A REAL-TIME SAMPLING BEAM POSITION MONITOR*

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Introduction

The beam position monitor system described below was developed for use with the Los Alamos Meson Physics Facility linear accelerator. The system features operation over a wide dynamic range of peak beam current. It uses a small, easily-made position-sensing device on the beam line.

By using the rf structure of the beam, high gain D.C. amplifiers and their attendant drift problems are avoided. Yet, the system depends only on the relative amplitudes of the beam sensor signals and not on their phase difference. The bandwidth of the detector circuits is sufficiently wide that their temperature stability is not a problem.

By using a real-time sampling system beam position versus time may be determined for long pulses without long circuit time constants and expensive matched signal channels. The circuit is such that, by multiplexing the timing signals, much of the electronics can serve a number of position monitoring stations.

Theory of Operation

Magnetic Field of a Linac Beam

The magnetic field resulting from an rf current inside a conducting cylinder may be found by considering the corresponding magnetostatic problem, provided that the dimensions of the cylinder are small compared to the free space wavelength of the rf current. For the LAMPF linac, with a beam bunch rate 200 MHz, and the LASL Electron Prototype Accelerator (EPA), with a beam bunch rate 800 MHz, this criterion is quite easily met for the fundamental Fourier component of the beam.

For an infinitesimally thin line of current on the axis of an infinitely long right-circular cylinder of radius a, the field is just

$$\vec{B}_o = \frac{\mu_o i \vec{r}}{2\pi r^2} \; ; \; o < r \leq a. \qquad (1)$$

For a beam displaced from the center by r, the field at the wall is given by Eq. (1) modified by a geometric factor, $g(r,\theta)$.

$$\vec{B}(\vec{a}) = \vec{B}_o(\vec{a})\; g(r,\theta) \qquad (2)$$

This problem may be solved in a straigthforward manner by the method of images, placing an image current $-i$ at $r' = a^2/r$ and superimposing the fields. The field at $r' = a$ is found to be

$$\vec{B}(a,\theta) = \vec{B}_o(a) \frac{1 - r^2/a^2}{1 + r^2/a^2 - 2(r/a)\cos\theta} \qquad (3)$$

where θ is the angle between $\vec{r}$ and $\vec{a}$, the location of the beam and the observation point, respectively, (see Fig. 1).

Let x be the relative displacement in the direction of the observation point and y the relative displacement in the perpendicular direction. If $y = 0$, $g(x,\theta)$ becomes

$$g(x,\theta) = \frac{1 - x^2}{1 + x^2 - 2x\cos\theta} \; . \qquad (4)$$

For $\theta = 0$, Eq. (4) becomes

$$g(x,o) = \frac{1 - x^2}{(1 - x)^2} = \frac{1 + x}{1 - x} \qquad (5)$$

and for $\theta = \pi$, Eq. (4) becomes

$$g(x,\pi) = \frac{1 - x}{1 + x} \; . \qquad (6)$$

For $\theta = \pi/2$ or $3\pi/2$, Eq. (4) is just

$$g\left(x,\frac{\pi}{2}\right) = g\left(x,\frac{3\pi}{2}\right) = \frac{1 - x^2}{1 + x^2} \; . \qquad (7)$$

Determination of Beam Position

An approximate measure of the relative position of a beam may be had by subtracting the field at $\theta = \pi$ from the field at $\theta = 0$. The resultant is a current-dependent measure of position.

$$B(x,o) - B(x,\pi) = B_o\left[g(x,o) - g(x,\pi)\right]$$

$$= B_o \frac{4x}{1 - x^2} \qquad (8)$$

The relative y position may be similarly determined.

$$B\left(x,\frac{\pi}{2}\right) - B\left(x,\frac{3\pi}{2}\right) = B_o\left[g\left(x,\frac{\pi}{2}\right) - g\left(x,\frac{3\pi}{2}\right)\right] = 0 \qquad (9)$$

A current-independent position measurement may be had by subtracting the logarithms of the pairs of signals.

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$$\log B(x,0) - \log B(x,\pi) = \log \frac{B_o g(x,o)}{B_o g(x,\pi)} \tag{10}$$
$$= \log \left(\frac{1+x}{1-x}\right)^2 \cong 4x$$

Similarly, for the relative y position, we find

$$\log B\left(x,\frac{\pi}{2}\right) - \log B\left(x,\frac{3\pi}{2}\right) = 0 \ . \tag{11}$$

Errors in determining the position resulting from x - y coupling in $g(r,\theta)$, Eq. (4), and from the logarithmic approximation, Eq. (10), can be held to less than 5% of the beam displacement r, for $r < 0.4$.

Fig. 2 shows an idealized position monitor using identical coupling loops parallel to the beam axis to measure the time-varying field of the bunched beam.

Sensitivity of Beam Coupling Loop

The amplitude factor relating the induced emf to the field at the wall must take into account the velocity of the beam and the velocity of the wave induced on the loop. Fig. 3 illustrates the notation for this calculation.

The fundamental Fourier component of beam current results in a magnetic field near the wall:

$$B = B'\cos\,(\omega t - k_1 z) \ . \tag{12}$$

B' depends on the current and beam position as discussed previously. The emf induced in the portion of loop dz at z and time t is

$$dE = -\frac{d\phi}{dt} = B' b\omega \sin\,(\omega t - k_1 z)\ dz \tag{13}$$

where b is a geometrical factor taking into account the width of the loop and the variation of B across the loop. At z_o a forward-traveling wave arrives from z in $(z_o - z)/c$ seconds, and its reflection arrives inverted in $(z_o + z)/c$ seconds. Thus at the time t the sum of the forward and reflected waves is

$$dE_f + dE_r = B' b\omega\ dz \Big\{ \sin\left[\omega t - k_2 z_o - \left(k_1 - k_2\right)z\right] - \sin\left[\omega t - k_2 z_o - \left(k_1 + k_2\right)z\right] \Big\} \tag{14}$$

where $k_2 = \omega k$. Integrating along the loop, the emf at z_o is

$$E = B' b\omega \left\{ \frac{1}{k_1 - k_2} \cos\left[\omega t - k_2 z_o - \left(k_1 - k_2\right)z\right] - \frac{1}{k_1 + k_2} \cos\left[\omega t - k_2 z_o - \left(k_1 + k_2\right)z\right] \right\}_0^{z_o} . \tag{15}$$

