias voltage that you apply, and you get very nonlinear phase shift versus bias voltage characteristics. There is a considerable amount of work in this area by the microwave industry because of the interest in radar systems. It may be that, by the time we have to buy these devices, we will be able to get them in, say, the one-to-five-watt region, but it is still essentially a low-power device. The modulation rates are quite fast, up to 10 Mc or more.

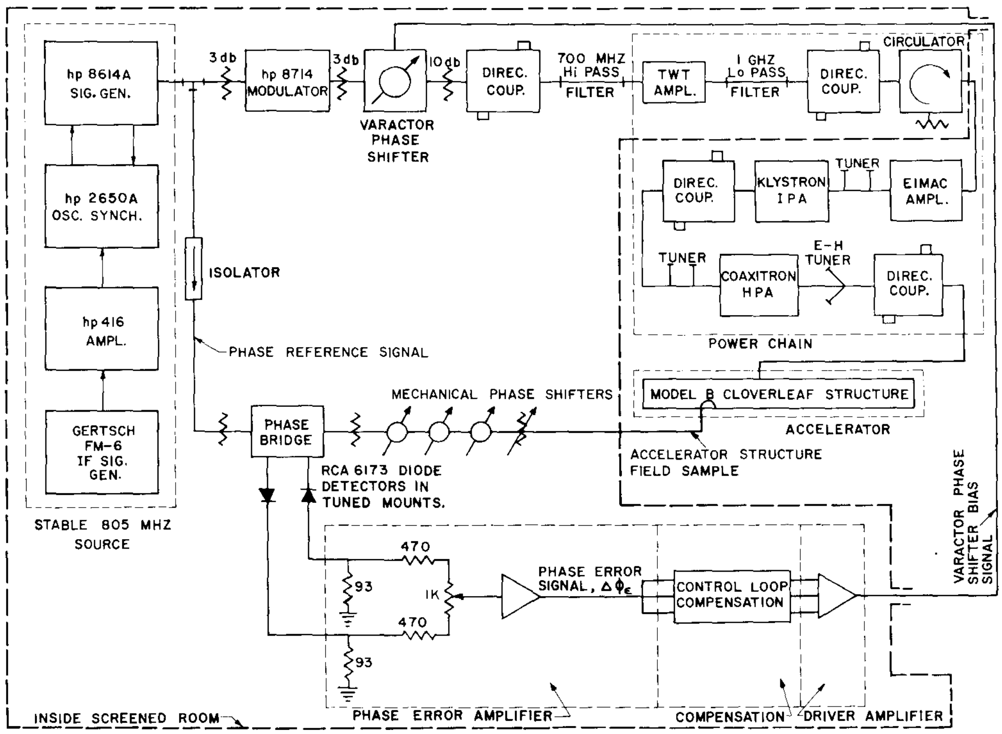

Fig. 1. 805-MHz rf phase control system for an accelerator module.

