FULL POWER OPERATION OF THE LAMPF 805 MHz SYSTEM*

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ABSTRACT

Results of system operation using the 1.25 MW, 805 MHz klystron rf amplifier and the side-coupled accelerator structure are reviewed from the several aspects of long and short term performance and the dynamic interaction between the amplifier and its load. Specific discussion of the latter aspect includes several new techniques for investigating detailed performance of accelerator systems operating under real, full-power conditions.

Introduction

The basic function of any rf linear accelerator system is to provide, at the proper physical intervals, an axial electric field of proper magnitude and phase. In a practical machine, the accelerator is split into sections of length dependent on the amount of rf power economically available from one rf amplifier and several parameters of the accelerator structure itself, such as bandwidth and the need for radial focusing. Figure 1 shows the arrangement of a typical LAMPF 805 MHz section. In modern high-duty factor designs, the accelerator fields are dynamically controlled, and this control must also be arranged to reunite the sections into an integral whole. Considerable operating experience has now been obtained with two such systems, the 805 MHz Electron Prototype Accelerator (EPA) and the first 805 MHz module of the LAMPF accelerator. This experience, outlined below, has emphasized the extent to which interaction among all system elements must be considered to obtain proper overall operation, and the broadness of view which must be adopted to fully optimize the system.

Real Generators - The 1.25 MW Klystron

Finding a controllable 805 MHz amplifier capable of high duty factor operation required a full-scale development program[1] and resulted in the selection of a 1.25 MW peak power, 150 kW average power klystron amplifier. Earlier questions about klystron controllability have been answered by the development[2] of fast, wide-range electronic phase shifters and amplitude controllers which modulate the rf drive to the klystron. The essential ruggedness of the amplifiers has been demonstrated by an accumulated lifetime of over 22,000 h on ten development tubes and successful operation into resonant and highly mismatched loads over a broad range of conditions. Once these basic qualities have been achieved, details of the amplifier's performance in its intended

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usage can be investigated to optimize overall performance. In particular, the interaction of the generator and its load may be used to advantage in the correction of beam loading, reduction of transients, and overcoming of multipactoring. In previously suggested applications of this type,[3,4] idealized generators were used in the analysis. To overcome this limitation, techniques and instrumentation[5] have been developed which allow the actual characteristics of the klystron amplifier to be determined at full power.

As an example, consider the problem of optimizing the response of the generator output amplitude to beam loading. The time-varying field amplitude and the impedance of a standing-wave accelerator structure during a normal pulse are shown in Fig. 2. At each of the two "steady-states" a certain amount of power must be delivered by the generator. Since the output of the klystron is varied by changing the rf drive with all other generator parameters fixed, contours of deliverable power as a function of load impedance and drive would clarify much of the system's natural response to the particular load presented by the accelerator. In the example of Fig. 3, it is seen that the system would, without change in drive level, deliver an additional 100 kW if the beam were present. As another example, if very fast pulse rise time were necessary to drive through a multipactor level, then a cavity impedance trajectory 180° from that in Fig. 2 would provide the fastest response; this could be achieved by adding a quarter wavelength of transmission line between the generator and the load.

The contours of Fig. 3 are typical of real generators,[6] and have been measured in detail for the 1.25 MW klystrons. The drive pulse to the tube is ramped, and the output connected through a directional coupler to an E-H tuner followed by a water load. The E-H tuner is set at 56 different load impedances covering the Smith chart to VSWR's of 7:1, and oscillographs are taken of the power transfer curve, as shown in Fig. 4, or other variables. Transparencies are made of the photographs and the information is put on punched cards using a projection reader. The data are processed using computer programs which first reference all points to a rectangular set of graticule fiducials and scale the coordinates to proper engineering units. From this point, many useful calculations and displays are possible, as shown in Figs. 5, 6 and 7. Presently, models are being developed which adequately describe the generator but are tractable enough to be useful in systems analysis. One such model produces the synopsis of klystron performance shown in Fig. 8. These models are adequate for system studies; however, the experiments were conducted with great care, producing accuracies of ± 5% or better in delivered power measurement, in order to provide a data base for improvements in klystron design. A two-dimensional klystron beam dynamics code[7] has been written at LASL, and an output gap code is in progress which will allow direct comparison with observed behavior.

RF-Accelerator System Measurements at Full Power

There is little question that the ability to probe system performance while operating under realistic conditions would be an invaluable aid to system design. In the past, such measurements have been very difficult, particularly with highly resonant standing-wave structures which must be operated under precisely controlled conditions of resonance to avoid high-voltage arcs and other system instabilities. However, engendered by the klystron studies mentioned above and precipitated by difficulties with the accelerator structure discussed below, a versatile and flexible method has been developed which allows broad variation of many parameters while the system is operating under completely realistic conditions of peak field and full duty cycle.

The crux of the method is that modern electronic technology provides fast, reliable, pedestal-free, relay type switching for signals of any frequency. FET switches are ideal for signals up to several megahertz, and PIN diodes are well suited for switching rf signals. Both types are easily synchronized and gated electronically from pulsed logic signals. The switches are interposed in the rf-accelerator system as shown in Fig. 9. Notice that switching is possible in all the major paths of the system and its control system; the rf drive, the sensor outputs, the controller references, and the controller outputs. A very broad spectrum of possible combinations is apparent -- a particularly useful one is shown diagramatically in Fig. 10. The first part of the pulse sequence is a normal 805 MHz pulse train of design peak power, pulse width and repetition rate, with the fast amplitude and phase closed-loop control systems controlling the cavity field. The system resonance control system[8] has been adjusted to maintain resonance. A second pulse follows, called the "diagnostic pulse" since its characteristics are completely flexible. As an example, if the structure stopband is to be determined, control variables are changed to keep the magnitude (and phase if desired) of the rf wave from the generator constant. This replaces the actual generator with an effectively ideal one and allows study of the structure alone. The rf signal is changed to another source which can be swept. The width, amplitude, and repetition rate of the diagnostic pulse are chosen so the average power delivered to the accelerator is not significantly changed. Figure 11 shows the cavity field swept over three modes, and the controlled incident wave. Extremely constant level control of the incident wave is possible using a slower sweep.

At present, this method is being exploited to develop a set of measurements which will verify at high power all of the important characteristics of the accelerator structure currently set at low power.

Real Loads - The 805 MHz Side-Coupled $\pi/2$-Mode Structure

From the system point of view, certain qualities of accelerator structures such as the time varying impedance of Fig. 2 qualify them as "non-ideal" loads. However, the basic requirement is for proper axial fields, and recent advances in the understanding of coupled resonator systems[9] promise much in terms of reduced sensitivity to manufacturing tolerances and improved coherence of field behavior. Having demonstrated its fundamental capability, practical hardware must then be developed and fit into the rest of the system. The system aspects of the 805 MHz structures, particularly the aspects of tuning and field stability during high-power operation, have been under close scrutiny for about eighteen months, and recent results show that compatible operation over a nonrestrictive range of conditions is indeed possible.

During detailed study of amplifier characteristics in the EPA,[10] it was noticed that the system would eventually drift out of control, and that full beam energy was not achieved at high duty factor. The measurement results of Fig. 12 isolated the problem to the accelerator structure and revealed that system operation in the vicinity of 6% duty factor was conditionally stable. One originally mistuned tank was retuned, with no improvement. The EPA cooling system used tubes attached with epoxy to the sides of the structure, with no cooling in the vicinity of the coupling cells, and it was conjectured that resultant thermal gradients detuned the structure. Additional cooling was added, and, after system optimization, the behavior at the bottom of Fig. 13 was achieved. Although much improved, the divergence of 6% (at 8% duty factor) from the field distribution established during tuning was completely unsatisfactory for operation with protons, for not only had the fields changed more than the acceptable tolerance established by beam dynamics, but a basic premise, that field coherence in a module would allow the sufficiency of one-point control, was violated. It was decided to pursue this problem on the lowest energy 4-tank 805 MHz accelerator structure for LAMPF in the Equipment Test Laboratory Building.

Studies began on three fronts. Development of the high-power techniques mentioned above was intensified. The required tolerances for phase and amplitude flatness were questioned anew, and tank tuning procedures were reviewed.

The tolerance study[11] showed that the tightest requirements are placed on the low-energy modules, with a ± 5% tank-to-tank average field amplitude tolerance producing acceptable beam dynamics in only 70% of a statistical sampling. Further, successful operation of a proposed accelerator adjustment procedure[12] during initial turn-on is contingent upon being able to measure fields to ± 2% (in which case tanks with a 5% spread could be readjusted to within 2%). These results constituted no relaxation of previously used tolerances.