Evaluating Eq. (15) at the limits of integration

$$E = B' b\omega \Bigg(\frac{1}{k_1 - k_2} \Big\{ \cos\left[\omega t - k_1 z_o\right] - \cos\left[\omega t - k_2 z_o\right] \Big\} - \frac{1}{k_1 + k_2} \Big\{ \cos\left[\omega t - \left(k_1 + 2k_2\right)z_o\right] - \cos\left(\omega t - k_2 z_o\right) \Big\} \Bigg) . \tag{16}$$

Rewriting Eq. (16)

$$E = 2B' b\omega \left\{ \left[\frac{1}{k_1 - k_2} \sin \frac{k_1 - k_2}{2}\right] \cdot \left[z_o \sin\left(\omega t - \frac{k_1 + k_2}{2} z_o\right)\right] - \left[\frac{1}{k_1 + k_2} \sin \frac{k_1 + k_2}{2}\right] \cdot \left[z_o \sin\left(\omega t - \frac{k_1 + 3k_2}{2} z_o\right)\right] \right\} . \tag{17}$$

This rather complicated expression has not yet been fully evaluated to determine what values of z_o as a function of β give a minimum output. However, for small β and $z_o = \beta\lambda/2$, it can be shown that

$$E \cong B' b\omega z_o \frac{4\beta}{\pi} \tag{18}$$

while for $\beta = 1$ and $z_o \ll \lambda$,

$$E \cong B' b\omega z_o . \tag{19}$$

Thus the sensitivity of a loop of length $\beta\lambda/2$ to a beam of $\beta < 1$ is reduced by a factor of approximately $4\beta/\pi$ relative to its sensitivity to a beam of $\beta = 1$.

Details of Circuit Design

Beam Position Sampling

The most direct scheme for deriving position information from the magnetic field of the beam, as illustrated in Fig. 2, is impractical because of the high cost of matched logarithmic detectors. Fig. 4 illustrates how, by real-time sampling, a single logarithmic detector can serve a set of position monitor loops, eliminating the need for matched logarithmic amplifiers.

Fig. 5 is a detailed block diagram of the beam position monitor electronics as used on the LASL EPA and planned for the LAMPF linac. The electronic loop selector consists of four rf mixers with a common output heterodyning the loop signal to a suitable intermediate frequency. The mixers are turned on sequentially by signals from the sampling time-base generator. The logarithmic detector is a logarithmic if amplifier of the progressive detection type. The de-multiplexer consists of a gated clamp, which stores the signal from one loop and subtracts it from the signal from the opposite loop, and a store-and-hold circuit which stores the difference (position) signal until a new sample has been made. Fig. 6 shows an extension of the above system to multiplex several position monitors into one set of electronics.

Monitor Loops

The monitor loops are a vacuum-tight assembly of four wire loops, parallel to the beam, 5 cm long and 1 cm wide, spaced at intervals of 90° in a cylinder of 5 cm radius, permitting reasonably accurate determination of position up to 2 cm deflection. The sensitivity of the loops is about 10 mv/ma for a high β beam.

Gated Mixers

The mixer circuit used at 805 MHz for the EPA beam position monitors is shown in Fig. 7. It is basically a simple diode mixer with tuned input, output, and local oscillator input circuits, modified to permit gating pulses to disable the mixing action.

A positive signal at the gate input back-biases the hot-carrier mixer diode reducing the if output by 40 to 50 db. A low-impedance zero voltage at the gate input allows the mixer to function normally with a conversion loss of 10 to 12 db.

The if outputs from four mixers, one for each loop of the position monitor (+x,-x,+y,-y), are summed in a grounded-base preamplifier and sent via a single coaxial cable to the logarithmic if amplifier.

The low-pass filter in the gate input circuit prevents noise spikes from the fast-rising gate pulses from getting into the if circuit.

An assembly of four mixer boards is shown in Fig. 8. The quarter-wave tuned lines for the input and local oscillator are plainly visible.

Logarithmic if Amplifier

The logarithmic if amplifier is shown in block diagram form in Fig. 8. The circuit, a modification of a commercially available unit, is a broad-band untuned amplifier of the progressive detection type. Each stage contributes to the sum line over a certain range of input signals until it saturates. The contribution of each stage may be adjusted to provide a logarithmic response within ±1 db or better over a 60 db dynamic range.

De-multiplexer

A simplified schematic of the de-multiplexer unit is shown in Fig. 10. The waveforms at the bottom of the figure follow the circuit through three cycles of determining the x and y positions. The signal into the de-multiplexer during time interval 1 is $\log \left| (ki)(1-x)/(1+x) \right|$ from the -x beam coupling loop. During this interval, switch S_1 is closed, allowing capacitor C_1 to charge up to the signal voltage. During time interval 2, S_1 is open, and the input amplifier sees the difference between the second signal, $\log \left| (ki)(1+x)/(1-x) \right|$ from the +x loop. During this time interval, switch S_2 has been closed, charging capacitor C_2 in proportion to the x-displacement of the beam. Switch 2 then opens and remains open until the cycle is repeated, storing the x-position signal in C_2 until it is re-determined, and providing a relatively smooth output for the A/D converter. An identical circuit with different timing signals processes the y-position signal. An additional circuit, a low-pass filter, effectively time averages the multiplexed signal from the log amp, giving an output proportional to the logarithm of the beam current.

Time Base Generator

The time base generator uses RTL integrated circuits to generate the sequences of sampling pulses during the beam on gate. The circuit has a self-completing feature to guarantee an integral number of sampling cycles during a beam pulse and to assure that the sampling cycle starts at the same place each beam pulse.

Each mixer is on for 5 µsec. Thus it takes 20 µsec to complete a cycle of position measurements. Approximately 25 position samples can be taken during a beam pulse, adequate for a video display of the position envelope.

