AUTOMATIC CONTROL OF RF AMPLIFIER SYSTEMS*

R. A. Jameson
University of California, Los Alamos Scientific Laboratory
Los Alamos, New Mexico

Introduction

Tolerances on the phase and amplitude of the rf field in the Los Alamos Meson Physics Facility (LAMPF) linac have been set at ~ ±2° and ±1.5% respectively, to be maintained continuously in the presence of heavy beam loading by a fast closed-loop control system. Since the last particle accelerator conference in 1967, the bulk of the rf control system work has been in component development — particularly the evaluation of three separate 805-MHz amplifier systems and the selection of one of these,[1] and in the use of the selected amplifier and other components as a complete system in conjunction with the Electron Prototype Accelerator (EPA)[2] to test the feasibility of the design work and prepare for further investigation. This paper summarizes the results of the latter effort, describes the current status of the rf control system and outlines the direction of future work.

The EPA RF System

The arrangement of the EPA system from the rf control point of view is shown in Figure 1. The accelerator itself is a 60-keV electron injector and two side-coupled structures, a six-cell unit named Model M, and a 100-cell unit named EPA. Model M is powered by a 100-kW (peak power) klystron rf system supplying 50 kW to the structure and up to 50 kW to the electron beam. The EPA is driven by a 1.25-MW klystron rf system supplying 500 kW to the structure (design value), and 400 kW to a 20-MeV, 20-mA peak beam. The entire system operates at 6% DF. The main drive system provides an rf drive signal to the amplifiers and is the reference to which the accelerator fields are phase locked. Amplitude control is accomplished in the low-level rf drive to the amplifiers. The system extends over a length of about 250 ft. This is somewhat longer than the most spread out module planned for the LAMPF accelerator; thus in all aspects this experiment is an excellent mockup for control investigations. Each of the various sub-systems influencing the rf control problem will now be treated in greater detail.

RF Reference System

The master oscillator itself is a quartz crystal oscillator at the seventh subharmonic of 805 MHz. Multipliers are used to generate coherent signals at 201.25, 402.5, and 805 MHz. Based on a comprehensive investigation, the decision has been made to use a hybrid (vacuum tube-varactor) multiplier chain, combining the efficiency and stability of varactor multipliers with the high interstage isolation of tubes.[3] Tests of the multiplier outputs have demonstrated excellent short-term phase stability and mutual coherence. The multiplier chain has ~ 7-W outputs; power amplification is necessary for distribution. The EPA system uses a 2-stage tetrode amplifier to provide 350 W to the 240-ft. long 3-1/8-in. coaxial main drive line. The final system will probably use a tetrode chain; however, an experiment to determine the short-term phase stability of a CW klystron amplifier is planned using a UHF TV klystron. The drive line furnishes signals to all areas of the EPA. Planned experiments include study of the effects of temperature, air pressure, and pulsed radiation on the short and long-term phase stability of the drive line.

Phase and Amplitude Detectors

Phase detection is accomplished by mixing a sample of the cavity field with the reference signal from the drive line in a strip-line hybrid ring, detecting and differencing the outputs with RCA 6173 pencil diodes in special mounts. Data on circular hybrid rings indicates that 10-20 dB better isolation than provided by the square $\lambda/4$ bridge is available; an investigation of these is now in progress. A packaging program to consolidate the various signal splitters, phase detectors, and amplitude detector (also a 6173 diode) located in the accelerator tunnel has been initiated.

Phase and Amplitude Controllers

The detected phase error and amplitude signals are shaped and compensated by integrated circuit operational amplifiers capable of large bandwidth and precise adjustment of compensation. The present phase modulators are electronically driven varactor diodes which form tuned terminations on two ports of a hybrid ring. These units are capable of very high modulation rates, but are limited to rf power levels of less than 1 W if a reasonably linear response is desired. An alternate device which may overcome this problem is currently under study; it uses tuned shunt varactor diodes in a delay-line configuration.

The power output of the 805-MHz klystron amplifiers is controlled by modulating the rf drive. This was done until recently with electronically controlled PIN diode attenuators. However, it was discovered that second-stage cathode modulation of the interface amplifier between the phase shifter and the 1.25-MW klystron input was reasonably linear, used fewer parts, and turned the drive off instead of full on when the control signal was removed. This amplifier is shown in Figure 2; it has a small signal gain of 24 dB,

---

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

decreasing to 14 dB at 1-W input. The modulation bandwidth is 1.6 MHz.