Substantial additions to the tuning techniques were made, including a set of measurements to insure the sufficiency of bridge coupler tuning, and compensation for a significant frequency shift in the coupling cells caused by evacuation. For cases with a stopband opened with the coupling cells low in frequency, high power performance, Figs. 13 and 14, was still unsatisfactory. However, when the stopband was opened purposely with the coupling cells high in frequency, a dramatic improvement in performance was noted. Again after some system optimization, the performance summarized in Fig. 15 was obtained. Long-term drifts of less than 1% over 60 h, and variation in cell fields of less than 1% over a duty-factor range of 2.4-12% testify that a method for adequate control of long-term, high-power field stability is in hand. The self-stabilizing effect of this type of stopband opening is not yet fully understood, although it is known that the coupling cell frequency is extremely sensitive to dimensional tolerances in the gap and plausible arguments can be made concerning temperature gradients and subsequent thermal expansion and contraction in the copper.

Setting cell frequencies and verifying field flatness have also been troublesome. Many of the difficulties proved to be procedural, and a substantial consolidation resulted from the development of techniques enabling individual tuning of each main or coupling cell. Another class of problems derives from the necessity to find empirically various correction factors due to mechanical and environmental effects which must be applied to the cell frequencies during tuning so they are correct in final operation. Part of these were circumvented by changing procedures so that operation was more realistic during the measurement; for instance, low-power bead pulls are now performed under a rough vacuum. Others must be found by experience. Four of the low-energy modules have been completely tuned, and curves of the important corrections are being generated to allow extrapolation to the next modules. The patterns are beginning to become clear and the tuning techniques are flexible enough to allow later fine adjustments to be made after a module is "buttoned up" if this should prove desirable. The present tolerance on setting average tank field flatness at low power is about ± 2%.

Verification of field flatness at high power is being vigorously pursued. The important quantities to be checked appear to be stopband, relative field stability, and absolute field level. As related above, stopband can be measured to a few kHZ, and relative fields can be measured both long and short term to better than 1%. Measurement of absolute fields is difficult; two methods are being tried. The first, involving calibrated probes, has little promise for absolute accuracy better than ± 10%. The second involves a bead pull at high power, either by running the system at 805 MHz and measuring the phase shift between the waveguide drive and the structure, or by running the whole system as the conventional oscillating loop. Both methods appear feasible. Experiments to find suitable string and bead materials and configurations are in progress. Polypropylene appears to have possibilities as a string material.

Fast Amplitude and Phase Control - Progress Report

Detailed investigation[2] of transient effects and beam loading in the EPA has been sidetracked for some time although numerous preliminary measurements have been made. It is planned to renew these studies and to complete final optimization of the field control systems in the near future. Two examples of typical operation with the linear controllers are presented to show current status and to illustrate the potential of high-duty factor (long pulse length) accelerators for extremely precise long and short term control of particle energy gain.

Figures 16 and 17 demonstrate performance of the EPA. At a given duty factor, the fields in the structure (see Fig. 13) remain stable indefinitely and, with pulse-to-pulse field control, this machine has been very successful as an electron accelerator. The top trace shows the cavity field, with the control loop gains adjusted for oscillation in Fig. 16, and for minimum transients in Fig. 17. The middle trace shows the beam current injected into the accelerator. The bottom trace shows the beam current after passing through ± 0.25% momentum analyzing slits in the target area. It is apparent that the beam passes through the slits whenever the field is of the proper magnitude, and that this magnitude is precisely maintained during the pulse. About 90% of the beam leaving the accelerator has been stably passed through these slits for long periods of time.

Figures 18 and 19 show the present performance of the amplitude control on Module 1 of the 201.25 MHz system.[13] About 2.5 mA peak beam current is being accelerated. Further work is expected to reduce the transients.

Field Coherence - A Figure of Merit

A more comprehensive and unified treatment of field stability and error tolerance in coupled resonator accelerator structures would benefit system design, not only within the accelerator fraternity, but especially in discussing such systems with potential users in practical applications. The term "field coherence" has been used several times in this paper to describe aspects of performance which pertain to the ability of a system to achieve and maintain precisely defined axial fields. The possibility of adopting this term as a standard descriptive parameter for linac systems is suggested.

The basic tools for developing such a concept appear to be available. The great body of structure design theory[14] considers steady-state performance. The transient behavior has been studied[15] but in general less thoroughly, and recent high-power work suggests that some extensions to the usual analytical models may be necessary to fully characterize a system. Many accurate experimental techniques are available. It is believed that a merger of all these aspects would be synergistic -- indeed, a recent resurgence of interest in the transient response of structures[16] resulted in considerable clarification of steady-state performance and a unification of the theory which immediately pointed toward new possible applications.[9,17] These results in fact suggest that the "field coherence" of a system could be defined as a figure-of-merit derived from an appropriate weighting of steady-state, transient, and high-power factors. For example, the perfect $\pi/2$ mode structure probably has the maximum overall field coherence, and could serve as a reference for comparison. This concept would be most useful if it were developed and accepted by the linac community at large.

Summary

Experience with operating systems has shown that a broad view, but with simultaneous strict attention to detail, is necessary to insure a satisfactory interaction of the various components. The LAMPF 805 MHz rf-accelerator system has been thoroughly tested and no major problems are now apparent, although considerable effort to achieve thorough understanding and optimum performance remains.

Acknowledgement

The authors gratefully acknowledge the capable assistance of Mrs. R. S. Mills in handling the klystron test data and of C. E. Manger in helping make the system measurements.

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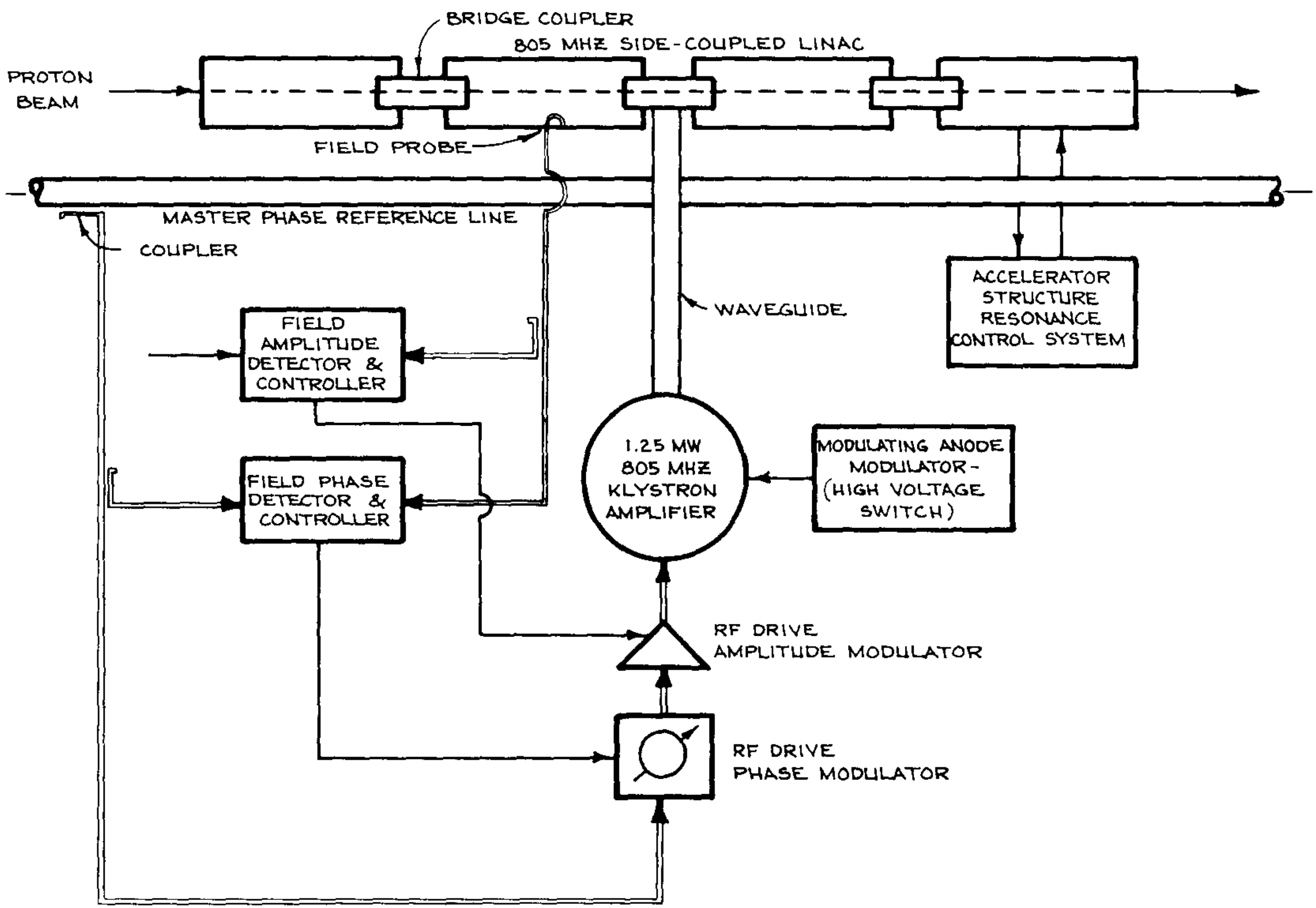

Fig. 1 System features of a typical module of the LAMPF 805 MHz accelerator section.