Operational Tests

The beam position monitor system described above has been bench-tested using an rf current or a wire to simulate the beam, and one unit has been tried out on the 1.5 MeV beam from Model M, the EPA injector.

Results of bench testing indicate that the system has no gross non-linearities or x - y coupling. It is necessary to adjust the sensitivity of the mixers in order that the electrical center of the monitor coincides with its mechanical center. It is also necessary to adjust the operating point of the mixer diodes so that the mixer sensitivities track over the operating range.

The system has been made reasonably independent of current over the range of 0.3 to 30 ma; larger currents could not be simulated with our test apparatus. The variation in indicated position with current can be made less than 1 mm over the range of currents tested. The beam can be returned to the electrical center of the monitor loop assembly to within 0.5 mm for a fixed current over the range of currents tested. Large deflections at small currents are somewhat less accurate because the -x signal is below the dynamic range of the log amplifier.

Tests with the EPA beam revealed no problems that had not been anticipated. Some means of matching the coupling loops before installing the monitor loop assembly on the accelerator must be devised. It would be useful to align more carefully the loop assembly with the steering magnets to facilitate adjusting the beam position.

No noise problems were noted, even when the 1.25 Mw klystron for EPA was operating. The sensitivity of the monitor loops seems to be about what was calculated; no exact measurement has been made.

Figs. 11, 12 and 13 illustrate typical beam position monitor signals. In each figure, the upper trace is from a toroidal beam current monitor. The second and third traces are the outputs of the gated clamps for the x and y positions respectively. These traces represent a position sensitivity of about 7 mm/cm. The lower trace is the output of the log if amplifier. Note that the first -x sample is missing because of the slow risetime of the beam current. This leads to an error in the first x-position sample. The output of the store-and-hold circuit is not shown in the pictures.

Fig. 11 indicates a centered beam of 5 ma. Fig. 12 shows the same beam displaced in the -x direction. Note the slight loss of beam current apparent from the upper trace. Fig. 13 shows the beam displaced in the -y direction.

