OPTIMUM GENERATOR CHARACTERISTICS OF RF AMPLIFIERS FOR HEAVILY BEAM-LOADED ACCELERATORS*

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Summary

As the beam loading is increased in a proton linear accelerator, it becomes increasingly more difficult to maintain the design gradient. To avoid excessive beam spill, this gradient must be controlled to a tolerance of ~ ± 1% during the initial transient of beam turn-on and during any subsequent fluctuation in beam loading due to uncontrolled or programmed variations in the amount of beam injected. Since the beam obtains its energy from the field, more power must be supplied by the rf generator when the beam is on. High-power microwave triodes, klystrons, and crossed-field amplifiers are being evaluated as generators to drive the accelerator structure of the LAMPF proton linac. The delivery of power from these tubes to the time-varying load impedance presented by the linac is a complicated interplay among such factors as the internal design of the tube's active region and output coupling section, the length of line between the generator and the load, and the coupling to the load. An optimum system design can enable the generator to provide a degree of self-compensation providing a programmed amount of power to match the changing load impedance. This eases the problem of providing fine control to the 1% tolerance by a closed-loop system. Experimental studies have been conducted on each tube type.

Description of Experiment and Results

A series of measurements were recently made to explore the performance of several types of high-power rf amplifiers as generators driving varying load impedances. This program stemmed from the thought that it might be possible to obtain some degree of inherent compensation for beam loading effects during particle acceleration in an open-loop manner. This would be accomplished by proper adjustment of the coupling from generator to waveguide and from waveguide to load, and of the physical spacing between the generator and the load. A simple example of such a self-compensating system is the case in which it is desired to deliver power to a load proportional to its resistance; automatic compensation is then provided by driving the load with a constant current generator.

The LAMPF performance criteria represent moderately heavy beam loading, viz., the power going into the beam at the 100-MeV point is approximately 21% of that appearing as copper losses in the accelerating structures and is about 45% at the 800-MeV point. As such, the corresponding VSWR's as seen by the generators will range from about 1.14:1 to 1.39:1 when no particle beam is present (assuming the structure is matched at full beam loading). The amplitude control system is required to hold the axial fields to within 1% absolute regardless of the degree of beam loading. Any level of self-compensation would, then, reduce the dynamic range required of the closed-loop amplitude control system.

The three types of high-power rf generators currently being evaluated by LASL as rf sources for the 805-MHz section of the LAMPF accelerator include a triode, a klystron, and a crossed-field amplifier. Measurements were made using each type. The general procedure was to measure the power delivered to the resistive part of the load as the load was varied by means of an E/H tuner such that all phases of various VSWR's, up to a safe limit, were presented to the generator. During the runs, the frequency was held constant at 805 MHz as was the rf drive level. During any given run, the tube voltage was also held constant. The recorded VSWR and the position of the standing-wave minimum were used to determine the impedance of the load as referred to the reference plane. The load impedance was then plotted on a Smith chart with the corresponding power delivered to the resistive component of the load. Constant power output contours were then sketched in. The results, sometimes called Rieke diagrams, formed the basis for evaluating the performance of the generator when driving varying load impedances.

The triode, an RCA A-15191A coaxitron, was run at a 3% duty factor (250-μs pulses at 120 pps) at plate voltages from ~ 15-35 kV; at the latter voltage, somewhat over 1 MW was delivered to the water load. An arbitrary plane was chosen as the generator reference plane. In the first series of measurements, the impedance was varied completely in phase and in magnitude to VSWR's of ~ 1.5 at six different plate voltages. The results at 17.5 kV and 35 kV are shown in Figs. 1 and 2. The trend is seen toward increasing output power from upper left to lower right on the Smith chart with no evidence of a maximum for either parameter. The shapes and slopes for the six plate voltages were very similar so a search was made for a maximum power output with a 17.5-kV plate voltage, where a high VSWR is less dangerous to the tube. The results are given in Fig. 3. Maximum power was delivered to the resistive component of the load at a VSWR of ~ 4.1:1.

The klystron, an EIMAC 4KM70LH, was operated at a 6% duty factor (500-μs pulses at 120 pps) at beam voltages from 15-30 kV; at the latter, approximately 100 kW was delivered to the water load. The detuned short plane of the klystron output cavity was chosen as the generator reference plane.

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The impedance was varied completely in phase and in varying magnitudes at four different beam voltages. The results are given in Figs. 4-7. Power levels are relative, scaled to the maximum power observed at 30 kV. The klystron output match is seen to be a function of the beam voltage, coming to the best match at the 30-kV design operating voltage.

