A PARALLEL PLANAR TRIODE ARRAY HIGH POWER RF SYSTEM FOR ACCELERATOR APPLICATIONS

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Introduction

A linear accelerator is far from an ideal load for an rf amplifier. It is a high Q resonant cavity which initially appears as a short circuit when the rf is turned on and is a source of rf energy as the cavity fields decay after turn-off. Abrupt changes in the cavity impedance occur when the cavity breaks down during conditioning and, to a lesser extent, when the beam is turned on. Good performance of the accelerator requires that the amplitude and phase be maintained accurately during the rf pulse.

It is not enough to specify amplifier performance based on operation with a resistive load. The rf amplifier output circuit, the transmission line, and the accelerator cavity should be designed as a system whose function is to most efficiently transform the tube electron beam energy into accelerated ion or electron beam energy. The amplifier must be able to handle the turn-on/off and breakdown transients without adverse effects. 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. For the AccSys line of commercial accelerators, a parallel planar triode array (PPTA) amplifier using Varian/Eimac YU-141's proved to be a cost-effective approach to providing rf power with the features needed for accelerator applications. Typical rf requirements for these applications are: frequency 425 MHz, power level 240 kW, pulse width 100 usec, duty factor 1%, amplitude control, ±0.5% phase control ±0.5°, and frequency control ±0.5 kHz.

Parallel Planar Triode Amplifiers

The concept of paralleling many planar triodes for a UHF amplifier is not a new idea. In 1949 Don Preist of Eitel-McCullough (now Varian/Eimac) reported on a 500 watt CW UHF amplifier that he built and tested using 14 2C39's in an annular cavity.[1] More recently in 1985, Bill Hoffert of Los Alamos National Laboratory developed a 106 kW, 425 MHz amplifier using 12 Machlett 8935's.[2] Hoffert also built two 85 kW amplifiers utilizing 8 Eimac 8941's for ground-based testing of the BEAR RFQ accelerator.[3]

There are several obstacles that must be overcome to achieve satisfactory high power UHF operation of a large number of tubes in parallel. To insure equal power from each tube, both the anode and cathode resonators must be symmetrical with no spurious resonances that could develop unequal rf potentials at the tubes. The input circuit must match the drive line to a cathode input impedance of a few ohms. The anodes require a load impedance of less than 100 ohms that must be matched to the output transmission line.

AccSys Technology has developed a novel amplifier that overcomes these problems in a straightforward way. One version develops 240 kW at 425 MHz from a parallel array of 12 Eimac YU-141's (a coaxial-based version of the 8941). A similar version develops 360 kW using 12 Eimac YU-176's.

The RF Power System

Figure 1 shows the AccSys model 12TW240 rf system using a 12 tube PPTA amplifier rated at 240 kW output at 425 MHz with a 60 usec pulse length and a 0.72% duty factor.

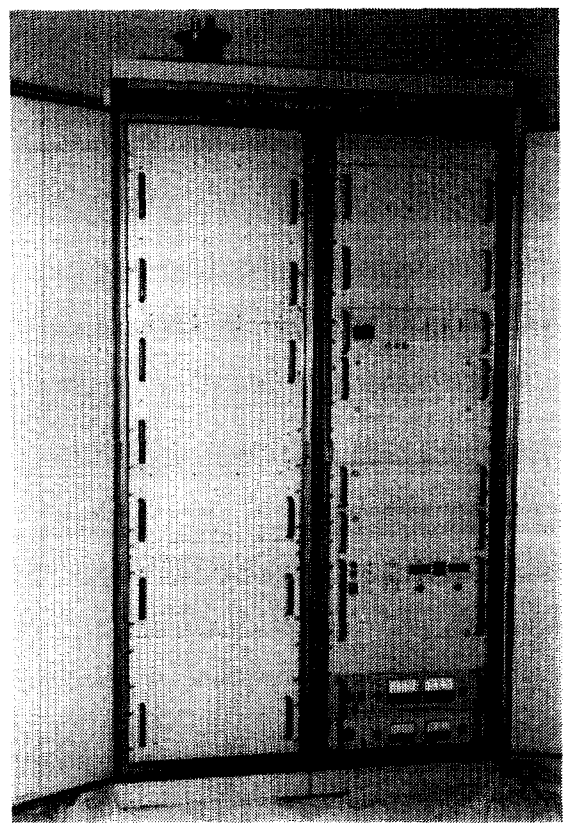

Fig. 1. Model 12TW240/425 RF System

Figure 2 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. For applications using multiple rf systems, the cavity phase can be controlled using a fast phase modulator in the low level rf system.