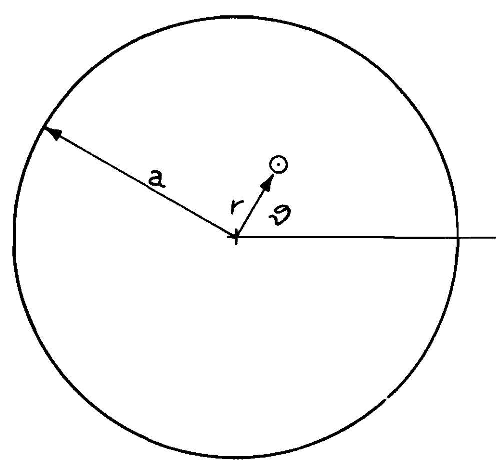

Figure 1. Beam Displaced from Center of Beam Pipe

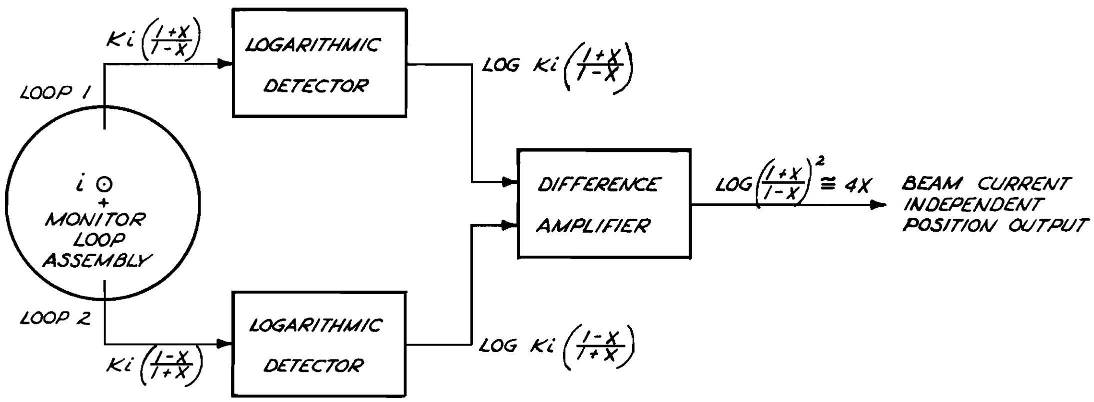

Figure 2. Basic Principle of Beam Position Monitor System

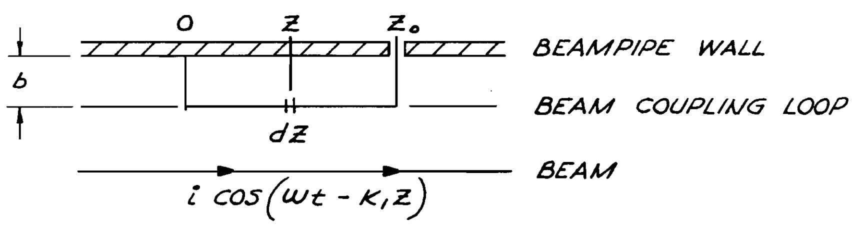

Figure 3. Emf Induced by Beam in a Loop

