ON THE HORIZON: NEW RF POWER SOURCES FOR LINEAR ACCELERATORS*

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Abstract

In the past, linear accelerators at frequencies below 3 GHz have been driven by klystrons or gridded tubes, with most of the small electron accelerators using conventional magnetrons. During the past few years, there have been several new rf amplifier developments that could be advantageous to the linear accelerator designer. Among these new devices are the cathode-driven crossed-field amplifier, Klystrode, high-power solid-state amplifier, lasertron, multiple-beam klystron, phase-locked magnetron, and a depressed collector for a high-power klystron. All of these devices are being worked on at this time. Each can contribute to a linear accelerator system by supplying better efficiency, lower cost, higher power, or longer life. This paper will review the present status of each device and, where current test data are available, they will be reviewed.

Introduction

In 1924, Ising proposed a method for accelerating particles that used a sequence of drift tubes and high voltage gaps. In 1928, Wideröe described an operating linear accelerator, along the same general lines, which used a high-frequency oscillator alternately connected to the drift tubes and to ground.[1] The first known accelerator that used an rf generator was built by Sloan and Lawrence in 1931 and used a homemade oscillator circuit operating at 20 kW cw at 7 MHz.[1]

In the early 1930s, gridded tubes operating at a few megahertz and at 20 to 100 kW were commercially available. However, the capability for generating large amounts of rf power at frequencies above 100 MHz, which was needed to accelerate electrons and heavier particles, was not available. World War II and the development of radar, which required large amounts of high-frequency, pulsed, rf power, created a windfall for the accelerator designer. The klystron was developed in 1937 by the Varian brothers,[2] and the magnetron underwent dramatic development in the early 1940s. At the same time, significant progress was being made in the ability of gridded vacuum tubes to generate high frequency rf power. After the war, the idea for the Stanford Linear Accelerator was born under W. W. Hansen,[3] and the idea for a proton linear accelerator was started under L. W. Alvarez at the University of California.[4] Both of these projects were possible because of the availability of high-frequency rf power devices that had been developed for radar purposes.

Today the three major devices that are used as rf sources for accelerators are the same as they were in 1950, namely, gridded tubes, klystrons, and magnetrons. However, there have been substantial improvements in reliability, power levels per device, and efficiency. With the advent of the Strategic Defense Initiative[5,6] it appears that another wave of potential device technology is about to break over the accelerator field with such devices as the Klystrode, the cathode-driven crossed-field amplifier, the lasertron and, in the next year, the first accelerator driven completely by solid-state amplifiers. The driving force to use new devices is the same as it has always been: better efficiency, better reliability, better stability, and the choice of widely varying power levels, both cw and pulsed.

Improvements to Conventional Devices

Depressed Collector

Depressing the collector, an electrical circuit scheme to enhance the efficiency of a linear beam rf device, has been used on traveling-wave tubes for several years. Only recently has a multistage depressed collector been designed and placed on a high-power klystron.[7] The sole purpose of adding this complexity to a standard klystron and klystron power supply is to enhance the efficiency.

Figure 1 is a schematic showing two possible power supply schemes to run a high-power klystron with a multistage depressed collector. The collector is constructed as shown in Fig. 2 with alternate collector plates and ceramic electrical isolation rings. The interior configuration of the collector plates is carefully designed using a beam-transport code to approximately equalize the current collection on each collector plate. The schematic shows the use of four separate dc power supplies, although a single power supply with a resistive divider could also be used. The latter scheme is not as efficient because of the leakage through the divider. Using this configuration it is theoretically possible to recover 60% of the energy remaining in the beam after it has passed the output gap. Thus, if the beam to rf output efficiency is 60%, it can be improved to approximately 84% with a properly designed multistage depressed collector.