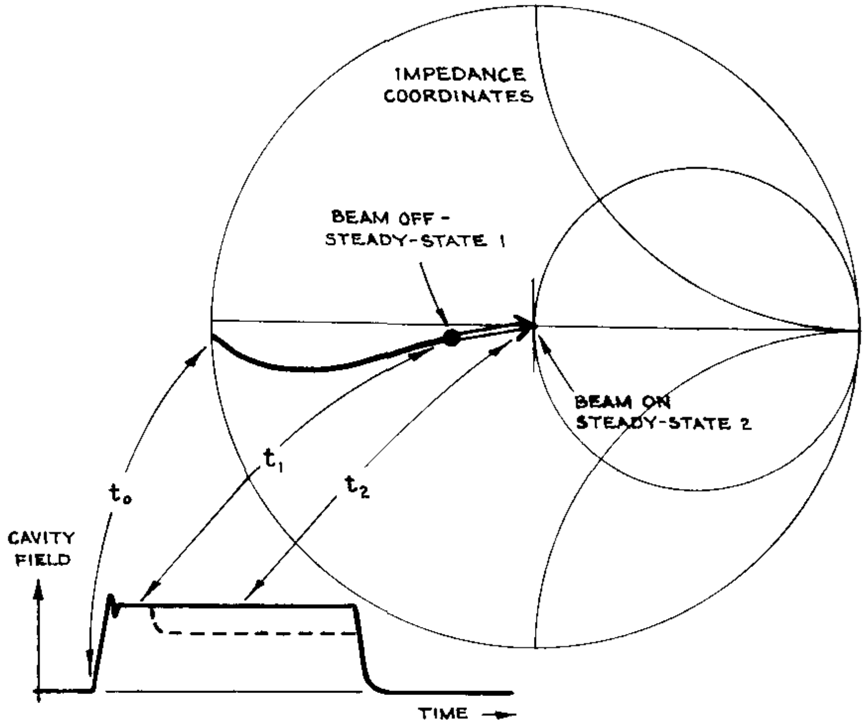

Fig. 2 Standing-wave Accelerator cavity field and impedance as functions of time.

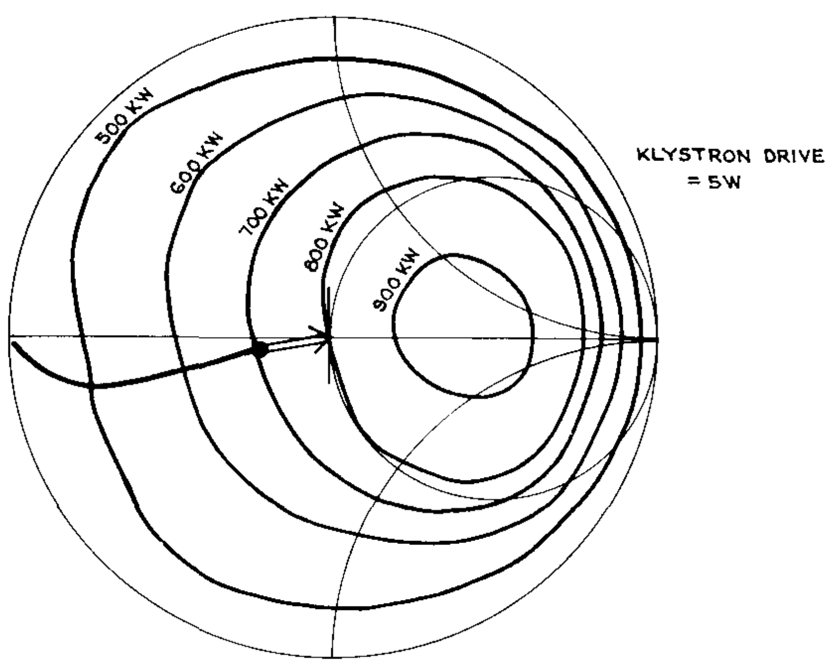

Fig. 3 Standing-wave accelerator time-varying impedance superimposed on contours of constant power delivered by a generator to the resistive part of its load.

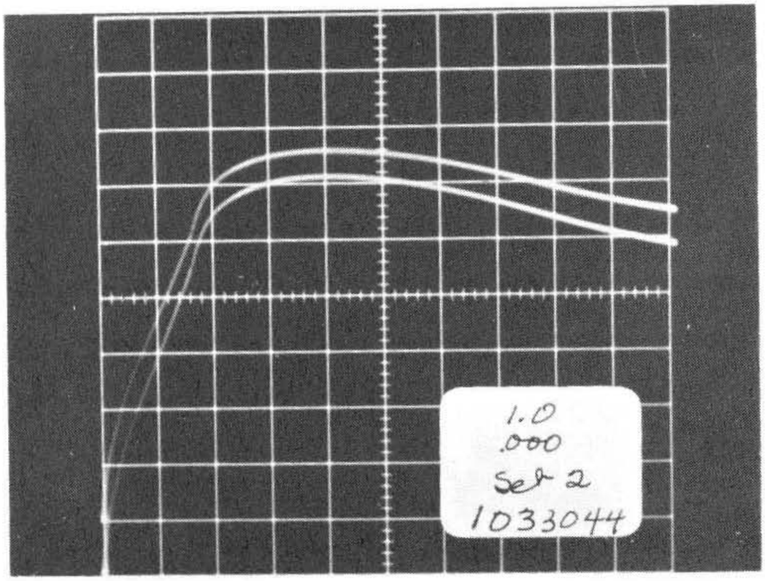

Fig. 4 Power in-power out characteristic of Varian 1.25 MW klystron SN 3 operating into a matched E-H tuner and water load. Operating parameters are 86 kV, 28 A, with focusing magnet current of 18 A and modulating anode resistor of 20 kΩ. Upper trace is the incident wave in front of the E-H tuner; lower is the incident wave behind the tuner. Scales are nonlinear; approximately 0-50 W on horizontal axis (pin), and 0-2200 kW on vertical axis.

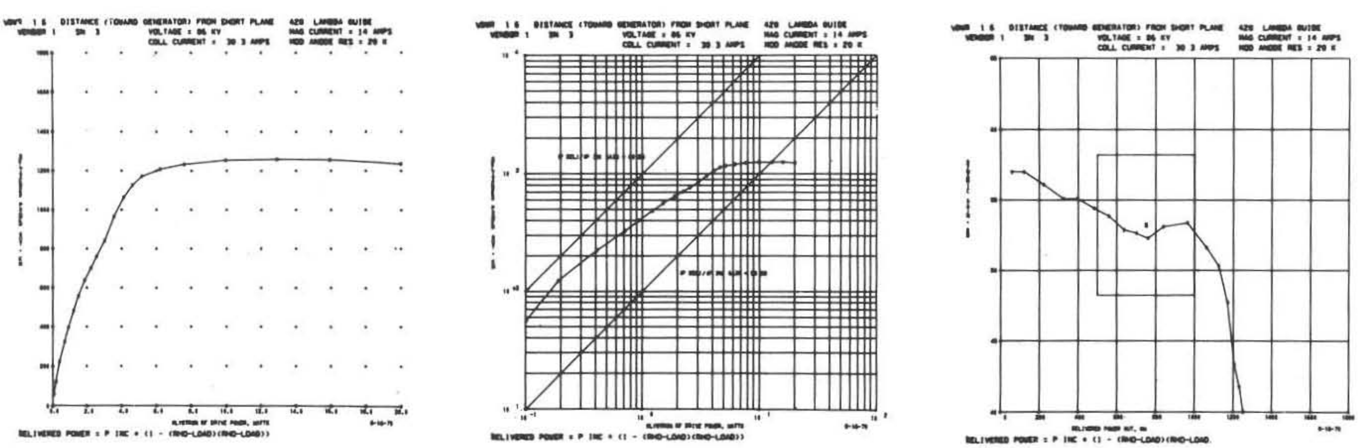

Fig. 5 Computer output showing the power transfer characteristic of Fig. 4 in scaled linear and logarithmic coordinates in the first two frames. The third frame is the dynamic gain of the klystron with this load impedance -- the derivative of the power transfer curve.

