IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

PHASE AND AMPLITUDE FEEDBACK CONTROL SYSTEM FOR THE LOS ALAMOS FREE-ELECTRON LASER*

M. T. Lynch, P. J. Tallerico, and E. F. Higgins, AT-5, MS H827
Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Summary

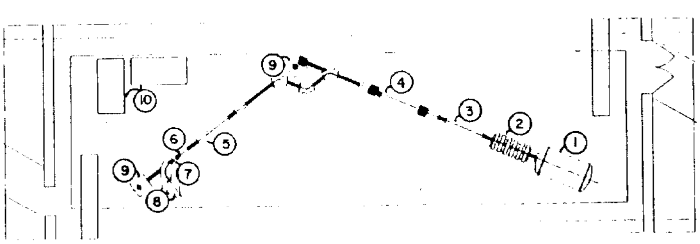
Phase and amplitude feedback control systems for the Los Alamos free-electron laser (FEL) are described. Beam-driven voltages are very high in the buncher cavity because the electron gun is pulsed at the fifth subharmonic of the buncher resonant frequency. The high beam loading necessitated a novel feedback and drive configuration for the buncher. A compensation circuit has been added to the gun/driver system to reduce observed drift. Extremely small variations in the accelerator gradients had dramatic effects on the laser output power. These problems and how they were solved are described and plans for improvements in the feedback control system are discussed.

Introduction

The FEL has operated for one year, during which many important experiments have been successfully completed.[1] The operation of the FEL places stringent requirements on the performance of the phase and amplitude feedback controls for the rf systems. In particular, the arrival time of electron micropulses in the optical cavity must have very little variation so that the electron micropulse can line up (to within 5 ps) with the optical pulse. To accomplish this, the rf systems (electron gun, buncher, and accelerators) must have excellent phase coherence and amplitude and phase stability.

The RF Control System

The principal components of the FEL are shown in Fig. 1. An electron gun provides a burst of electron pulses once per second. The individual pulses (micropulses) are delivered at a 21.67-MHz rate throughout the 100-μs length of the macropulse. The micropulses are bunched by a subharmonic buncher to boost the peak current by an order of magnitude and are then accelerated to just over 20 MeV in two consecutive accelerators. The high-energy electron pulses are injected into the optical cavity where the lasing takes place. Phase and amplitude control circuits for the electron gun, the buncher, and the accelerators are described below.



1. 80-keV Electron Gun
2. 108-MHz and 1300-MHz Bunchers
3. 10-MeV Linac Tank
4. 11-MeV Linac Tank
5. Wiggler
6. Slow Vertical Deflector
7. 1300-MHz Vertical Deflector
8. Electron Spectrometer
9. Optical Resonator Mirrors
10. Optical Diagnostics

Fig. 1. FEL block diagram.

*Work performed under the auspices of the Dept. of Energy and supported by the Dept. of Defense Ballistic Missile Defense Advanced Technology Center.

The Electron Gun

The FEL uses a hot-cathode, gridded electron gun, operating at 80 kV, which is driven by a trigger generator and an 800-V pulser. The original configuration of the FEL electron gun led to a monotonic lengthening in the spacing between micropulses during the 100-μs macropulse. As much as a nanosecond variation in the micropulse spacing was observed (Fig. 2). To regularize and control the electron-gun timing and remove the sensitivities to external factors, the phase-lock circuit shown in the block diagram of Fig. 3 was incorporated into the trigger circuitry of the electron gun. The phase-lock circuit compares the phase of the gun's electron beam, derived by a wall-current monitor, with the 21.67-MHz rf reference oscillator signal and automatically stabilizes the triggering of the electron gun. The trigger correction signal is proportional to the time difference between the wall-current signal and the zero crossings of the reference oscillator.

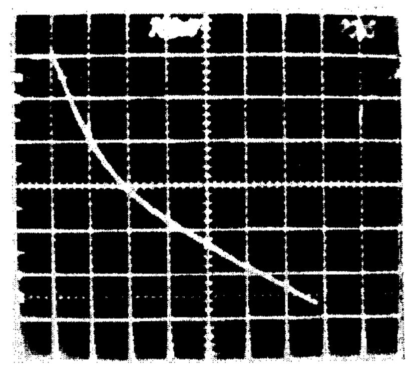


Fig. 2. Change in gun micropulse spacing. Vertical = 175 ps/div, horiz = 20 μs/div.