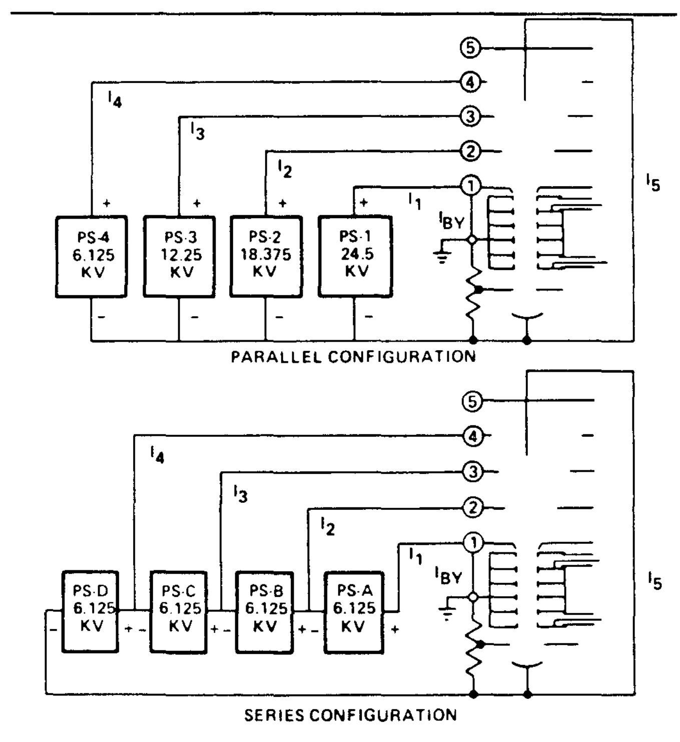

Fig. 1. Multistage depressed-collector schematic.

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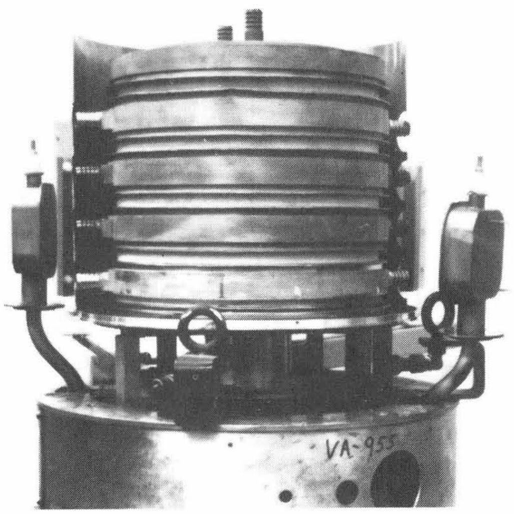


Fig. 2. Depressed-collector construction.

Figure 3 shows a Varian TV klystron, the VKP7990 with a four-stage depressed collector, a 60-kW tube that is mechanically tunable from 470 to 860 MHz. The efficiency of the production tube was approximately 50%. With a multistage depressed collector, the efficiency improved to 70%.

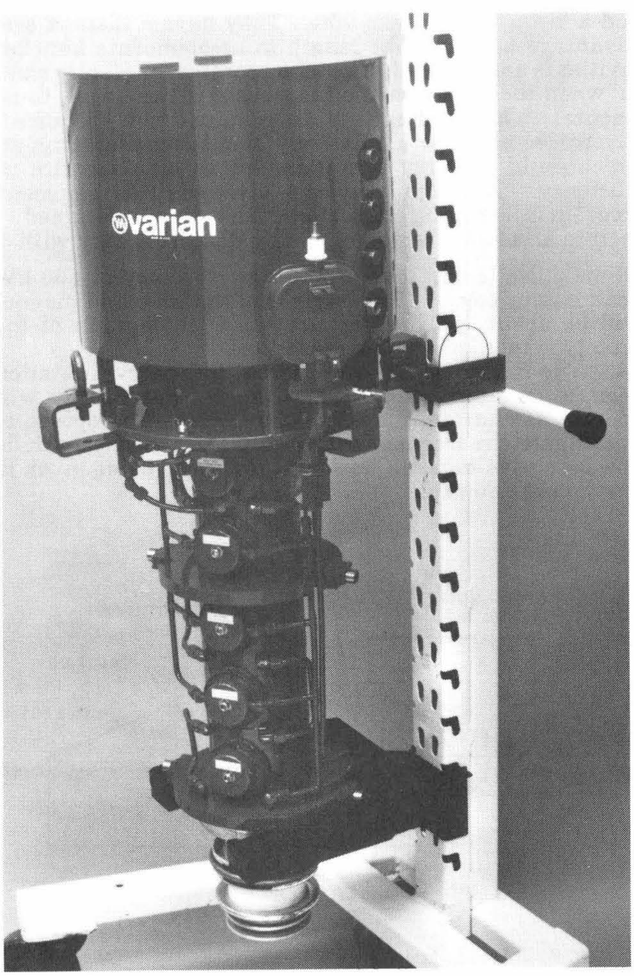


Fig. 3. Varian VKP7990 klystron with depressed collector.

