A NEW RF POWER SYSTEM FOR ACCELERATORS

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A novel RF power amplifier using multiple parallel Planar triodes has been developed. This unique amplifier provides a low-cost, reliable source of pulsed RF power to 500kw peak at frequencies from 200 to 850 MHz with little change in efficiency and power. Pulse width up to 1 ms and duty factor to 5% are feasible with this design. The power system is designed for operation wi . a high Q resonant load. Circuits for controlling the phase and amplitude of the load RF fields are built in. The design parameters are described and performance data are presented.

1. Introduction

A linear accelerator is far from an ideal load for an rf amplifier. First, it is a high Q resonant circuit which presents a poor impedance match to the amplifier during the cavity fill time after the rf pulse is turned on. And, it couples rf power back to the amplifier after the rf pulse is turned off. Second, because of the high electric field level in the accelerator cavity, it is inevitable that the load impedance changes abruptly when the cavity breaks down during the high voltage conditioning process. Third, in modern accelerators where the beam absorbs a significant fraction of the total rf power, both the resistive and reactive components of the load impedance change with beam current. Good performance of the accelerator requires that the amplitude and phase of the rf fields in the cavity be maintained accurately during the beam pulse.

It is not sufficient to specify an amplifier performance based on stand-alone operation. The rf amplifier output circuit, the transmission line, and the accelerator cavity must be designed as a system whose function is to most efficiently transform electron beam energy into ion beam energy. The amplifier must be able to handle the turn-on/off and breakdown transients without adverse effects. And, the amplitude and phase control systems must take into account the presence of a high Q resonant cavity in the control loops.

A key factor in making rf linear ion accelerators practical for industrial and medical applications is the availability of a compact, reliable, and inexpensive rf power source. Typical rf requirements for commercial accelerator applications are: frequency 425 MHz, pulse width 100 usec, duty factor 1%, and power level 240 kW. A power level of 240 kW per rf unit is convenient for both RFQ and DTL applications. One rf power unit suffices for the RFQ, including beam power, while three units would be required for a typical DTL. The DTL itself would serve as the power combiner. Each amplifier would be connected to the DTL through the same size drive loop and transmission line as used for the RFQ. This approach is more cost effective for fabrication and maintenance than using a completely different rf power system to provide 720 kW to the DTL.

2. Accelerator RF Power Systems

Amplifier types considered for this application are designated by the type of active device at the high power rf output stage: solid state, klystron, klystrode, crossed-field tube, single gridded tube, and parallel planar triode array. Table I summarizes the relative merits of these types of rf power systems for the typical commercial application. Obviously the judgment indicated in the table is subjective. Different requirements, such as cw operation, space flight capability, or much higher frequency operation, would alter the evaluation.

For the AccSys line of commercial accelerators, the parallel planar triode array using Varian/Eimac 8941's, was found to be the most cost effective approach to providing rf power. The same tubes used in the power amplifier are used in the intermediate power amplifiers (IPAs). The quantity of identical tubes used in the system (15) leads to reduced initial tube cost because quantity discounts and reduces the cost of the spare tube inventory for maintenance. The tubes used are also more readily available than types capable of providing the same power level in one envelope. Recent development of the parallel planar triode array began at Los Alamos in 1985[1].

Figure 1 is a block diagram of the rf power system for the AccSys model PL-2 2 MeV proton RFQ accelerator. A high level modulator controls the rf amplitude in the accelerator cavity dynamically, through a feedback system. In addition to the amplitude control feature, the rf power system has provision for phase-locked frequency control of either the rf source through a frequency modulation input on the rf oscillator or by a stepping-motor driven tuner on the accelerator cavity. If required, because there is more than one accelerator cavity being used in an accelerator system, the cavity phase can be controlled using a fast phase modulator in the low level rf system.

