# 60 KW UHF, SOLID STATE RF POWER SUPPLY*

Carlton D. Davis
Westinghouse Electric Corporation
Box 1897, M.S. 709
Baltimore, Maryland 21203

Micheal T. Lynch, Don W. Reid
Los Alamos National Laboratory
Los Alamos, NM 87545

## ABSTRACT

Solid state RF amplifiers are now being used as RF power sources for accelerators. Because of the power and duty cycle requirements, solid state amplifiers are particularly suited to driving Radio Frequency Quadrupole accelerators. Los Alamos National Laboratory and Westinghouse Electric Corporation have designed a space flight qualified UHF RF system for a 1 MeV RFQ. The RF system borrows technology from solid state radar transmitter designs. This paper describes the RF system and the unique capabilities of the RF amplifier.

## THE BEAR EXPERIMENT

A Neutral Particle Beam (NPB) accelerator is one of the directed energy technologies which is being developed under the Strategic Defense Initiative Organization (SDIO)[1]. The Beam Experiments Aboard a Rocket (BEAR) project began in 1985 and represents the earliest opportunity for testing an NPB accelerator in space. BEAR is a suborbital rocket flight with a 1-MeV NPB accelerator payload launched from the White Sands Missile Range on an ARIES booster. The payload will spend over 400 sec. above 135 km in altitude during which time the accelerator experiments will take place. Like all space borne experiments, the hardware must meet stringent size, weight, and environmental requirements.

## THE BEAR ACCELERATOR SYSTEM

The Los Alamos National Laboratory is responsible for the design and construction of the linear accelerator and its control systems as well as the beam neutralizer. The Electronic Systems Group of the Westinghouse Electric Corporation designed and built the high-power rf amplifiers under contract with Los Alamos. The BEAR accelerator system block diagram is shown in Fig. 1 consisting of a negative hydrogen ion linear accelerator, associated power and control subsystems, and a neutralizer to convert the negative ions to neutral hydrogen atoms. The linear accelerator contains a negative ion injector, a radio frequency quadrupole (RFQ) accelerator, the rf power system, and a high energy beam transport system (HEBT). The RFQ, which accelerates a 30 keV ion beam from the injector to an output energy of 1 MeV, requires about 100 KW at 425 MHz. This rf power is supplied by the two solid state rf amplifiers which have a minimum power capability of 60 KW. The additional power capability of 20 KW is required for reliability and to provide for sufficient amplitude control margin. The amplifiers must accurately change amplitude and phase in less than a microsecond and withstand high VSWR.

The pertinent specifications for the rf system are shown in Table 1. The average beam current during the 60µs rf pulse will be 26 mA with an output energy of 1 MeV. A block diagram of the rf system is shown in Fig. 2.

*Work performed under the auspices of the U.S. Dept. of Energy and sponsored by the Strategic Defense Initiative Organization.

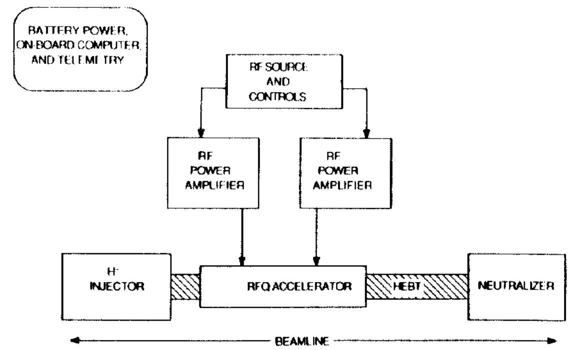


FIGURE 1 BEAR ACCELERATOR SECTION

TABLE 1

BEAR RF SYSTEM SPECIFICATIONS

| | |
|---|---|
| RF Specifications: | |
| Frequency | 425 MHz |
| Pulse Length | 60 µs |
| Repetition rate | 5 Hz |
| Total mission time | 400 s |
| Power required by RFQ | 100 KW |
| Power capability | 120 KW (min) |
| Output beam energy | 1 MeV |
| Control Specifications: | |
| Amplitude control | Preset ± 1% |
| Frequency range | 425 ±0.5 MHz |
| Frequency control | $F_{res.}$ ±20 KHz |
| Environmental Specifications: | |
| Shock | 50 G |
| Vibration | 0.025 $g^2$/Hz |
| Temperature | -65 to 130°F |
| Ambient Pressure | 1 atm, nitrogen |

## THE RF CONTROL SUBSYSTEM

Successful operation of the accelerator, beam transport system, and beam diagnostics requires precise control of the accelerator parameters as described in Table 1. Each rf power amplifier has its own internal phase and amplitude control system. The amplifiers internal loops provide stable operation over the required operating range and also allow dynamic control of the amplifiers in external control loops.