At 201.25 MHz, the amplitude controller signal drives a hard-tube modulator which changes the plate voltage on the 3-MW 7835 amplifier. A well-behaved modulator with a control bandwidth of 200 kHz has been developed using ITT 7560 triodes.[4]

1.25-MW Klystron and EPA Accelerator Tank

Experience to date has been with the first 1.25-MW klystron prototype, which operates essentially to specifications except for discontinuous steps in power output of 5-10% at certain combinations of the operating parameters. The rf input range needed for control depends on the choice of other parameters such as beam voltage and beam current; it is generally in the range 2-10 W. The change in phase shift across the klystron over this range is on the order of 10-15°. The nominal operating beam voltage is 80-85 kV; phase sensitivity to this voltage is about 14°/kV.

The EPA tank is a 100-ft. long, side-coupled $\pi/2$-mode structure designed for 500 kW peak rf power, with an (unloaded) Q of 23,800 and cold VSWR at the klystron end of a 240-ft. waveguide run of 1.44:1 overcoupled. The design maximum electron beam is 20-mA peak at 20 MeV, requiring an additional 400 kW from the klystron. Tank field sampling, coupling from the main drive line, and phase comparison are done near the accelerator, and signals are piped back to the klystron area through high propogation velocity ($\beta = 0.96$) 1/2-in. coaxial lines about 240-ft. long. This physical size introduces a pure time delay of ~1.0 μsec into the 1.25-MW rf control systems.

Operation of the EPA

From the initial operation of the EPA on December 21, 1967, the fields in both sections of the linac have been controlled in phase and amplitude simultaneously. The phase difference between the sections is readily adjusted by shifting the reference phase of one section. At present, the controllers use integral and proportional terms in their control equations. These equations were designed using a simple but adequate linearized model in which the accelerator tank is characterized by single lag, and the remainder of the plant, including the interface amplifier, by a critically damped, second-order lag at about 1.6 MHz. The controller compensation effectively cancels the pole of the tank. The control bandwidth thus achieved would be about 1 MHz with a 45% phase margin except for the time delay of 1.0 μsec. When this is included in the model, the bandwidth falls to ~200 kHz, which agrees very closely with that actually obtained, as shown in Figure 3. Here the EPA cavity field, 1.25-MW klystron forward power, and cavity phase (referred to the drive line) are shown with a short beam pulse at the center of the rf pulse. Incident power rises about 15% to handle the beam loading. The peak transients on field amplitude and phase are about 7-1/2% and 4° respectively; each is about half of the beam loading disturbance, indicating that the minimum attenuation at the edge of the control band is about 6 dB. During the steady-state part of the beam pulse, very good correction, within the stated tolerances, is obtained. As the loops are tightened to their maximum bandwidth, the interactions between them due to phase-amplitude interactions in the components can be noticed, but they do not appear to be a limiting factor.

These results are a very encouraging experimental verification of the approach to phase and amplitude control of the rf power for a heavily beam-loaded accelerator. We have (a) made a careful and quite complete definition of the rf control problem, (b) assembled the necessary equipment and hardware to furnish and control the rf output, and (c) operated the entire system as a controlled unit demonstrating the approach to first order. The following section outlines the next step — results from and plans for detailed analysis and design of the control system based on the dynamic in-circuit behavior of the entire system and each sub-system.

EPA System Studies

Transient Aspects

The time delay due to the physical size of the system is a limiting factor on the ability to handle high-speed transients. To minimize the effect, the development of each component has been carefully monitored to insure that its bandwidth is as high as possible while performing its other functions, or as high as needed in conjunction with the remaining components. The present components are nearly optimum in this respect. This having been done, fast transients must be attacked at their source if possible, or with more sophisticated control techniques. Since beam loading is normally the only transient of importance, an obvious solution would be to turn the beam on at a slower rate, say in 10-15 μsec, so the frequencies involved in the transient are within the loop bandwidth

Alternate approaches could involve state variable predictive techniques, nonlinear control functions, or both. Since the average $\beta = 0.5$ of the accelerated beam through the linac implies an ~6 μsec transit time, an injected beam current signal could be relayed through a high-propagation velocity coax to provide up to ~2 μsec of anticipation at the far end. This signal could be used as feedforward control[5] providing a significant reduction in transients. The open-loop addition of an approximately shaped "beam pulse" with anticipation can also reduce transient effects.