The crossed-field amplifier, a series arrangement of two Raytheon QKS-1461 Amplitrons, was operated at a 2.5% duty factor (210-μs pulses at 120 pps) at an anode potential of ~ 31 kV. A maximum power output of ~ 380 kW was delivered to the water load. An isolator was employed in the drive arm. During the experimental runs, the second tube of the series arrangement exhibited a strong tendency to oscillate over a rather substantial area of mismatch combinations. It was later found that the cathode of this second tube was severely contaminated and was probably responsible for the observed instability. Rather than present these data, performance data[1] on a QK520 Amplitron are shown in Fig. 8. Qualitatively these data are very similar to the data from the series arrangement.

All three tube types exhibit some degree of self-compensation. At the high-energy (800 MeV) point, the triode could be expected to provide nearly 60% of self-compensation in programming the power from the unloaded to full beam configuration; the klystron nearly 50%; and the CFA ~ 30%. The degree of self-compensation of the triode drops to about 40% at the low-energy (100 MeV) point; the klystron to 30%; and the CFA to 20%. These figures were obtained by selecting the radii of maximum slope from the applicable Rieke diagrams.

None of the tubes used in the described experiments are directly applicable to an actual system. The particular triode used was badly internally matched. Neither the klystron nor the CFA used have the output capability required by the LAMPF criteria. Thus, the results are meaningful only in that all three types of tubes do display a load/generator interaction such as to offer some degree of inherent compensation for beam loading effects during particle acceleration in an open-loop manner. While decidedly not a panacea for the amplitude control criteria, it nonetheless offers an inexpensive mechanism for easing the closed-loop dynamic range requirement. In addition, the method described is a powerful tool for understanding the operation of tubes of this class under full output conditions.

Reference

1. W. Brown, "Description and Operating Characteristics of the Platinotron--A New Microwave Tube Device," Proc. IRE, v. 45, Sept., 1957, pp. 1209-1222.

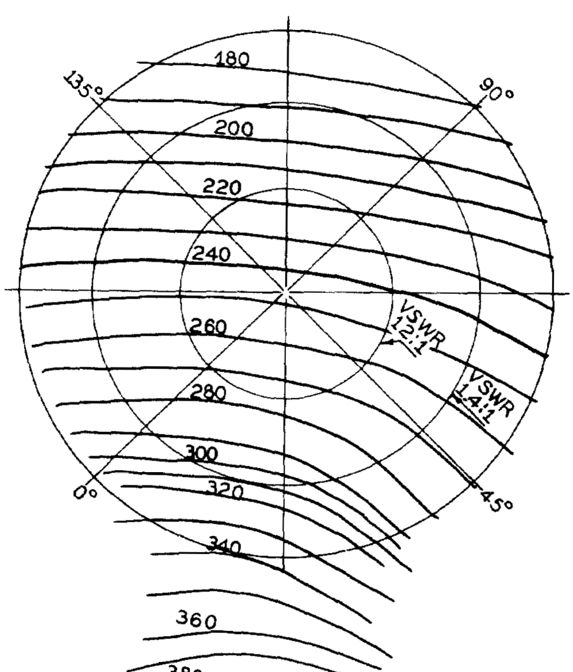

Fig. 1. Coaxitron power output as a function of load impedance at a plate voltage of 17.5 kV. Power output in kW.

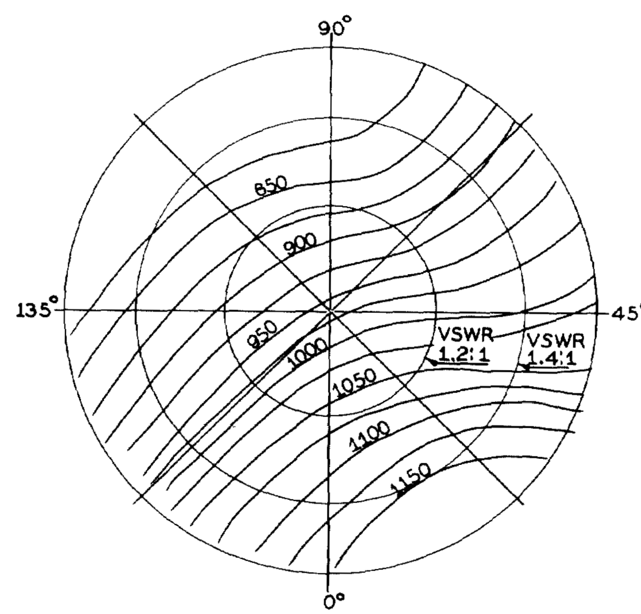

Fig. 2. Coaxitron power output as a function of load impedance at a plate voltage of 35 kV. Power output in kW.

