PHASE AND AMPLITUDE STABILIZATION OF SHORT-PULSED, HIGH-POWER MICROWAVE AMPLIFIERS*

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Abstract

In recent years, much effort has gone into research on high-power, short-pulsed free-electron lasers (FELs) and relativistic klystrons (RKs) driven by linear induction accelerators (LIAs). These devices are potential power sources for future linear colliders several kilometers in length. The new high-power devices must meet certain practical requirements on such parameters as stability, efficiency and cost. In this paper, we address the problem of phase and amplitude stability of the rf pulse and present a technique for improving it in these devices to a level that is acceptable for accelerator applications. We summarize the results of bench tests and computer simulations, and discuss a proposed high-power klystron experiment aimed at establishing the feasibility of the overall concept and the workability of the stabilization circuits.

INTRODUCTION

The required amplitude and phase stability for future linear collider power sources, during the useful portion of the pulse flattop, is on the order of $< \pm 1\%$ and $< \pm 2°$, respectively[1]. A program underway at LLNL has reduced the beam energy variations in one LIA[2] to $< \pm 1\%$, a significant achievement. As LIA beam-driven high-power microwave amplifiers (HPMAs) are usually constructed and operated, however, beam energy and current variations during the pulse flattop can result in output rf amplitude fluctuations of 20% or more and phase variations of ±20 to 30 degrees. For such machines, it will be extremely difficult to achieve the level of stability necessary for powering particle accelerators without a method of compensating for the beam-caused fluctuations. Given such a method, on the other hand, the requirements for beam stability could be relaxed, resulting in important savings in the complexity and cost of the LIA driver.

In the operation of present-day RKs and FELs, it is observed that the fluctuations in the electron beam energy and current, and the resulting fluctuations in output rf phase and amplitude, are very repeatable from pulse to pulse. This is no doubt due to the systematic nature of the causes of beam variations. This repeatability is exploited in the stabilization technique described in detail below. It enables the rf output phase and amplitude error signals to be sampled on one pulse, held in memory circuits and suitably processed, then applied on the next pulse at the input of the HPMA in such a manner that errors on subsequent pulses are reduced. This feed-forward or delayed-feedback approach is especially suitable for repetitive, short-pulsed devices whose physical size causes excessive signal propagation delays that preclude the use of directly-closed feedback loop correction.

PHASE STABILIZATION SYSTEM

The 11.4-GHz RK phase stabilization system described below applies equally well to other HPMAs such as FELs, klystrons and cyclotron auto-resonance masers (CARMs). The RK is considered a worst-case example because of the retarding effect of its stored energy on response time.

Figure 1 shows a block diagram of the new phase-stabilizing system. A key component of the correction circuit is a fast varactor phase shifter, PS-1. The RK output phase signal is compared to the phase of the reference signal in the CC-1 circuits, generating a phase error signal which is processed and held in memory circuits. On the next machine pulse, this error-correction pulse is read out and sent to the varactor phase shifter. The device produces an offsetting phase shift in the RK input drive signal, compensating for the RK output phase error produced in the previous machine pulse by beam energy fluctuations.

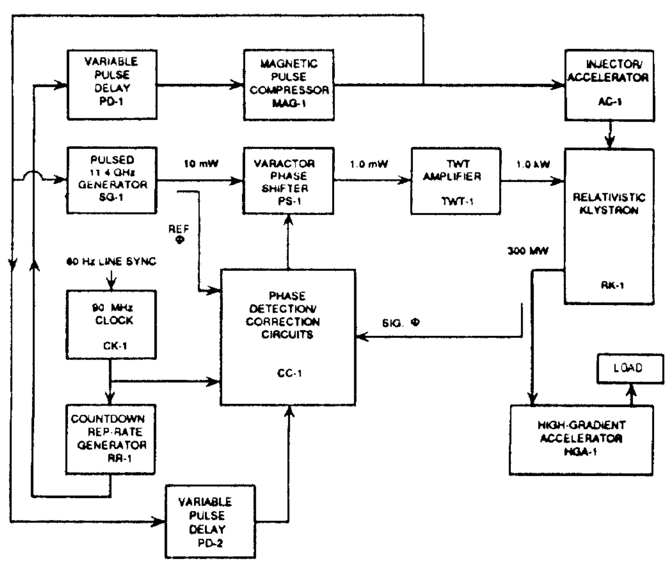

Fig 1 Block Diagram of a Phase Stabilization System

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Two techniques for implementing the CC-1 correction circuits have been considered in this paper. The first employs fast track-and-hold modules for sampling the phase error signal during ten sampling periods over the 40-50 ns pulse. On the next machine pulse, the signals are sequentially gated out of these ten memory units on a single line and, following appropriate amplifying, filtering and possibly inverting, sent to control the varactor phase shifter. This is likely to be the lower-cost approach and lends itself to miniaturized packaging. The second technique uses fast digitizers to sample the phase error signal and a microcomputer to process the correction samples and to program a fast waveform generator. On the next pulse, the generator is triggered and its output pulse commands the varactor phase shifter. A delayed feedback system using this technique was used to correct transverse position variations of a short electron pulse on an induction accelerator[3]. This approach has the advantages of flexibility and the use of existing instrumentation but its initial cost is higher. For both of these techniques, the error-correction process goes on continuously from pulse to pulse.