Since time optimum control nearly always requires nonlinear correction using all available resources, a dual-mode controller was tested. This controller uses linear control within prescribed error limits; if the error exceeds these limits, full correction to the saturation limits of the drivers is applied. A preliminary result is shown in Figure 4, where a 40° step disturbance has been applied to the phase shifter in the EPA phase loop in the middle of the pulse. The linear controller was adjusted to be underdamped, as shown by the initial turn-on transient. Error and error rate were used to set the switching lines for the nonlinear system to optimize the response to this disturbance. A companion experiment using the linear integral-plus-proportional controller is shown in Figure 5. The transient responses are very similar both in magnitude and duration. (The higher jitter level on Figure 5 is believed due to misadjustment of the 1.25-MW klystron and is not typical — see Figure 3. Figures 4 and 5 were made on different days.) The point of interest is that in this system the gain may stably be made high enough to use the full saturated output of the drivers without the necessity for the additional complexity of the nonlinear addition. Such studies from the nonlinear point of view are being continued, particularly to investigate in more detail the constraints imposed by the saturating elements.

Other experiments are in progress to examine the coupling between the phase and amplitude loops and the effects of the accelerator tank being slightly off resonance. The required analytical expressions to describe these effects have been derived[6] — the off-resonance effect is described by expressions of the same form as those used to give the effect of adjacent cavity modes, with the mode separation frequency replaced by the effective frequency deviation from resonance.

A model, which grows in complexity and completeness as the work progresses, has been set up on a hybrid digital-analog computer to aid in analysis of the experimental work. The present model includes the linear, nonlinear and time-delay aspects above.

Steady-State Aspects

A program of parameter variation studies and other measurements of a steady-state nature is being pursued on the EPA systems as a foundation for further control design. In particular, the detailed interaction of the klystron amplifiers with the accelerator load, which is complicated both during a pulse and over longer periods by its resonant nature, must be investigated. The benefits to be gained from such studies include the possibility of adjustment for self-compensation for some of the beam loading effects, thus easing the task of the control loops, and optimization of the system parameters over the required range of operating conditions. Most of these measurements must be made quickly with later data analysis, because the high-Q nature of the system makes it difficult to achieve steady-state conditions at each desired data point.

To facilitate gathering of this information, it was decided to use the control computer mockup system, allowing the rf system tests to serve two purposes. Thirteen analog data channels have been set up and calibrated for each klystron stand: time, frequency, rf output forward and reflected power, cavity phase angle, reflection coefficient phase angle, average and peak cavity field, mod-anode voltage, klystron cathode current, cooling water demand, cooling water temperature error, and copper temperature error (latter three from the resonance control system[5]). The 1.25-MW klystron test stand also has data channels for dc high voltage, rf drive and collector current. Electron beam current can be monitored at five points along the accelerator. A substantial amount of programming has been done by the computer group to allow data storage and some semi-automatic sequencing of the proposed experiments. The present data storage program stores data from up to 16 channels at a selected rate — it can easily run once per second if desired. Another program calculates VSWR on-line from the forward and reflected power data.

The first experiments were designed to study the interaction of klystron and cavity as the cavity goes off resonance. Cavity resonance was controlled by varying the cooling water temperature or, separately, by varying the rf frequency. Since the computer can change the water controller set point, a program was written to automatically cycle the cavity through resonance by incrementally changing the water temperature, watching VSWR until it reaches a given limit, reversing the water temperature demand until the VSWR passes through a minimum and back to the limit, and so on. These two experiments were run on both the 100-kW and 1.25-MW systems using all combinations of the following conditions: (1) cooling water resonance control and frequency resonance control, (2) beam on and beam off, and (3) amplitude control loop open and closed. In all runs, the cooling water resonance control systems were provided with rf information, and on the beam runs, both systems were phase locked and relatively phased for maximum beam at resonance.

The raw data is printed out by the control computer as a listing and on paper tape. Programs have been written which convert the paper tape to cards or magnetic tape in the CDC6600 format, perform scaling or calibration curve fitting to put the data in proper units, and plot the data files against time or against each other with the 4020 plotter. These plotting programs have now evolved into a very useful and simple to use format which will be an important tool in the testing programs. A sample graph is shown in Figure 6. At the present time, most of the data from the experiments above has been processed to graphical form and is ready for analysis to begin.

Summary

Design of the rf control system for the LAMPF accelerator has now entered the final phase. Prototype versions of all hardware are operating together in the EPA system and have been used to verify the design approach. Measurements are being made to investigate system interactions, nonlinearities, and second-order effects in detail as the basis for final design. The application of the real-time control computer system to the testing program provides an extremely versatile and powerful tool.

Acknowledgments

Many people have contributed in a major way to this effort, including W. J. Hoffert, J. L. Davis, and C. E. Woodard in the development of the rf reference system; D. I. Morris, J. D. Wallace, and J. R. Eichor in the setup and operation of the rf control systems; the control computer group; and D. D. Simmonds in the programming of the data conversion and plotting routines. Their help is gratefully acknowledged.