Crossed-Field Amplifier (CFA)

During the late 1950s and early 1960s, considerable work was done to develop techniques to convert a magnetron circuit, which is an oscillator, into an amplifier. One of the earliest devices of this type was the Amplitron, introduced by Raytheon, of Waltham, Massachusetts. These were interesting devices because of their high-power handling capability and relatively high efficiency. However, they had low gain and poor isolation between the rf input and output of the device. This latter problem caused them to be unstable under radically changing load conditions, which is typical for an accelerator.

These problems appear to have been largely overcome with the introduction, again by Raytheon, of the cathode-driven CFA.[8] Figure 4 is a cross section of both a conventional CFA and a cathode-driven CFA. The cathode is actually a cylinderical, slotted antenna that bunches the electrons as they leave the cathode surface as shown in Fig. 5. The result is a tube that has ~ 30 dB of input-to-output isolation, ~ 25 dB of signal gain, and 75 to 80% efficiency at 3.3 GHz. Because of the potential for high specific weight (kg/kW) at good efficiency, Raytheon is conducting a series of tests on their experimental tube at 3.3 GHz. These tests are designed to determine the effects on gain, efficiency, phase stability, and amplitude stability, with the tube operating into a resonant cavity. These tests are scheduled to be completed in the fall of 1988.

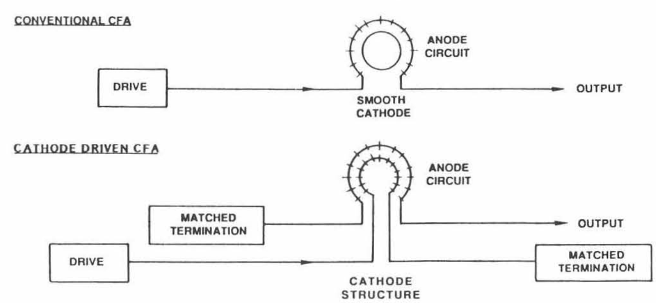


Fig. 4. CFA schematic showing a conventional CFA and a cathode-driven CFA.

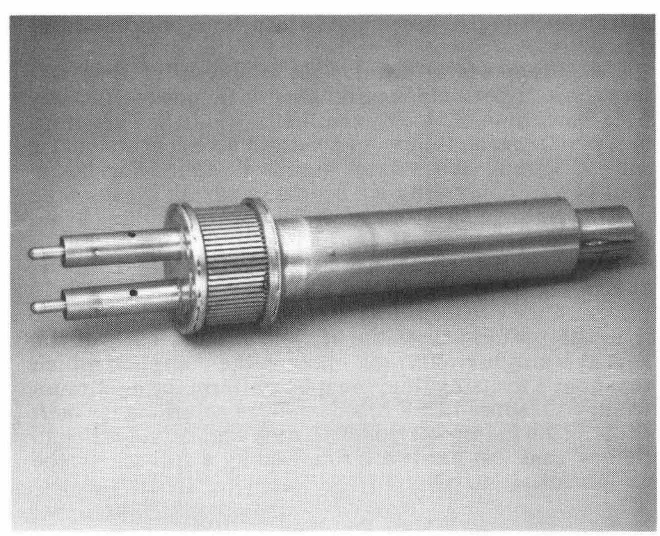


Fig. 5. Cathode structure for a cathode-driven CFA.

Phase-locked Magnetron

Currently, most of the small electron accelerators used for cancer therapy and radiography use a magnetron as the rf source. Because the magnetron is an oscillator, it typically has poor phase stability and, hence, has not been used on machines where good emittance or multiple drives are required.

Personnel at Varian Associates in Beverly, Massachusetts have recently been working on a scheme in which they used a very short (100 to 150 ns) prepulse to lock the phase of a magnetron.[9] They found that the best time to inject the locking pulse was during the voltage rise time. Using a pulser scheme as shown in Fig. 6, they have achieved a pulse-to-pulse phase shift of <1°. They have also measured the phase shift during the pulse and found it heavily dependent on the shape of the modulator pulse but controllable to ~1°.

