OPERATIONAL RESULTS OF THE BEAR FLIGHT RF SYSTEM*

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ABSTRACT

The Beam Experiments Aboard a Rocket (BEAR) flight rf control system has been completely designed and has been operated as a part of the flight accelerator system in the actual flight configuration. The accelerator has been vertically integrated onto the flight support structure (space frame) and has been operated in this configuration in preparation for the actual flight which is scheduled for late Spring, 1989. The rf control system consists of redundant voltage controlled oscillators, redundant amplitude controllers which maintain the proper fields in the RFQ, a frequency controller to maintain operation at the resonant frequency of the RFQ, and the necessary system monitors and interfaces required for the amplifiers, onboard system controller, and telemetry. The rf controller had to meet the electrical and environmental requirements while staying with its weight limit. This paper describes the final design of the rf controller and results from operation of the controller in its final flight configuration.

INTRODUCTION

BEAR is a suborbital rocket flight to demonstrate the autonomous operation of a Neutral Particle Beam accelerator and to observe the propagation and interaction of the beam in space. The payload will reach an apogee of approximately 200 km, the flight will last about 500s. The pertinent rf and beam parameters for the experiment are given in Table 1. Further details about the BEAR experiment and accelerator results can be found in a companion paper.[1]

TABLE 1

RF SYSTEM SPECIFICATIONS AND BEAM PARAMETERS

Frequency	**425 ± 0.5 MHz**
Pulse Length	**60μs**
Repetition Rate	**5 Hz**
RF Power Capability	**120 kW**
RF Power Required	**100 kW (nominal)**
H- Output Current	**26 mA**
Output Beam Energy	**1 MeV**
Flight Time	**500 s**
Mission Apogee	**200 km**

RF SYSTEM

A block diagram of the RF system is shown in Figure 1. The RF amplifiers were built by the Westinghouse Electric Corporation under contract to Los Alamos and are described in a companion paper.[2] These amplifiers provide from 1 to 60kW of RF power determined by a 0 to 10 V control signal. The amplifier is actually built as two halves which are combined to give the full output power. Reductions in output power are obtained by misphasing the two halves of the amplifier with respect to each other while maintaining a constant phase of the output.

The RFQ accelerates a 30 keV injected beam to an energy of 1 MeV. The RFQ body is an electroformed aluminum/copper structure with a loaded Q of 2500.[3] The copper power required is approximately 70 kW to establish the appropriate fields in the RFQ. The RFQ has two input loop couplers which are located at the midpoint of the RFQ length. The loops are each driven by separate power amplifiers. For proper operation the two drives must be in phase with each other over all power ranges. This is the primary reason for the internal phase control described above for the rf amplifiers. The RF controller links the different parts of the rf system to each other and to other parts of the accelerator payload and provides the system control.

RF CONTROLLER

The basic design of the rf control system has been described previously.[4] In the final configuration the rf controller which contains everything except the 40 V regulator, was packaged in a box 6"x10.25"x14" and weighs 16.25 lbs. The redundant parts of the RF Controller are the amplitude controller and the rf source. Another redundant circuit which is not shown in Figure 1 is the 40-V regulator (40-V is required by the rf amplifiers). The 40 V regulator was packaged separately for thermal considerations and weighs 4 lbs in a package 8.5"x8.5"x1.6".

The dual amplitude controllers have both integral and proportional compensation. The switchover circuitry for the amplitude controller uses a window comparator to monitor the rf control voltage being sent to the rf amplifiers. If the rf control voltage is not between the two threshold levels of the window comparator, the switching circuit selects the other amplitude controller. All switching, including the switching between the two Voltage Controlled Oscillators (VCO's), is done during the interval between rf pulses.