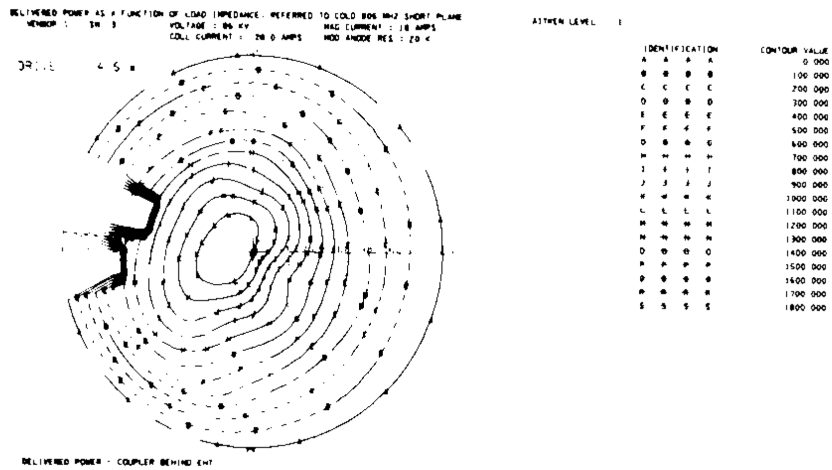

Fig. 6 Computer output showing contours of constant power delivered by the klystron described in Fig. 4 into the resistive part of its load. Drive is 4.5 W, maximum output is 1100 kW. The blank region at the left indicates that the tube oscillated for loads in this vicinity.

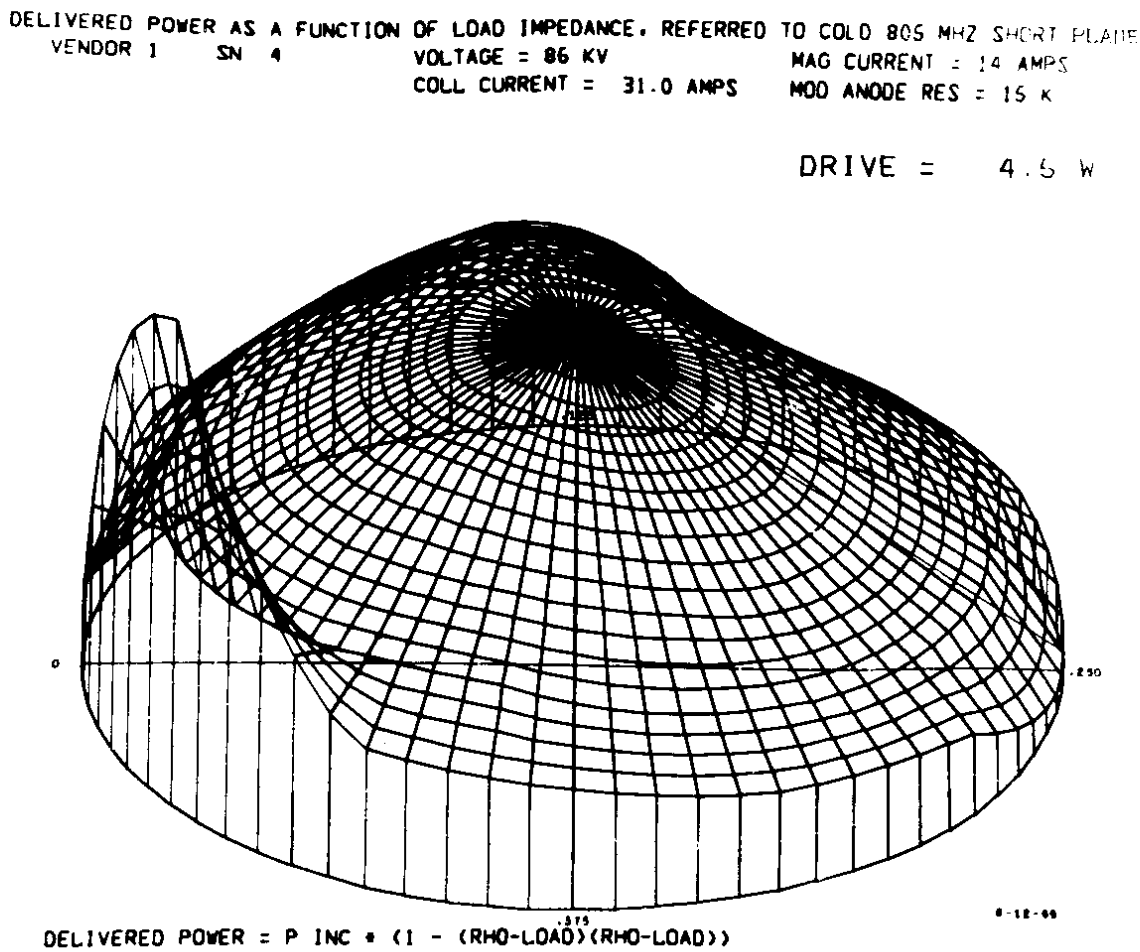

Fig. 7 A three-dimensional display of the contours similar to those described in Fig. 6. The high "ears" at the edge indicate regions of oscillation.

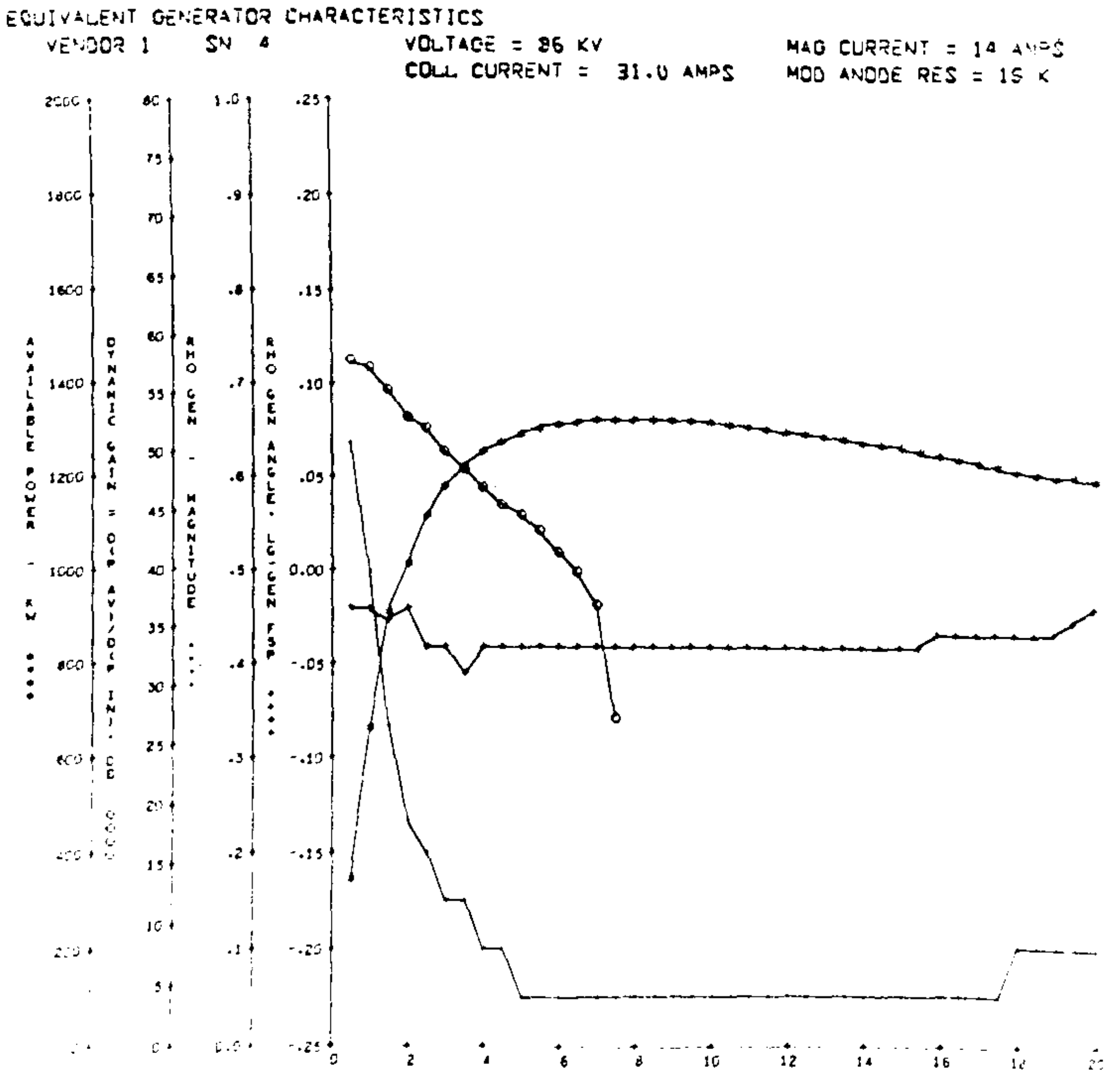

Fig. 8 Composite behavior of the klystron amplifier as a function of drive level with other parameters fixed. Equivalent generator characteristics of available power, dynamic gain, and the magnitude and angle of the generator reflection coefficient are derived from data similar to that of Fig. 6.