The attractiveness of magnetrons as rf sources for linear accelerators is obvious. They are an oscillator, hence no drive system is required. They typically operate at over 60% efficiency at UHF- and L-band frequencies. A 2-MW-pulse tube operates at a relatively low voltage, ~ 40 kV. It is small, compact, and relatively inexpensive.

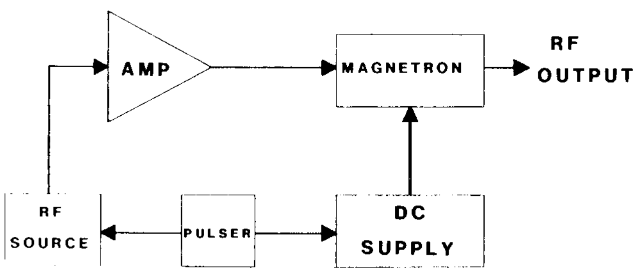


Fig. 6. Phase-locked magnetron block diagram.

Multiple-Beam Klystron

During the 1960s, workers at General Electric did a substantial amount of work on the multiple-beam klystron or MBK.[10] The emphasis of this work was to achieve a klystron with much wider bandwidth than was available at the time.

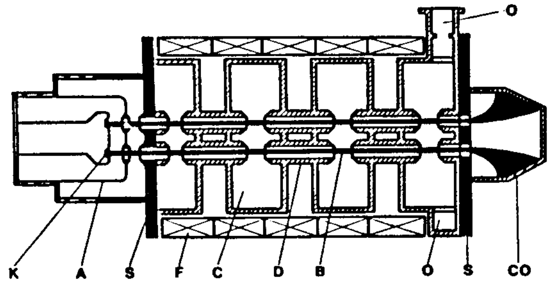
Requirements to develop an rf amplifier that was lightweight, relatively small, and with good efficiency caused Thomson/CSF to re-examine this idea.[11] They have proposed a klystron that would contain six separate beams arranged around the axis of a tube designed for 1-MW output power. Operating six beams in parallel lowers the operating voltage to about 40 kV at an individual beam perveance of about 1 x 10^{-6}, which will, in turn, enhance the efficiency. A schematic cross section of such a tube is shown in Fig. 7.

There are two technical concerns about such a device. One is the uniformity of the rf field around each of the beams in a single cavity; the other is the degree to which the magnetic focusing field must be uniform for maximum efficiency. Thomson/CSF has developed solutions for both of these potential problems. The next logical steps are to build and cold test hardware followed by a full-scale tube development.

New Devices

Klystrode

A schematic of a Klystrode is shown in Fig. 8, a device originally conceived by RCA.[12,13] The tube belongs to a class of devices called emission-gated devices. These



K : MULTI-CATHODE A : MOD.ANODE S : MAGNETIC SHIELDING
F : FOCUSING COIL C : MULTI-GAP CAVITY D : DRIFT TUBE
B : ELEMENTARY BEAM O : OUTPUT CIRCUIT CO : COLLECTOR

Fig. 7. Multiple-beam klystron cross section.

are linear beam devices in which electron bunches are emitted from the cathode, pass through an accelerating voltage as an electron bunch, and the rf energy is extracted in a conventional output cavity. In the case of the Klystrode, an rf field is placed on the grid. When the grid swings positive, an electron bunch is injected into the high-voltage area and the electrons are accelerated. Because the grid is swinging plus and minus at the rf frequency, bunches are emitted at that frequency.

Klystrodes are now in production for use in TV transmitters. They operate at 60 kW cw, have 23-dB gain, and a beam efficiency of 75%. They have a distinct size advantage because tube length to accommodate buncher cavities is not required. The tube operates inherently class C: when the rf is turned off the beam is turned off, thus, elaborate high-voltage pulsers are not required. Klystrodes also use a relatively small focusing magnet, which could probably be eliminated at some sacrifice in efficiency. A high power Klystrode development program is just being completed. The tube was designed to operate at a fixed frequency of 425 MHz, 10% duty with a 10-ms pulse length, and 70% beam efficiency at 500-kW peak output power. Total weight of the tube and magnet will be about 150 lbs. Figure 9 is a photograph of the prototype tube being prepared for test.

The Klystrode has an inherent frequency limitation because of interelectrode capacitance. It certainly will operate satisfactorily up to 1000 MHz. A proposal to investigate the frequency limitations of the Klystrode is now being evaluated. Consideration is also being given to developing a cw tube.