Since each power amplifier has an internal phase control loop, external phase control is required only if there are multiple accelerator components which must be phased precisely together. For the BEAR experiment, an external phase control loop is not required. Any experiments which follow BEAR will certainly have multiple accelerating cavities and will therefore require dynamic phase control of each rf power system.

Dynamic amplitude control is required for BEAR to ensure the proper ion beam energy during fluctuations in the beam current or in the RFQ resonant frequency. The relative amplitude in a resonant cavity falls off as the input frequency varies from the resonant frequency.

CH2669-0/89/0000-0162$01.00©1989 IEEE

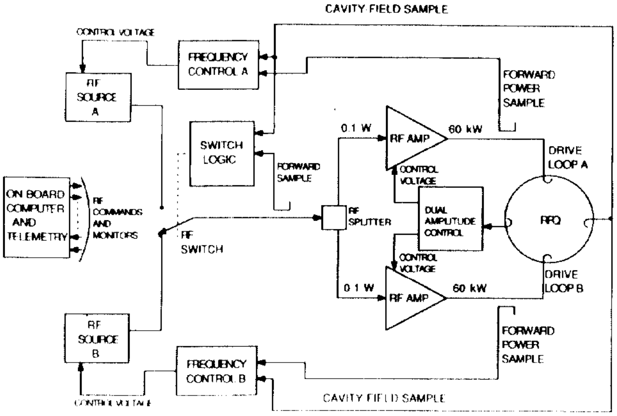


FIGURE 2 BEAR RF SECTION

To reduce the effects of changes in RFQ resonant frequency, the external rf control system also includes a dynamic frequency controller which will track the resonant frequency of the RFQ and keep the input frequency within ±20 KHz of the RFQ resonant frequency.[2]

## BEAR RF AMPLIFIER

The RF amplifier is a 60 kW peak , solid state, 142 lbs package. Westinghouse designed the RF amplifier to drive the RFQ at 425 MHz. For the BEAR RF system, the amplifier will be pulsed at a 5 Hz rate with a 60µs pulse width. Due to the low repetition rate, the amplifier draws only 2 amperes from its supply. During the flight, the amplifiers power supply will be a 40 volt battery pack. The RF output power and phase are adjustable and can be set by externally supplied control voltages.

Figure 3 is a block diagram of the amplifier. With seven stages of amplification, the amplifier has a gain of 58 dB. The amplifier is divided into halves. Each half contains one preamplifier module and twelve power modules. The output power is controlled by changing the relative phase between the halves. When both halves are in phase, the output power is maximum. As shown in Fig. 3, the phase and amplitude module varies the phase between the halves as well as vary the phase of the entire amplifier.

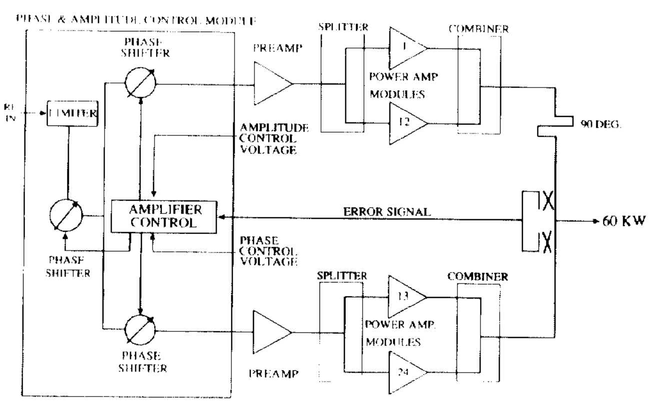


FIGURE 3 RF AMPLIFIER BLOCK DIAGRAM

By varying the external control voltages, the RF amplifiers phase and output power can be adjusted. The control voltages are derived from a sample of the RFQ field. This feedback path forms a closed loop around the RFQ. The RF output power can be adjusted anywhere from 60 KW to 500 watts peak. The phase is adjustable because the RFQ requires two phase matched 60 KW RF amplifiers. The RF amplifiers relative phase can be adjusted anywhere between ±45 degrees.