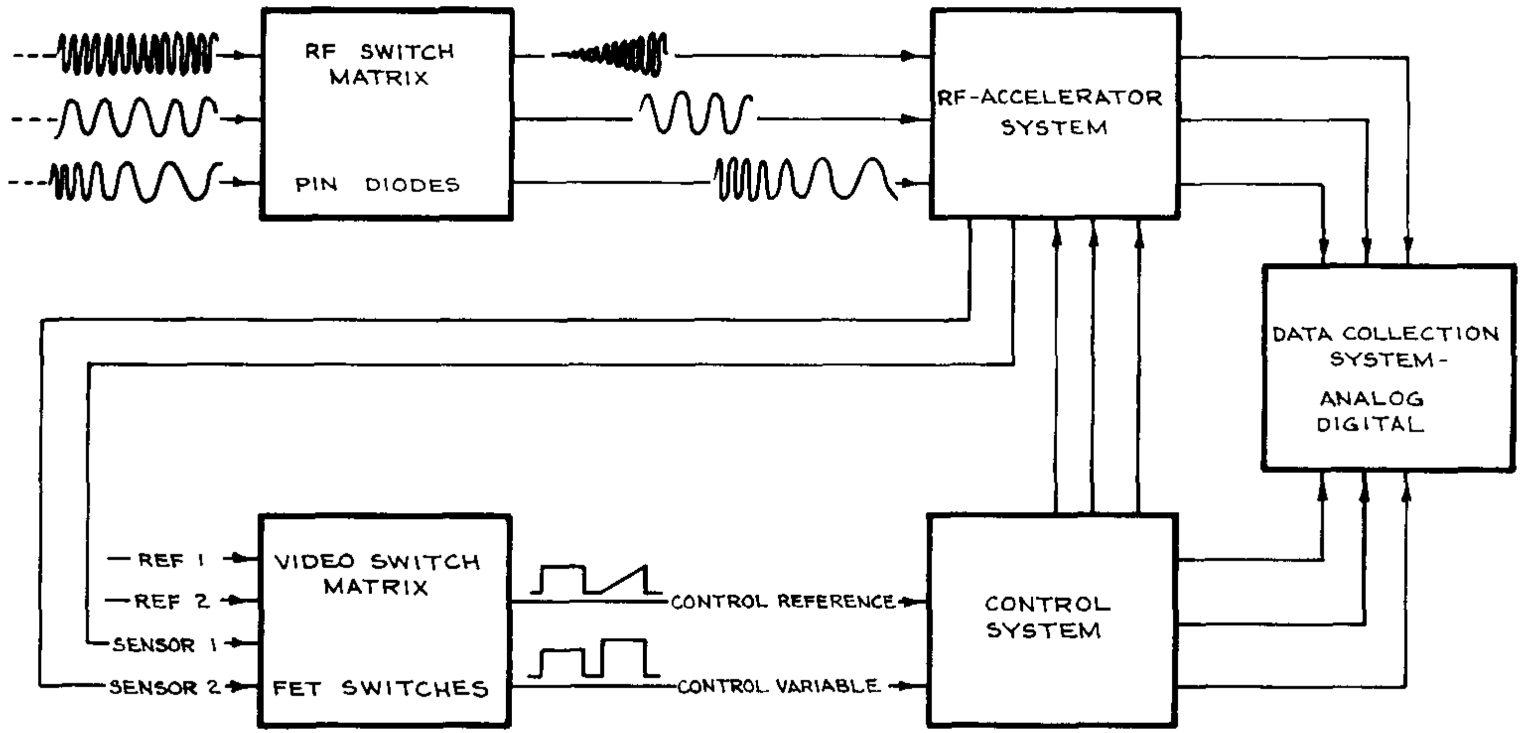

Fig. 9 Block diagram of a versatile and flexible system for high power measurements of an rf-accelerator system.

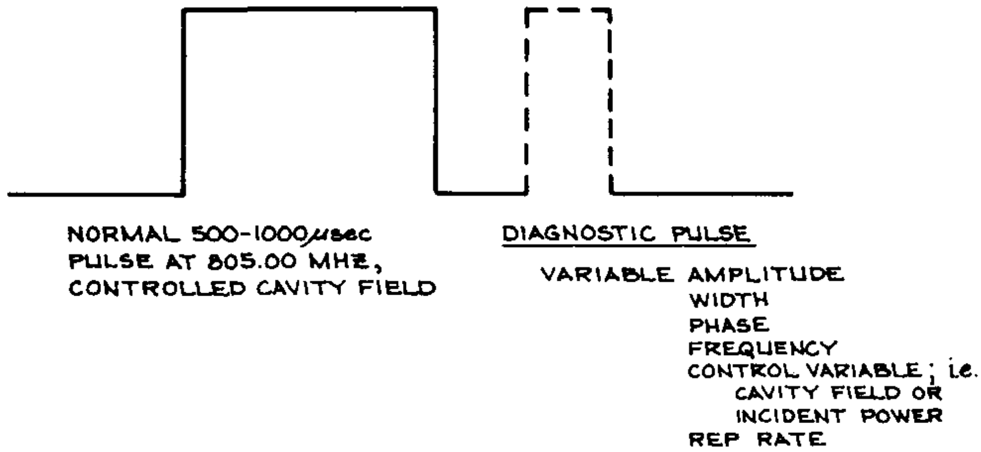

Fig. 10 **Pulse sequence** for system diagnosis while at full average and peak power.

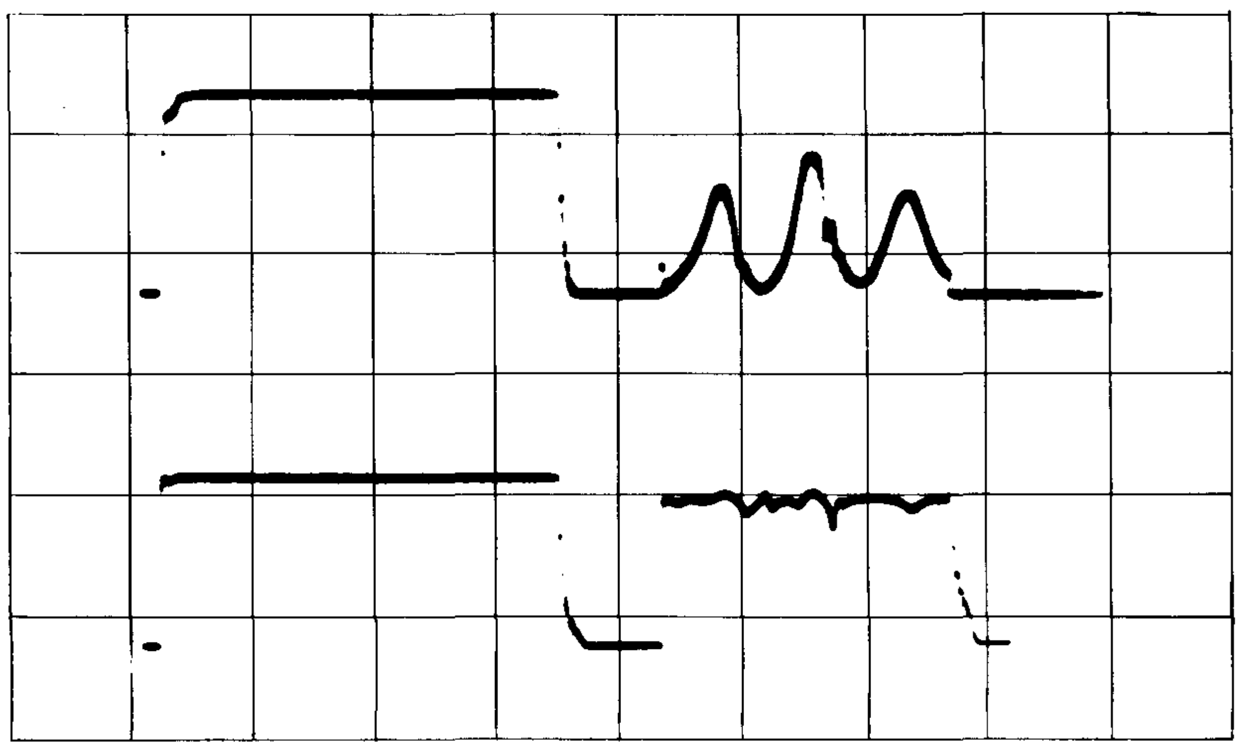

Fig. 11 Oscillograph illustrating measurement of $\pi/2$ mode structure stopband while operating at high power. Top trace - cavity field; bottom trace - forward power wave from the klystron.