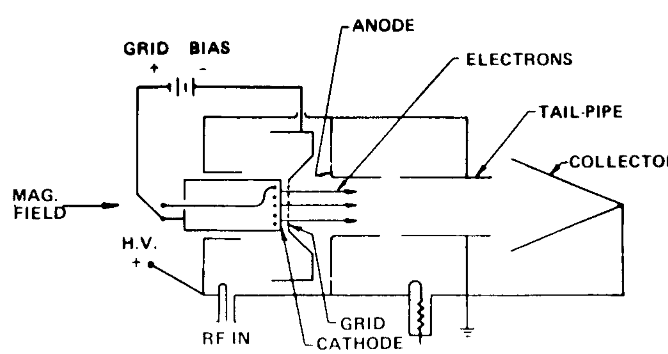


Fig. 8. Klystrode schematic.

Fig. 9. Klystrode ready for test.

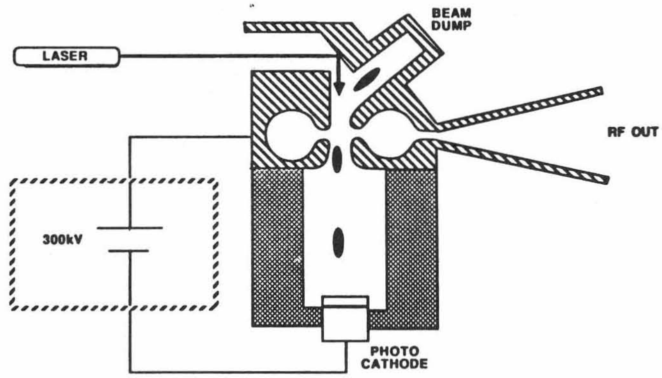


Fig. 10. Lasertron schematic.

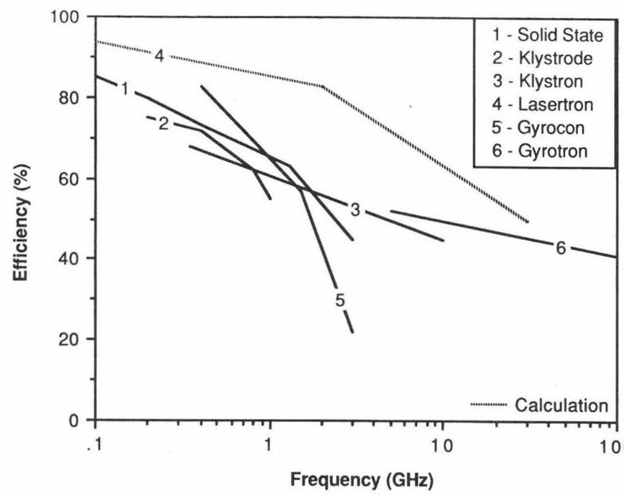


Fig. 11. (Efficiency vs frequency for various rf power devices.

Lasertron

Another emission-gated device is the lasertron. The concept for this device has been patented.[14] Figure 10 is a schematic diagram of the lasertron. Instead of a grid, as in the Klystrode, the lasertron uses a laser light pulse and a photoemissive cathode to generate the electron bunch that is injected through a dc potential. The rest of the device is identical to the Klystrode.

Several investigators have been working on the lasertron for the past few years. These include SLAC,[15] KEK in Japan,[16] the University of Paris South,[17] Texas A&M University[18] and Los Alamos.[14] The maximum frequency at which the device can operate is limited by how fast the laser can be pulsed and by space-charge debunching. This makes the lasertron a possible rf driver for a linear collider. The device also has relatively good beam efficiency compared to other tube types as shown in Fig. 11. It should be pointed out that the lasertron data in Fig. 11 are calculated data, whereas the other devices shown are measured data.

It appears that the major stumbling block to building a reliable, high-power lasertron is the cathode. A long-life photocathode of the size and quantum efficiency required is not yet available. Work is being done by several institutions to solve this problem.

Solid-State Amplifiers

Considerable progress has been made in the last three years in high power, solid-state amplifiers. Individual transistors are now available that will produce 700 peak watts at a few percent duty and a few hundred microsecond pulse length at UHF frequencies. Transistors are also available at 250 W cw in the UHF frequency range. These transistors typically have a collector efficiency of about 75%, which translates to a complete amplifier efficiency of about 55%.