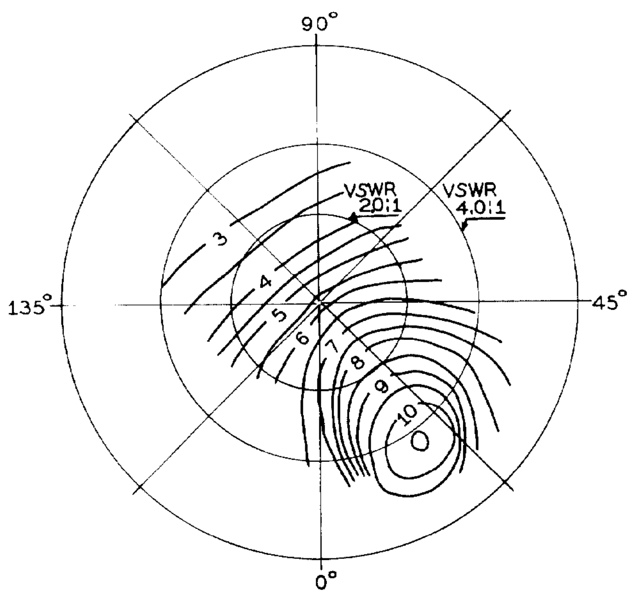

Fig. 3. Coaxitron power output as a function of load impedance at a plate voltage of 17.5 kV. Power outputs are relative levels.

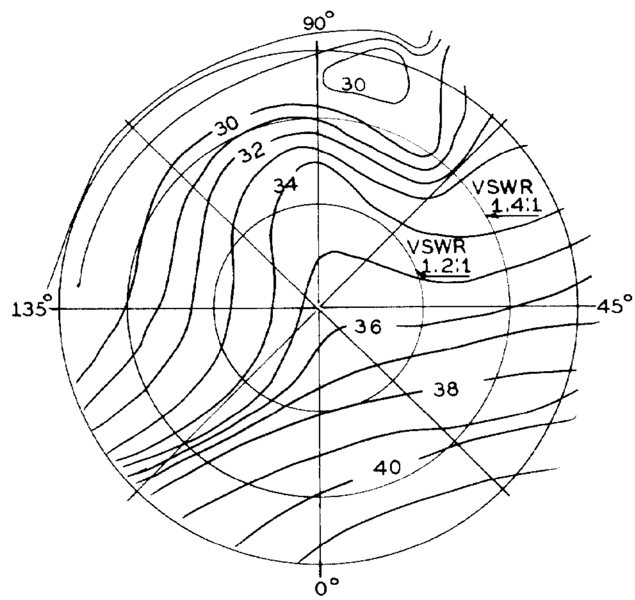

Fig. 4. Klystron power output as a function of load impedance at 15-kV beam voltage. Power levels normalized to maximum output at 30 kV.

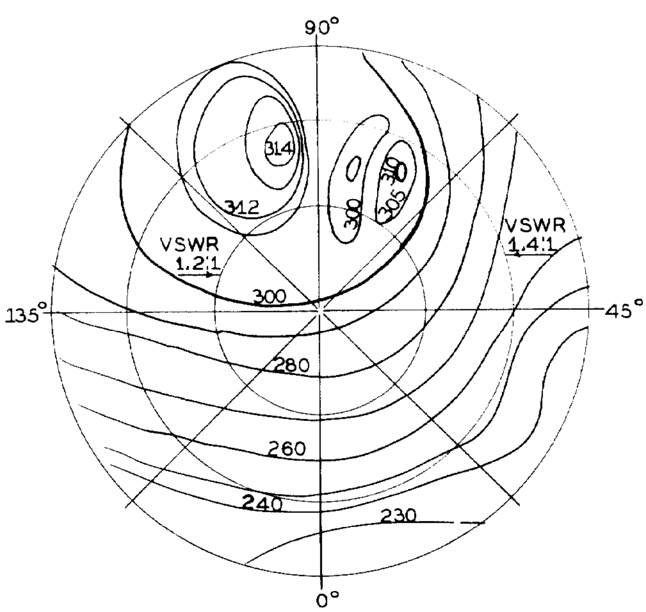

Fig. 5. Klystron power output as a function of load impedance at 20-kV beam voltage. Power levels normalized to maximum output at 30 kV.