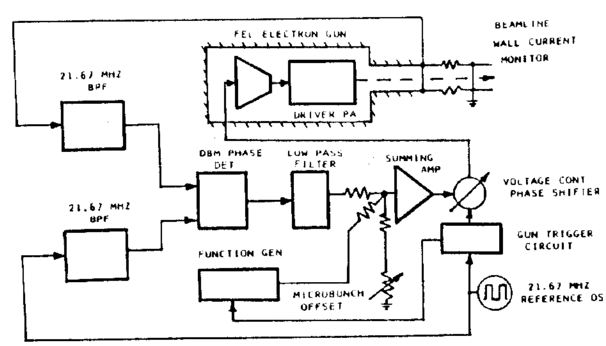


Fig. 3. Electron gun phase-lock circuit.

The following describes the functions of the circuit shown in Fig. 3. The wall-current monitor signal (representing the actual micropulse timing data) is filtered by a twin-"T", constant-impedance band-pass filter tuned to 21.67 MHz. The filter converts the pulses of the wall-current signal into a sinusoidal signal suitable for phase comparison purposes. This filtered "beam" signal is applied to a low-level, double-balanced mixer (DBM) along with the rf reference signal. The DBM, configured as a phase detector, produces a signal that, after additional filtering, is proportional to the timing error between the beam-derived signal and the reference. This actuating signal is then applied to a voltage-controlled phase

0018-9499/85/1000-2159$01.00© 1985 IEEE

shifter with a linear range of ~30° (±4 ns). The phase shifter is inserted directly in the electron gun triggering path and is thus able to modulate the triggering phase (time) of the gun in accordance with the actuating signal. In this way, the 1-ns timing variation shown in Fig. 2 is reduced to about 9 ps as shown in Fig. 4. The large change during the first 20-µs of Fig. 4 are due to turn-on transients and should be ignored.

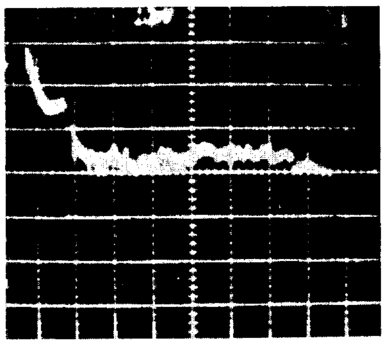


Fig. 4. Change in gun micropulse spacing after application of phase-lock circuit. Vertical = 9 ps/div, horiz = 20 µs/div.

An added "program" signal (Fig. 3), developed by a triggered integrator,[2] is added to the phase detector's output signal to help suppress the timing error. The program signal provides a factor-of-6 improvement in reducing total timing error in an open-loop mode; whereas, combining the program signal and phase-detector error signal provides a factor-of-120 timing improvement in the closed-loop feedback arrangement shown. The response time of the feedback loop is set to ~5 µs by a single-pole, operational amplifier filter, which gives adequate correction response.

In addition to the active feedback control signal, a dc (static) offset voltage is applied to the circuit's phase shifter to adjust the timing of the entire macropulse pulse train by ±0.5 ns (±4°). This offset control is very advantageous in machine tune-up (to set the gun/buncher timing) and for use in diagnostics.

The Buncher System

A single subharmonic buncher operating at 108.33 MHz was used to bunch the electron gun pulses. Typical operation gave ~40-A peak bunched current, (the maximum obtainable bunched current was 50-A peak). A difficulty arose in the buncher operation because the electron gun is driven at the fifth subharmonic (21.667 MHz) of the buncher frequency. The Fourier component of the electron beam at the resonant frequency of the buncher cavity is strong enough that the electron beam can deliver over 20 kW of rf power to the buncher.

This beam-driven voltage does not provide proper beam bunching. In some cases, partial detuning of the cavity can be used to overcome this difficulty.[3]

Figure 5 shows a phase representation of this technique; I_B and V_B are the beam current and voltage, respectively. The generator current and voltage are I_G and V_G, respectively; V_C is the cavity voltage, and ψ is the detuning angle of the buncher cavity. The rf generator current can be made to be in phase with the cavity voltage. The rf generator voltage then exactly cancels the decelerating component of the beam-induced voltage. This method allows one to use an rf generator of relatively low power, combined with relatively large beam-developed drive, to obtain the correct level of bunching voltage and nearly correct phase.