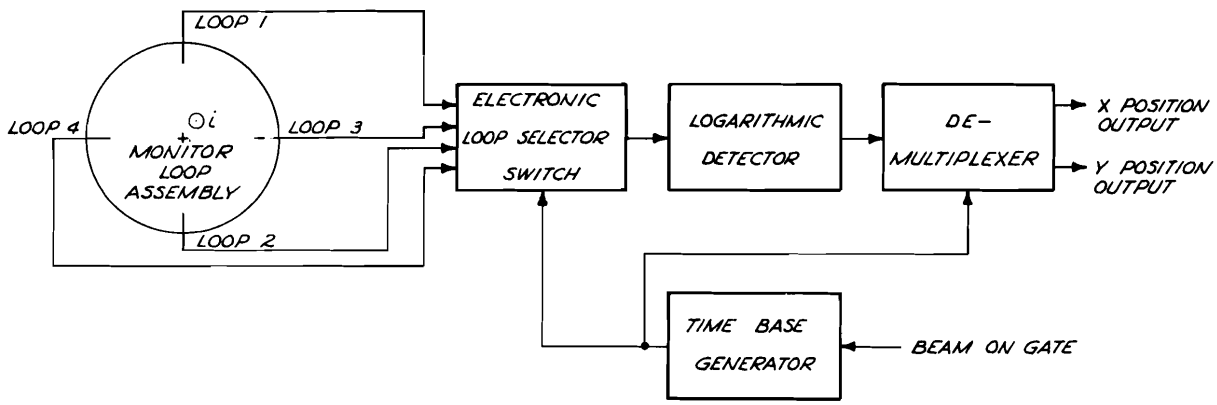

Figure 4. Modified Basic Beam Position Monitor System

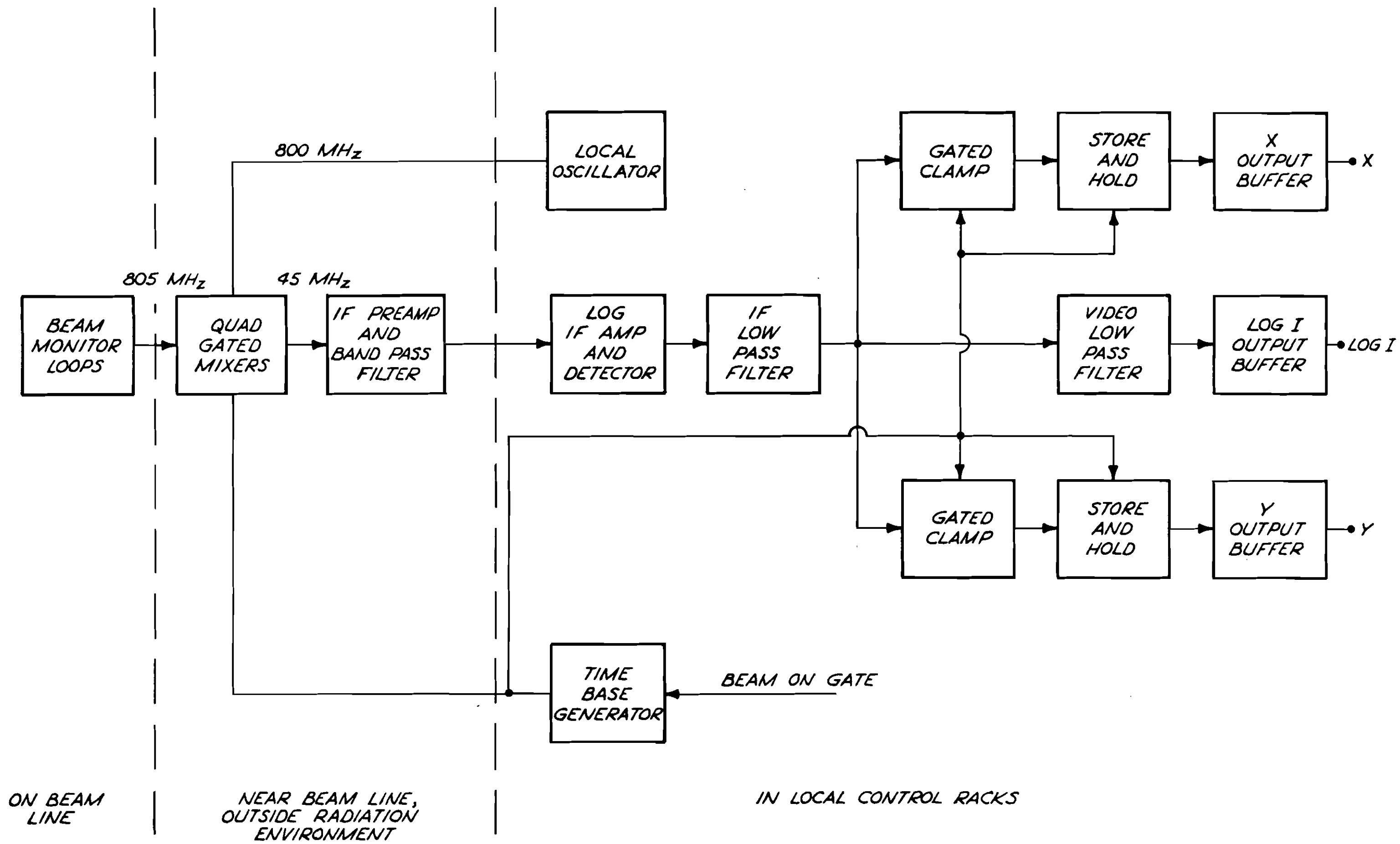

Figure 5. A Practical Beam Position Monitor System

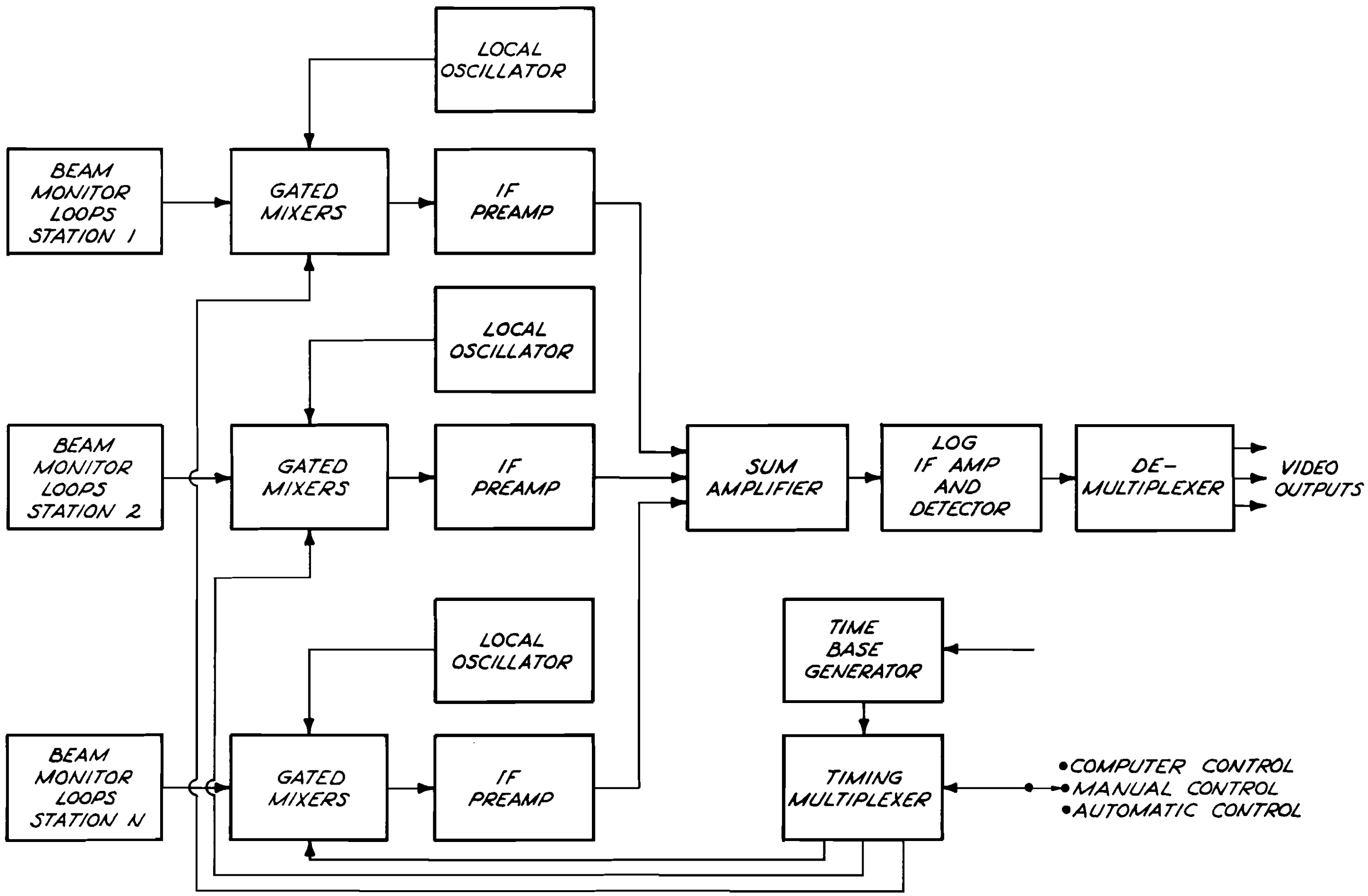