Bear RF System

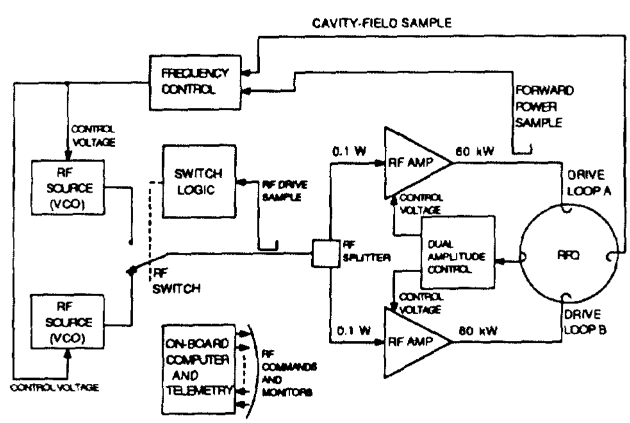

Figure 1. Block Diagram of the BEAR RF System

The logic of the window comparator is as follows. A loss of the feedback signal from the RFQ would cause the control voltage to peg at the maximum level. This condition would be sensed by the high level of the window comparator. A loss of the setpoint level would cause the control voltage to go to zero, which would be sensed by the low level of the window comparator. If the limits are exceeded because of a failure in another part of the rf system, no harm is done by switching back and forth between the controllers because they have been adjusted to operate as much alike as possible. Thus if a power amplifier has degraded enough that the rf control voltage is pegged at the maximum level in order to get as much out of the amplifiers as possible, there would be no harm caused by switching between the two controllers.

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In the original design of the rf system there were redundant frequency controllers. After more experience with the system, we found that the frequency contoller design was quite robust and the logic required to determine if the frequency controller was malfunctioning was difficult to implement. As a result the redundant frequency controller was eliminated.

The frequency controller is a phase locked loop (PLL) comparing the output phase of one of the amplifiers with the phase of a sample of the RFQ fields (Figure 1). A phase difference between these two signals arises when the RFQ resonant frequency changes (most likely due to a change in temperature). The output of the phase detector is the error signal for the PLL which changes the VCO frequency in order to bring the error to zero. In actual practice this loop has maintained the resonance to within ±0.015 MHz over a range of approximately 0.25 MHz. The full range of frequency control by the PLL is 425 ±0.5 MHz, limited by the range of the VCO. The RFQ has been adjusted for a resonance of 425.262 MHz at a temperature of 70°F (under vacuum with 11 psi ambient pressure). The rate of change of this resonance is approximately -8 kHz/°F. On a typical day of operation in the laboratory, the resonant frequency changes from approximately 425.2 MHz at startup to approximately 425.0 MHz by the end of the day.

External inputs to the rf controller include 28-V and 50-V from battery packs or ground power and four signals from the onboard microcomputer controller: RF Enable, RF Prefire, RF Sync, and the Amplitude Setpoint. The 28-V input is used by the RF Controller and the 50-V is regulated down to 40-V for the RF amplifiers.

RF Enable is essentially an on-off switch for operation of the rf controller. RF Prefire is a signal required by the rf amplifiers approximately 400μs before the RF Sync. The Prefire signal wakes up circuits which shut down during the interpulse interval in order to conserve power. The Prefire signal is also used by the RF Controller for some of the Sample/Hold functions. The RF Sync is the signal which actually defines the 60μs rf pulse, and the Amplitude Setpoint establishes the level for the RF fields in the RFQ.

Outputs from the RF system to the onboard controller and telemetry system include an assortment of state-of-health signals such as power supply levels and rf drive levels to the amplifiers. In addition, several signals are sent which indicate the current status of operation. These include amplitude control level, high VSWR indication, operating frequency, and five pulsed waveforms.

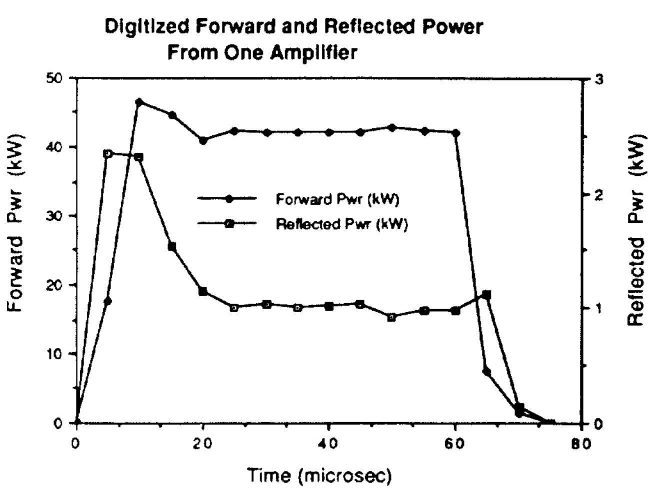

Figure 2. Digitized forward and reflected power from one amplifier. The sampling time is every 5μs. When compared to Figure 4, most of the finer details of the signal are lost.