## VSWR PROTECTION

When the amplifiers output power is reduced, the excess power is reflected back to the twenty four power modules. Each power module contains a circulator which routes the reflected power to a high power termination. Therefore, the power module never operates into a high VSWR, because the circulator isolates the module from the load.

The circulator also allows the amplifier to operate into a short circuit at any phase angle. During portions of the pulse, the RFQ will reflect all the power delivered by the RF amplifier. Therefore, the RFQ will appear to be a short circuit. Normally high power solid state amplifiers cannot operate into short circuits, because the reflected power would destroy the transistors. The circulators isolate the transistors from the reflected power, so the amplifier can operate indefinitely into a short circuit. Therefore, the amplifier is well suited to drive the RFQ.

## PACKAGING

Figure 4 is a photograph of the RF amplifier. Because of the rocket flight application, the RF amplifier is not housed in a cabinet. The individual subassemblies provide the structural support. A cabinet would add unnecessary weight and reduce the amount of available space in the rocket. The RF amplifier weights 64.25 Kg (1 gram/watt) and occupies a volume of .13 $m^3$ (7.5 watts/$cm^3$).

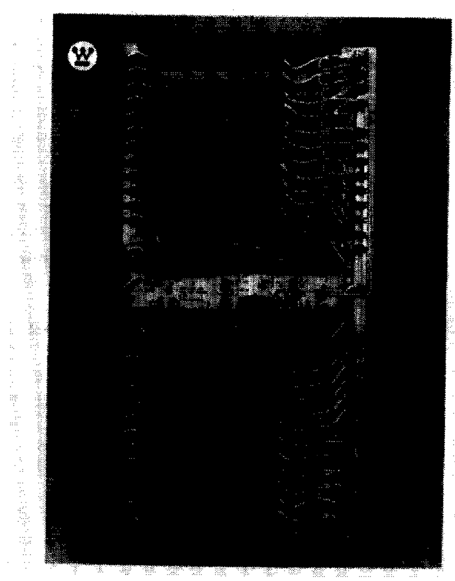

FIGURE 4 60 KW RF AMPLIFIER

## POWER AMPLIFIER MODULE

As shown in Fig. 3, the power amplifier module is the fundamental building block for the BEAR RF amplifier. The RF amplifier uses 24 power amplifier modules. Figure 5 shows a photograph of the module. The module weights 1.26 Kg. The module will operate anywhere in the 420 to 430 MHz band and will deliver 3 KW peak.

Each module contains ten 500 watt bipolar transistors. For reliable operation, transistor junction temperatures should be kept below 120°C. Due to the short pulse width and low repetition rate, the junction temperature will not exceed 95°C with convection cooling.

The transistors are operated Class C so that the variations of gain , and phase due to ambient temperature fluctuations are minimized. Class C operation is also more efficient than Class A or B.

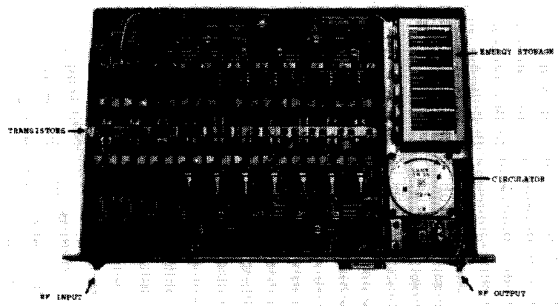


FIGURE 5 3 KW POWER AMPLIFIER MODULE

## HIGH POWER RF COMBINER

The power combiner combines the 24 power amplifier modules RF outputs into a single port. For low loss, the combiner is an air dielectric stripline design. At 425 MHz, the loss is less than 0.15 dB.

As shown in Fig. 3, the two RF amplifier halves are combined in quadrature. The power combiner has two loop couplers which provides an accurate sample of the RF output power. The phase and amplitude control circuits use this sample to adjust the proper phase length and power level. By combining power in quadrature, the doubly reflected signal (caused by mismatched circulator loads) is cancelled and the integrity of the RF output power sample is preserved.

## PHASE AND AMPLITUDE CONTROLS

The phase and amplitude control module controls the RF amplifiers amplitude and phase. The module contains two closed loops. Both loops contain voltage controlled linear phase shifters.