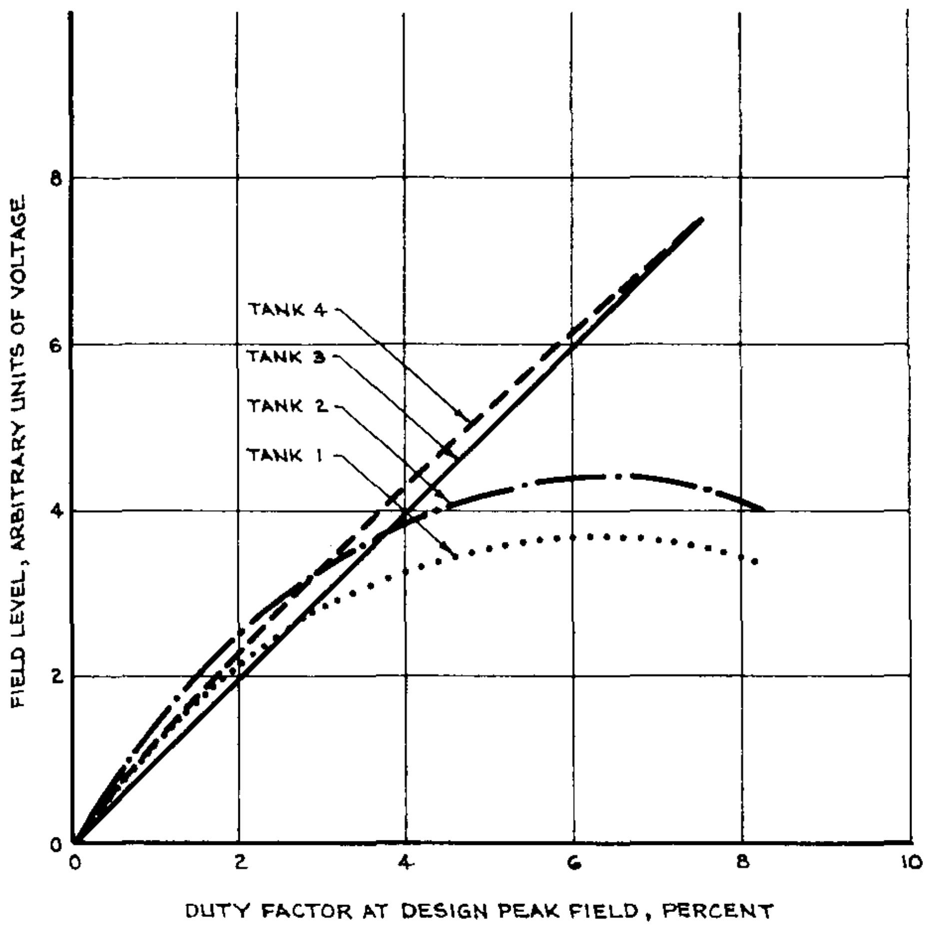

Fig. 12 Distribution of rf peak fields in the four tanks of the Electron Prototype Accelerator (EPA) as a function of the average power delivered to the structure; before corrective action. Data from 4 magnetic probes, one in each tank. Field level controlled at probe in Tank 3.

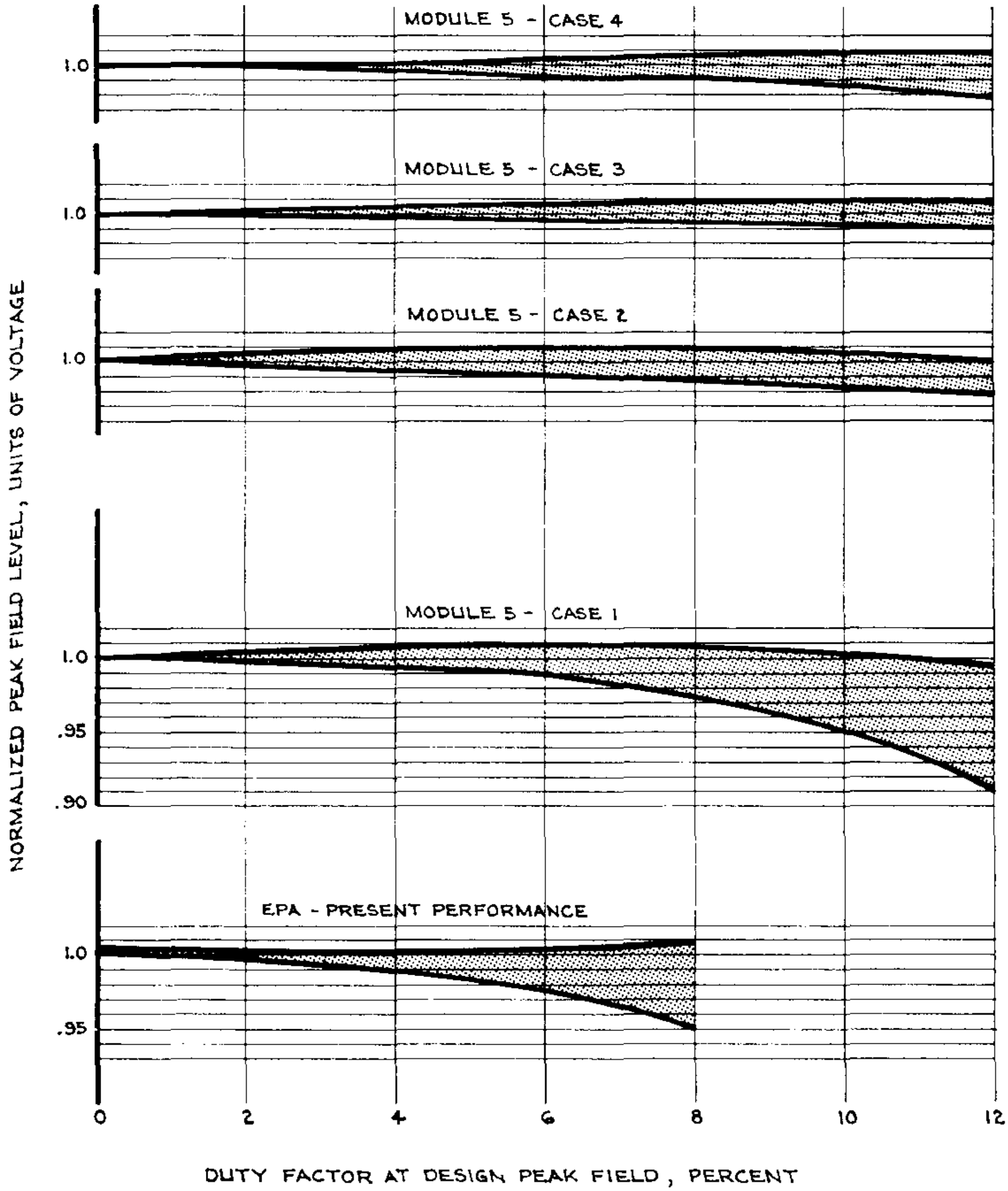

Fig. 13 Distribution of rf peak fields in EPA after corrective action and in Module 5 of the LAMPF accelerator as a function of average power and the stopband of the structure. Composites of H and E-probe data. Fields are normalized to readings taken at less than 1% duty factor. Each case corresponds to a different structure stopband, as shown in Fig. 14.