Table I

Relative Merits of Various RF Power Systems

for RF Linear Ion Accelerator Applications

Type	Suitability to Application	Power Supply Requirements	"Fail Soft" Capability	Size	Efficiency	Cost	Overall Evaluation
Solid State	+	+	+	+	0	--	-
Klystron	0	-	-	-	0	-	-
Klystrode	0	-	-	0	+	-	-
Crossed-Field Device	--	-	-	+	0	+	-
Hi Power Gridded Tube	0	0	-	+	-	0	0
Parallel Planar Triode Array	+	0	+	+	+	+	+

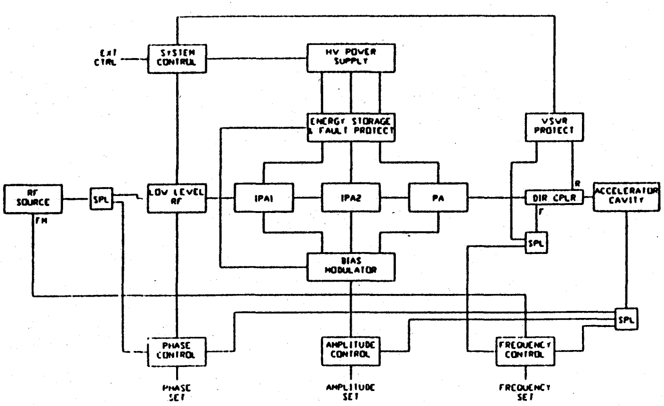

Figure 1.

Block diagram of a 240 kW rf power system for accelerator applications.

3. Features of the Power Amplifier

AccSys Technology has developed a novel high power rf amplifier using a parallel array of planar triodes. The amplifier is the heart of a 425 MHz rf power system that has been designed especially for linear accelerator applications. This rf power system is being built by AccSys for use with its commercial radio frequency quadrupole (RFQ) accelerators and drift-tube linacs (DTL). The power amplifier is a parallel planar triode array consisting of 12 Varian/Eimac type 8941 tubes operating cathode driven (i.e. grounded grid). The effective rf circuit for each tube is shown in Fig. 2. Each tube has an individual set of components (coupling capacitors, rf chokes, etc.) except that they all share one cathode cavity and one anode cavity. Both the cathode and anode cavities are low impedance TEM mode coaxial resonators operating as shortened quarter wavelength lines. Impedance matching is accomplished by the cavity geometry and the choice of components in the rf circuit. Figure 3 is a schematic representation of the rf circuit of the 12 tube amplifier.

Two features of the amplifier make possible satisfactory operation with so many tubes in parallel. The first is that the anode and cathode cavities are so short that the nearest interfering modes are much higher in frequency. This makes it easy to achieve a uniform distribution of rf voltage to the anodes and cathodes. The second important feature is the separate capacitive coupling to each tube, making it possible to bias each tube independently. By adjusting the bias for each tube it is possible to balance the power output from each tube without selecting matched sets of tubes by compensating for variations from tube to tube. This function is accomplished automatically by the bias circuit, as described below. Supplying the anode voltage separately to each tube makes it possible to use individual energy storage capacitors and current limiting resistors for each tube. By this technique the fault energy dissipated in a tube due to an internal arc can be limited to a level that will not damage the tube. If twelve tubes were operated with one energy storage capacitor it would have to be 12 times larger than the individual capacitors for the same anode voltage droop. And, the current limiting resistor would have to be one twelfth the value for individual resistors for the same anode voltage drop. An arc in one tube would discharge all of the energy storage for the

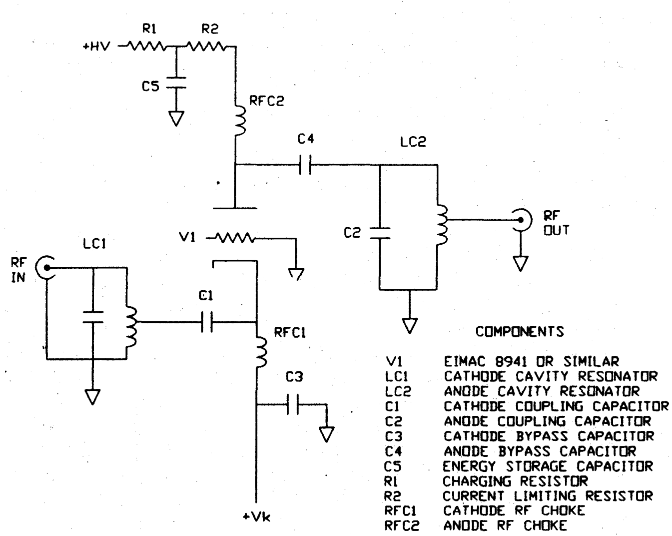

Figure 2.

Effective electrical circuit for one tube of the parallel planar triode array.

