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HIGH-POWER RF CONTROLS FOR THE NBS-LOS ALAMOS RACETRACK MICROTRON*

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Summary

The high-power rf system for the National Bureau of Standards (NBS)-Los Alamos racetrack microtron (RTM)¹ uses waveguide power splitters² and waveguide phase shifters to distribute rf power from a single 500-kW cw klystron to four side-coupled accelerating structures. The amplitude and phase of each structure is controlled by a feedback system that uses the waveguide variable power splitters, waveguide phase shifters, and klystron drive as the active control elements. A block diagram of this system is shown in Fig. 1. Figure 2 shows a subset of the complete system on which the measurements reported in this paper were performed. The feedback controls on the capture section use low-level rf amplitude and phase controls on the rf drive to the klystron. These controls are very fast with an open loop gain bandwidth of approximately 40 kHz. The feedback loop is identical to the feedback loop used in the chopper/buncher system described in another paper at this conference.³

Fig. 1. Block diagram of the high-power rf system that uses waveguide power splitters and waveguide phase shifters to distribute and control rf power from a single 500-kW cw klystron to four side-coupled accelerating structures.

Waveguide Feedback System

A waveguide power divider is shown in Fig. 3. The input rf power is divided equally by a short-slot waveguide hybrid⁴ (A) with a 90° phase relationship between Ports A2 and A3. A short section of waveguide connects Port A2 to Port B1, and a waveguide phase shifter connects Port A3 to Port B4 of a second waveguide hybrid (B). The waveguide phase shifter varies the phase relationship of the power arriving at Ports B1 and B4 of Hybrid B. The relative phase of the power arriving at B1 and B4 determines the ratio of power coupling to output B2 and to output B3. A 180° phase shifter can smoothly change the ratio of the power coupled to either output from less than 1% to more than 99% of the input power (neglecting losses).

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Fig. 2. Diagram of a subset of the high-power rf system used to distribute and control rf power from the klystron to two side-coupled accelerating structures. This is a subset of the system shown in Fig. 1.

Fig. 3. In the waveguide power divider, rf power is divided equally by a short-slot waveguide hybrid (A). The waveguide phase shifter can control the phase relationship of the rf power arriving at Ports B1 and B4 of the hybrid (B). This phase relationship determines the ratio of power coupling to outputs Ports B2 and B3.

When the power at one output is a maximum, the other is a minimum and vice versa. Power at Port A4 is very low if the outputs are connected to a well-matched load. If the resonant loads on B2 and B3 are not well matched, some of the power reflected from the loads will appear at this port. Therefore, a 35-kW water-cooled flat rf load is placed on Port A4 to terminate that arm of the hybrid properly.

The waveguide phase shifter can shift the phase 180° for 13 turns of the stepping motor used to operate the phase shifter. Because the stepping motor has 200 steps per turn, one step of the stepping motor shifts the phase by 0.07°. The percentage change in the power split for one step of the stepping motor depends on the position of the phase shifter, but the

maximum percentage change in rf power out of either port is 0.12% for one step of the stepping motor. The amplitude of the rf field in a cavity is proportional to the square root of the power. Therefore, the percentage change in the cavity fields is only 0.06% for one step of the stepping motor. The goal of the feedback system is to regulate the amplitude to within $\pm 0.1\%$ and to regulate the phase to within $\pm 0.5^\circ$. Because one step of the stepping motor can change the amplitude by as much as 0.06%, the $\pm 0.1\%$ regulation of the amplitude may be marginal, but is at least theoretically possible. The stepping motors are controlled with a microstepper controller. This controller can divide the step size by 16, which provides much finer control of the amplitude. The mechanical linkages of the stepping motors to the phase shifter are very nearly backlash free, so that the finer control provided by the microstepper controller can be realized.

The principle of the feedback systems (shown in Figs. 1 and 2) that control the stepping-motor-driven waveguide phase shifters and power splitters is shown in Fig. 4. An rf sample probe in the cavity provides a small amount of rf to a phase and amplitude detector. A low-barrier Schottky diode detects the amplitude of the rf sample, and a double-balanced mixer (DBM) is used to compare the phase of the rf sample with the phase of the reference. The signal from the DBM is a voltage, proportional to the phase error, that can be positive or negative. The amplitude signal is compared with the amplitude reference, and the result is a voltage that is proportional to the amplitude error. The polarity of this signal can also be positive or negative. In both cases, the error signals are bipolar and the device that is to be driven is a stepping motor. Therefore, the electronics that processes the error signal and drives the stepping motors is identical for the phase and for the amplitude feedback loops.