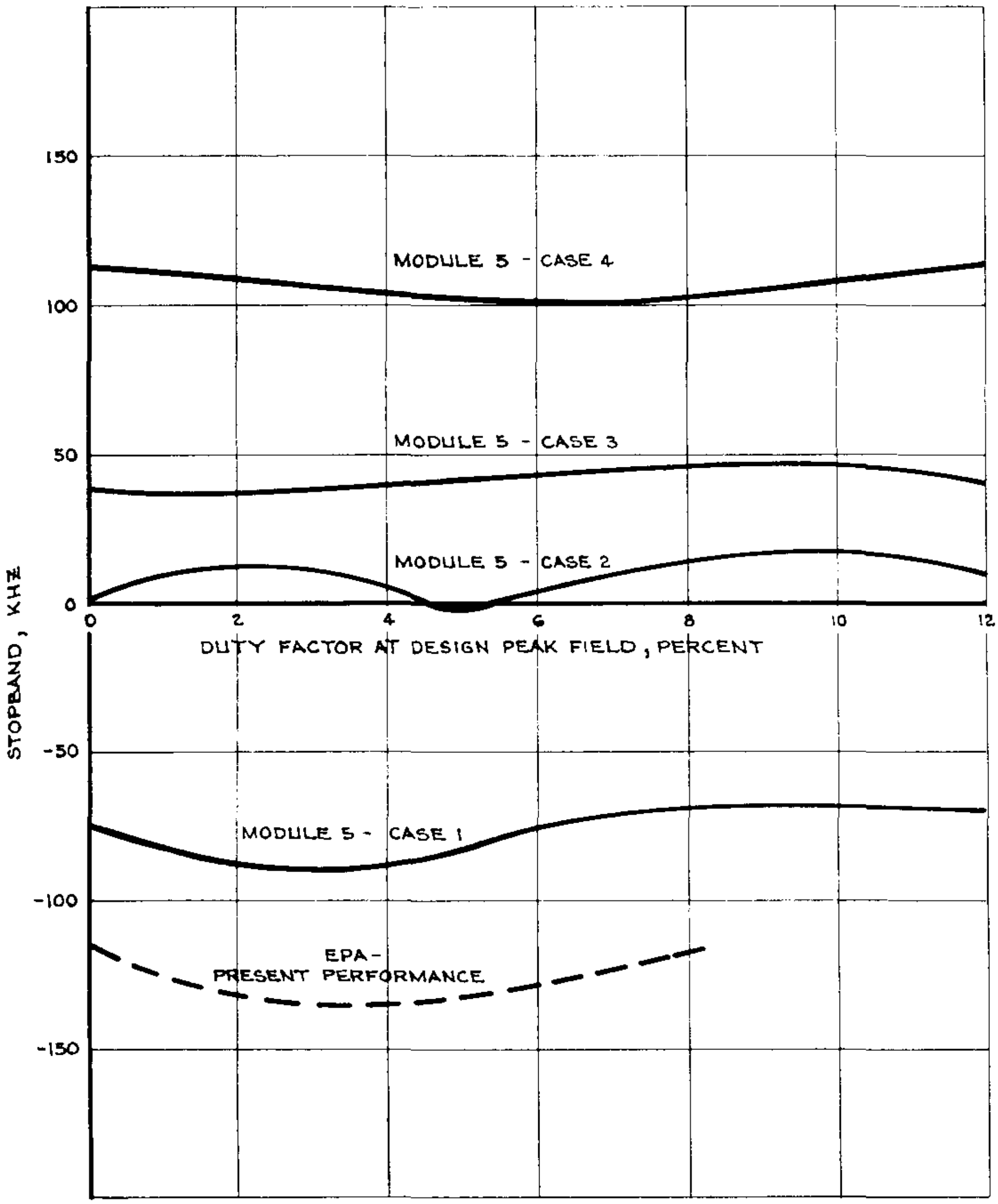

Fig. 14 Variation of stopband in the EPA and in Module 5 as a function of average power.

MODULE 5 SYSTEM DRIFT TEST

DURATION: 100 HOURS

TANK	PROBE	MAXIMUM DRIFT	DIRECTION - ROOM TEMPERATURE DECREASING
1	H1	0.7% (FIELD)	DOWN
2	H2	0.7%	DOWN
3	H3	< 0.2% (CONTROLLED)	-
4	H4	0.75%	UP

MODULE 5 PEAK FIELD VS. AVERAGE POWER TEST

TANK	PROBE	CHANGE IN PEAK FIELD - 2.4% - 12% DUTY FACTOR	DIRECTION OF CHANGE - 2.4% - 12% DUTY FACTOR
1	E1	(BAD PROBE)	-
	H1	0.6% (FIELD)	UP
	E2	0.75%	UP
2	E3	0.25%	DOWN
	H2	0.85%	UP
	E4	0.27%	DOWN
3	E5	0.25%	BALANCED
	H3	< 0.2% (CONTROLLED)	-
	E6	0.4%	DOWN
4	E7	0.3%	DOWN
	H4	0.8%	DOWN
	E8	0.25%	DOWN

Fig. 15 Drift and average power sensitivity of Module 5 fields with stopband opened + 40 kHz by setting the coupling cells high in frequency.

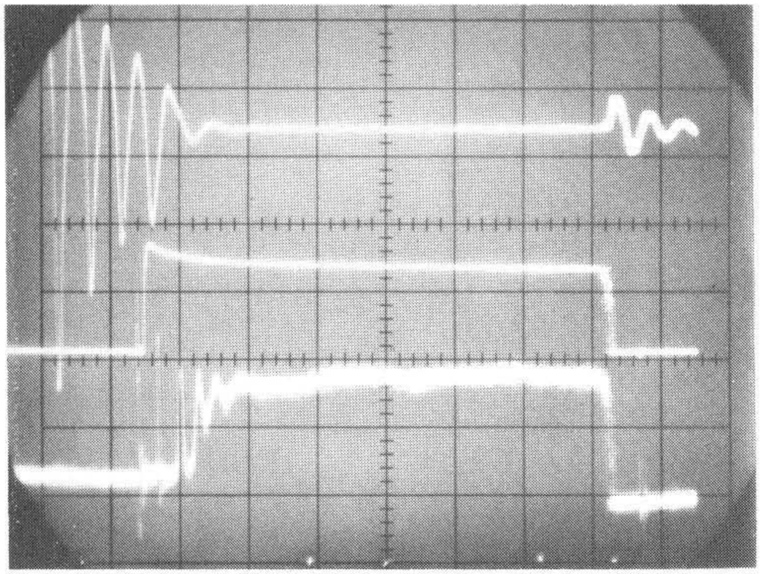

Fig. 16a Amplitude controlled behavior of the EPA while accelerating beam with deliberate field oscillation introduced. Upper trace is an expanded scale showing the top of the cavity field pulse at ~ 10%/cm.
Center Trace: beam current into EPA, 5 mA/cm.
Bottom Trace: beam current through ± 0.25% momentum analyzing system, 1 mA/cm.
Time Scale: 50 μsec/cm.

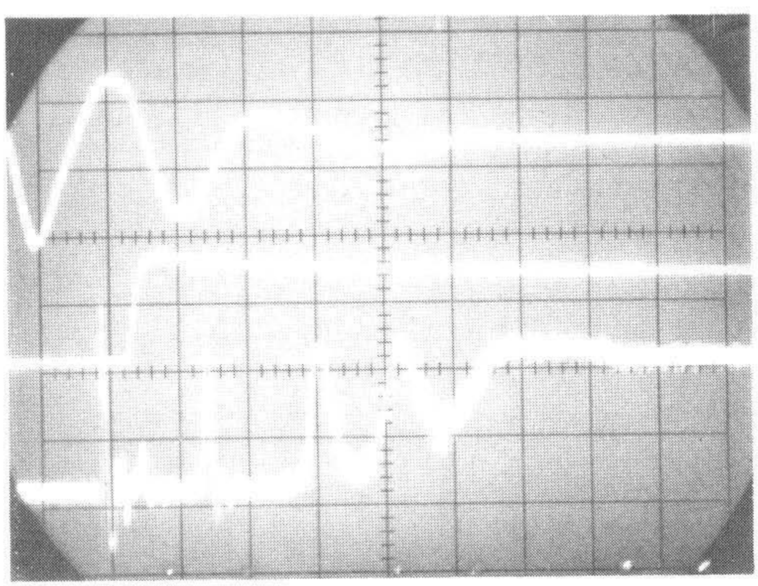

Fig. 16b Same as 16a except time scale is 10 μsec/cm.