Figure 6. Practical System with Multiplexing Added

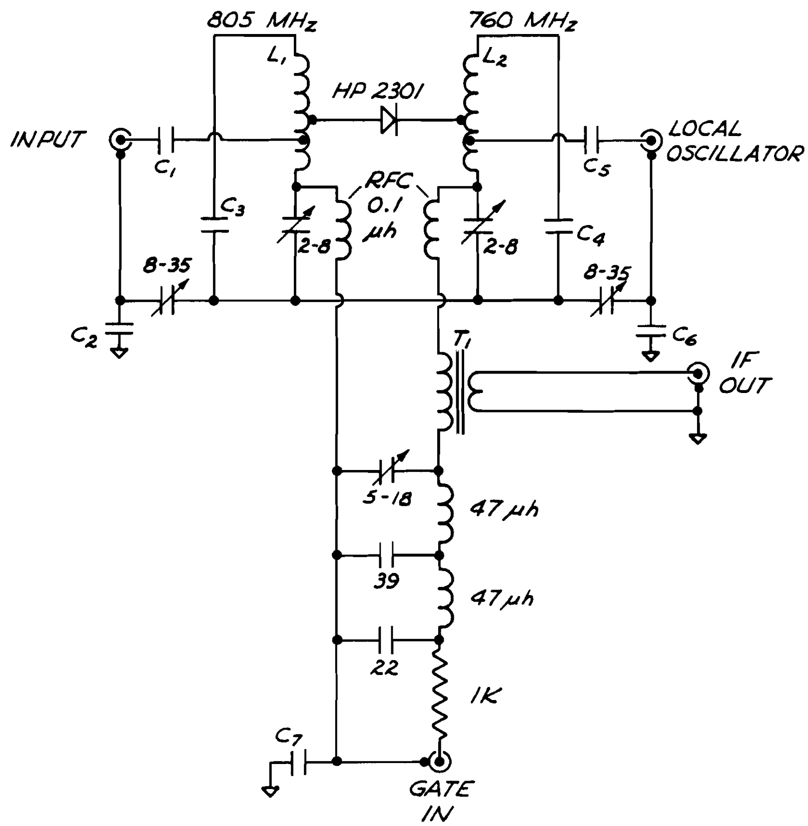

Figure 7. Schematic of 805 MHz Gated Mixer

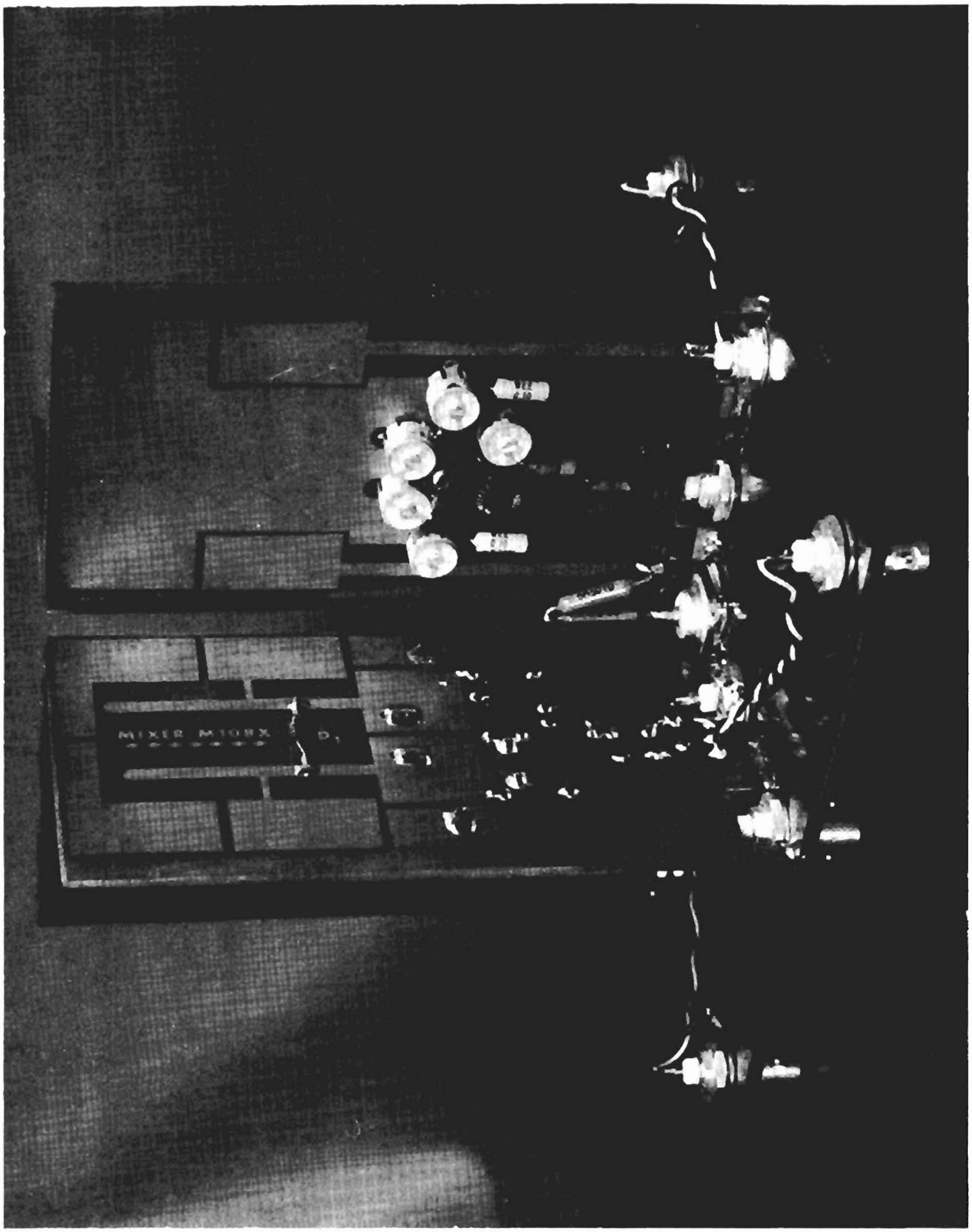

Figure 8. Assembly of Four Gated Mixers

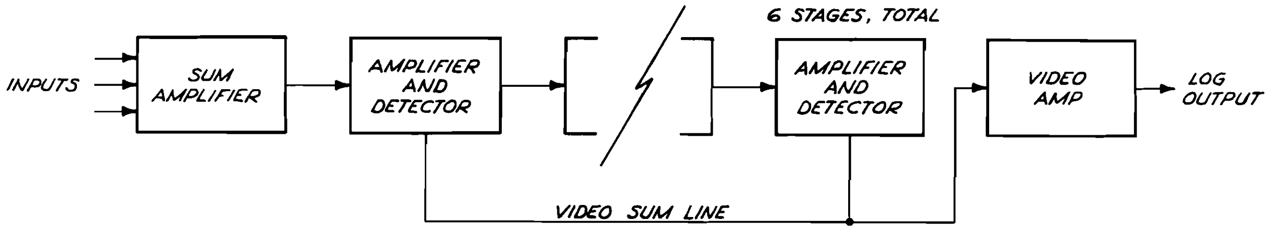