The AccSys PPTA Amplifier

The PPTA amplifier is the heart of this 425 MHz rf power system that has been designed especially for linear accelerator applica-

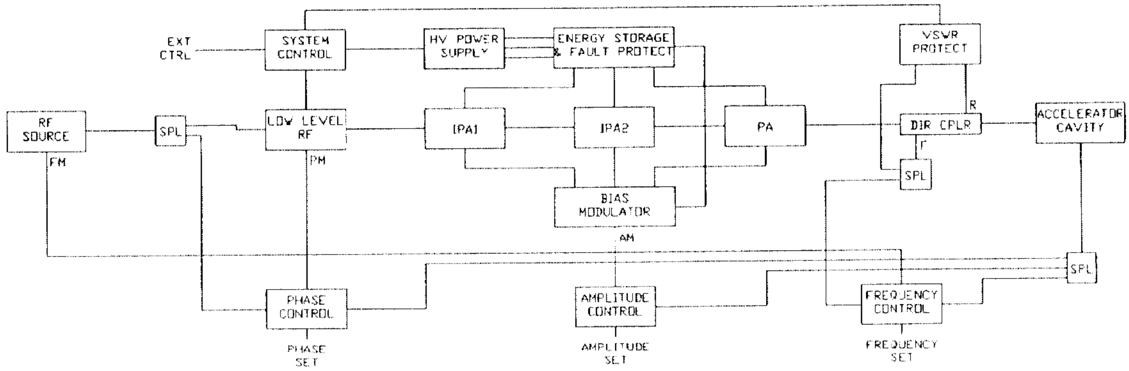

Fig. 2. Accelerator RF System Block Diagram

tions. Figure 3 shows the 12 tube PPTA amplifier cavity extended from the cabinet.

The twelve planar triodes are cathode driven in a grounded grid circuit. 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. The tubes operate in parallel for rf but are individually connected to the anode, cathode and heater power supplies.

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 design and the choice of components in the rf circuit.

Capacitively coupling the tubes to the rf circuit makes it possible to bias each tube independently. A circuit for each tube adjusts the bias to hold the cathode current constant, compensating for variations from tube to tube and balancing the power output from each tube without selecting matched tubes. If an individual tube has weakened with age it will contribute to the output the maximum power available from it.

Supplying the anode voltage separately to each tube with individual energy storage capacitors and series resistors limits the energy dissipated in a tube due to an internal arc to a level that will not damage the tube. It is possible to take a faulty tube out of the circuit without removing it by disconnecting its anode supply voltage and turning off its heater. Operation can continue at a reduced power level. Alternatively, because of the tubes' reserve emission capability, the rf drive level and bias can be adjusted to obtain full power output with fewer than the full complement of tubes, at the expense of reduced tube lifetime.

The same tubes used in the power amplifier are used in the intermediate power amplifiers (IPAs). The quantity of identical tubes used in the 240 kW system (15) leads to lower tube cost and reduces the spare tube inventory needed for maintenance. Furthermore, the small planar triodes used are more readily available than larger tubes capable of providing the same power level in one envelope.

Characteristics of the YU-141

The Varian/Eimac YU-141 has several properties which make it an ideal choice for commercial accelerator applications:

1. High peak cathode current rating - 600 mA rms because of a 2 cm^2 cathode area.
2. Low heater power requirement - 16 W.
3. Planar geometry - no transmission line effects in the tube and good efficiency at UHF because of low transit time.
4. High voltage capability - 15 kV peak, combined with high peak current capability, yields >20 kW rf output per tube.
5. Compact size - parallel operation of many tubes in moderate size cavities.