References

1. D. C. Hagerman, "805-MHz Power Sources for LAMPF," Proceedings this conference. p.76
2. E. A. Knapp, "Initial Performance of a 20-MeV High Current Side Coupled Cavity Electron Accelerator," Proceedings this conference.p.635
3. "Quarterly Status Reports on the Medium Energy Physics Program for Period Ending October 31, 1967," LA-3828-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, and subsequent progress reports.
4. T. G. VanVessem, "High Duty Factor Floating Deck Modulator for Los Alamos Meson Physics Facility," Proceedings this conference. p.91
5. G. R. Swain, R. A. Gore, and R. A. Jameson, "Temperature Control for Maintaining Resonance of Linac Tanks," section on the EPA, Proceedings this conference. p.159
6. 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, 1965.

DISCUSSION

(R. A. Jameson)

TUNNICLIFFE, AECL: As a point of clarification, is it your aim to reduce the amplitude and phase transients caused by beam loading to the tolerances you stated, and do you expect to achieve this? Otherwise, you will get progressive beam loss initially on the onset of the pulse.

JAMESON, LASL: That is my aim, and I hope I can achieve it. I sometimes doubt that I can. There is, I think, a valid and unanswered question regarding the meaning of the specified "tolerances" with regard to the transient period. Those tolerances were derived from steady-state beam dynamics using random tank-to-tank errors. We do hope, of course, to be able to reduce the systematic errors to within the same limits, but assuming this could not be done, the question is how much beam is really lost during a systematic transient when the whole machine is undergoing a more or less coherent phase and amplitude fluctuation. The answer obviously depends on many factors, particularly the tightness of the injected bunch. It is a more difficult problem, because time must be retained in the calculation. I have referred this question to the beam dynamicists.

TUNNICLIFFE, AECL: You may have to go to slow beam turn-on.

JAMESON, LASL: I may. It is comforting to have a way out, but I still have some interesting things to try.

BAYLY, AECL: You spoke of a one microsecond delay. Is this because the loop is about 1000 feet?

JAMESON, LASL: It isn't 1000 feet long. The distance between the rf amplifiers and the most distant tank (we have clustered rf amplifiers) is about 155 feet. Most of the delay, about 400 nsec, is in the transmission lines, waveguide and the lines bringing the signals back. There is also an effective time delay of about 250 nsec in the rf chain and the big klystron, giving a total of some 700 to 800 nsec. The EPA system is more spread out and has almost 1 μsec delay, which is even more difficult.

BAYLY, AECL: Your slide shows a random phase noise of about one degree peak-to-peak.

JAMESON, LASL: Some of this is introduced by the operational amplifier circuitry and some by the prototype interface amplifier being used when this picture was made. I plan to go through the system piece by piece and eliminate most of this noise. As we go from the prototype to final design stage. I expect the random noise to decrease significantly.

BAYLY, AECL: How do you sense the condition of resonance when the beam is on?

[†] For estimation of control loop performance, the cavity field and incident power figures were scaled directly from the oscillograph without compensation for the detection law of the crystal detectors. The detectors were operating in an rf input range where their outputs were approximately proportional to cavity field. Beam current was ~ 10 mA; assuming 500 kW copper loss in the EPA tanks and 20 MeV energy gain, beam loading was ~ 30%.

JAMESON, LASL: You must make a definition of resonance - as the point of minimum reflected power in the waveguide, or as peak field in the cavity, or whatever you like. You can vary the tank temperature by varying the water temperature or change the frequency to see how the defined condition reacts with or without the beam.

WATERTON, AECL: What is the 7th subharmonic of 805 MHz?

JAMESON, LASL: 805 MHz divided by 128, that is, divided by $(2)^7$.

WATERTON, AECL: You modulate the klystron by modulating the drive power. This implies to me that the output must be an integral number of half wavelengths from the connections to the tank. If you make the same type connection for the triode, you can modulate the triode by modulating its drive because the triode is also a high impedance source.

JAMESON, LASL: We find that the 7835 doesn't like that at all. This I believe has been everyone's experience with 7835's. However, Tom Boyd and Ross Faulkner are getting ready to initiate a program of varying all parameters to search for some combination of all of the "knobs" so that you can modulate the drive. This would be a big advantage. The control of the hard-tube modulators has presented one of the biggest problems of the hardware. This was true when we were using the amplitrons also.

WATERTON, AECL: You were talking about proportional and integral terms in your controller. Is this sort of approach as powerful and as flexible as the loop amplitude and phase plots of Bode?

JAMESON, LASL: The linear controllers, used to date, were designed using Bode plots and other such linear system design techniques. The terms I used are a way of saying what operations are performed on the error signals. My point is that if you have to beat the time delay, you have to go to something more powerful than these linear techniques.