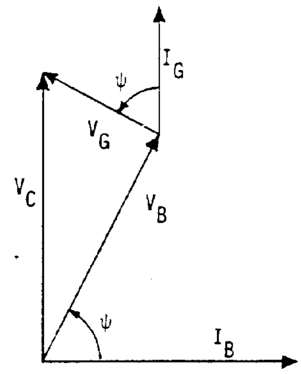


Fig. 5. Detuning technique used to obtain cavity voltage V_C perpendicular to beam current I_B and in phase with generator current I_G.

The use of this cavity-detuning technique was complicated by several problems. First, the available 3-4 kW of rf power was barely sufficient to produce correct bunching. Second, the bandwidth of the feedback control loop was only 40 kHz, primarily limited by the response of the buncher cavity. Finally, the electron gun initially displayed large drifts in both phase and amplitude, giving the microstructure excessive modulation content. Over the length of a macropulse (2000 micropulses, 100 µs), there was a gradual 40° change in phase and a 10% reduction in micropulse magnitude. The gun-correction circuit mentioned above greatly reduced the phase drifts, but even better stability was needed. To achieve lasing, system phase-coherence requirements are ±1°.

The method eventually used for more stable operation of the buncher system involved a variation of the cavity-detuning technique described above. The cavity was detuned as above so that most of the required bunching voltage was obtained from the very large beam-induced drive. The rf generator was then phased 90° with respect to the beam-driven voltage to accomplish two things: to bring the phase of the resulting cavity voltage close to the optimum bunching phase and to provide a mechanism to maintain this cavity phase in the presence of phase slippage by the beam-driven voltage component (Fig. 6). As the phase of V_B changed, V_G increased or decreased to maintain a constant phase for V_C.

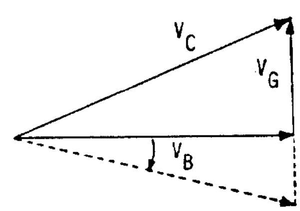


Fig. 6. Vector representation of generator voltage V_G compensating for phase drift in beam-induced voltage V_B.

This technique involved using phase information from a cavity pickup loop to control the amplitude of the rf generator voltage. A DBM was used to compare the phase of the signal from the cavity with the phase of the 108.33-MHz reference oscillator. The output of the DBM was a signal linearly proportional (within a range of ±30°) to the phase change in the cavity. This signal was the feedback signal for the buncher-amplifier amplitude controller. A block diagram of both the buncher and accelerator feedback loops is shown in Fig. 7. The circuits used for amplitude and phase control were the same as those used in the FMIT accelerator controllers.[4] Only the proportional (fixed-gain) part of the controllers was used for the buncher amplitude control because of the long filling time of the FEL buncher cavity (~20 µs).

With the feedback control scheme shown in Fig. 7, the phase of the buncher cavity was held to variations less than ±1°. Also, the operational setup and tuning procedure was simple because only the phase of the cavity voltage was controlled. Small variations in the cavity amplitude had a small effect compared to changes in the phase of the cavity field. The primary effect of amplitude fluctuations in the buncher was a slight reduction in the peak amplitude of the bunched current. Typical operation of the FEL subharmonic bunching system, with a 4-A gun current, required detuning the cavity by 65°. The operating frequency was then 30 kHz from the resonant frequency of the cavity.

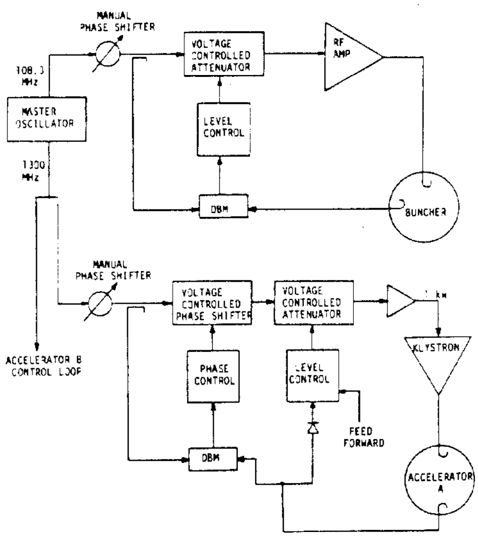


Fig. 7. Block diagram of buncher and accelerator feedback loops.