The question of the feasibility of such a system centers on overall response time, adequate circuit component performance and the general workability of the stabilization circuit. The response time required at SLAC to make a 180° phase change in the output of a high-power 8.56 GHz klystron was measured to be 20-30 ns[4]. A several-hundred megawatt, 11.4 GHz LLNL RK had an input buncher cavity with a Q ≈ 170. The typical 1.5-kW peak input power could produce a calculated phase-change rate of about 37 deg/ns in this cavity. Higher-power RKs could have lower Q-values and thus even faster response. We can conservatively take worst-case values of 20 deg/ns for the RK response rate and 20° for the maximum required phase correction from pulse to pulse. Making realistic estimates for the risetime contributions from the remainder of the stabilization circuit components, we calculate that the worst-case phase-change risetime for each correction step is ≤ 2.5 ns. If no further signal processing took place, during the correction pulse risetimes small error spikes of phase modulation would result. To minimize these, the CC-1 signal processing circuits can provide a smoothing, interpolating action during the risetime of each correction step.

To measure relevant risetimes and demonstrate phase-error correction, we assembled the test circuit shown in Figure 2. For the varactor phase-shifter, we purchased an 11.4 GHz, narrow-band, 0 to 100° unit custom-fabricated to our specifications and optimized for fast risetime. It has a nominal insertion loss of about 9 dB and operates with a 0 to −16V control pulse. It was also found to have an insertion loss that varied several dB over the control voltage range (see Amplitude Stabilization System, below). The circulator, fast PIN diode switch and short-circuit within the dotted enclosure (Figure 2) are used to produce a fast phase-change by changing the electrical path length traveled by the 11.4 GHz signal as it passes from port 1 to port 3 of the circulator. This phase-modified signal and the reference signal are the inputs to a phase detector consisting of a mixer and a back diode. The mixer IF bandwidth is specified as 3.0 GHz. The net response time, i.e. 10-90% step risetime, of the overall phase modulation and detection process was measured to be 0.8 ±0.1 ns (after subtracting the scope/plug-in contribution).

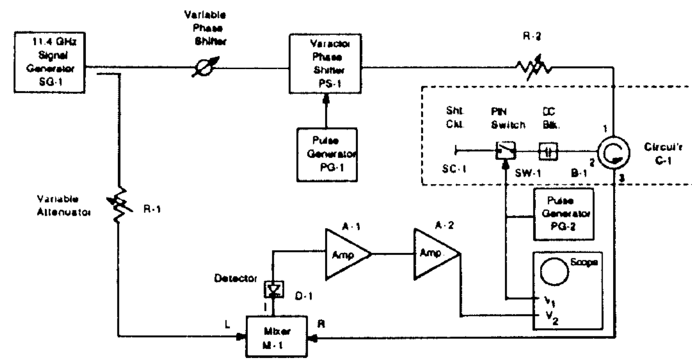

Fig 2 Test Circuit for Phase Error Correction

Once a phase-error signal is produced, detected and displayed on the scope, the PG-1 pulse generator can drive the PS-1 varactor phase shifter and demonstrate cancellation of the phase error. Being adjustable in amplitude and dc offset biasing, PG-1 permits the exploration of the PS-1 control parameter space. It simulates the output of the phase correction circuits in CC-1 of the full RK system. One can view the phase-error signal as a simulation of that being produced by an RK on one machine pulse, and the PG-1 output pulse as that simulating the phase-correction signal gated out of the CC-1 circuits on the following pulse. The scope can conveniently display the error signal before and after phase correction is performed. The lower trace of Figure 3a shows an uncorrected phase-error pulse simulated by the test circuit with the PG-1 pulser inactive. The upper trace is the waveform of the PIN switch driver pulse. Figure 3b shows a partial correction effected by adjusting the PG-1 pulser amplitude correctly (but whose pulse width is too short). Figure 3c shows correction that is complete except for some leading and trailing edge aberrations. This experiment thus demonstrates the basic feasibility of the correction technique and the adequacy of circuit components for achieving the desired response time.