WEITMAN, BNL: On your test with both amplitude and phase loops closed, was the cavity frequency exactly at the drive frequency? If it was on one side or the other, was there any difference in the stability or interactions depending on the side?

JAMESON, LASL: With both loops closed, we varied the frequency on either side of resonance to a VSWR of 3:1 and didn't observe alarming behavior of these loops. We didn't observe the behavior in detail however, this will be done in the near future. However, the settling time and transients seemed to be about the same over this range. It doesn't look like interactions will be a major problem.

LOEW, SLAC: Recently at SLAC we have experienced "gulches" in the analyzed beam current pulses coming out of the beam switchyard when we increase the current from the injector. This affects the statistics of some of the experimenters. The effect seems to be due to beam loading or some other transient that we do not understand. We can try to fill these gulches with short rf pulses if you have a spare klystron. Recently we have been modulating one of our klystron inputs with short 200 nsec pulses. We then move these pulses in time to try to fill the gulches. The long filling time of our accelerator (0.8 μsec filling time) makes this somewhat difficult. However, if you have enough parameters at your disposal, you might be able to fill any gulch.

JAMESON, LASL: We put beam loads of 17 mA peak, 1 mA average through the EPA, equal to our expected proton loads. During the steady state part of the pulse, assuming a reasonably flat injected beam pulse, we get extremely good correction and the fields are flat. We have run this accelerator with 6% beam, i.e., 500 μsec beam pulses, and it looks very nice. I would like to try, as I mentioned, to use the beam envelope to "beat" the time delay. It can also be done with open loop pulses positioned in time where you want them, as you have done. This works but it is not as nice as having something with a closed loop. I think this closed loop feature can be attained if you can feed information along the accelerator faster than the beam.

TUNNICLIFFE, AECL: Have you measured the phase shift in the feed line necessary to compensate for beam loading in the cavities?

JAMESON, LASL: The shift for the slide I showed was 8 or 10 degrees. That is a little larger than we would expect in the electron accelerator. However, the injection optics for the electron accelerator are not as good as that which will be used with protons. We will study this effect in more detail -- a chopper at the front end of the EPA would be helpful.

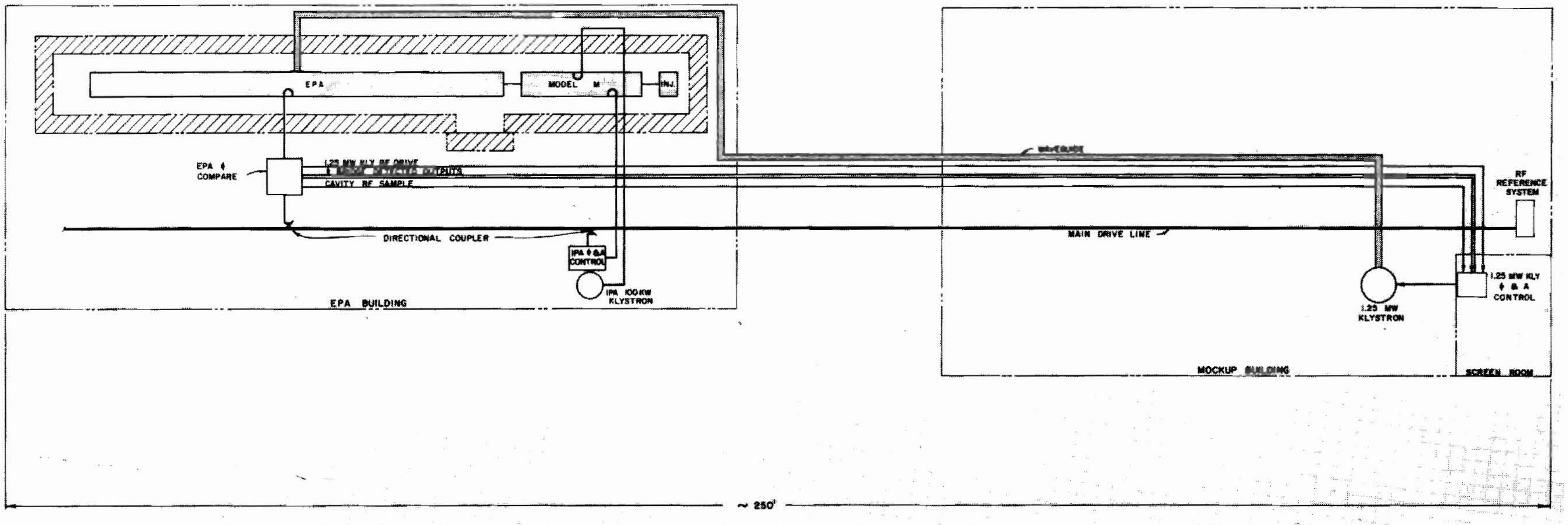

Figure 1 — Physical arrangement of Electron Prototype Accelerator system stressing the rf control system.