The five waveforms which are sent are the forward and reflected power from each amplifier and a sample of the RFQ fields. The waveforms are digitized by transient digitizers in the onboard microcontroller. The transient digitizers sample only every 5μs, so each trace will only have twelve sample points. More sample points would certainly be preferable, but we have found that the twelve sample points give enough information to satisfactorily analyze the system condition.

ENVIRONMENTAL TESTING

The entire rf system has been successfully environmentally tested. The environmental tests include shock testing to 50 G in both directions along all three axes, vibration testing at .042 G^2/Hz (9 G rms) along all three axes, and thermal cycling through three complete cycles from -24°C to +65°C.

OPERATION IN FLIGHT CONFIGURATION

A sample of the digitized forward and reflected power and RFQ field data are shown in Figures 2 and 3. For comparison, oscilloscope data of the same signals are shown in Figures 4 and 5. The digitized data show the reflected power spikes at the beginning and end of the traces and the forward power peak at the start of the trace. During this initial burst of forward power the amplifiers put out full power in order to bring the rf fields up in the RFQ as quickly as possible. The digitized RFQ signal shows initial overshoot, but the finer details of the data are lost due to the low sampling rate.

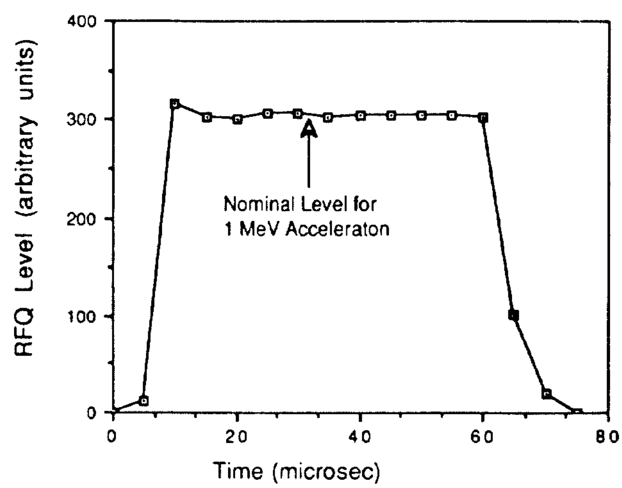

Figure 3. Digitized sample of the RFQ fields. When compared to Figure 5, most of the finer details of the signals are lost.

In order to simplify the operation of the RF controller, we have used internal pots to adjust the gain/compensation level of the controller. These pots are set up for operation with a beam out of the RFQ on the order of 25 mA. The control system has been designed with the pole due to the RFQ acting as the single dominant pole. Since the beam loading reduces the loaded Q as seen by the control system, a change in beam level (especially to zero) changes the location of the pole due to the RFQ in the frequency domain. As the beam is reduced the pole moves to a lower frequency. This movement reduces the phase/gain margins of the control system and leads to a more unstable system. Analysis and measurements of the control system show that the phase margin without beam is only about 27°. With a nominal amount of beam (12-15mA), the phase margin is about 55°. This effect is seen in the ringing and overshoot of the RFQ fields with and without beam. Figure 5 shows the cavity fields with beam (about 12 mA). Only a small overshoot and almost no ringing is seen. Without beam, Figure 6, the cavity field shows a very high overshoot and many cycles of ringing.

The very high initial overshoot tends to make the RFQ arc which has caused problems during conditioning of the RFQ. In the test stand operation and in the initial operation on the space frame, we ran the rf system in an open loop mode or actually adjusted the gain/compensation of the controller just to do the conditioning and then readjusted for beam. The flight system does not allow either of those options, so special care must be used when operating without beam. However, as the RFQ has gone through more conditioning cycles and more hours of operation, the arcing problems due to this overshoot have diminished.

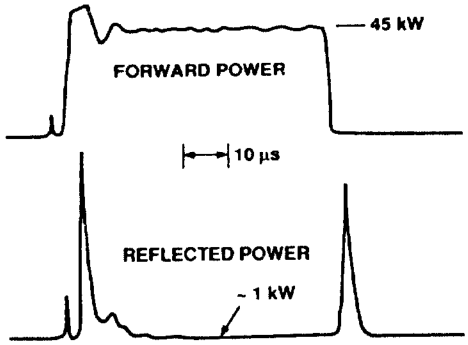

Figure 4. Forward and reflected power signals from one of the high power amplifiers obtained on an oscilloscope.