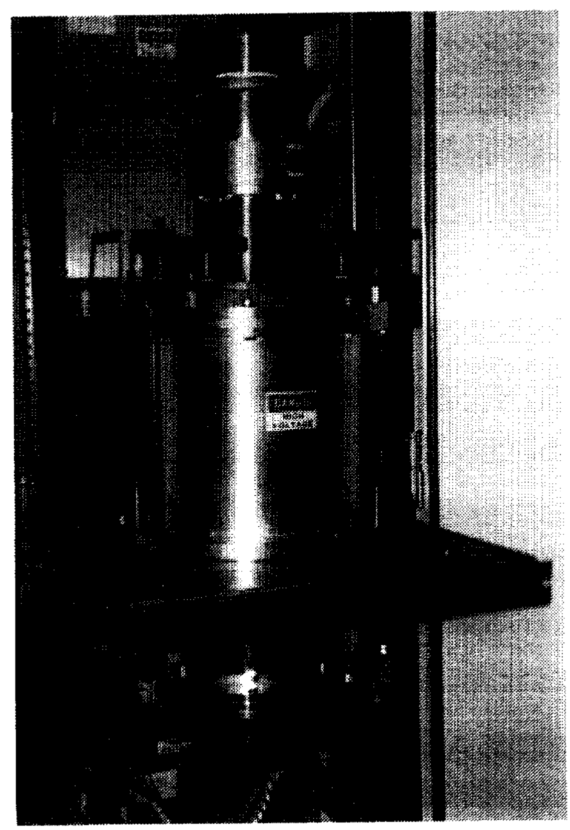

Fig. 3. 12 Tube PPTA Cavity

Table I 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.

Control Circuits

The individual biasing of the tubes to balance the power provided by each tube is

Table I. YU-141 Parameters

Parameter	Calculated	Measured
Anode Supply Voltage	8500 V	8500 V
Minimum Anode Voltage	2700 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	
Input Resistance	22.6 ohms	
Power Gain	13.2 dB	11.1 dB

accomplished automatically by using a clamped shunt regulator current source for each cathode. The current source sets the bias to the value 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 to within ±10%.

The bias circuit is also the modulator used to control the total rf power output. Over a wide range, the rf output amplitude is approximately proportional to the cathode current. Since the cathode input impedance increases with reduced cathode current, the IPA stages must be controlled to avoid overdriving the final power amplifier. This is accomplished by using the same bias circuit on the IPA tubes. Figure 4 shows the cavity field at 240 kW and its response to a 1 dB power demand with the amplitude control circuit enabled. The lower trace shows the timing of the demand signal.

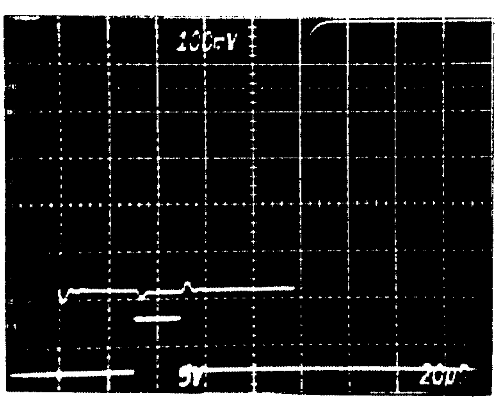

Fig. 4. Cavity Field Level with 1 dB Demand

In accelerator applications, the accelerator cavity field is controlled by a feedback signal derived by comparing a reference voltage to the amplitude from a diode detector sampling the accelerator cavity field.

The automatic frequency control system is a phase-locked loop that holds the phase of the cavity field fixed relative to the phase of the forward wave of the rf drive. Frequency tracking may be implemented by using the error signal to electronically control the rf source frequency or to mechanically control the cavity frequency using a stepping motor actuated tuner.

Extrapolation of Performance

The maximum power available per tube is limited by the RMS cathode current, the grid dissipation, and the anode dissipation. The duty factor can be as high as 2.5% with proper cooling and reduced power output. Over 450 kW output can be achieved at short pulse lengths using the YU-176 tubes. The maximum pulse length is limited by cathode current droop due to depletion of the virtual cathode. The constant-current bias system can compensate for the droop, making lengths up to 1 ms possible in some applications.

The 12 tube amplifier can be tuned from 300 MHz to 550 MHz without modification. With slight design changes, 650 MHz operation can be achieved. A four tube version of the PPTA amplifier has provided 60 kW at 850 MHz. Operation at lower frequencies is limited only by the practicality of the physical dimensions, since the anode and cathode cavities must be lengthened. At lower frequencies, it is possible to parallel even more tubes.

Conclusion

The PPTA amplifier is an economical approach to providing rf power at the 100's of kW level for accelerators in the upper VHF and lower UHF range. The oxide coated cathode makes high peak power per tube possible with low heater power and low total tube cost compared to other high power gridded tubes. The small tube size and low heater power result in highly efficient operation at 1-2% duty factor and permit the design of compact systems in the 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.

Acknowledgments

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