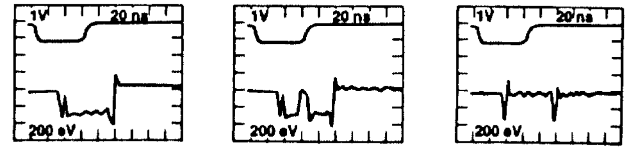

Fig 3 Phase Error and Correction Pulses

We further investigated the minimum resolvable phase correction that could be produced as limited by signal-to-noise considerations. By using a standard low-noise amplifier after the phase detector, it is clear that a stability (and minimum correction) of ≤ ±2° can be achieved within the desired bandwidth of about 300 MHz. The minimum system dynamic range is then determined to be ±2 to 50°, or 14 dB, with the existing varactor phase shifter.

A 1.6-MeV RK was realistically modeled along with the other elements of the phase stabilization system on Extend software. Simulated output phase errors were generated by simulating variations in the RK beam voltage. Figure 4a shows the open-loop (i.e. uncorrected) amplified and filtered phase-error signal resulting from a simulated ±7.5%, 200 MHz square-wave modulation of the beam voltage. The ±45% phase error thus produced resulted in a ±0.3 V error signal. Figure 4b shows the closed-loop error signal (note the vertical scale-change) settling to <1.0 mV in <1.5 ns. This corresponds to a phase stabilization level of 0.3%, or ±0.15°, clearly demonstrating the workability of the circuit.

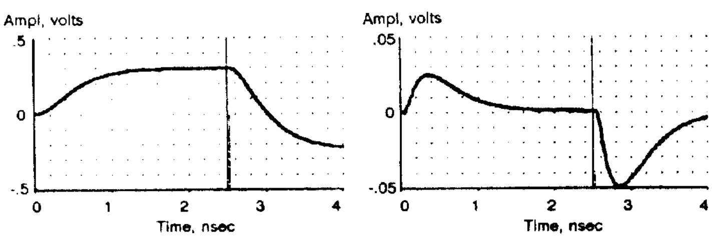

Fig 4 Open (a) & Closed (b) Loop Phase Correction Simulation

Amplitude Stabilization System

The amplitude stabilization system is similar to that shown in Figure 1 except that an amplitude comparator replaces the phase detector and a voltage-controllable attenuator replaces the varactor phase shifter. It may be difficult to achieve the desired bidirectional response time with PIN diode attenuators. A better solution is to make use of the fast amplitude modulating capability of the varactor phase shifter. This single unit can then become the dual-purpose controlling element in a combined phase and amplitude stabilization system. To avoid instabilities, the settling times, i.e. the poles of the response functions, of the two correction loops can be widely separated.

Bench tests of amplitude error cancellation were performed with results appearing nearly identical to those shown in Figure 3 for phase correction. We also showed that a minimum resolvable amplitude correction of < ±1.5% was achievable and that a maximum correction of ≥ ±20% was easily achieved by the use of the varactor amplitude moduiator. The results of Extend computer simulations of the stabilization circuit performance are shown in Figure 5 for a 500 MHz, ±25% square-wave modulation of the RK beam current. Figure 5a shows the open-loop behavior, e.g. the resultant 11.4- GHz amplitude fluctuations and the amplitude error signal settling to ~ ±0.6 V. Figure 5b shows the closed-loop results with the amplitude error settling to < ±1.0 mV in about 1.0 ns. This corresponds to a 0.17% amplitude stabilization level.

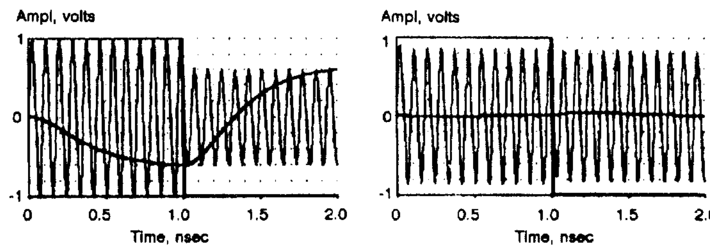

Fig 5 Open (a) & Closed (b) Loop Amplitude Simulation

High-Power Klystron Experiment

We will be performing tests of a delayed feedback system to control the rf phase on the choppertron[5], an 11.4-GHz high power source now being studied at the Microwave Source Facility at Livermore. At modest currents the choppertron has so far produced 100-MW, 30-nsec rf pulses. Modifications should increase the amplitude of single output to several hundred megawatts without shortening the pulse width. Additional amplitude and phase variation in the rf output for testing the feedback system can be imposed by inducing a voltage variation during the pulse. The first experiments will determine how changes in the driver's phase will affect the phase of the rf output from the tube. The elements for a feedback control system using the second technique described above have been procured, and are undergoing bench test. In these tests the varactor phase shifter will be placed between the signal generator and the TWT. The rf pulse from the TWT is amplified to about 1 MW by a Thompson-CSF pulsed klystron before it is coupled to the drive cavity of the choppertron.

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