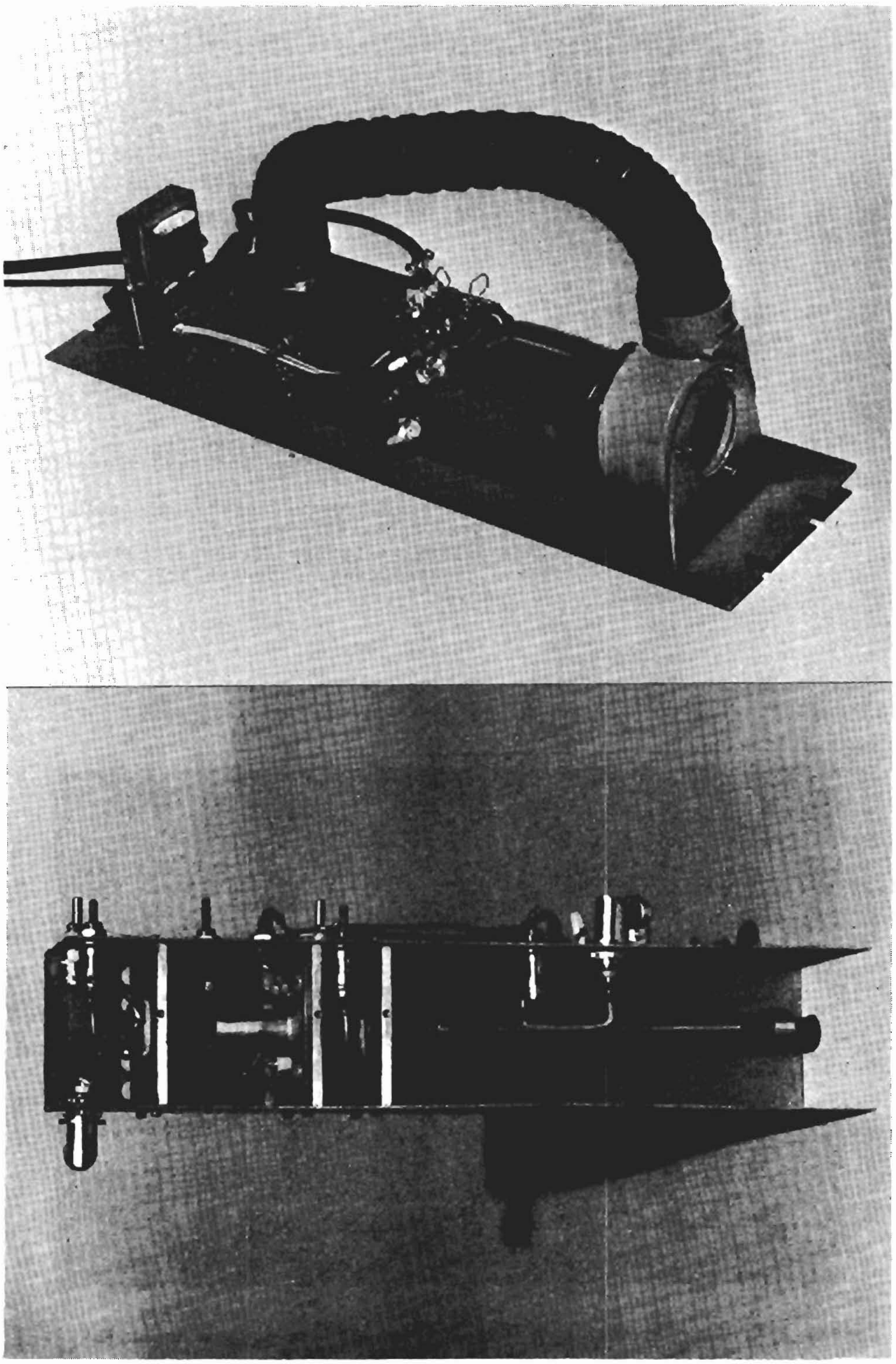

Figure 2 — Two views of the 805-MHz rf interface amplifier.