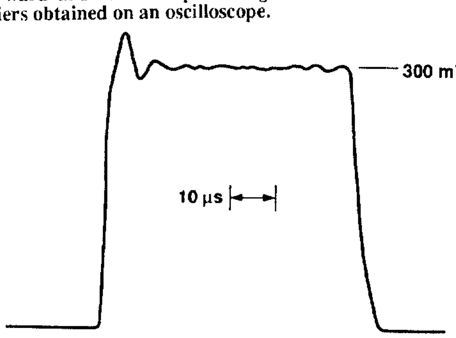

Figure 5. RFQ field sample obtained on an oscilloscope. Beam out of the RFQ is ~12mA.

OPERATIONAL RESULTS

The rf power levels required for successful operation of the accelerator depend primarily on the Q of the RFQ, the field level needed for acceleration to 1 MeV, and on the amount of beam. There are other more minor loss mechanisms in this system. These include reflective losses due to drive loop mismatches and operating frequency errors and phasing losses due to mismatched cables from the two amplifiers.

The minor loss mechanisms turn out to be very small. In actual operation, the reflected power values are typically a few kW out of 100. The power loss due to improperly phased amplifiers is proportional to the square of the cosine of half of the phase angle (where 0° implies amps in phase). This is a very slow function around 0°, and in fact a misphasing of 10° leads to power loss of less than 1%. In actual assembly of the flight payload, the amps were phased to within 2°. As mentioned above, the operating frequency has been maintained within ±0.015 MHz of the resonant frequency. This amount of error would lead to reflective power losses of less than 1%.

The RFQ design required a drive loop coupling factor of 1.5 (overcoupled) for the design value of beam (26-30 mA). The actual coupling obtained was about 1.42 for one loop and 1.65 for the other. The power loss that occurs because of improper coupling is more due to variations in beam current than to improper coupling factors. That is, the daily operation shows variations in RFQ current of about 50% because of changes in the operating characteristics of the injector. The variation in current, not incorrect adjustment of the coupling loops, is the primary reason for coupling errors. The power losses due to these coupling errors amounts to only a few kW in the worst case.

The field level necessary for proper acceleration of the beam to 1 MeV has been determined in a number of ways. Calculations based on the Q of the RFQ and the required intervane voltage determined that 71 kW was necessary copper power. This level of power was then used to determine what value the RFQ field samples should be. In another measurement a beam spectrometer was used to monitor the level of beam obtained at 1 MeV as the RFQ field level was adjusted. The final method was to record the x-ray energy emitted from the RFQ and then use this data to determine what the intervane voltage was. The results, taken as a whole, indicate that we tend to operate with intervane voltages that are about 10% above the design value (44 kV). However, higher intervane voltages tend to give slightly higher values of output current. In the end the operating value chosen will be a trade off between the highest fields obtainable vs. the minimum number of cavity arcdowns. The primary problem with arcdowns for this experiment is the loss of data. With a total mission time of only about 300 s, a few seconds of arcing imply a loss of a significant fraction of the total number of beam pulses available.

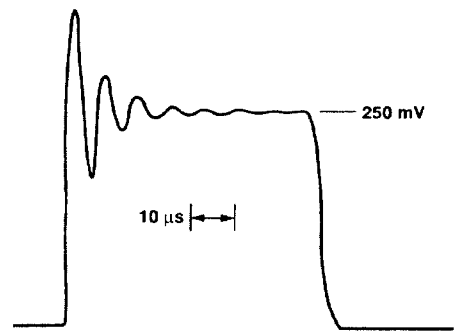

Figure 6. RFQ field sample obtained on an oscilloscope. The signal was obtained with no beam entering the RFQ. Note the large overshoot and ringing due to the reduced phase/gain margins in the control system.

Another rf power related problem on the BEAR experiment is the amount of beam power required. The beam should require approximately 1 kW for every mA of current. We have consistently found however that we need about 50% more beam power than that estimated from the amount of output current. For example, if the output current is 20 mA and we are running at the field level in the RFQ which requires about 70-kW of copper power, we find that the total power going into the RFQ is on the order of 100 kW instead of the 90 kW which might be expected. With 120 kW of available power this has not been a problem, but it was unexpected in the initial stages of the project. We believe this phenomenon is due to imperfect matching of the input beam to the RFQ, which arises because the permanent magnet matching section allows only very limited adjustment. Some of the beam that enters the RFQ is partially accelerated before being lost to the structure walls. This beam absorbs power but does not exit the RFQ.

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