The amplitude control loop adjusts the relative phase between the halves of the amplifier. This phase interference method beats the RF of each half together. The output power varies as a function of $\cos^2\theta$, where $\theta$ is the phase difference between the two halves. For illustrative purposes, let $K=\cos^2\theta$, where K is the power reduction factor. Therefore when $\theta=0°$, K=1 and the amplifiers output power is 60 KW. When $\theta=45°$, K=.5 and the output power level is 30 KW. Theoretically when $\theta=90°$, K=0 and the output power level should be zero. Because the halves of the amplifier are not perfectly matched in amplitude, the minimum output power is about 500 watts. The output power also varies as the square of the externally supplied amplitude control voltage. The amplitude control voltage range is 0 to +10 volts. The output power is 60 KW when the amplitude control voltage is 10 volts.

The phase control loop adjusts the amplifiers overall electrical length. The amplifiers phase is directly proportional to the externally supplied phase control voltage and is continuously adjustable from +45 to -45 degrees.

The externally supplied control voltages do not need to be constant or monotonic. The control voltage can be a ramp, a step, a sinusoid or any type of amplitude modulated voltage. The amplifiers amplitude and phase response is fast enough to follow many types of waveforms. Figure 6 is an oscilloscope photograph of the amplifiers RF output power changing from 10 KW to 60 KW when a 4 to 10 volt step is applied.

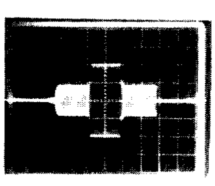

FIGURE 6

10 KW TO 60 KW
AMPLITUDE STEP RESPONSE

10 μs/ horiz. div.

## RF AMPLIFIER PERFORMANCE

In order to provide proper drive to the RFQ, the amplifiers phase and amplitude response and rise times must be fast. Therefore the amplifiers RF output power and phase length must respond quickly to changes in the control voltage levels. At the start of a pulse, the RFQ must be hit with full RF power. Normally RFQs are quite sluggish and must be subjected to full power to fill the cavity. The cavity fill time is approximately 3μs. As shown in Figure 6, the BEAR amplifier RF output power changes from 10 to 60 KW in less than 1μs. The rise time (10 to 90%) is also less than 1μs.

Without amplitude control, the RF output power would be 70 KW peak and would droop during the pulse (Fig. 7). The droop is caused by the limited amount of energy storage available in the amplifier. Since the RFQ requires only 60 KW per amplifier, the amplitude control loop uses the excess RF power to eliminate the droop. As shown in Fig. 8, the RF output power is constant during the pulse. Table 2 highlights the amplifiers capabilities.

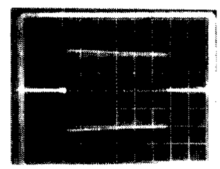

FIGURE 7 (70 KW peak)
RF OUTPUT W/O
AMPLITUDE CONTROL

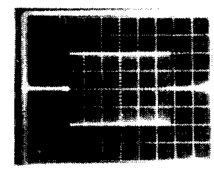

FIGURE 8 (60 KW peak)
RF OUTPUT WITH
AMPLITUDE CONTROL

TABLE 2

BEAR RF AMPLIFIER SPECIFICATIONS

| | |
|---|---|
| Maximum output power | 60 KW |
| Gain | 58 dB |
| Frequency range | 425 ± 1 MHz |
| Maximum pulse length | 60μs |
| Maximum duty cycle | 0.05% |
| Load VSWR | Short circuit (any phase angle) |
| Amplitude response times | 1 dB change in less than 1μs |
| Phase response times | 30° change in less than 1μs |

The amplitude response time is the time it takes the output power to settle to within ± 0.05 dB of the new level. The phase response time is the time it takes the phase to settle to within ±1 degree of the new level.

## CONCLUSIONS

Accelerator designers are now including solid state RF amplifiers in their systems. The amplifiers are capable of driving harsh loads by using novel combining and control techniques. By paralleling more bipolar devices and using lower loss combiners, higher power RF sources are possible. Longer pulse widths and higher repetition rates are also possible, by cooling the transistors.

## REFERENCES

[1] "Neutral Particle Beams Show Potential For Decoy Discrimination", Aviation Week and Space Technology, December 8, 1986, pp.45-52.

[2] M.T. Lynch, L.N. Sorum, and D.R. Keffeler, "RF Control System for a Rocket-Borne Accelerator", Proceedings of the 1987 Particle Accelerator Conference, Washington, D.C. March 16-19, 1987