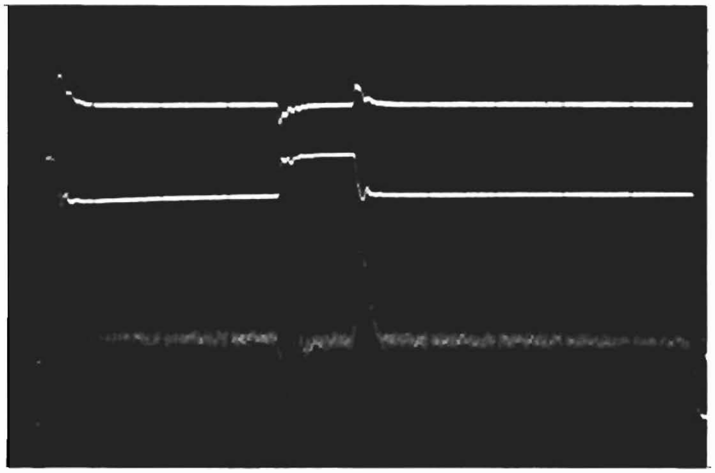

Figure 3 — EPA operation under rf phase and amplitude control.

Top Trace:	EPA cavity field, baseline 1 cm from bottom of graticule.
Middle Trace:	1.25-MW klystron forward output power envelope, baseline at bottom of graticule.
Lower Trace:	Phase difference between EPA cavity field and drive line reference. Inverted, 2.5°/cm.
Time Scale:	50 μsec/cm.

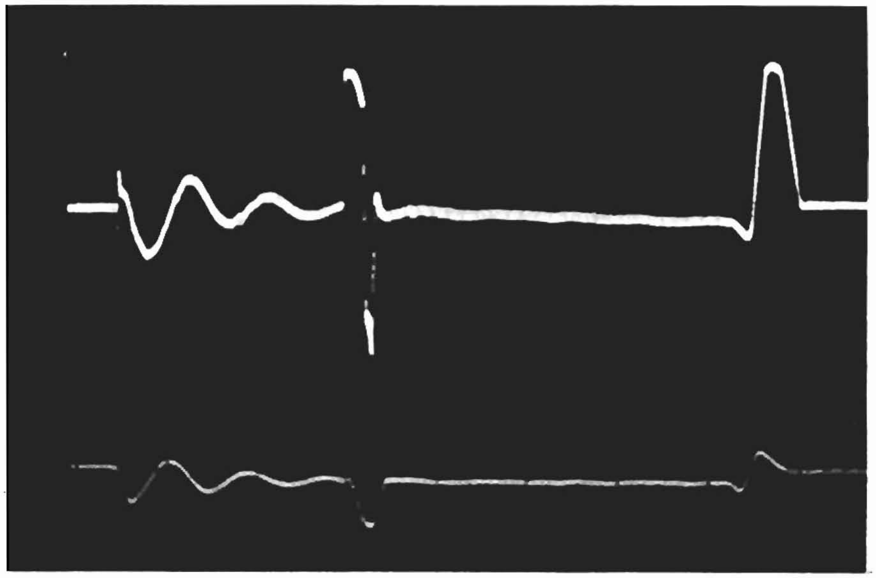

Figure 4 — Phase control of a 40° phase disturbance using a dual-mode nonlinear controller.

Top Trace:	Drive signal to varactor phase shifter, 0.5 V/cm, -1.5 V bias.
Bottom Trace:	Phase error signal, ~55°/cm.
Time Scale:	15 μsec/cm.

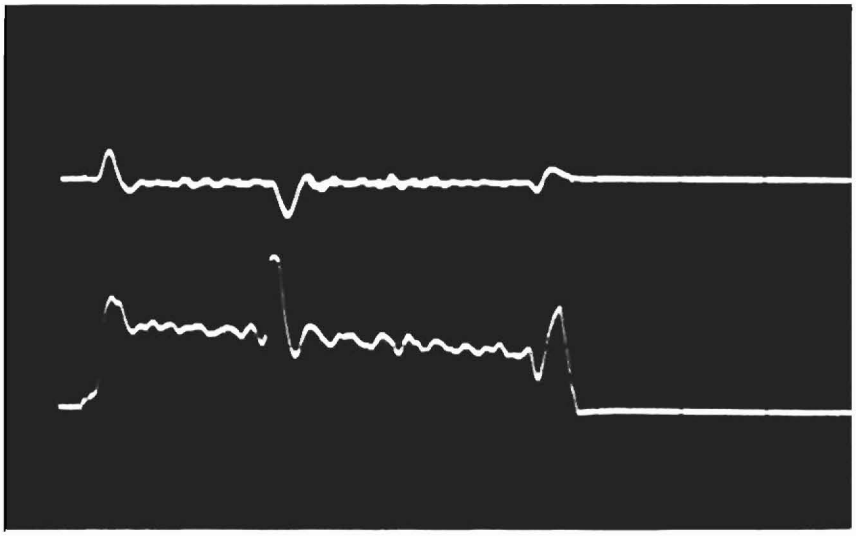

Figure 5 — Phase control of a 40° phase disturbance using a linear controller.
Top Trace: Phase error signal, 40°/cm.
Bottom Trace: Drive signal to varactor phase shifter, 0.5 V/cm, -1.5 V bias.
Time Scale: 20 μsec/cm.