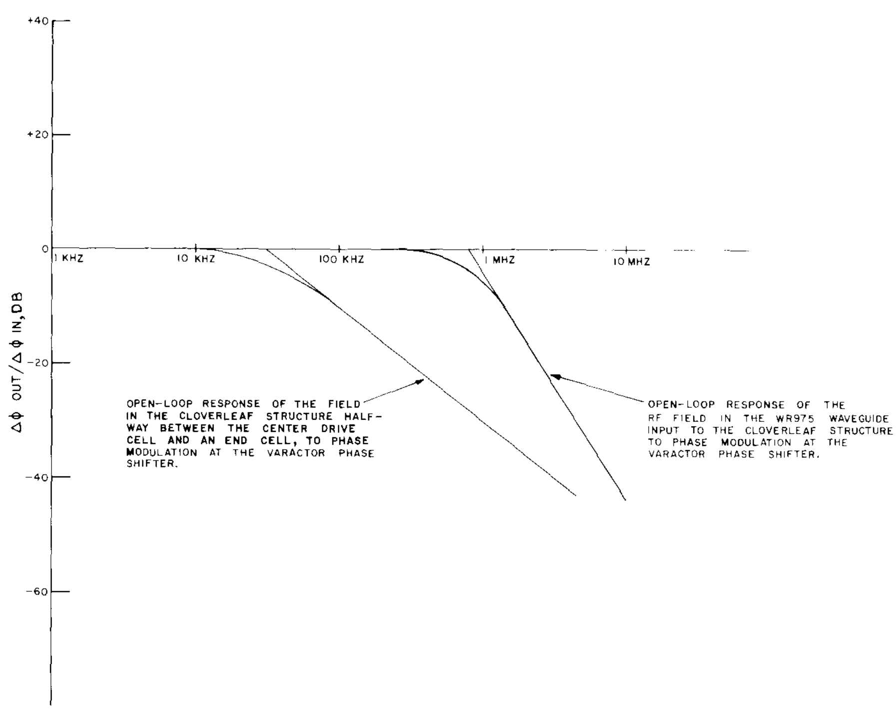

Fig. 2. 805-MHz rf power chain open-loop phase modulation characteristics.

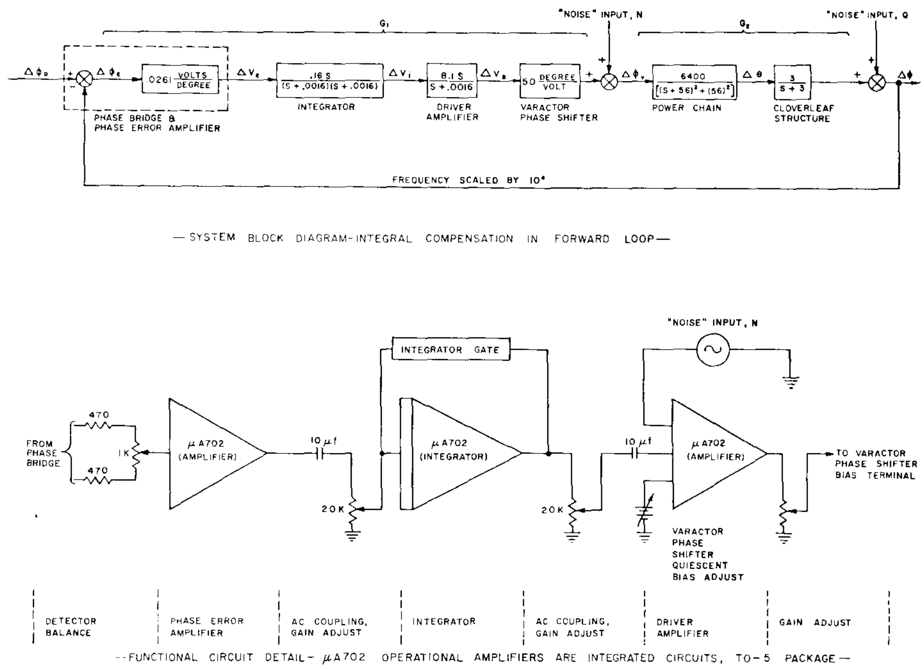

Fig. 3. Closed loop phase control experiment (integral compensation).