A typical transistor amplifier block diagram is shown in Fig. 12. Although several schemes are available, the basic concept is to have several transistors feeding a combiner to provide the rf output. It is possible to provide circulator protection at various stages of the amplifier to protect the transistors, although tests have been run on several rf transistor types that show them to be extremely rugged. Different combining schemes also provide some protection.

Figure 13 is a photograph of the amplifier that will be used on the BEAR (Beam Experiment Aboard a Rocket) experiment slated for flight in early 1989.[19] This will be the first time that an accelerator has been driven solely by solid-state amplifiers. Each amplifier has ~60-dB gain, 60-kW peak power at a 60-μs pulse length. Because the duty factor is extremely low, the amplifiers are not cooled. Operational time and duty factor allow the amplifiers to simply rise in temperature during their operational life.

A transistor amplifier has several advantages. It runs inherently class C; thus, the amplifier is off when the input rf is turned off. It is also very reliable. When used in a combined configuration, it seldom suffers catastrophic failure. The amplifier's performance tends to slowly degrade. The solid-state amplifier is typically built with about 60 dB of gain, the power supply is low voltage, high current, and all power conditioning is built into the amplifier.

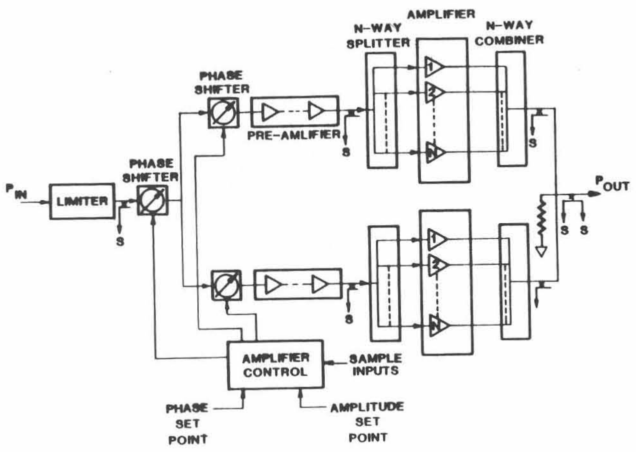


Fig. 12. Solid-state amplifier block diagram.

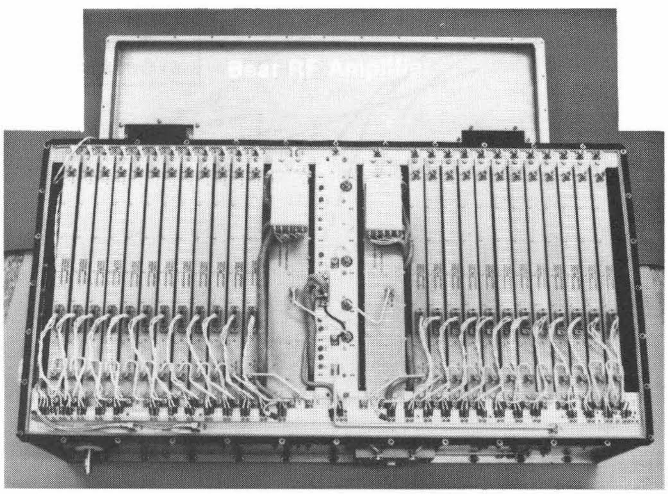


Fig. 13. BEAR rf amplifier.

Conclusion

There are several new rf amplifiers as well as improvements to old rf amplifiers that are of interest to the linear accelerator designer. For the first time, a solid-state amplifier is being used to drive an accelerator. The Klystrode, an emission-gated vacuum tube, has been developed specifically for accelerator applications. On the more distant horizon is the lasertron that several institutions are actively working on. In addition to these new rf amplifiers, several important improvements to existing technology are being actively pursued. A depressed collector can now be used to substantially improve the efficiency of a standard klystron. The multiple-beam klystron is being revisited. The technique of driving the cathode of the CFA has substantially improved its phase stability. A scheme now appears to be in hand to phase lock a standard magnetron. All of these new rf amplifiers and improvements to the old amplifiers are intended to improve the reliability and efficiency while at the same time decreasing the physical size and weight. These factors are of keen interest to the accelerator designer who is upgrading an old machine or who is designing a new machine.

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