Figure 9. Logarithmic if Amplifier of Progressive Detection Type

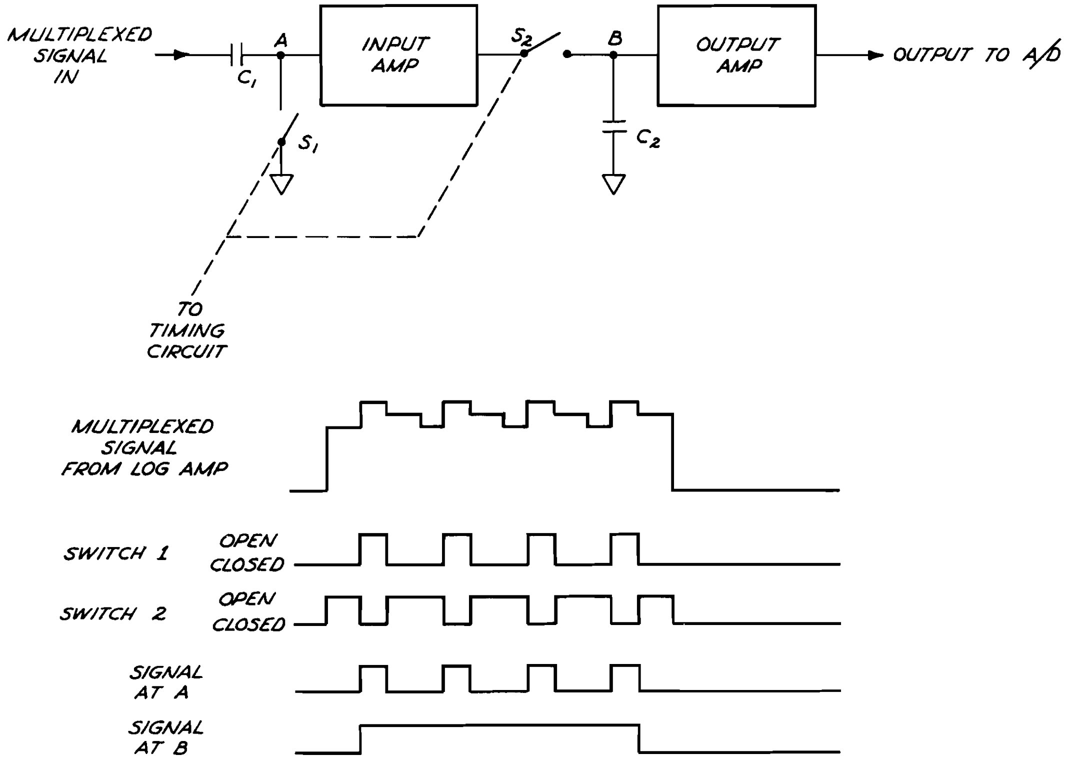

Figure 10. Simplified Diagram of the De-multiplexing Circuit

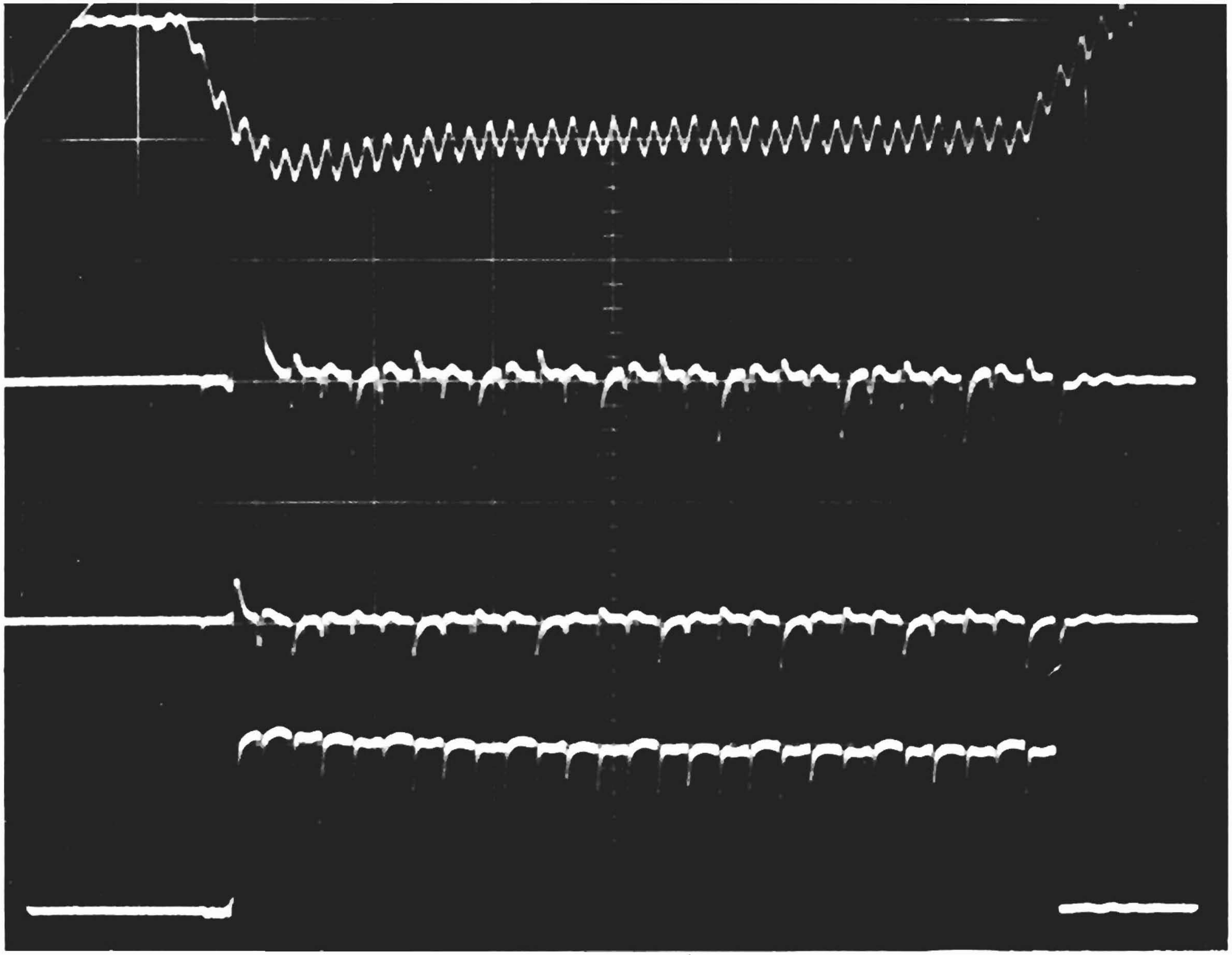

Figure 11. Signals From a Centered Beam (see text)