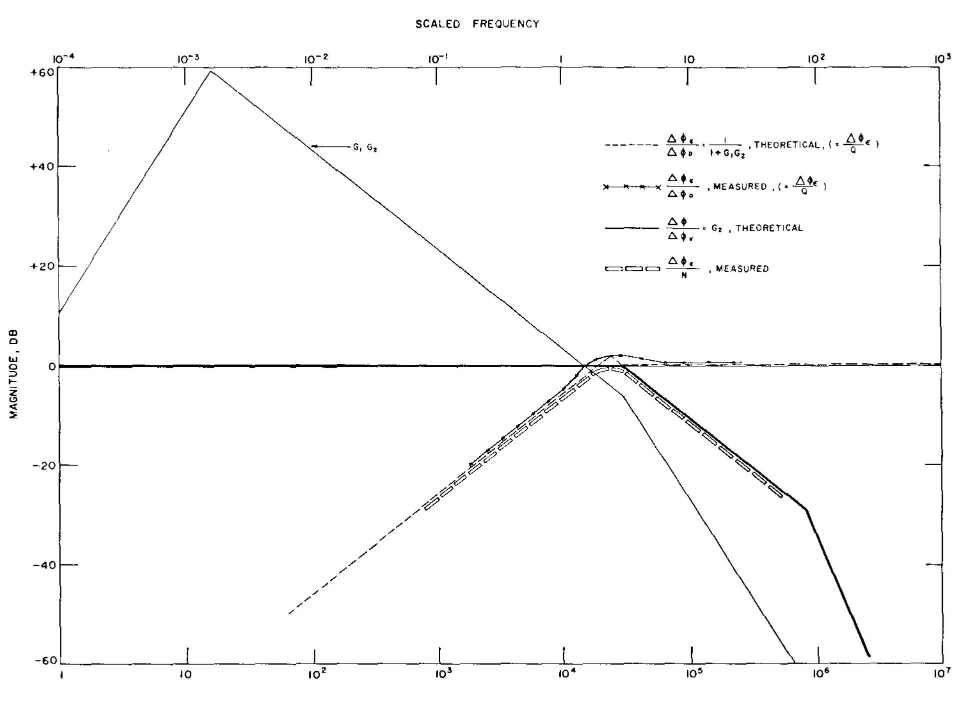

Fig. 4. Transfer functions for the phase control loop in Fig. 3.

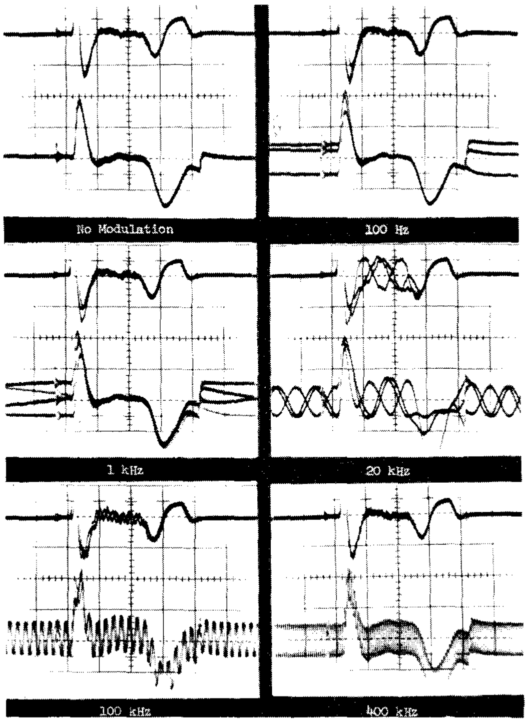

Fig. 5. Behavior of system in Fig. 3 when modulated by "noise" signal, corresponding to 10° peak-to-peak, added to varactor bias voltage, ΔV_B. (Top traces: phase error $\Delta\phi_E$, 8°/cm, 50 μsec/cm; bottom traces: ΔV_B, 0.2 V/cm, 50 μsec/cm.)

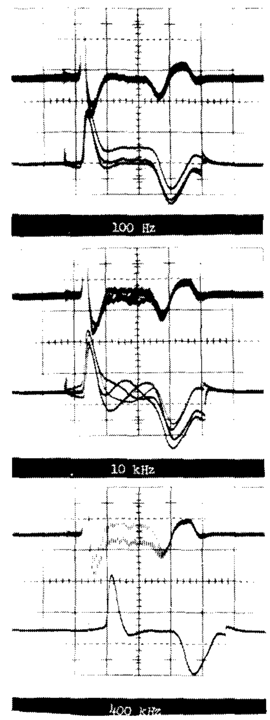

Fig. 6. Behavior of system in Fig. when reference phase, $\Delta\phi_D$, is modulated sinusoidally. (Conditions as in Fig. 5.)