Table III

Calculated Average 8941 Performance at 1% Duty Factor

Parameter	Value	Rating
Anode Supply Voltage	8500 V	16 kV*
Anode Current	39 mA	
Anode Input Power	328 W	
Anode Dissipation	135 W	750 W
RMS Cathode Current	510 mA	600 mA
Grid Dissipation	0.9 W	2 W

* Maximum peak anode voltage

reduced cathode current. Because reducing the cathode current increases the input impedance at the cathode, it is necessary to reduce the drive level somewhat as the cathode current is reduced. This is accomplished by using a similar bias circuit on the preceding amplifier stage.

The bandwidth of the amplitude control input is high enough that it is feasible to use the bias circuit in an feedback system to control the rf power output during the pulse. If the feedback signal is derived from a diode detector sampling the accelerator cavity field, the control circuit can regulate the cavity field level.

The automatic frequency control (AFC) system is a phase-locked loop. The phase of the cavity field is held fixed relative to the phase of the forward wave of the rf drive. If the loop is set so that minimum phase error corresponds to the cavity being driven at resonance, the feedback will correct the frequency error as the cavity frequency drifts. If there is only one resonator the tracking may be implemented electronically by using the error signal to control the frequency of the rf source through the frequency modulation input of the oscillator. If there is more than one resonator in the accelerator system the error signal is used to control a stepping motor actuated mechanical tuner to vary the cavity frequency to keep it locked to the fixed frequency of the rf source.

Figure 5 is a photograph of a 4 tube parallel planar triode amplifier rated at 60 kW, 250 usec pulse length, and 2.5% duty factor. The amplifier is opened at the grid plane to show the tubes seated in their sockets in the cathode resonator. Figure 6 shows a 12 tube amplifier (left) and a 4 tube amplifier (right) mounted in their rack cabinets. The units are part of a 480 kW, 100 usec, 1% duty factor system operating at 350 MHz. The output from the 4 tube amplifier is split to drive two 12 tube amplifiers the outputs of which are combined in the accelerator cavity.

4. Fault Protection Features

It is possible to remove a faulty tube from the circuit by disconnecting its anode supply voltage and turning off its heater. Operation can continue at 92% of the maximum power level. Alternatively, because of the reserve emission capability of the tubes, the rf drive level and bias can be adjusted to

Figure 5.

Interior view of a 4 tube, 60 kW paralle planar triode amplifier.

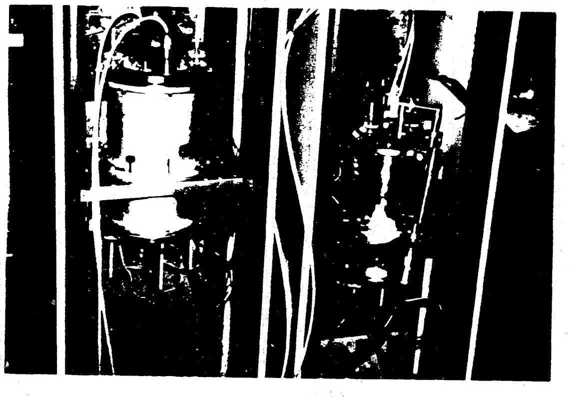

Figure 6.

Rear view of a 480 kW, 350 MHz rf system showing one 4 tube, 60 kW unit (on the right) and one 12 tube, 240 kW unit (on the left).

obtain full power output with fewer than 12 tubes, at the expense of tube lifetime. If the tubes are not otherwise abused, the tube lifetime will only be reduced in inverse proportion to the increase in cathode current.

5. Conclusion

The parallel planar triode array is an economical approach to providing rf power at the 100's of kw level for accelerators in the upper VHF and lower UHF frequency range. The oxide coated cathode makes possible high peak power per tube with low heater power and low total tube cost compared to other high power gridded tubes. The small tube size and low heater power results in highly efficient operation at 1-2% duty factor and permits the design of compact systems in th 200-850 MHz frequency range. The multiplicity of tubes reduces the cost of the spare tube inventory and results in a fail-soft system that can continue near normal operation in spite of the failure of a tube.

References

1. Reid, Don W., RF Power Sources for 1990 and Beyond, 1986 Linear Accelerator Conference Proceedings, June 2-6, 1986, SLAC-303, pp. 29-32

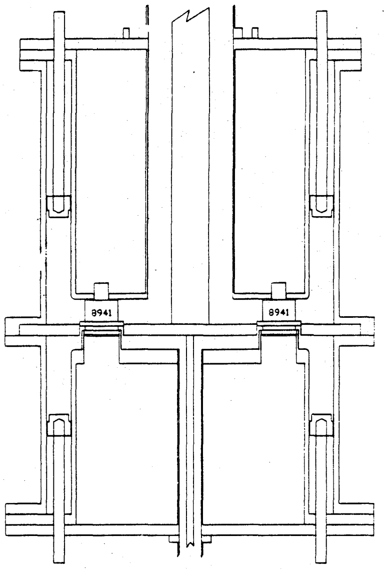

Figure 3.