The Accelerators

Operation of the FEL is critically tied to the overlap between the optical micropulse and the electron micropulse in the optical cavity. This overlap is most easily changed by fluctuations in the phase or amplitude of the accelerator cavity fields. A phase change of 1° in the 1.3-GHz accelerator cavity fields can alter the optical output power by 30%. Similarly, an energy change in the electron beam also affects the optical power.[5] This sensitivity to energy fluctuations is related primarily to the 60° bending magnets that inject the electrons into the optical cavity. These bending magnets are nonisochronous; therefore, electrons of different energy have a different path length through the bends. Thus, an energy variation in the electron beam is converted to a change in arrival time of the electron micropulse, and the overlap of the electron and optical micropulses is adversely modified. For typical conditions, a 0.1% change in energy causes a 30% change in optical power.

For the reasons discussed above, we are striving to improve the phase and amplitude control of the accelerators. The "best" performance to date is less than 0.5% fluctuation in amplitude and less than 0.3° fluctuation in phase at 1.3 GHz. Two factors contributed to difficulties in further improving these controls. One factor was the long transit time of the feedback loop paths, which was over 400 ns and which restricted the feedback system bandwidth capability. The other factor was the heavy beam loading in the accelerators, particularly in the first accelerator.

Imperfect bunching before the accelerators and inadequate focusing of the beam (because of magnet heating problems) caused extremely high beam loading of the first accelerator. A large fraction of the accelerator power was absorbed by off-axis or incorrectly phased electrons. Measurements indicate that the first accelerator often ran with almost 50% beam loading: 30% from the accelerated portion of the beam and the remaining 20% from the off-axis and incorrectly phased beam. As a result, the first accelerator was always run with a minimum gain for feedback control and was very difficult to tune and control.

To reduce demands on the closed-loop amplitude controllers in both accelerators, a "feedforward" square pulse was used to bring the gradients to within a few per cent of the required level (Fig. 7). The feedback control was then switched to closed-loop operation (3 to 5 μs after the start of the feedforward pulse) to finalize and actively hold the proper accelerator gradient. To simplify the setup and operation of the feedback system, only integral control was used in the accelerator amplitude control loops. Phase control of the accelerators was accomplished using proportional and integral control. The phase and amplitude control loops for the accelerators had a bandwidth of approximately 70 kHz.

Improvements in the Feedback Control System

Enhanced operation of the FEL, which is planned for late 1985, will require a much improved feedback control system. Many upgrades in all system areas are now being made. The klystron/modulator tank assemblies are being moved much closer to the accelerators to reduce the loop transit time by a factor of 4 (to ~100 ns). Wider bandwidth, higher gain feedback circuits are being developed to ensure adequate control beyond the 200-kHz bandwidth. A stainless steel buncher is being installed that will reduce the filling time by a factor of 6.5 compared to the present copper buncher. A higher power amplifier (100 kW) for the buncher is being purchased that can provide the full bunching voltage. This amplifier will allow more control of the bunching process. A second buncher operating at the fundamental frequency (1.3 GHz) will be installed at the input to the accelerator. This buncher will "fine tune" the electron bunches and reject any off-axis or out-of-phase electrons before they enter the accelerator. This measure will reduce the accelerator beam loading and allow for more precise control of the accelerator fields. Finally, the electron gun will be modified to provide a steady, rather than pulsed, current over the length of the macropulse. Micropulse timing errors that are due to the electron gun will then disappear.

Acknowledgments

The authors wish to thank J. O. Hornkohl, C. M. Humphry, and J. R. Chavez who were responsible for the daily operation and maintenance of the FEL rf system.

References

1. B. E. Newnam, R. W. Warren, R. L. Sheffield, W. E. Stein, M. T. Lynch, J. S. Fraser, J. C. Goldstein, J. E. Sollid, T. A. Swann, J. M. Watson, and C. A. Brau. "Optical Performance of the Los Alamos Free-Electron Laser," submitted to IEEE J. Quantum Electron, special issue on free-electron lasers.
2. J. I. Smith, Modern Operational Circuit Design, (Wiley Interscience, New York, 1971), Chap. 12.
3. P. B. Wilson, "High Energy Electron Linacs," in Physics of High Energy Particle Accelerators, AIP Conf. Proc. No. 87-450, 492, 1982.
4. M. Fazio and R. Patton, "Prototype Phase and Amplitude Feedback Control Systems for the FMIT Accelerator," IEEE Trans. Nucl. Sci., 30 (4), 2253 (1983).
5. M. T. Lynch, R. W. Warren, and P. J. Tallerico, "The Effects of Linear Accelerator Noise on the Los Alamos Free-Electron Laser," submitted to IEEE J. Quantum Electron, special issue on free-electron lasers.