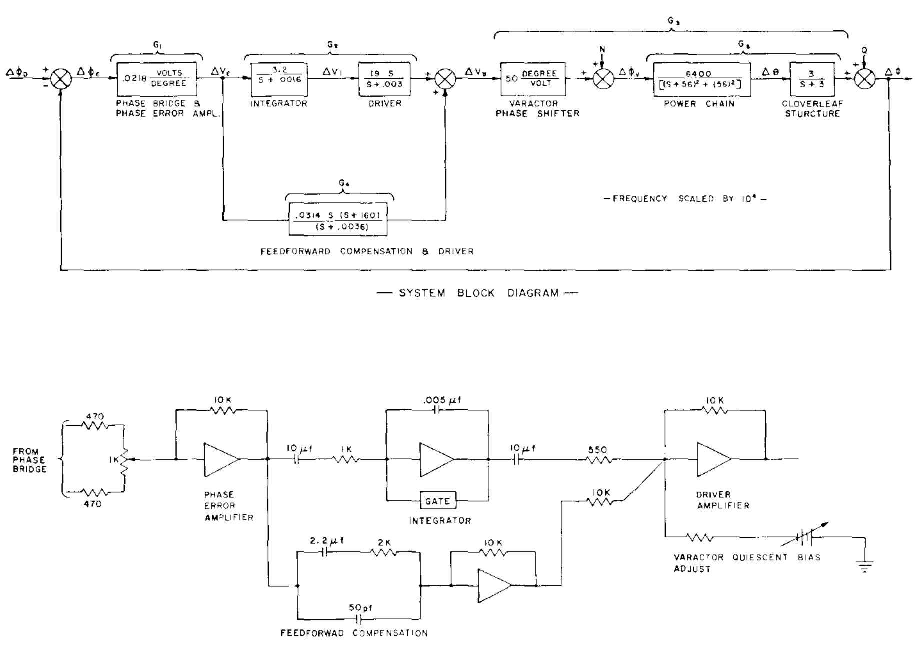

Fig. 7. Closed loop phase control experiment (integral compensation plus feed-forward derivative and proportional compensation).