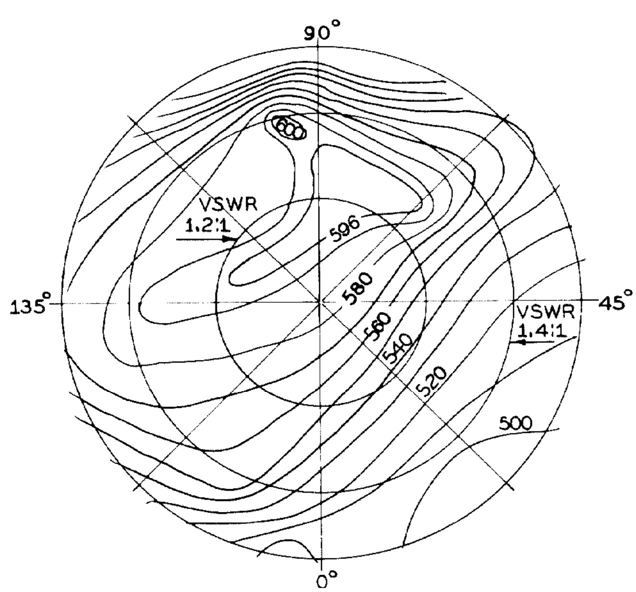

Fig. 6. Klystron power output as a function of load impedance at 25-kV beam voltage. Power levels normalized to maximum output at 30 kV.

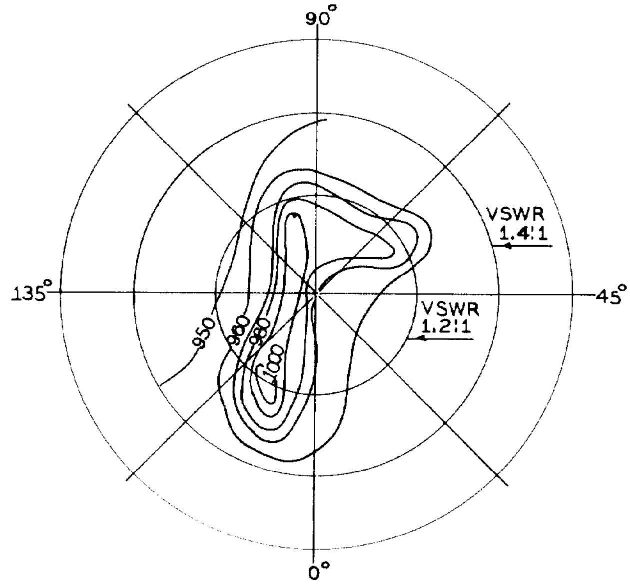

Fig. 7. Klystron power output as a function of load impedance at 30-kV beam voltage. Power levels normalized to maximum output at this voltage.

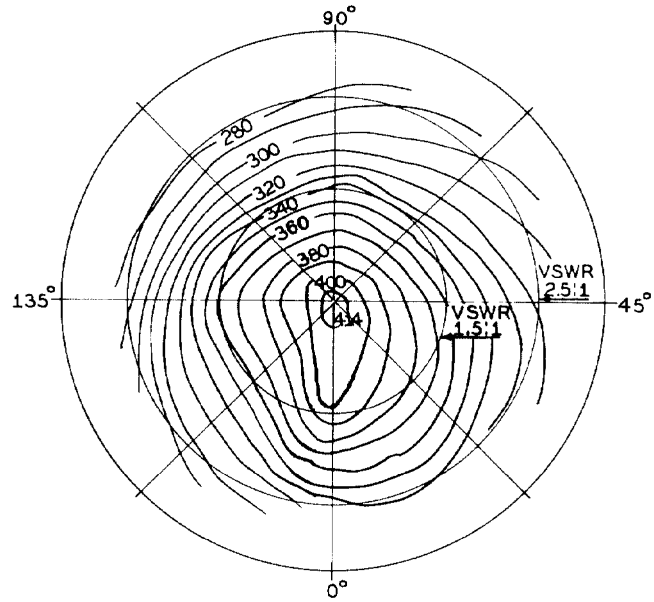

Fig. 8. Amplitron power output as a function of load impedance. Power output in kW.