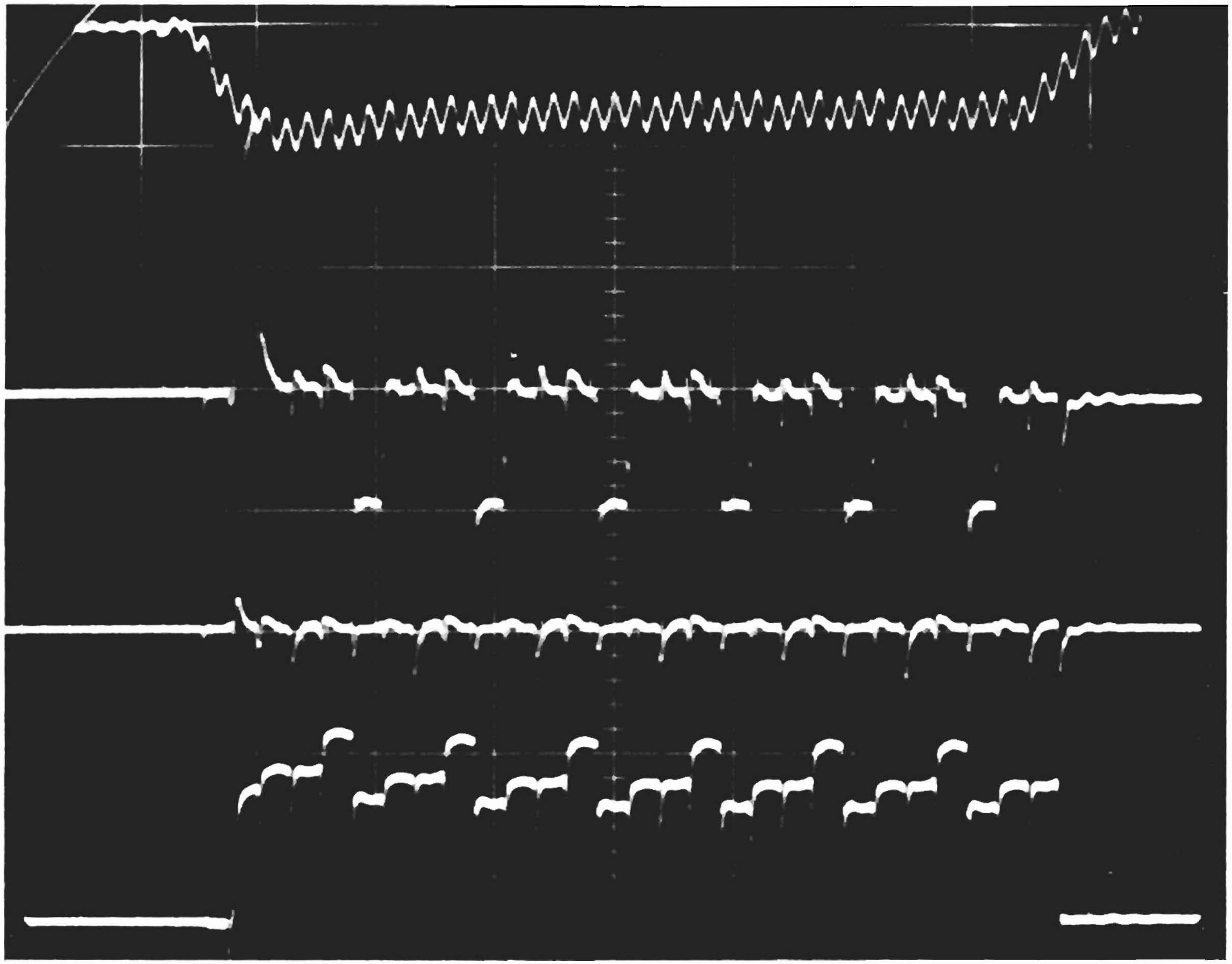

Figure 12. Beam Displaced in -x Direction

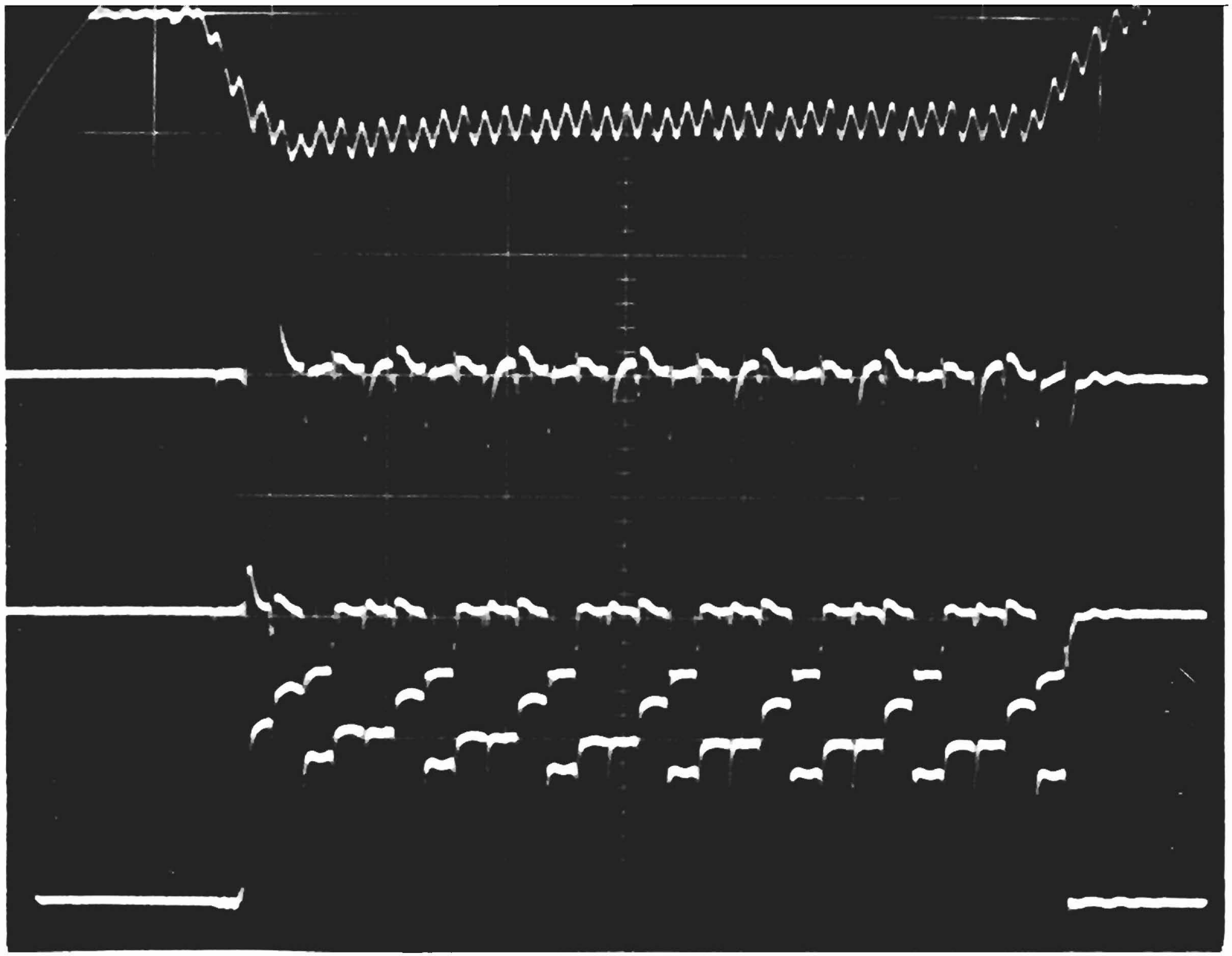

Figure 13. Beam Displaced in -y Direction