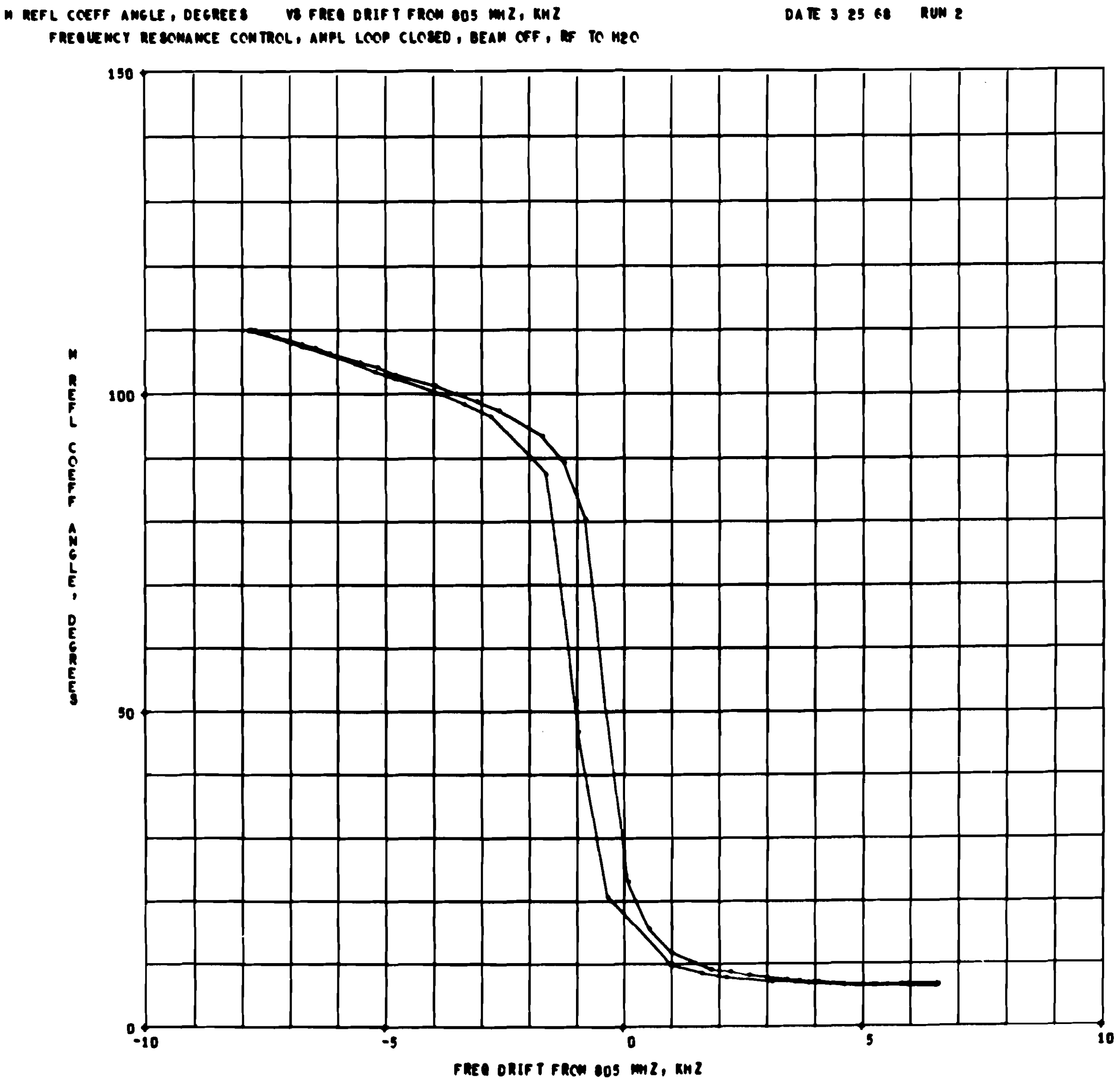

Figure 6 — Typical output from digital computer data collection, reduction and plotting system showing relation between reflection coefficient angle and frequency, as frequency is varied about the resonant frequency of the Model M cavity.