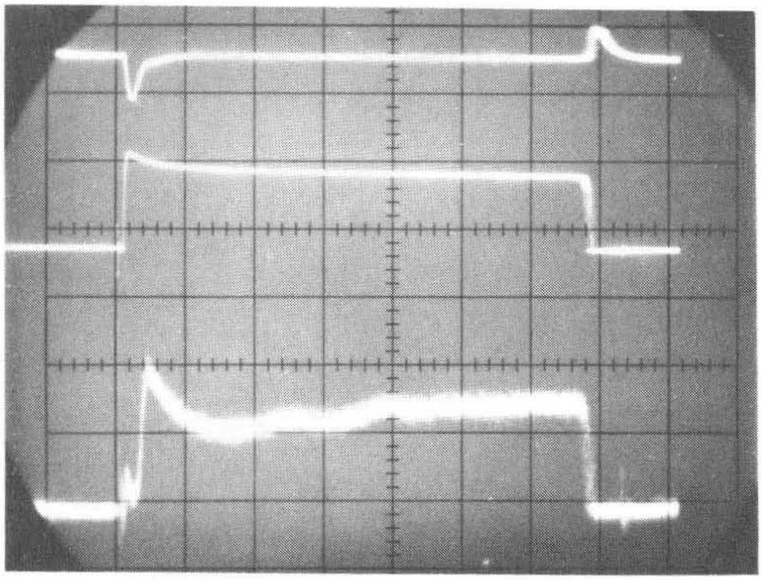

Fig. 17a Amplitude controlled EPA behavior while accelerating beam, with system adjusted for minimum transients. Scales same as Fig. 16a.

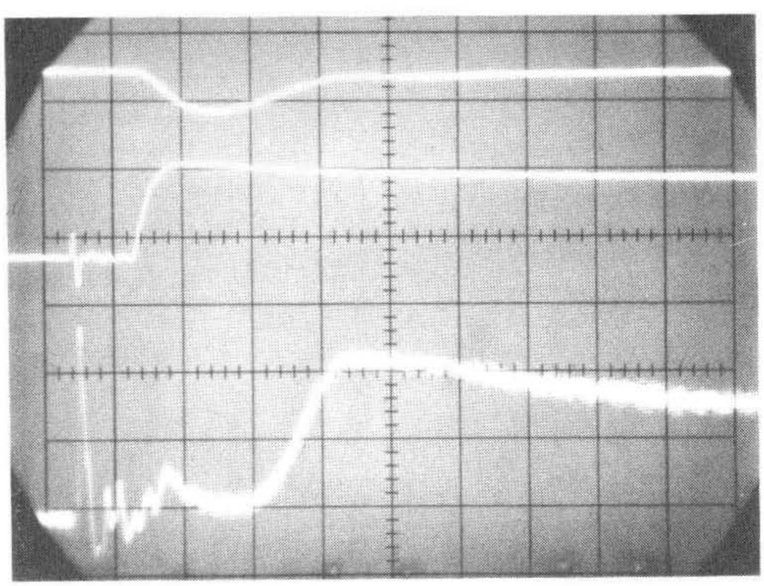

Fig. 17b Same as 17a except time scale is 10 μsec/cm.

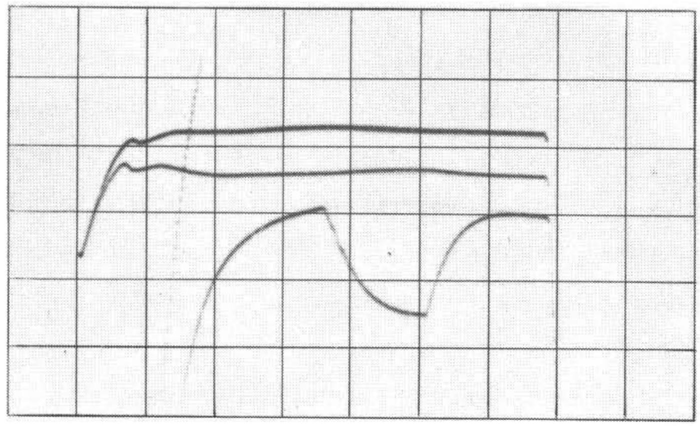

Fig. 18 Tank field behavior in the 201.25 MHz Module 1 of the LAMPF accelerator while accelerating about 2.5 mA of beam with no amplitude control. Top trace shows incident power from amplifier; scale is ~12.5% of design power/cm. Bottom trace shows cavity field at ~1% of design field/cm. Beam loading is clearly evident. The steeply rising line at left is cavity field on the alternate half of the power line cycle. Time scale is 50 μsec/cm.

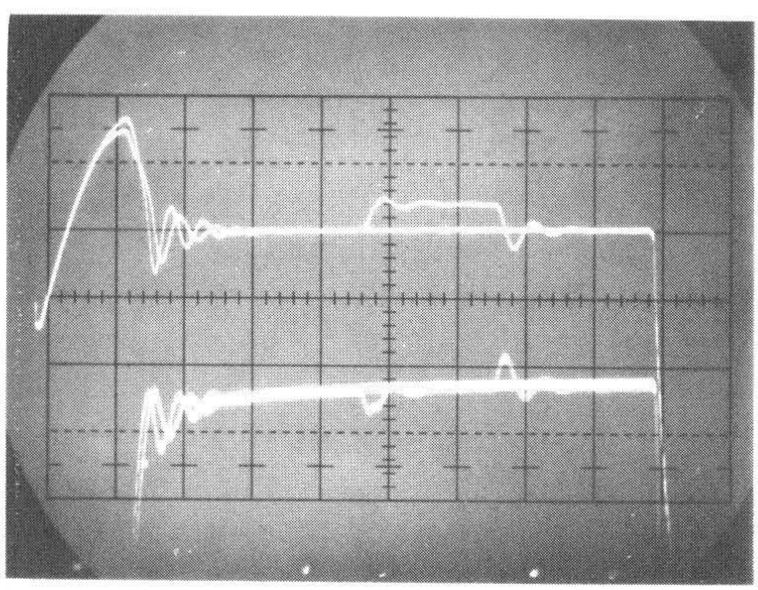

Fig. 19 Amplitude controlled behavior of Module 1 under same conditions as in Fig. 18 except slightly different pulse lengths. Scales are same as Fig. 18. Top trace shows upper part of incident power from the amplifier, bottom trace shows cavity field. RF pulse repetition rate was 120 pps; beam repetition rate was 15 pps.

DISCUSSION

R. P. Featherstone (Central Engineering): I didn't quite understand the changes in behavior with high-duty cycle that you observed. Are they all thermal effects?

R. A. Jameson (LASL): We don't completely understand what the basic mechanism is. What we have found is an effect at high power that apparently is not completely included in the theory that we use now. We think that there should be an electrical parameter in circuit theory that would explain this effect but we have not yet had time to tie this down.

R. P. Featherstone: But as you observe these phenomena, do you see, as you make a sudden change in duty factor, something that would correspond to a thermal effect?

R. A. Jameson: You can see that, and it's fairly obvious that what happens is due to the thermal effects (expansion), but it is a fundamental problem that's happening. The stop band, for instance, does change somewhat. It will open slightly although not too much. Apparently, if you can get the stop band tuned on the high side, at low power, then you will have good behavior at high power and the stop band won't move very much. We want to continue this investigation so that we understand exactly what this phenomenon is in terms of electrical behavior and structure design.

I want to mention one other thing. We are becoming more and more convinced that we have to be able to measure at high power all of the basic fundamental things that you have said about the structure at low power; for instance, the question of field flatness becomes extremely interesting when you see field walking around as we have seen it walk around when the stop band is open on the low side. I am quite interested to know if the absolute value of the field and also the relative field through the structure are the same at high power. It's a very difficult problem. We would like to do bead pulls at high power. We didn't get quite enough done to have anything definite to say, but we have found a string material, polypropylene which comes in water-ski ropes, that you can put in, and we have run it at peak field in a short model for a period of an hour. It looks feasible to try to string these through the accelerator structure and pull through a bead. We have found a bead design that apparently doesn't dissipate enough power to melt the string, it also stayed in the field for long periods of time. We can't run the duty factor out very far, but that is not necessary. So with that plus this new way of developing instrumentation, we think we can rig up a way to make bead pulls at high power either by measuring the phase shift between the drive to the cavity and the cavity field (and watching that swing back and forth as the bead goes through) or even by letting the whole system, including the big klystron, act as an oscillator. I am going to try that too and see what happens. I see no reason why it isn't feasible.