Cross section of the effective rf cavity circuit for the parallel planar triode array.

Table II

8941 Performance Characteristics

Parameter	Calculated	Measured*
Anode Supply Voltage	8500 V	8500 V
Minimum Anode Voltage	27[illegible] V	
Cathode Bias Voltage	118 V	75 V
Maximum Cathode Voltage	-90 V	
Peak Cathode RF Voltage	208 V	
Anode Conduction Angle	160°	
Anode Current	3.91 A	4.2 A
RF Output Power	20.0 kW	20.8 kW
Anode Input Power	32.8 kW	35.7 kW
Anode Dissipation	13.5 kW	
Efficiency	61%	58%
Cathode Current	5.13 A	6.5 A
RF Drive Power	956 W	1600 W
Grid Dissipation	91 W	
Cathode Input Resistance	22.6 ohms	
Power Gain	13.2 dB	11.1 dB

* Average per tube for 12 tube amplifier

amplifier at a much higher current which would be much more likely to damage the tube.

The Varian/Eimac 8941 has several properties which make it a nearly ideal choice for commercial accelerator applications:

1. High peak cathode current capability, 600 mA rms because of a 2 cm^2 cathode area.
2. Low heater power requirement, 16 W.
3. Planar geometry, reduces transmission line effects internal to the tube and yields good efficiency at UHF because of the low electron transit time from cathode to anode.
4. High voltage capability, 15000 V peak combined with high peak current yields 20 kW or more per tube.
5. Compact size, permits parallel operation of many tubes with practical size anode and cathode cavities.

Table II summarizes the operating parameters during the rf pulse of each tube in the parallel array. The first column lists the calculated parameters and the second lists the measured values based on the average per tube for a 12 tube amplifier. Figure 4 is a computer plot of the 8941 constant current curves showing the load line corresponding to the data in table II. Table III lists the average parameter values for 1% duty factor and compares them to the tube maximum ratings.

The individual biasing of the tubes to balance the power provided by each tube is accomplished automatically by using a clamped current source in each cathode. Since the current is supplied by the cathode, the bias circuit is essentially a shunt regulator. When no rf drive is applied the current source is off and the bias is clamped to a value well beyond cutoff for the tube. When rf drive is applied the current source sets the bias to whatever value is required to obtain the desired cathode current. If the desired cathode current cannot be obtained the bias is clamped to a minimum value slightly beyond cutoff.

During normal operation no tube will exceed the desired cathode current. Any tube with insufficient emission to reach the desired cathode current will continue to operate, but at reduced output, enhancing the "fail-soft" performance of the system. Experimentally it has been determined that this biasing scheme balances the power supplied by each tube within ± 10%.

Each cathode bias circuit is controlled by an input voltage that sets the regulated current to any level between 0 and 10 A. By connecting these inputs to a common input a means is readily provided for varying the amplifier power level. The power output is reduced by setting the bias circuits for

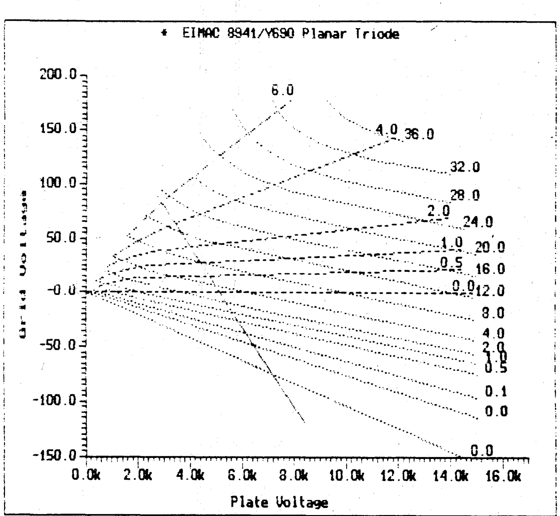

Figure 4.

Constant current curves for the 8941 with typical load line for 20 kW power level (per tube).