Fig. 4. Block diagram of the feedback controls showing the interface to the stepping-motor-driven phase shifters.

The amplified error signal is converted to a unipolar signal in an absolute-value circuit. The sign of the error signal is determined by a comparator circuit and is used by the stepping motor-driver to define the direction to turn the motor. The absolute value of the error signal goes to a voltage-to-frequency (V-to-F) converter. The V-to-F converter produces pulses at a rate proportional to the voltage on its input. These pulses go to the microstepper stepping-motor driver. The stepping-motor driver then provides the appropriate current to the stepping-motor windings to turn the motor 1/16 of a step in the appropriate direction for each pulse received. Because the change in output of the waveguide phase shifter depends on how far the motor has moved the phase shifter and not on how fast the motor is turning, this device is an integrator in the feedback loop.

The torque on the motor and the inertia of the load determine the maximum acceleration available from the motor. Acceleration of the stepping motor armature is proportional to the rate of change (s⁻² or rate) of the error signal on the input to the V-to-F

converter, provided the maximum acceleration available from the motor is not exceeded. If that occurs, the motor will stall. To prevent the stepping motor from stalling, slew rate of the error signal must not exceed 150 V/s. The feedback amplifiers have a maximum slew rate of 12×10^6 V/s, which is much too fast for the stepping motor. Therefore, a slew-rate-limiter circuit was added to the feedback amplifiers that limits the slew rate to 125 V/s. Because the stepping-motor-driven phase shifters are integrators, they contribute a minimum phase shift of 90° in the feedback loop at all frequencies. In addition, the acceleration limit of the stepping motors is reached at a frequency of ~ 6 Hz, which introduces additional phase shift. Therefore, the open-loop gain of the feedback system must be limited to about unity at 6 Hz to prevent oscillation of the feedback system. The gain of the feedback amplifiers was adjusted to provide unity gain near 3 Hz for these tests.

Because the measurements of the response of this feedback system were done at high power, it was not possible to measure the open-loop gain of the feedback system. Therefore, the closed-loop gain and the magnitude of the error caused by a perturbation were measured versus frequency. The results of these measurements are shown in Figs. 5 and 6 for the amplitude and phase, respectively. Note that the closed-loop gain of the phase loop is very nearly unity almost to 3 Hz and then falls at 6 dB/octave--just as expected--for a closed-loop feedback system. However, the closed-loop gain of the amplitude control loop deviates from unity well below 3 Hz, an effect caused by the measurement technique. The feedback gain was measured by modulating the amplitude reference at each frequency of interest and measuring the error. To produce an observable error, the amplitude reference was modulated $\sim 20\%$, which modulated the rf power flow to the structure $\sim 40\%$. This modulation resulted in temperature changes in the accelerating structure, which caused varying amounts of the rf power to be reflected by the structure. The feedback system, therefore, had to correct for this effect too, which was not accounted for in calculating the gain of the feedback system.

As shown in Figs. 5 and 6, the high-power waveguide feedback system has very little effect on perturbations to the accelerating field above 3 Hz. However, the only expected source of perturbations to the accelerating field above 3 Hz are variations in beam loading. If care is taken to prevent fast changes in beam current when beam loading is a significant fraction of the rf load, this limitation of the feedback system should not be a problem.

Fig. 5. Measured closed-loop gain versus frequency of the amplitude controls and response of the amplitude to a perturbation versus frequency.

Fig. 6. Measured closed-loop gain of the phase control and the response of the phase to a perturbation versus frequency.

Variations in gain of the klystron caused by power-supply ripple at ~ 120 Hz are effectively removed by the fast-feedback loop controlling the drive to the klystron. Perturbations caused by variations in the tuning of the individual cavities, which are caused by temperature variations, are slower than 3 Hz and are effectively neutralized by the waveguide feedback system.

Figures 7 and 8 show the response of the amplitude and phase controls to a square-wave modulation of the amplitude reference and phase references, respectively. Also shown are control signals that show the effect of the slew-rate limiter. The modulation of the reference signals was made large enough to cause the control signals to reach their maximum value of ± 10 V. These are the signals that go to the absolute-value circuit and then to the V-to-F converter. At ± 10 V, the stepping motors reach their maximum velocity.

Fig. 7. Response of the cavity rf amplitude to a square-wave modulation of the amplitude reference.

Conclusions

Steady-state measurements show that short-term phase variations are less than $\pm 0.1^\circ$ and that the amplitude variations are less than $\pm 0.1\%$. Fast changes in beam loading will cause amplitude variations that are greater than this; therefore, beam loading should only be changed slowly.

Fig. 8. Response of the cavity rf phase to a square-wave modulation of the phase reference.

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