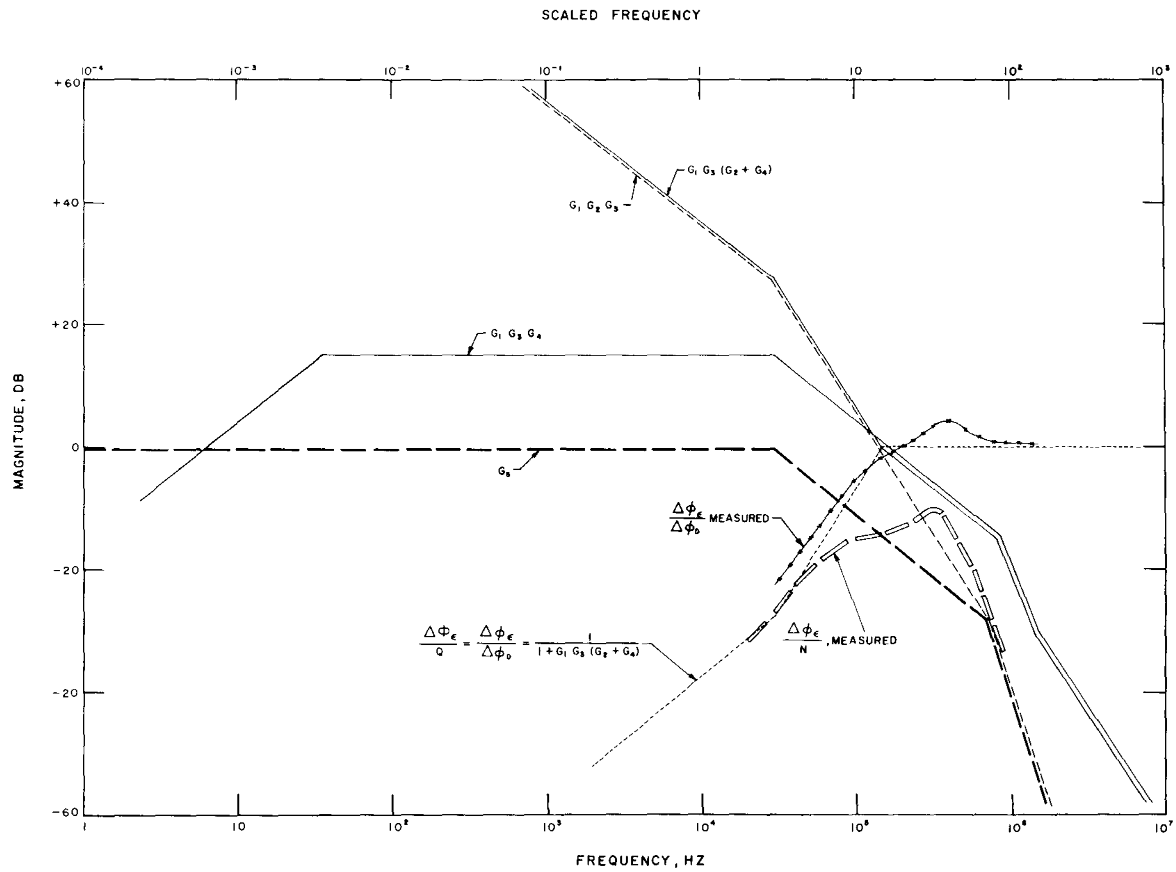

Fig. 8. Transfer functions for the rf phase control loop in Fig. 7.

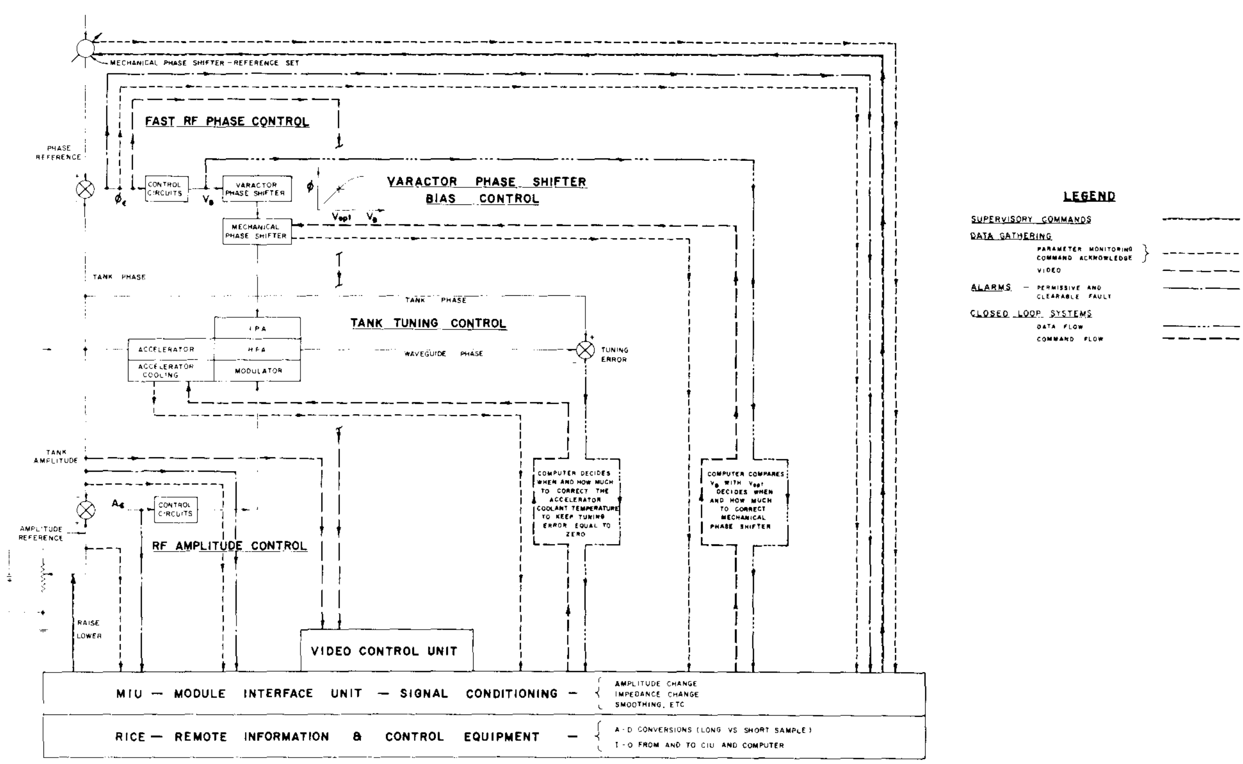

Fig. 9. Interplay between the fast rf phase and amplitude control systems and the central control system, which is based on a real-time control computer.